FREQUENCY & DUTY CYCLE CONTROL CONSIDERATIONS FOR SOFT-SWITHING BUCK CHOPPER

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ABSTRACT

This paper presents considerations on the switching frequency and duty cycle & operating equations of soft-switching BUCK chopper. These considerations are discussed and applied to selected soft-switching families such as *ZVS-QRC, ZCS-QRC, ZVS-QSW-CV, ZCS-QSW-CC, ZVT-PWM* and *ZCT-PWM* [1]. The limitations on switching frequency and duty cycle are derived in terms of: chopper input voltage (V_g), chopper output current (I_F), Resonant elements values including (C_r, L_r), Voltage and current of filter capacitor and reactor or initial values of capacitor and reactor respectively (V_I, I_I).

I. INTRODUCTION

With the beginning of this millennium, computers, telecommunication and internet find growing interest in all areas of our society (industry, politics, media, press, public) and there is no doubt that the information technology (IT) is a main key for economic growth in the future. However, the availability of energy and its quality is an important condition for any growth. In the public mind this aspect is sometimes neglected so that energy seems always available, just as a subject of trade and tax. The generation and transport of energy, however, is a challenging task now and in the future. Saving energy can partly solve it. Minimizing the losses during transmission and conversion of electrical power presents one way of saving energy. This can be best realized by power electronics [2], which is a recognized technology for a large power range. High efficient power conversion is not only important for large consumers but also for small ones if the number of devices is very high, which is the case for most electronic consumers. As an example the stand by mode of video recorders and computers can be mentioned where millions of systems are involved. In the lower power range (up to 1kW), which also covers the power, demand of most IT products, switched mode power supplies SMPS can be used for converting and conditioning electrical power efficiently [3, 5]. Applying the soft switching circuits to reduce the semiconductor switch losses is an efficient solution. In this paper, it will be shown that there is a trade off between minimizing the losses and full control of switching duty cycle for a chosen switching frequency.

II. CONTROL STRATEGIES OF CHOPPERS

The chopper configurations shown in fig 1 operate from a fixed dc input voltage V_g. The average value of the output voltage $I_F.R$ is controlled by periodic opening and closing of the switches where R is the load resistance. The various control strategies for operating the switches are :

1) *Pulse Width Modulation (PWM),*
2) *Constant Pulse Width, Variable Frequency*,
3) *Current Limit Control*,
4) *Variable Pulse Width and Frequency.*

In the all cases the frequency or duty cycle or both of them may be varied to obtain a particular value of determined T_{on}/T. [4] Using above mentioned control strategies, operation equations carried out in the next section.

III. OPERATION EQUATIONS

If we desire to have the advantageous of the soft switching together with the mentioned control strategies we should consider some constraints between circuit elements and variables and also take some limits on frequency and duty cycle of switching into account. These limits and constraints are in terms of V_g, I_F, C_r, L_r, V_I, I_I. Also for the simplicity of analysis we will assume that the output current is ripple free and we can simulate it as a current source I_F.

A. Quasi-Resonant-Converter Cells

The structure of this type of soft switching cells is illustrated in figs. 1(a)-(b), and the waveforms of the voltage and current of the resonance elements and duty cycle of switch S and diode D_s are presented in figs. 2 (a)-(b) respectively.

