MODES OF CURRENT CONDUCTION IN 2-PULSE PWM AC/DC CONVERTER

M. U. Agu,

Member NSE & IEEE
Department of Electrical Engineering
University of Nigeria, Nsukka

ABSTRACT

The paper reports the result 0f a study on the load current conduction modes in the one phase two-pulse PWM AC/DC converter. The various load current conduction modes are identified by the signs of the instantaneous load current values at selected load voltage discontinuity points under an assumed continuous load current operation over relevant ranges of the modulation index. From the derived load current conduction equations, boundary curves are plotted to illustrate the converter current conduction characteristics that help predict converter performance under given modulation index and load conditions. This work provides first hand information on current conduction modes in the single pulse modulation of the one phase full bridge converter and the analysis approach used provides more detailed information on load current conduction than the approach adopted in (2, 3, *4) for the phase controlled converter*.

Key words*: AC/DC converter, pulse width modulation, current conduction modes.*

1. INTRODUCTION

Current conduction modes in the line-commutated phase controlled AC/DC converters have been extensively studied and reported [1, 2, 3, 4]. But the same study has yet to be reported for the pulse width modulated (PWM) *AC/DC* converter [3,4] which has been shown to have much better ac input power factor than the *AC/DC* converter controlled by any of the phase angle control techniques. Furthermore, improved power semiconductor device fabrication technology has resulted in the easy availability of power semiconductor devices (such as the MOSFET, MCT, IGBT) that have lower gate drive power requirements and faster speed than the conventional silicon controlled rectifiers that are most often used for phase control. This has made the PWM ac/dc converter very attractive for high performance applications requiring controlled dc output from an ac input source [5, 6, 7, 8]. In this paper the current conduction modes in the one phase full bridge 2-pulse *AC/DC* converter, operating in both the rectification and the inversion regions, are presented. The identification of the current conduction modes is carried out by determining the instantaneous converter output current values at points of the converter output voltage discontinuity under an assumed condition of continuous load current. The sign of these instantaneous current values is then used to identify the current conduction mode for specified converter load and modulation index. This method of identification provides a more detailed information about the load current than the method adopted in [1, 2, 3] because the load current values at points of load voltage discontinuity can additionally be determined from the derived equations.

2. CONVERTER POWER CIRCUIT AND PWM CONTROL

Figures 1a and 1b show illustrative forms of the *AC/DC* one phase full bridge converter which can be controlled by pulse width modulation. The converter input voltage V_s, is a sinusoid (V_m sint) while the converter output voltage is designated V_o. In Fig. la, only self commutated unidirectional bipolar gate insulated transistors (IGBTs) are used as the converter semiconductor switches while the switches in Fig. 2b are a combination of line commutated high speed thyristors and IGBTs. The converter output load is generalized as a series combination of a resistance, R, an inductance, L and a load emf E_c.

Fig. 2a and 2b show the method of generating the PWM control signals for one voltage/current modulated pulse output per half cycle of the ac input supply frequency for the operation of the circuits of Fig.2 in both the rectification and the inversion regions. The reference signal is a dc signal V_r while the carrier signal is a triangular waveform V_c with amplitude V_{cm} .The angular length of the gate drive signals, v_{g2} and v_{g4}, for the lower switches, T_2 and T_4, are fixed at radians and are alternatively high for half the period of the ac input supply. On the other hand, the on and off duration of gate drive signals, v_{gl} and V_{g3} , for the upper converter switches, T_1 and T_3 , are determined by the points of intersection of the reference dc signal, V_r ,and the triangular signal, V_c In the half cycle (of the ac supply frequency) where v_{g2} is high, v_{gl} is high only if $V_c < V_r$ and in the half cycle where v_{g2} is low, v_{gl} is high only if $V_c > V_r$.The same can be said of v_{g4} and v_{g3}.

The modulation index, M, is defined as the ratio of the reference dc signal V_r to the amplitude V_{cm} of the triangular carrier signal V_c.

$$M = V_r/V_{cm}, 0 \leq M \leq 1 \qquad (1)$$

In most applications, V_{cm} is kept constant while V_r is varied in the range of zero to V_{cm} in order to vary M from zero to unity. For convenience in the analysis that follows, the switching angle β is defined as

