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A METHOD OF DETERMINING MODES OF CURRENT CONDUCTION IN A CLASS OF AC TO DC CONVERTERS

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ABSTRACT

This paper presents a method of determining the different modes or aspects of current conduction in ac to dc converters. The phase-controlled converter (with or without current free/fly wheeling) is discussed in detail to show the application of this method. In the discussion, the control delay angle range is limited to π radians (which is the half cycle angular distance of the ac source voltage) while the duration of the semi-conductor switch turn on signal is maintained constant throughout the control delay angle range. In the method, continuous load current mode is initially assumed and the instantaneous converter output currents are determined at points of the converter output voltage discontinuities and/or at points of minimum output current values. From the signs of these instantaneous current values, the converter output current modes are identified. The reported method has the advantage of giving more information about the nature/shape of the converter output current waveform and the degree of load current continuity or discontinuity from the transition of continuous to discontinuous current conduction modes.

INTRODUCTION

Studies on current conduction in phase-controlled ac to dc converters have been widely reported in literature (1, 2, 3). For a given converter control delay angle and load conditions, it is important to know whether the converter output current is continuous or discontinuous. This knowledge helps in the selection of an appropriate series filter inductance to minimize the relatively high power loss and slow speed of response associated with discontinuous current conduction.

For the conventional fully phased controlled converter, Dewan and Straughen used iterative method to plot boundary curves between continuous and discontinuous current modes for switching instants where the ac source voltage instantaneous value is greater than the load emf or the load dc voltage (1). Further work by Dubey and others identified discontinuous current modes for switching instants where the ac source voltage instantaneous value is less than the load emf (2, 3). But, to identify current conduction modes, this further work assumes initial zero converter output current value at minimum load current instants.

The method employed in this paper initially assumes continuous load current, which allows progressive determination of the true value of the instantaneous converter output voltage and/or the instant of minimum load current. With these known instantaneous current values, the modes of current conduction, the nature of the converter output current waveform and how far the output current is from being continuous or discontinuous are more effectively determined. For the fully phase controlled converter with any output pulse number, a generalized analysis is given. For the phase-controlled converter with controlled fly wheeling, only the two-pulse converter is treated in detail. In all the analysis, the range of the control delay angle is limited to the practical value of 180 degrees or less depending on the converter output pulse number. The analysis technique used can easily be extended to other forms of the ac to dc converter.

THE AC TO DC CONVERTER

Figure 1 is a general configuration of the two-pulse and the six-pulse ac to dc converter. The semiconductor switches T1 to T6 represent any of the currently available semiconductor power switches (line/force-commutated thyristors, self turn on thyristors or transistors [4, 5, 6, 7, 8]). The converter ac source (reference) input voltage is designated as $V_m \sin\omega t$. The switch turn on signal duration is assumed to be maintained at π radians for converter output pulse number equal to one and $2\pi/N_p$ for an N_p-pulse midpoint converter for all values of the control delay angle. The control delay angle is also assumed to vary from 0 to π radians for all converter configurations. For the multistage connected converter, turn on signal duration is assumed equal to that of one of the identical individual midpoint converters that make up the multistage connection. The converter output load is generalized as an RLE load which is a series combination of a resistance R, an inductance L and a load emf E. These assumed turn on signal duration and the range of the control delay angle is used in the following analysis and discussions. Also, in the analysis, the load current and the load emf are normalized with the peak (V_m) of the ac source voltage as the base voltage and the load impedance magnitude ($Z=\sqrt{(R^2+(\omega L)^2)}$) as the base impedance

The Fully Phase-Controlled N_P-Pulse Converter

Modes of Discontinuous Load Current

For a general RLE load, there are three modes (Fig. 2) of discontinuous load current conduction in the fully phase-controlled N_p-pulse converter. In a cycle of the converter ac input voltage, these modes are explained as follows:-

Mode 1: This mode occurs in the α control delay angle range given by

$0 \le \alpha + \omega t_a \le \psi$ for $m \ge 0$, where $\psi = \sin^{-1}|m|$ (1)

ωt_a is the value of the angular distance (from $\omega t=0$) at zero control delay angle (that is $\alpha = 0$) and it has the general expression

$\omega t_a = 0$ for $N_p = 1 = \pi(\frac{1}{2}-1/N_p)$ for $N_p>1$ (2)

The parameter m is the normalized load emf.