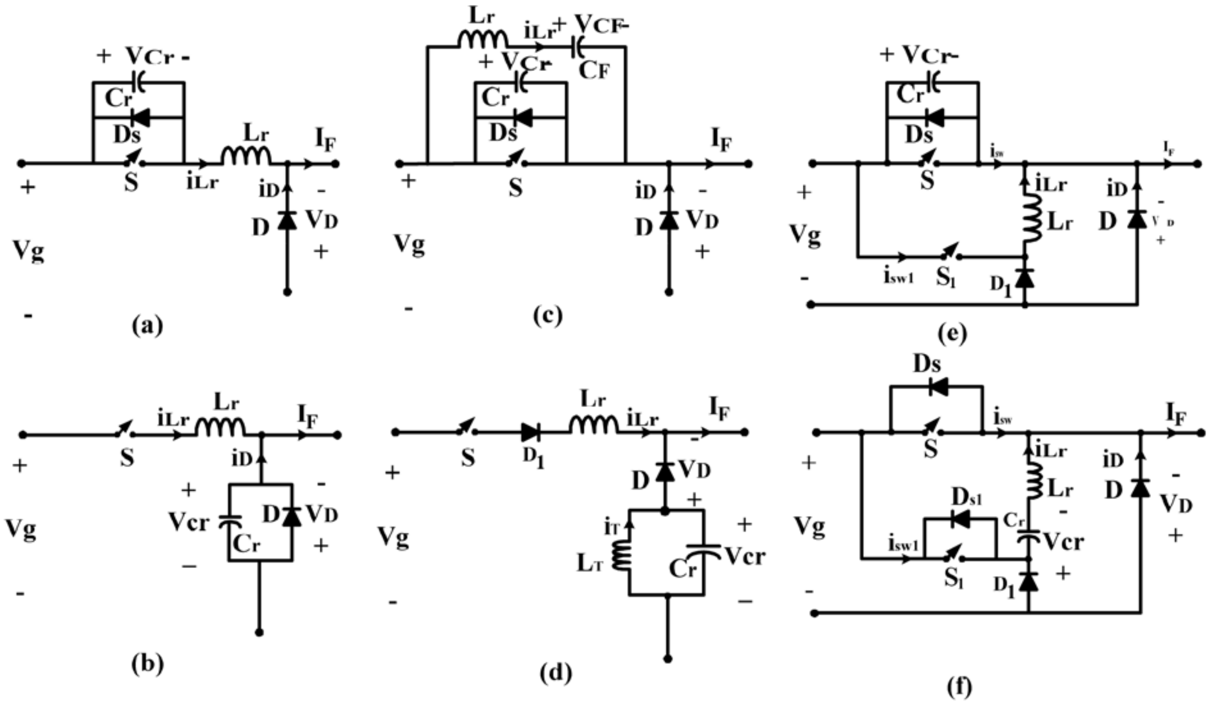

Figure 1. Switching cells (a) ZVS-QRC, (b) ZCS-QRC, (c) ZVS-QSW-CV, (d) ZCS-QSW-CC, (e) ZVT-PWM, (f) ZCT-PWM.