$$\beta = (1 - M)\pi/2, \qquad 0 \leq \beta \leq \pi/2 \qquad (2)$$

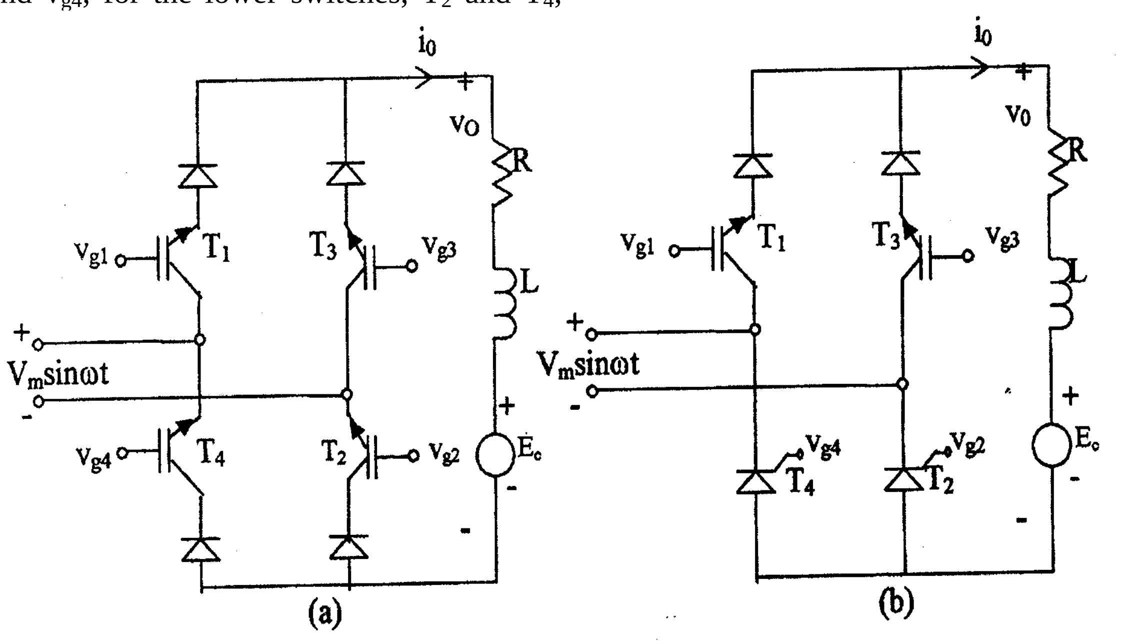


Fig. 1 Illustrative forms of the PWM AC/DC Converter

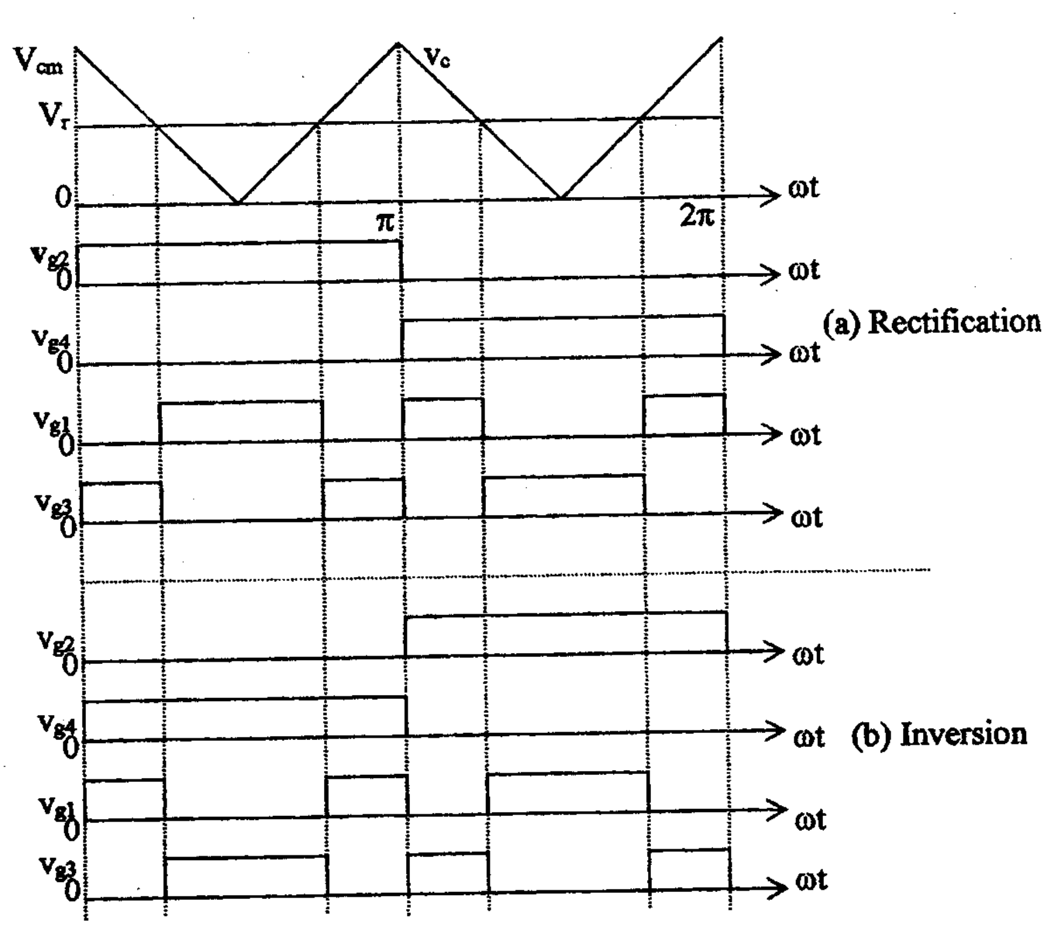


Fig. 2: PWM Gating Signals for the AC/DC Converter of Fig. 1.

3.MODES OF LOAD CURRENT CONDUCTION

During converter operation, the load current can be continuous or discontinuous. The types or modes of continuous and discontinuous load current operation are mainly determined, for a given ac input supply voltage, by the load parameters and the switching angle β. The major load factors on the load current mode are the load power factor angle ϕ and the ratio m (-1 ≤ 1) of the load emf to the peak of the ac input voltage.

$$Z\angle\phi = \sqrt{(R^2(\omega L)^2\ )}\angle\ (tan^{-1}(\omega L/R \quad (3a)$$
$$m = E_c/V_m, \quad \mu = sin^{-1}|m| \quad (3b)$$

where Z is the load impedance magnitude, ω rad./s is the ac input supply frequency and is the first angular distance (from ωt = 0) in a cycle of the ac source voltage at which the instantaneous value of the source voltage v_s, is equal to the load emf E_c.