In mode 1 discontinuous current conduction the k^{th} load current pulse (in a cycle of the ac source voltage) naturally starts from zero value at $\omega t_a = \psi + (k-1)\,2\pi/N_p$ where $k \le N_p$.

If this pulse current goes to zero before the appropriate unidirectional semiconductor switches are turned on at $\omega t = \alpha+\omega t_a + k\,(2\pi/N_p)$ for the $(k + 1)^{th}$ converter output voltage pulse , then the current conduction is in mode 1A. Under mode 1A operation, these turned on semiconductor switches remain reverse biased and therefore do not conduct current until at $\omega t = \psi + k(2\pi/N_p)$ when the $(k+1)^{th}$ load current pulse rises from zero value. If on the other hand, the k^{th} pulse current does not go to zero before the instant $\omega t = \alpha+\omega t_a + k(2\pi/N_p)$ but goes to zero before the instant $\omega t = \psi+k(2\pi/N_p)$, then mode 1B where the $(k+1)^{th}$ input voltage phase appears across the converter output from $\omega t = \alpha + \omega t_a + k(2\pi/N_p)$ till the instant load current goes to zero will be the case.

Generally, it is important to point out that mode I discontinuous current conduction can only occur during the converter rectification mode.

Mode II: Mode II discontinuous load current operation occurs in the α control delay angle range given by

$\psi \leq \alpha + \omega t_a$ for $m \geq 0$, $\alpha + \omega t_a \leq (N_p - 1)2\pi/N_p - \psi$ for $m < 0$ and $N_p>1$ (3)

In this mode of operation, the k^{th} load current pulse starts from zero value at the switching instant $\omega t = \alpha+\omega t_a + (k - 1)2\pi/N_p$ and goes to zero again before the $(k+1)^{th}$ phase of the converter input voltage is switched across the load at $\omega t = \alpha + \omega t_a + 2k\pi/N_p$. As can be seen from equation 3, Mode II current conduction can occur during both the converter rectification and inversion conditions of operation.

Mode III discontinuous load current conduction occurs at the control delay angle range given by

$(N_p - 1)2\pi/N_p - \psi \leq \alpha+\omega t_a \leq \omega t_a + \pi$ for $m< 0$ and $N_p>1$ (4)

In this mode of discontinuous load current conduction, the first section of k^{th} load current pulse naturally rises from zero at $\omega t=(N_p - 1)2\pi/N_p - \psi +(k - 1)2\pi/N_p$ and this current will be non zero at $\omega t = \alpha+\omega t_a + (k - 1)2\pi/N_p$ when the k^{th} phase of the ac source voltage is switched across the load. However, the load current goes to zero before the instant $\omega t = \alpha + \omega t_a + 2k\pi/N_p$ when the next load current pulse (due to $(k+1)^{th}$ phase of the ac source voltage) starts from zero value. As indicated in equation 4, mode III discontinuous load current conduction can only occur during the converter operation in the inversion/regenerative region.

Case of $N_p = 1$

There is no Mode III for $N_p = 1$. Only modes I and II apply in one pulse converter ($N_p=1$). If $m<0$ and a non self turn off thyristor is used as the switch, then, for line commutation to be reliably sustained, the resultant converter output current which rises from zero at the instant of switch turn on must go to zero before or at the instant given as

$$\omega t = 2\pi - \arcsin|m| - \omega t_q \qquad (5)$$

where t_q is the thyristor turn off time.