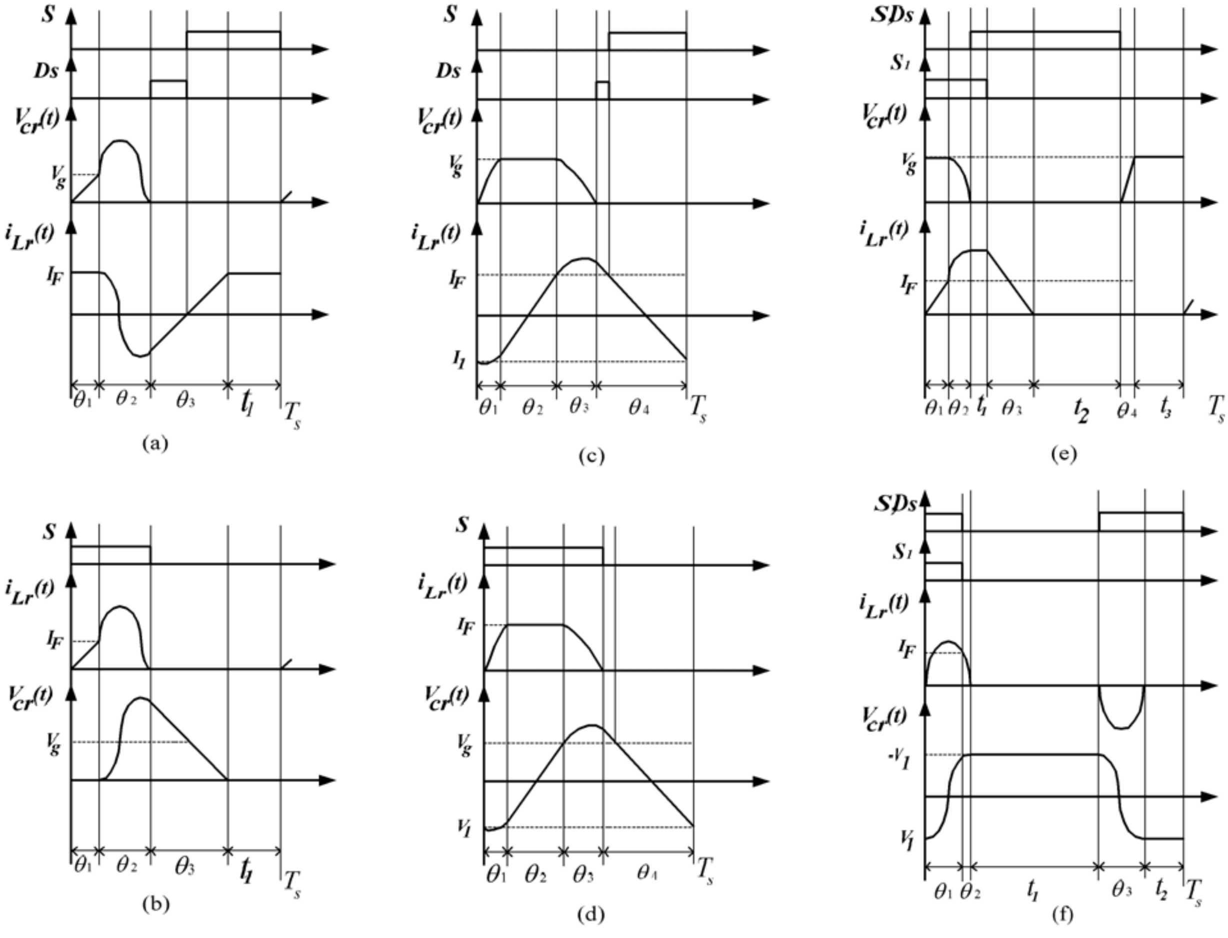

Figure 2. Switching cells resonant components voltage, current waveforms and T_s & D (a) ZVS-QRC, (b) ZCS-QRC, (c) ZVS-QSW-CV, (d) ZCS-QSW-CC, (e) ZVT-PWM, (f) ZCT-PWM.

A.1. QRC-ZVS

For the QRC-ZVS as shown in fig. 2(a) there is only one degree of freedom $\boldsymbol{t_1}$, to control the $\boldsymbol{T_s}$, $\boldsymbol{D}$. (In this paper $\boldsymbol{D}$ is defined as duty cycle of switch $\boldsymbol{S}$ and diode $\boldsymbol{D_s}$).

$$\boldsymbol{T_s} = (\theta_1+\theta_2+\theta_3+\boldsymbol{t_1}) \tag{1}$$

Thus the maximum switching frequency, $(\boldsymbol{f_s})_{\boldsymbol{max}}$ is achieved by setting $\boldsymbol{t_1}=0$, or:

$$(\boldsymbol{f_s})_{\boldsymbol{max}} = 1/(\theta_1+\theta_2+\theta_3) \tag{2}$$

And for any chosen value of $\boldsymbol{f_s}$ where: $\boldsymbol{f_s} \leq (\boldsymbol{f_s})_{\boldsymbol{max}}$:

$$\boldsymbol{D} = 1-(\theta_1+\theta_2)\boldsymbol{f_s} \tag{3}$$

A.2. QRC-ZCS

Also for the QRC-ZCS as shown in fig. 2(b) there is one degree of freedom $\boldsymbol{t_1}$, to control the $\boldsymbol{T_s}$, $\boldsymbol{D}$.