Under both rectification and inversion operation of the converter, distinct load current conduction modes occur in two ranges of switching angle given as

$$0 \leq \beta \leq \mu \quad (4a)$$

And

$$\mu \leq \beta \leq \pi/2 \quad (4b)$$

The analysis that follows in the next section is carried out with all currents normalized to base V_m/Z.

3.1 Current Conduction Modes in the Rectification Region.

In the rectification region, the converter load current, i_o average load voltage, V_o and the load emf E_c, are positive.

3.1.1 Conduction modes in the range $0 \leq B \leq \mu$.

In the switching angle range of $0 \leq B \leq \mu$. characterized by $V_s \leq E_c$ at the switching instants under rectifying operation, there are one continuous load current mode (Rc-l) and three discontinuous load current modes (Rd-l to Rd-3) as shown in Fig. 3.

Under continuous load current mode, the load current is minimum or maximum at the point in time when $V_s = i_o R + E_c$ for V_s increasing or decreasing respectively. In the limit of i_o, approaching zero at its minimum point, the converter operation, in this switching angle interval approaches the boundary between continuous and discontinuous modes of operation in which the load current is only zero at the instant t_b given by

$$\omega t_b = sin^{-1} Ec/Vm + (K-1)\pi = \mu + (K-1)\pi \qquad (5)$$

where k is any non zero positive integer that denotes the half cycle number of V_s from $\omega t=0$.

Consequently, the load current in this range of is continuous (Mode Rc-l) if and only if its instantaneous value $I_{o\mu}$ at $\omega t = \mu + (K-1)\pi$ is greater than or equal to zero. This current $I_{o\mu}$ in per unit of V_m/Z can be shown to be given by

$$I_{o\mu} = -m/\cos\phi + \sin(\mu-\phi) + \{\sin(\beta+\phi)e^{(\beta+\mu)/\tan\phi} - \sin(\beta-\phi)e^{(\beta+\mu)/\tan\phi}\}/(1-e^{-\pi/\tan\phi}) \qquad (6)$$

Instantaneous load current values $I_{o\beta}'$ and $I_{o\beta}''$ at other load voltage discontinuity points, namely $\omega t = K\pi-\beta$ and $\omega t = K\pi+\beta$, under continuous current operation can be shown to be given by

$$I_{o\beta'} = \sin(\beta+\phi) - m/\cos\phi + \{I_{o\mu} + m/\cos\phi - \sin(\mu-\phi)\}e^{(\beta+\mu-\pi)/\tan\phi} \qquad \text{.....(7)}$$

$$I_{o\beta''} = -m/\cos\phi + \{I_{o\beta'} + m/\cos\phi\}e^{-2\pi/\tan\phi} \qquad (8)$$

Under discontinuous load current operation, a load current pulse rises from zero at, say, $\omega t = \mu + (k-l)\pi$ in the k^{th} half cycle of the ac source voltage V_s and falls to zero again before the instant $\omega t = \mu + K\pi$ in the $(k+1)^{th}$ half cycle of v_s., This condition of operation is confirmed if, with given converter input and load conditions, $I_{o\mu}$ in equation (6) is negative. Since the load current cannot go negative, a negative value of $I_{o\mu}$ is not real but only a confirmation of load current discontinuity.

In Fig. 3, modes of discontinuous load current operation are identified by the intervals between successive load voltage discontinuity points during which the load current pulse goes to zero before the end of the pulse period.

In mode Rd-l discontinuous load current operation, the load current i_o in the k^{th} half cycle of V_s goes to zero in the interval of $(k\pi+\beta) < \omega t < (K\pi+\mu)$ before the end of the pulse period and, under this condition, $I_{o\mu}$ is calculated as being less than zero from equation 6 while $I_{o\beta}'$ and $I_{o\beta}''$ respectively determined by substituting $I_{o\mu} = 0$ in equations 7 and 8, are positive. In mode Rd-2, the load current falls to zero in the interval $(K\pi-\beta) < \omega t \leq (k\pi+\beta)$ and, in this case, $I_{o\mu} < 0$ from equation 6, $I_{o\beta}' > 0$ with $I_{o\mu} = 0$ in equation 7, while $I_{o\beta} \leq 0$from equation 8. In the Rd-3 conduction mode, the end zero point of the load current pulse is in the range of $(K-1)\pi + \mu) < \omega t \leq (K\pi-\beta)$ resulting in $I_{o\mu} < 0$ from equation 6, $I_{o\beta}' \leq 0$with $I_{o\mu} = 0$ in equation 7 and $I_{o\beta}'' < 0$ from equation 8.

3.1.2 Conduction modes in the range

In the switching angle range of $\mu \leq \beta \leq \pi/2$

in the converter rectification region, there is one mode each of the continuous and the discontinuous converter load current operation (Fig. 4). In the Re-2 continuous load current mode of operation, the source voltage V_s is switched across the load at a switching angle β when $v_s, \geq E_c$ to cause the decaying load current to start rising again from its value $I_{o\beta}$ at ωt = (k-l) π+β. The current lop is $I_{o\beta}$ is given by the relation

$$I_{o\beta} = -m/\cos\phi + \{\sin(\beta+\phi)e^{-2\beta/\tan\phi} - \sin(\beta-\phi)e^{-\pi/\tan\phi}\}/(1-e^{-\pi/\tan\phi}) \qquad (9)$$

It is obvious therefore that in this switching angle interval in the rectification region, the load current i_o is continuous (mode Rc-2) if $I_{o\beta} \geq 0$ and discontinuous (mode Rd-4) $I_{o\beta} < 0$.