Identification of Modes of Discontinuous Load Current

Identification of Modes I-III

For modes I-III, mode identification is easily carried out by initially assuming continuous load current for given control delay angle α, per unit load emf m and load power factor angle ϕ. Then the instantaneous value of the load current at the angular distance where, at the boundary between continuous and discontinuous load current operation, the load current is zero is determined. It can be shown that, under assumed load continuous current operation, the instantaneous load currents whose values determine the modes of current conduction are $I_{0\psi}$, $I_{0\alpha}$ and $I_{0\psi}^{/}$ at the angular distances of ψ, $\alpha+\omega t_a$ and $(N_p - 1)2\pi/N_p - \psi$ for modes I, II and III respectively.

$$I_{0\psi} = -m/\cos\phi+\sin(\psi-\phi)-2\sin(\alpha-\phi)\cos\omega t_a e^{x1}/(1-e^{-2\pi/(N_p\tan\phi)}),\quad \alpha + \omega t_a \le \psi \tag{6}$$

$$I_{0\alpha} = -m/\cos\phi+\cos(\alpha-\phi)\sin\omega t_a - \sin(\alpha-\phi)\cos\omega t_a(1+e^{-2\pi/(N_p\tan\phi)})/(1-e^{-2\pi/(N_p\tan\phi)}),\quad \psi \le \alpha+\omega t_a \le \psi^{/} \tag{7}$$

$$I_{0\psi}^{/} = -m/\cos\phi-\sin(\psi+\phi)-2\sin(\alpha-\phi)\cos\omega t_a e^{x2}/(1-e^{-2\pi/(N_p\tan\phi)}),\quad \psi^{/} \le \alpha+\omega t_a \le \omega t_a +\pi \tag{8}$$

where:

$$x1 = (\alpha+\omega ta-\psi)/\tan\phi \tag{9}$$

$$x2 = (\alpha+\omega ta-2\pi+\psi)/\tan\phi \tag{10}$$

$$\psi^{/} = 2\pi(N_p-1)/N_p -\psi \tag{11}$$

In each control delay angle range specified in equations 6 to 8, the load current is continuous or discontinuous according as the corresponding instantaneous current value is positive or negative. For example, if $I_{0\psi}$ is negative for a given ϕ, m and α for $0 \le \alpha+\omega t_a < \psi$, then the current conduction is mode I discontinuous load current. Modes II and III discontinuous load current operation are similarly identified in their respective delay angle control ranges. For mode I load current, modes IA and IB are identified by determining the instantaneous load current $I_{0\alpha}$ value at $\omega t = \alpha + \omega t_a$ for $I_{0\psi} = 0$.

$$I_{0\alpha} = - m/\cos\phi -\sin(\alpha-\omega t_a-\phi)+\{m/\cos\phi - \sin(\psi-\phi)\}e^{x3};\quad \alpha + \omega t_a \le \psi \tag{12}$$

$$\text{where } x3 = \psi-\alpha+\omega t_a-\pi \tag{13}$$

Load current conduction is mode 1A and 1B according as $I_{0\alpha}$ given by equation 12 is negative or positive.

For non-self turn off thyristor as the switch in one pulse converter, it can be found whether, for m < 0, the load current is continuous or discontinuous by determining the instantaneous load current $I_{0\psi}{}''$ at $\omega t = 2\pi-\psi$. The determination of this instantaneous load current is carried out by assuming that the initial current at the switch on instant of $\omega t = \alpha+\omega t_a$ is zero. Under this condition, $I_{0\psi}{}''$ can be shown to be

$$I_{0\psi}{}'' = -m/\cos\phi-\sin(\psi+\phi)+\{m/\cos\phi -\sin(\alpha-\phi)\}e^{x2}, \quad m < 0,\ N_p=1, \qquad (14)$$

i. If $I_{0\psi}{}'' \geq 0$, load current is continuous.

ii. If $I_{0\psi}{}'' < 0$, load current is discontinuous.