$$\boldsymbol{T_s} = (\theta_1+\theta_2+\theta_3+\boldsymbol{t_1}) \tag{4}$$

Thus the maximum switching frequency, $(\boldsymbol{f_s})_{\boldsymbol{max}}$ is achieved by setting $\boldsymbol{t_1}=0$, or:

$$(\boldsymbol{f_s})_{\boldsymbol{max}} = 1/(\theta_1+\theta_2+\theta_3) \tag{5}$$

And for any chosen value of $\boldsymbol{f_s}$ where: $\boldsymbol{f_s} \leq (\boldsymbol{f_s})_{\boldsymbol{max}}$:

$$\boldsymbol{D} = (\theta_1+\theta_2)\boldsymbol{f_s} \tag{6}$$

Where:

Table 1. Quasi-Resonant converter

	QRC-ZVS	QRC-ZCS
θ_1	$C_r \frac{V_g}{I_F}$	$L_r \frac{I_F}{V_g}$
θ_2	$\sqrt{L_r.C_r}(\pi+\sin^{-1}(\frac{V_g}{I_F}\sqrt{\frac{C_r}{L_r}}))$	$\sqrt{L_r.C_r}(\pi+\sin^{-1}(\frac{I_F}{V_g}\sqrt{\frac{L_r}{C_r}}))$
θ_3	$L_r\frac{I_F}{V_g}+\sqrt{(L_r\frac{I_F}{V_g})^2-L_r.C_r}$	$C_r\frac{V_g}{I_F}+\sqrt{(C_r\frac{V_g}{I_F})^2-L_r.C_r}$

Moreover to the above conditions we must satisfy the followings in order to have soft switching conditions:

For the *ZVS-QRC*:

$$I_F.\sqrt{\frac{L_r}{C_r}} \geq V_g \tag{7}$$

For the *ZCS-QRC*:

$$V_g.\sqrt{\frac{C_r}{L_r}} \geq I_F \tag{8}$$

B. Quasi-Square-Wave Cells

The topologies of this type of soft switching cells are illustrated in figs. 1(c)-(d), and the waveforms of the voltage and current of the resonance elements and duty cycle of switch $\boldsymbol{S}$ and diode $\boldsymbol{D_s}$ are presented in figs. 2 (c)-(d) respectively. In the QSW family, for any chosen circuit and initial state ($\boldsymbol{V_1}$, $\boldsymbol{I_1}$), there is a unique $\boldsymbol{f_s}$ and $\boldsymbol{D}$ that is equal to the specified values:

$$\boldsymbol{f_s} = 1/(\theta_1+\theta_2+\theta_3+\theta_4) \tag{9}$$

For the *QSW-ZVS-CV:*

$$\boldsymbol{D} = (\theta_4)\boldsymbol{f_s} \tag{10}$$

For the *QSW-ZCS-CC:*

$$\boldsymbol{D} = 1-(\theta_4)\boldsymbol{f_s} \tag{11}$$

Where:

Table 2. ZVS Quasi-Square-Wave Clamped-Voltage

θ_1	$\sqrt{L_r.C_r}(\pi+\tan^{-1}(\frac{I_1-I_F}{V_1}\sqrt{\frac{L_r}{C_r}}))-\cos^{-1}(\frac{V_g-V_1}{\sqrt{(I_1-I_F)^2\frac{L_r}{C_r}+V_1^2}})$
θ_2	$L_r.\frac{\sqrt{(I_F-I_1)^2+\frac{C_r}{L_r}(2V_1V_g-V_g^2)}}{V_g-V_1}$
θ_3	$\sqrt{L_r.C_r}\cos^{-1}(\frac{V_1}{V_1-V_g})$
θ_4	$\frac{(I_F-I_1)L_r+\sqrt{C_rL_r.(V_g^2-2V_1V_g)}}{V_1}$