3.2 Current Conduction Modes in the Inversion Region

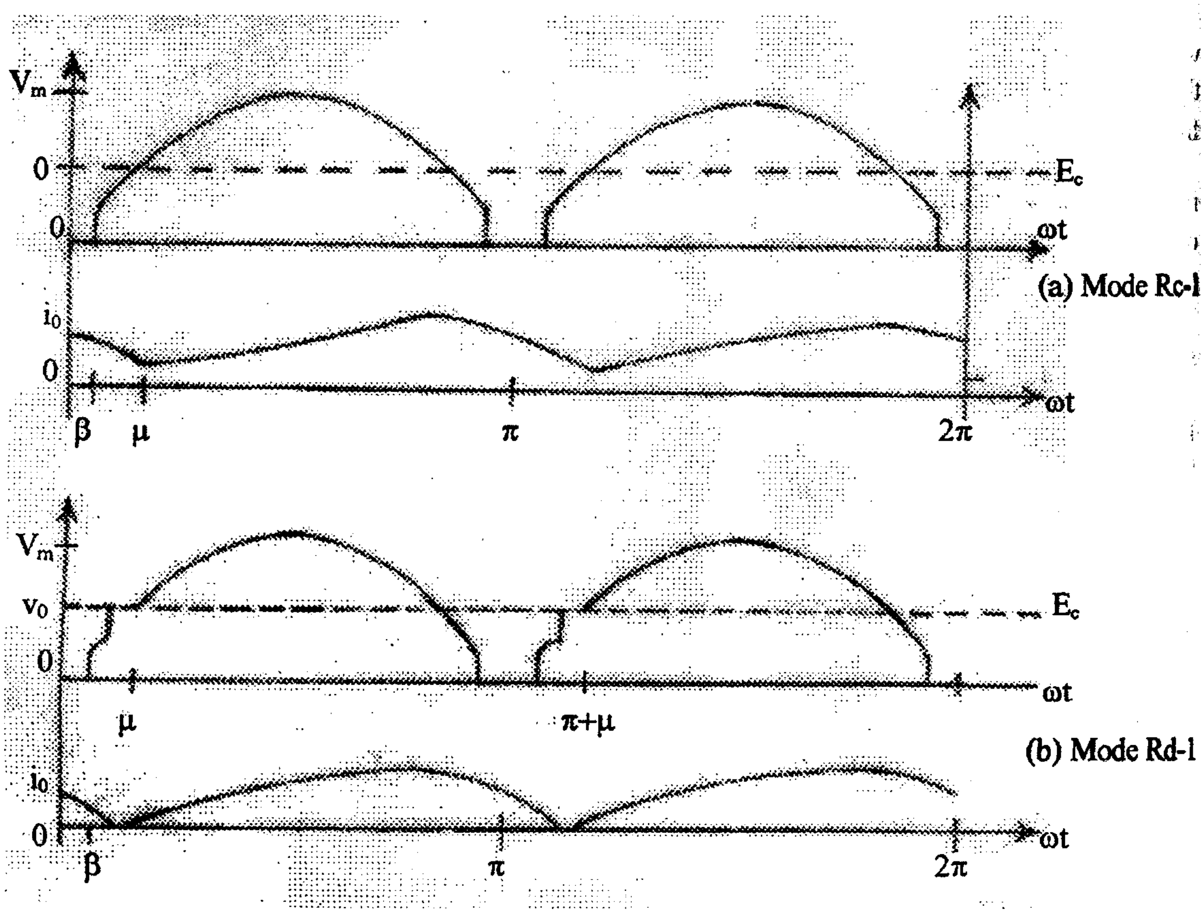
In the inversion region of the converter operation, the power flow is from the load to the ac input source. Consequently, both the average load voltage and the load emf are negative while the load current remains positive.

3.2.1 Modes in the range 0 ≤ β ≤ μ

Two current conduction modes (Fig. 5) are possible in this inverting range where the semiconductor device switching actions occur at instants when $|V_s| \leq |E_o|$. These modes are identified by the sign of the instantaneous load current $I_{o\mu}'$ at the instant ωt = kπ -μ where the boundary between continuous and discontinuous load current modes occurs. The current $I_{o\mu}'$ is expressed as

$$I_{o\mu''} = -m/\cos\phi - \sin(\mu+\phi) + \sin(\beta-\phi)e^{(\beta-\mu)/\tan\phi} - \sin(\beta+\phi)e^{\frac{\beta-\mu-\pi}{\tan\phi}}\}/(1-e^{-\frac{\pi}{\tan\phi}}) \qquad (10)$$

The load current is continuous (mode Ic-1) or discontinuous (mode Id-1) according as $I_{o\mu}' \geq 0$ or $I_{o\mu}' < 0$.Negative $I_{o\mu}'$ implies that the k^{th} load current pulse rises from zero at ωt = Kπ-μ and falls to zero again at ωt = kπ-μ + λ where λ is less than π.