Limit of ϕ in Identification Analysis

If the occurrence of division by zero is to be avoided, the analysis in this section covers the load range given by

$$0 < \phi < \pi/2 \qquad (15)$$

This limit, expressed by equation 15, is placed on ϕ because, for pure resistive load, the term $(1/\tan\phi)$ in the current equations will result in the unbounded term of $x/\tan\phi$ for $\phi = 0$, while, for pure inductive load, the term $(1/\cos\phi)$ will result in the unbounded term $m/\cos\phi$ for $\phi = \pi/2$. However, values of ϕ very close to zero and very close to $\pi/2$ will essentially, with negligible loss in accuracy, predict the desired converter instantaneous currents under pure inductive or resistive loads.

Boundary between Continuous and Discontinuous Current Modes

At the boundary between continuous and discontinuous current modes for given α, ϕ and m for $0<\phi<\pi/2$, the instantaneous currents, $I_{0\psi}$, $I_{0\alpha}$ $I_{0\psi}{}'$ and $I_{0\psi}{}''$ as given by equations 6, 7, 8 and 14 are each zero. Therefore, for any parameter out of the two required parameters of α and m for a given load angle ϕ, the remaining parameter (α or m) that ensures operation at the boundary (Fig. 3) between continuous and discontinuous current modes can be obtained by setting the appropriate expression (equation 6, 7, 8 or 14) of the instantaneous current equal to zero.

For pure resistive, pure inductive and RL impedance loads, simplified expressions can accordingly be derived for specified ranges of α to readily calculate the per unit load emf m_b for a given α that satisfies the condition for converter operation at the boundary between continuous and discontinuous current modes. These expressions for m_b are

$m_b(\phi = 0) = -\sin(\alpha-\omega t_a),\ \ 0 \le \alpha \le +\pi/2 + \omega t_a$
$= -1,\ \ \pi/2 + \omega t_a \le \alpha \le \pi$ (16)

$m_b(\phi = \pi/2) = N_p \cos\alpha \cos\omega t_a/\pi,\ \ 0 \le \alpha \le \pi$ (17)

$m_b(0<\phi<\pi/2) = \cos\phi\{\cos(\alpha-\phi)\sin\omega t_a - \sin(\alpha-\phi)\cos\omega t_a(1+e^{-2\pi/(Np\tan\phi)})/(1-e^{-2\pi/(Np\tan\phi)})\}$,

$\psi \le \alpha+\omega t_a \le \psi'$ (18)

On the other hand, iterative method has to be used to determine $m_b(0<\phi<\pi/2)$ in the delay angle ranges of $0\le \alpha+\omega t_a \le \psi$ and $\psi' \le \alpha+\omega t_a \le \pi+\omega t_a$. For a converter operating condition specified by α, m and ϕ, the load current is discontinuous if m_b is less than the specified operating m or if the boundary value α_b of the delay angle for the specified m and ϕ is less than the specified α; otherwise the load current is continuous.

The Phase-Controlled Converter with Controlled Flywheeling

In the phase-controlled converter with controlled fly wheeling, converter operation is distinctively divided into rectification and inversion conditions. For converter pulse number greater than two, two source voltage phases can be switched across the load per cycle of the converter output voltage. This makes the current conduction analysis a little bit more cumbersome than in the fully phase-controlled converter. For illustration therefore, only the two-pulse full bridge converter is considered in these controlled type of converters.

Rectification Region (m>0)

For the rectification region, the positive half of the full bridge converter has its delay angle α_1 varied from 0 to π, while the control delay angle α_2 of the lower half is kept constant at zero. This control action varies the average converter output voltage from its maximum value at $\alpha_1=0$ to zero at $\alpha_1=\pi$.

Discontinuous Current Modes

There are two major modes (Fig. 4a) of discontinuous current in the rectification region and these modes are described as follows for the two pulse full bridge converter:

Mode I: This mode occurs when the control delay angle is within the range described by $0\le\alpha_1\le\psi$. In this mode, the source voltage in the positive half cycle is naturally switched across the load at $\omega t=\psi$ and the load current rises from zero at this instant of switching.

a. If the load current falls back to zero before $\omega t = \pi$ when fly wheeling action starts, mode IA obtains.

b. If the load current falls back to zero in the interval of $\pi < \omega t < \pi + \alpha_1$ during which fly wheeling action takes place, the discontinuous current conduction is in mode IB.

c. Mode IC discontinuous load current is the case if the load current falls back to zero in the range of $\alpha_1 + \pi < \omega t < \psi + \pi$. At $\omega t = \alpha_1 + \pi$, the negative of the source voltage is switched across the converter output.