Table 3. ZCS Quasi-Square-Wave Clamped-Current

θ_1	$\sqrt{L_r.C_r}(\pi+\tan^{-1}(\frac{V_g-V_1}{I_1-I_F}\sqrt{\frac{C_r}{L_r}})-\cos^{-1}(\frac{I_1}{\sqrt{(V_g-V_1)^2\frac{C_r}{L_r}+(I_1-I_F)^2}}))$
θ_2	$C_r.\frac{\sqrt{(V_g-V_1)^2+\frac{L_r}{C_r}(I_F^2-2I_1I_F)}}{I_1}$
θ_3	$\sqrt{L_r.C_r}\cos^{-1}(\frac{I_1-I_F}{I_1})$
θ_4	$\frac{V_1-V_g}{I_1-I_F}.C_r+\sqrt{L_rC_r.(\frac{2I_1I_F-I_F^2}{(I_1-I_F)^2})}$

In order to have soft switching condition we must hold the following conditions:

For the *ZVS-QSW-CV*:

$$(I_F-I_1)^2\frac{L_r}{C_r}+V_1^2 \geq (V_g-V_1)^2 \tag{12}$$

$$V_g \geq 2V_1 \tag{13}$$

Where I_1 is the initial current of L_r , V_1 is the voltage of the filter capacitor C_F . $I_1<0$ and $V_1>0$

For the *ZCS-QSW-CC*:

$$(V_1-V_g)^2\frac{C_r}{L_r}+(I_1-I_F)^2 \geq I_1^2 \tag{14}$$

$$2I_1 \geq I_F \tag{15}$$

Where V_1 is the initial voltage of C_r and I_1 is the current of the filter inductor L_T . $V_1<0$ and $I_1>0$

C. Transition PWM Cells

The structure of this type of soft switching cells is illustrated in figs. 1(e)-(f), and the waveforms of the voltage and current of the resonance elements and duty cycle of switch $\boldsymbol{S}$ and diode $\boldsymbol{D_s}$ are presented in figs. 2 (e)-(f) respectively.

C.1. ZVT-PWM

For the ZVT-PWM as shown in fig. 2(e) there is three degree of freedom $\boldsymbol{t_1}, \boldsymbol{t_2}, \boldsymbol{t_3}$, to control the $\boldsymbol{T_s}$, $\boldsymbol{D}$.

$$T_s = (\theta_1 + \theta_2 + \theta_3 + \theta_4 + t_1 + t_2 + t_3) \tag{16}$$

Thus the maximum switching frequency, $(f_s)_{max}$ is achieved by setting $t_1=0$, $t_2=0$, $t_3=0$, thus:

$$(f_s)_{max} = 1/(\theta_1 + \theta_2 + \theta_3 + \theta_4) \tag{17}$$

And for any chosen value of f_s where: $f_s \leq (f_s)_{max}$:

$$D = 1 - (\theta_1 + \theta_2 + \theta_4 + t_3) f_s \tag{18}$$

Or

$$D = (t_1 + \theta_3 + t_2) f_s \tag{19}$$

C.2. ZCT-PWM

For the ZCT-PWM as shown in fig. 2(f) there is two degree of freedom $\boldsymbol{t_1}, \boldsymbol{t_2}$, to control the $\boldsymbol{T_s}$, $\boldsymbol{D}$.