Vm
0
0
Ec
ωt
(a) Mode Rc-1
i0
0
ωt
β
μ
π
2π
Vm
v0
0
Ec
ωt
μ
π+μ
(b) Mode Rd-1
i0
0
ωt
β
π
2π

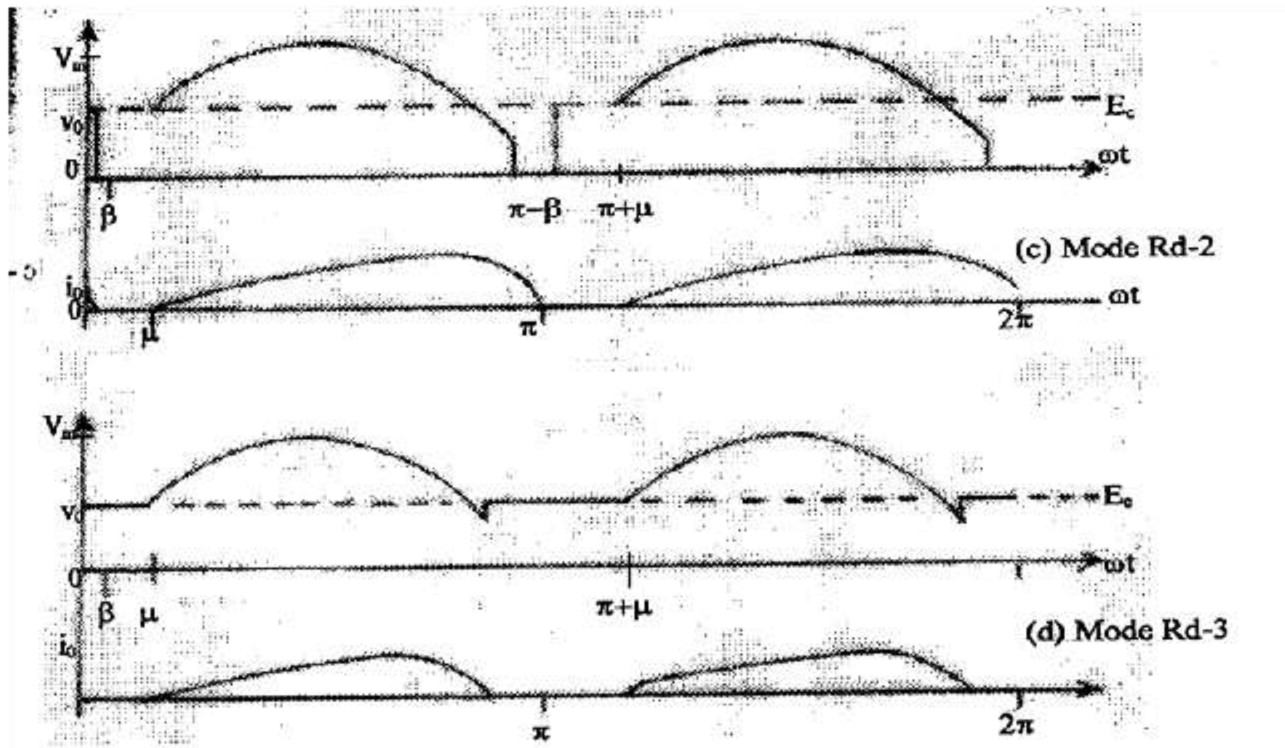


Fig. 3: Load Current Modes in the Switching Angle Range of 0<β<μ (Rectification).