Mode II: Mode II occurs when the control delay angle is in the range of $\psi \le \alpha_1 \le \pi$. In this mode, the source voltage in the positive half cycle is switched across the load at $\omega t = \alpha_1$ and the load current rises from zero at this instant.

a. If the load current falls back to zero in the interval of $\alpha_1 < \omega t < \pi$, Mode IIA current conduction obtains.

b. If the load current falls back to zero in the interval of $\pi < \omega t < \alpha_1 + \pi$, Mode IIB conduction is the case.

Mode Identification

The discontinuous current conduction mode is identified by initially assuming continuous load current and determining the instantaneous current value $I_{0\psi}$ or $I_{0\alpha 1}$ at the instant $\omega t = \pi$ or $\omega t = \alpha_1$ according as the control delay angle α_1 is less or greater than ψ. A positive value of the appropriately determined instantaneous load current for a given control delay angle and load parameters (m, ϕ) indicate continuous current mode of operation and using this value of $I_{0\psi}$ or $I_{0\alpha 1}$, the corresponding instantaneous load current value $I_{0\pi}$ at the instant $\omega t = \pi$ can be determined. On the other hand, a negative value of the calculated instantaneous current indicates discontinuous load current mode of operation implying that $I_{0\psi}$ or $I_{0\alpha 1}$ is zero and this value is used to determine other instantaneous load current values (such as $I_{0\pi}$) that enables discontinuous current mode identification.

$0 \le \alpha \le \psi$

For the control angle range of $0 \le \alpha \le \psi$, under assumed continuous load current mode in the rectification region $I_{0\psi}$, $I_{0\alpha 1}$ and $I_{0\pi}$ are

$$I_{o\psi} = -m/\cos\phi + \sin(\psi - \phi) + \{\sin\phi e^{-\psi / \tan\phi} - \sin(\alpha_1 - \phi) e^{(\alpha 1 - \psi) / \tan\phi}\} / (1 - e^{-\pi / \tan\phi}) \quad (20)$$

$I_{0\pi}$ = $-m/\cos\phi+\sin\phi+\{I_{0\psi}+ m/\cos\phi-\sin(\psi-\phi)\}e^{(\psi-\pi)/\tan\phi}$ (21)

$I_{0\alpha 1}$ = $-m/\cos\phi+\{m/\cos\phi+ I_{0\pi}\}e^{-\alpha 1/\tan\phi}$ (22)

In the identification process, the current $I_{0\psi}$ (being the minimum current close to discontinuous current mode) is first of all calculated. The load current is continuous or discontinuous according as $I_{0\psi}$ is positive or negative.

For discontinuous current mode, $I_{0\pi}$ for $I_{0\psi} = 0$ is determined from equation 21. If $I_{0\pi}$ is negative, mode IA is the case and the load current conduction interval is $\psi\leq\omega t<\pi$. If, with $I_{0\psi} = 0$, $I_{0\alpha 1}$ is negative but $I_{0\pi}$ positive, mode IB is the case and the load current conduction interval in a half cycle is $\psi\leq\omega t\leq\pi+\alpha$. If $I_{0\alpha 1}$ for $I_{0\psi} = 0$ is positive, the converter is in mode IC conduction.