$$T_s = (\theta_1 + \theta_2 + \theta_3 + t_1 + t_2) \tag{20}$$

Thus the maximum switching frequency, $(f_s)_{max}$ is achieved by setting $t_1=0$, $t_2=0$, thus:

$$(f_s)_{max} = 1/(\theta_1 + \theta_2 + \theta_3) \tag{21}$$

And for any chosen value of f_s where: $f_s \leq (f_s)_{max}$:

$$D = 1 - (\theta_2 + t_1) f_s \tag{22}$$

Or

$$D = (\theta_1 + \theta_3 + t_2) f_s \tag{23}$$

Where

Table 4. Transition Pulse-Width-Modulation cells

	ZVT-PWM	*ZCT-PWM*
θ_1	$L_r \frac{I_F}{V_g}$	$\sqrt{L_r.C_r}(\pi - \sin^{-1}(-\frac{I_F}{V_1}\sqrt{\frac{L_r}{C_r}}))$
θ_2	$\sqrt{L_r.C_r}(\frac{\pi}{2})$	$\sqrt{L_r.C_r}(\sin^{-1}(-\frac{I_F}{V_1}\sqrt{\frac{L_r}{C_r}}))$
θ_3	$L_r \frac{I_F}{V_g} + \sqrt{L_r.C_r}$	$\pi\sqrt{L_r.C_r}$
θ_4	$C_r \frac{V_g}{I_F}$	-

The V_1 is the initial voltage and also the peak voltage of the C_r in the ZCT circuit. $V_1<0$

For the PWM soft-switching family there is no more constraints between $\boldsymbol{V_g}$, $\boldsymbol{I_F}$, $\boldsymbol{C_r}$, $\boldsymbol{L_r}$ and $\boldsymbol{V_1}$ in order to have soft switching condition.

IV. COMPARISON AND DISCUSSION

In the QRC and QSW families the duty ratio $\boldsymbol{D}$ is a function of any chosen value for $\boldsymbol{f_s}$. But for the Transition PWM cells there is a maximum and minimum for $\boldsymbol{D}$, for any chosen value of $\boldsymbol{f_s}$. For the ZVT-PWM cell the maximum $\boldsymbol{D}$ can be achieved by setting $t_3=0$ and increasing $\boldsymbol{t_1}$ and $\boldsymbol{t_2}$ and the minimum $\boldsymbol{D}$ can be achieved by setting $t_1=0$, $t_2=0$ and increasing $\boldsymbol{t_3}$. For the ZCT-PWM cell the maximum $\boldsymbol{D}$ is achieved by setting $t_1=0$ and increasing $\boldsymbol{t_2}$ and the minimum $\boldsymbol{D}$ is achieved by setting $t_2=0$ and increasing $\boldsymbol{t_1}$.

Table 5. : f_s & $\boldsymbol{D}$ limits for the Transition PWM cells

	ZVT-PWM	ZCT-PWM
$f_{s,max}$	$1/(\theta_1+\theta_2+\theta_3+\theta_4)$	$1/(\theta_1+\theta_2+\theta_3)$
$f_{s,min}$	0	0
D_{max}	$1-(\theta_1+\theta_2+\theta_4)f_s$	$1-(\theta_2)f_s$
D_{min}	$(\theta_3)f_s$	$(\theta_1+\theta_3)f_s$

V. CONCLUSION

A complete analysis has been done on the three families of soft switching Buck Chopper cells. And some conditions were developed to guarantee the zero voltage or zero current switching of the cells. Also it has been shown that for the QRC and QSW family cells, in order to have a desired value of $\boldsymbol{D}$, we must vary the $\boldsymbol{f_s}$. *(**D** and **f** are not independent from each other).* Also in the QSW family cells, in order to change the $\boldsymbol{f_s}$, we have to vary the initial state of circuit ($\boldsymbol{V_1}$, $\boldsymbol{I_1}$), but we have a unique $\boldsymbol{f_s}$ and $\boldsymbol{D}$ for any specific initial values, $\boldsymbol{V_1}$ & $\boldsymbol{I_1}$. And in the Transition PWM family cells, for any chosen value of switching frequency $\boldsymbol{f_s}$, we can achieve to a limited range of $\boldsymbol{D}$ that is between $\boldsymbol{D_{min}}$ and $\boldsymbol{D_{max}}$, but we cannot fully control the $\boldsymbol{D}$ between 0 and 1.

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