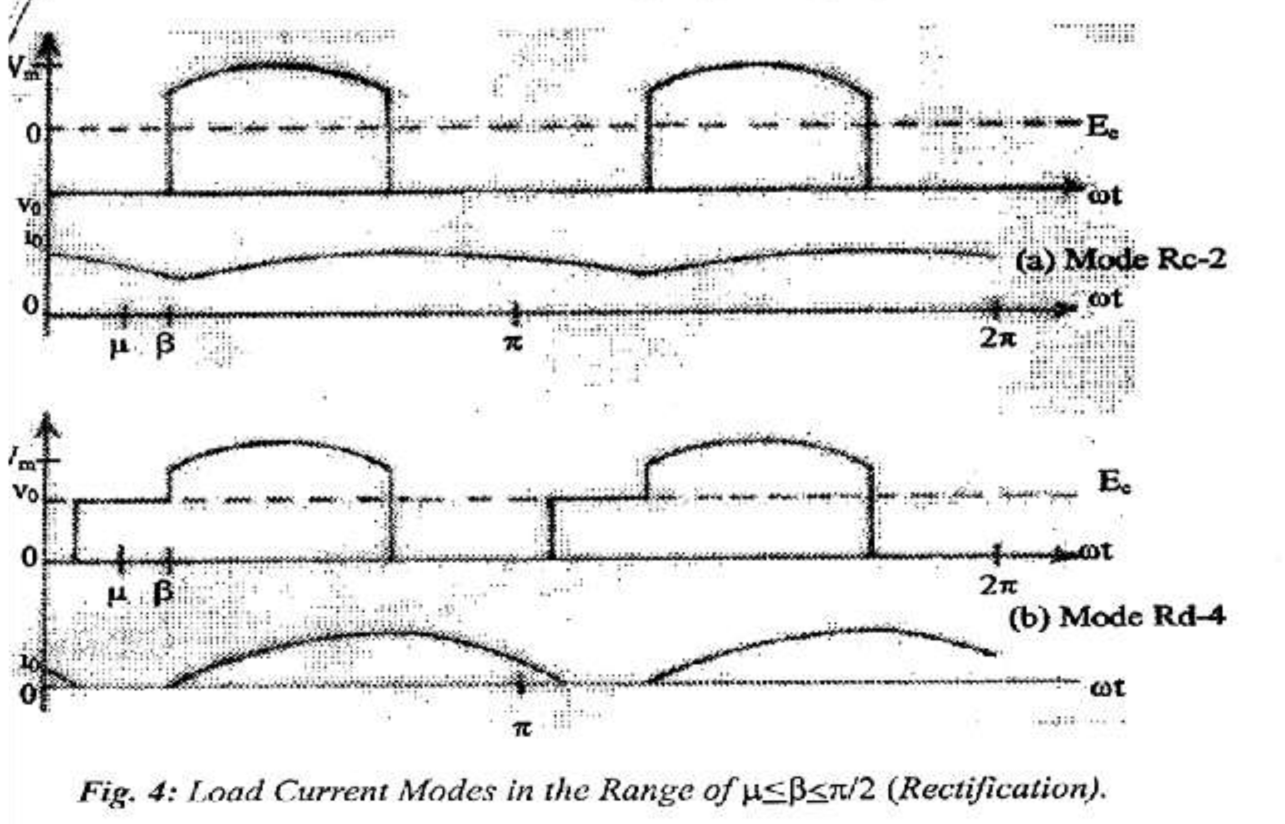


Fig. 4: Load Current Modes in the Range of μ≤β≤π/2 (Rectification).

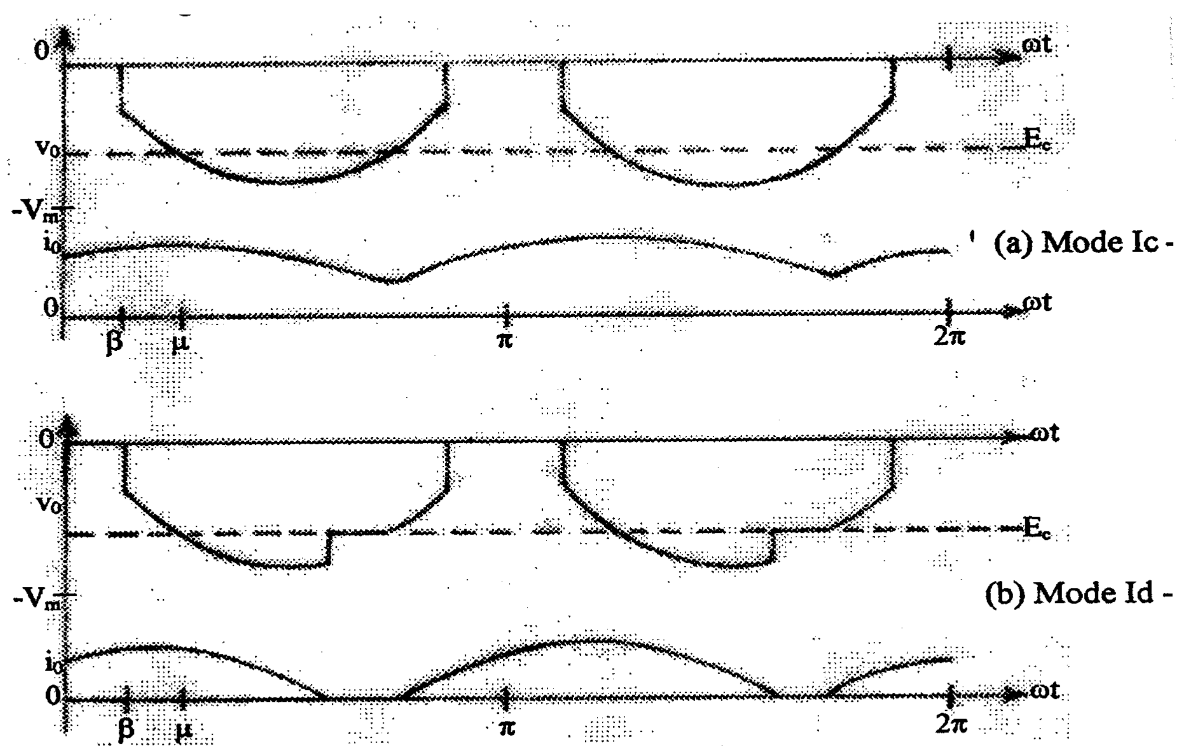


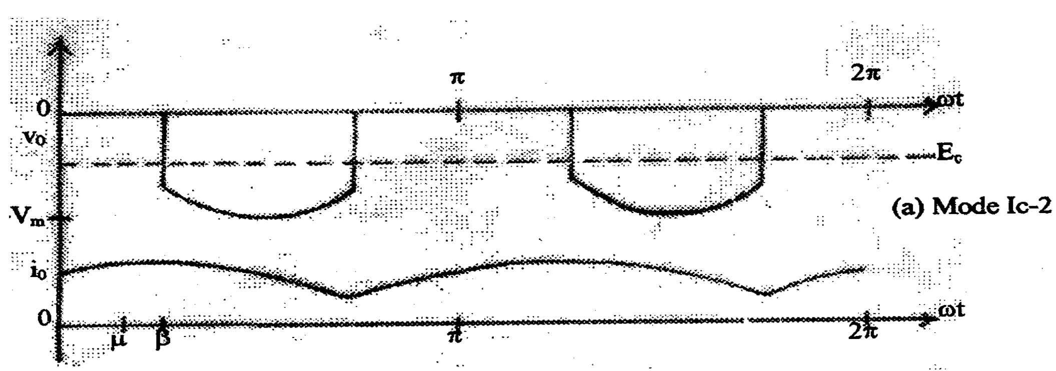
Fig. 5: Load Current Modes in the Range of 0<β<μ (Inversion).