$\psi\leq\alpha_1\leq\pi$

In mode II, the relevant instantaneous currents are $I_{0\alpha 1}$ and $I_{0\pi}$ with $I_{0\alpha 1}$ being the minimum current at operations close to the discontinuous current mode. These instantaneous currents are expressed as

$I_{0\alpha 1} = -m/\cos\phi+\{\sin\phi e^{-\alpha 1/\tan\phi} - \sin(\alpha_1 -\phi) e^{-\pi)/\tan\phi}\}/(1- e^{-\pi/\tan\phi})$ (23)

$I_{0\pi} = \sin\phi - m/\cos\phi+\{I_{0\alpha 1}+ m/\cos\phi - \sin(\alpha_1 -\phi)\}e^{(\alpha 1-\pi)/\tan\phi}$ (24)

Positive $I_{0\alpha 1}$ indicates continuous load current mode. Negative $I_{0\alpha 1}$ indicates discontinuous load current mode. Negative $I_{0\pi}$ for $I_{0\alpha 1} = 0$ indicates that the current conduction interval is $\alpha\leq\omega t<\pi$ (i.e. mode IIA) while positive $I_{0\pi}$ with $I_{0\alpha 1} = 0$ indicates current conduction interval $\alpha_1\leq\omega t<\pi+\alpha_1$ (i.e. mode IIB).

Inversion/Regenerative Method (m<0)

In the inversion region, the control delay angle, α_1, of the positive half of the full bridge converter is maintained at π while the control delay angle, α_2, of the lower half of the bridge is varied from 0 to π to vary the converter average output voltage from zero to its negative maximum value.

Discontinuous Current Modes

Two major modes (Fig 4b) of discontinuous current occurs in the inversion region and these modes are:

Mode III: This mode occurs when the control delay angle α_2 is in the range of $0\leq\alpha_2\leq\pi-\psi$ In mode III discontinuous current operation, zero voltage is switched across the converter output at $\omega t = \alpha_2$ and the load emf drives the load current to rise from zero at this instant. Then the source voltage is switched across the load at $\omega t = \pi$ and this causes the load current to go to zero in the interval $\pi+\psi<\omega t<\pi+\alpha_2$.

Mode III is identified for $0\leq\alpha_2\leq\pi-\psi$ by first of all assuming continuous load current and then determining the instantaneous load currents, $I_{0\alpha2}$ and $I_{0\pi}$, at the converter output voltage discontinuity points of $\omega t = \alpha_2$ and $\omega t = \pi$. These currents are

$$I_{0\alpha2} = -m/\cos\phi - \{\sin\phi e^{-\alpha2 / \tan\phi} + \sin(\alpha_2 - \phi)\}/(1-e^{-\pi/\tan\phi}) \quad (25)$$

$$I_{o\pi} = -m/\cos\phi + \{m/\cos\phi + I_{o\alpha2}\}e^{(\alpha2-\pi)/\tan\phi} \quad (26)$$

For given control angle α_2 and load parameters (m, ϕ), $I_{0\alpha2}$, which is the minimum of the two currents, is first of all determined. The operation is continuous or discontinuous load current mode according as $I_{0\alpha2}$ is positive or negative.

Mode IV:

The second major mode of inverting operation is in the control angle delay range of $\pi-\psi\leq\alpha_2\leq\pi$. In this discontinuous current mode of operation, the negative of the source voltage is naturally applied across the load at $\omega t=\pi-\psi$ and the load current rises from zero at this instant. At $\omega t=\alpha_2$, zero voltage is switched across the load and the load current continues to rise. At $\omega t = \pi$ the source voltage is switched across the load and this causes the load current to eventually decrease to zero in the interval $\pi+\psi<\omega t< 2\pi-\psi$.

In the mode IV identification, continuous load current is assumed and the instantaneous currents $I_{0\psi}'$, $I_{0\alpha2}$ and $I_{0\pi}$, at $\omega t = \pi-\psi$, $\omega t = \alpha_2$ and $\omega t = \pi$ are respectively determined from the following equations:

$$I_{0\psi}' = -m/\cos\phi - \sin(\psi+\phi) - \{\sin\phi + \sin(\alpha_2 - \phi) e^{(\alpha2-\pi)/\tan\phi}\}e^{(\psi-\pi)/\tan\phi}/(1 - e^{-\pi/\tan\phi}) \quad (27)$$

$$I_{0\alpha2} = -m/\cos\phi - \sin(\alpha_2-\phi) + \{I_{o\psi}' + m/\cos\phi + \sin(\psi+\phi)\}e^{(\pi-\alpha2-\psi)/\tan\phi} \quad (28)$$

$$I_{o\pi} = -m/\cos\phi + \{m/\cos\phi + I_{o\alpha2}\}e^{(\alpha2-\pi)/\tan\phi} \quad (29)$$