3.2.2 Modes in the range μ ≤ β ≤ π /2

In this range of inversion operation, the semiconductor turn on and turn off instants occur at angular distance points where $|V_s| \geq |E_c|$ as, shown in Fig. 6. This makes the zero load current point at the boundary between continuous and discontinuous load current operation to occur at the instant ωt = kπ-β The sign of the load current $I_{o\beta}{}^{/}$ at this instant is therefore used to determine the load current conduction mode in this interval of inverting operation.

$$I_{o\beta/} = -m/\cos\phi + \{\sin(\beta-\phi)e^{(2\beta-\pi)/\tan\phi} - \sin(\beta-\phi)\}/\left(1-e^{-\pi/tan\phi}\right) \qquad (11)$$

If $I_{o\beta}{}^{/} \geq 0$, the load current is continuous (mode Ic-2) but if $I_{o\beta}{}^{/} < 0$ the load current is discontinuous (mode Id-2).



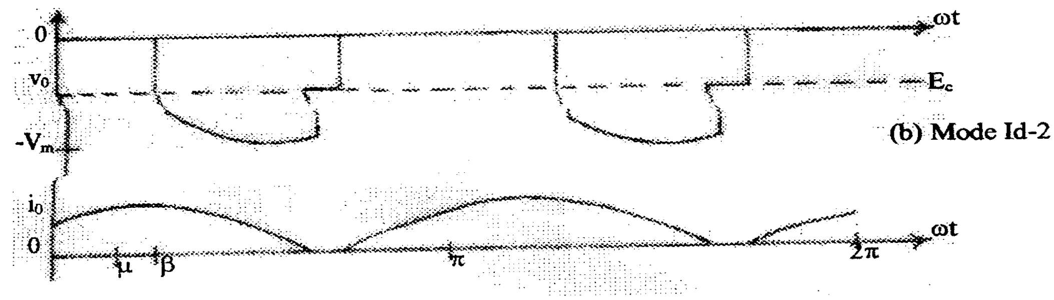


Fig. 6: Load Current (Ic-2 & Id-2) in the Range $\mu \leq \beta \leq \pi/2$

4.0 BOUNDARY BETWEEN CONTINUOUS AND DISCONTINUOUS LOAD CURRENT MODES

The boundary between the continuous and the discontinuous load current modes can be obtained (for given load angle ϕ and varying normalized load emf m and switching angleβ) by respectively setting to zero $I_{o\mu}$ and $I_{o\beta}$ A in equations 6 and 9 for rectifying operation and $I_{o\mu}'$ and $I_{o\beta}'$ in equations 10 and 11 for inverting operation. Fig. 7 shows these boundary curves plotted in the m versus β plane with the load angle ϕ as the parameter. For a given load angle, a converter operating point (m, β) above the corresponding boundary curve has discontinuous load current but an operating point (m, β) on or below the boundary curve has continuous load current