For given α_2 and load parameters $I_{0\psi}'$ is first of all calculated. Negative value of $I_{0\psi}'$ indicates discontinuous load current mode while positive value indicates continuous load current.

Boundary between Continuous and Discontinuous Current Modes:

Rectification Mode:

In the rectification region, continuous load current mode is not possible for pure resistive load as shown by negative values of $I_{0\psi}$ (equation 20) and $I_{0\alpha 1}$ (equation 23) for all α_1 for m>0 and $\phi = 0$. For load angle values in the range $0<\alpha_1<\pi/2$ and a given value α_1, $I_{0\psi}$ in equation 20 for $0\leq\alpha\leq\psi$ or $I_{0\alpha 1}$ in equation 23 for $\psi\leq\alpha\leq\pi$ can be set to zero to determine the value of the normalized load emf m_b that just makes the load current continuous. For pure inductive load m_b can be shown to be given by

$$m_b = 2\cos^2(\alpha_1/2)/\pi\ , \quad 0 \leq \alpha_1 \leq \pi\ , \ \phi = \pi/2 \qquad (30)$$

Inversion Mode:

In the inversion mode, m_b (derivable from equation 25) for pure resistance load is the same as with the fully phase-controlled converter but with the control delay angle designated as α_2

$$m_b(\phi{=}0) = -\sin\alpha_2\ , \quad 0 \leq \alpha_2 \leq \pi/2 = -1, \quad \pi/2\leq\alpha_2\leq\pi \qquad (31)$$

Values of m_b for $0<\phi<\pi/2$ are obtained by setting to zero $I_{0\alpha 2}$ in equation 25 for $0\leq\alpha_2\leq\pi-\psi$ or $I_{0\psi}'$ in equation 27 for $\pi-\psi \leq \alpha_2 \leq\pi$.

For pure inductive load,

$$m_b(\phi{=}\pi/2) = 2\sin^2(\alpha_2/2)/\pi\ , \quad 0 \leq \alpha_2 \leq \pi\ , \qquad (32)$$

CONCLUSION

In this paper, an improved method for the identification of continuous and discontinuous load current modes in phase-controlled converters has been described. In the method, continuous load current operation of the converter is initially assumed. If the load current is eventually continuous as assumed, the instantaneous load current values determined at the converter output voltage discontinuity points give an information on how far the continuous current operation is from being discontinuous. The reverse is the case if the continuous instantaneous load current values at designated output voltage discontinuity points show discontinuous load current operation. Under the later condition, the actual instantaneous current values will show how far the discontinuous current mode is from being just continuous. The method described can easily be extended to similarly analyze current conduction in other types of converters.

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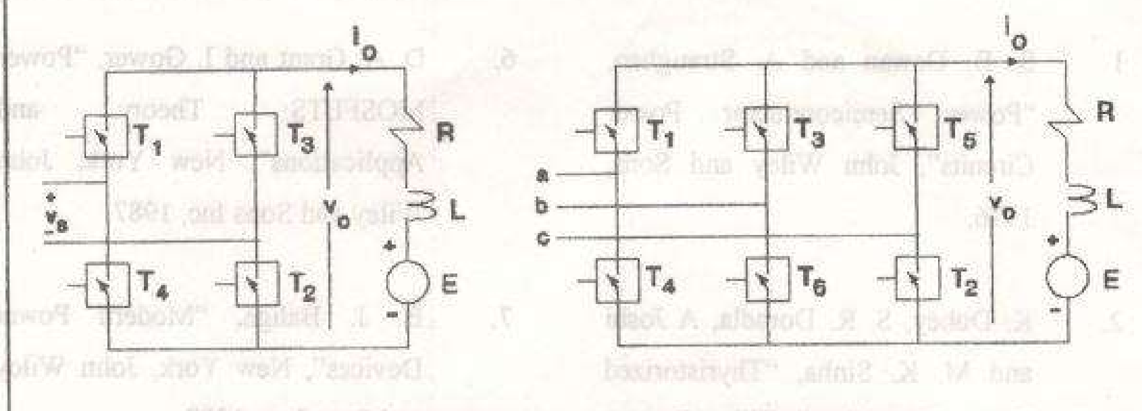