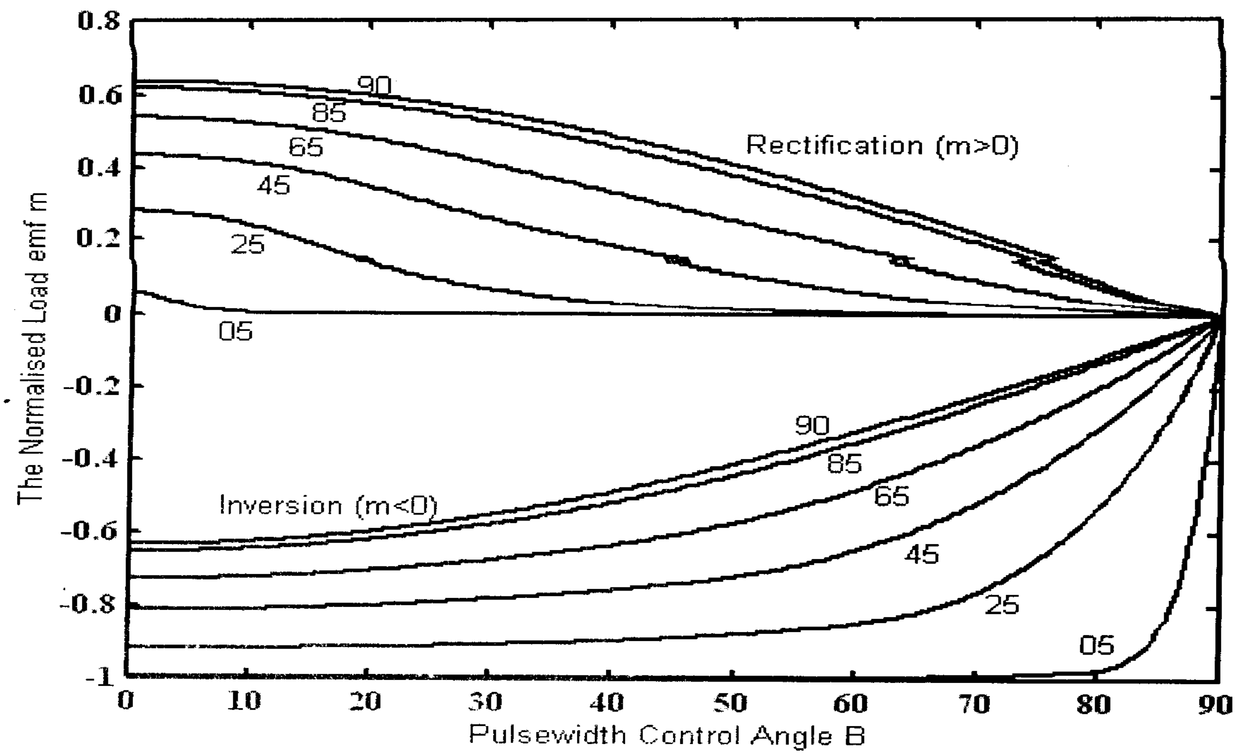


Fig. 7: The p.u. Boundary Load emf m Versus Switching Angle β.

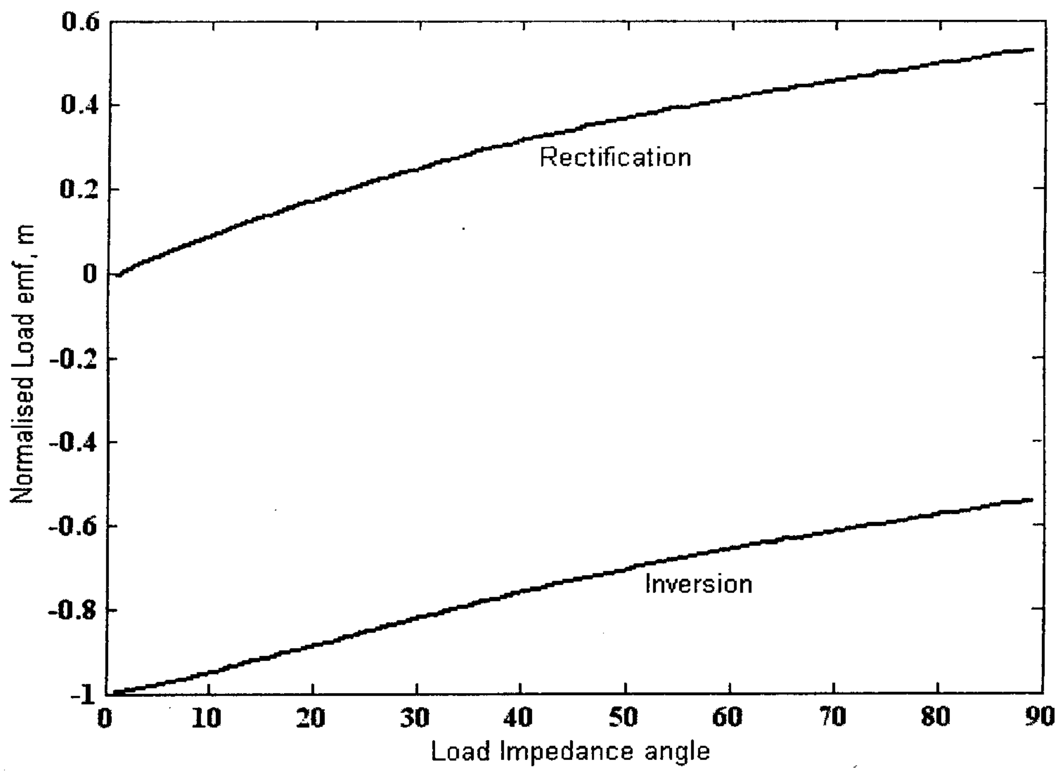
Fig. 8 is a plot of the transition value of the normalized load emf m (on the boundary curve of *Fig.* 7) which corresponds to the point where the converter operation changes from the switching angle interval of $0 \leq \beta \leq \mu$ to the switching angle interval of $\mu \leq \beta \leq \pi/2$. Therefore, for any given load angle abscissa ϕ in Fig. 8, the corresponding ordinate m is the transition value which satisfies the relation $\beta = \mu = \sin^{-1}|m|$ on the boundary curve of the load angle.

For pure resistive load impedance ($R \neq 0$, $L=0$), that is $\phi=0$, the load current, in practice, is only continuous at the operating point ($m=0, \beta = 0$) in the rectification while region in the inversion region the line $m = -1$ represents the boundary curve for $\phi=0$.

For pure inductor as the load impedance ($R = 0$, $L \neq 0$), that is $\phi = \pi/2$, the boundary curve is a quarter of a cosine cycle for both rectifying and inverting operations and the curve is given by the equation,

$$m = \pm 2\cos\beta/\pi, 0 \leq \beta \leq \pi/2 \qquad (12)$$

where the *plus sign* represents rectifying operation and the minus sign inverting operation.



ig. 8: The Transition Points of $\beta = \mu$ at Boundary Points from Continuous to Discontinuous Current Modes.

5. CONCLUSIONS

A method of predicting load current conduction modes in the 2-pulse full bridge one phase AC/DC converter with one modulated voltage pulse per ac source half cycle has been presented. The analysis method uses the sign of the instantaneous load current values at *points* of load voltage discontinuity under varying load and switching instants to determine the load current modes. The method represents an effective analysis approach for determining current modes in the PWM AC/DC converter which *is* currently gaining increasing interest as a better alternative, in most applications, to the phase controlled *AC/DC* converter.

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