Fig.1 1-phase 2-pulse and 3-phase 6-pulse converters

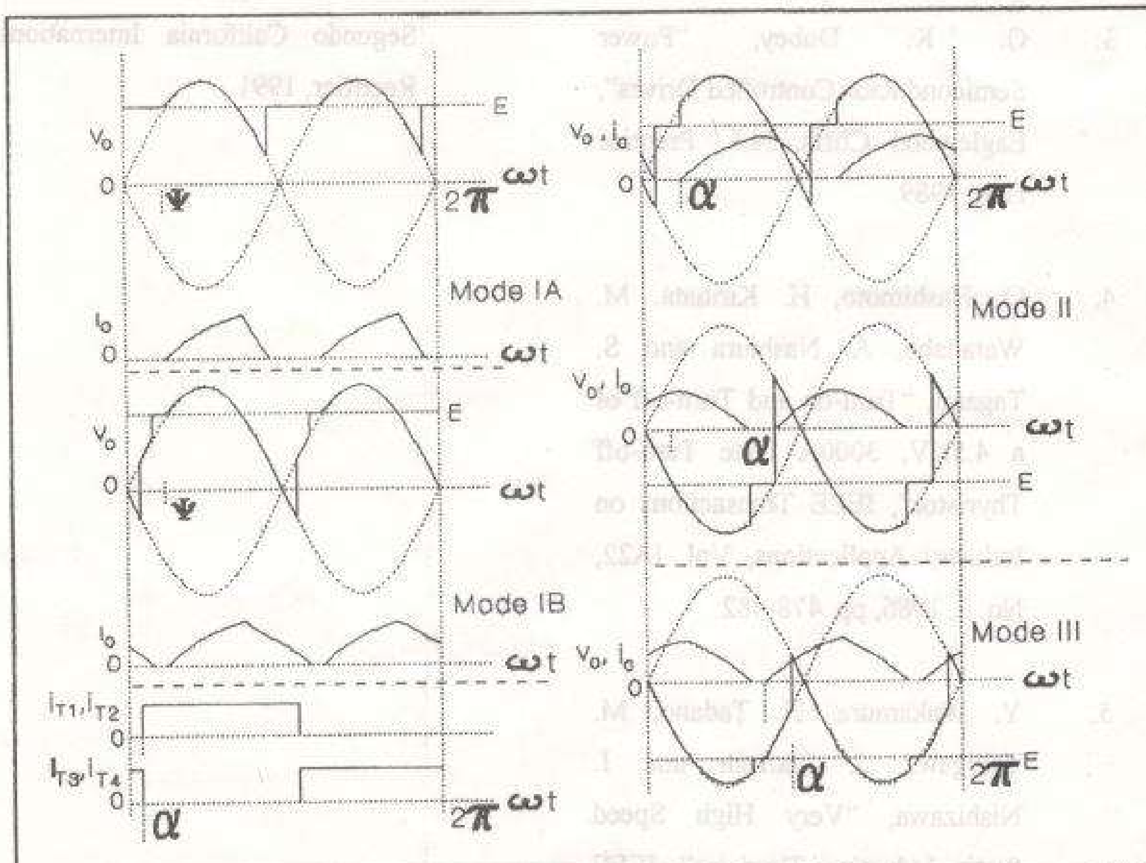

Fig. 2 Discontinuous load current modes in 2-pulse fully phase controlled converter

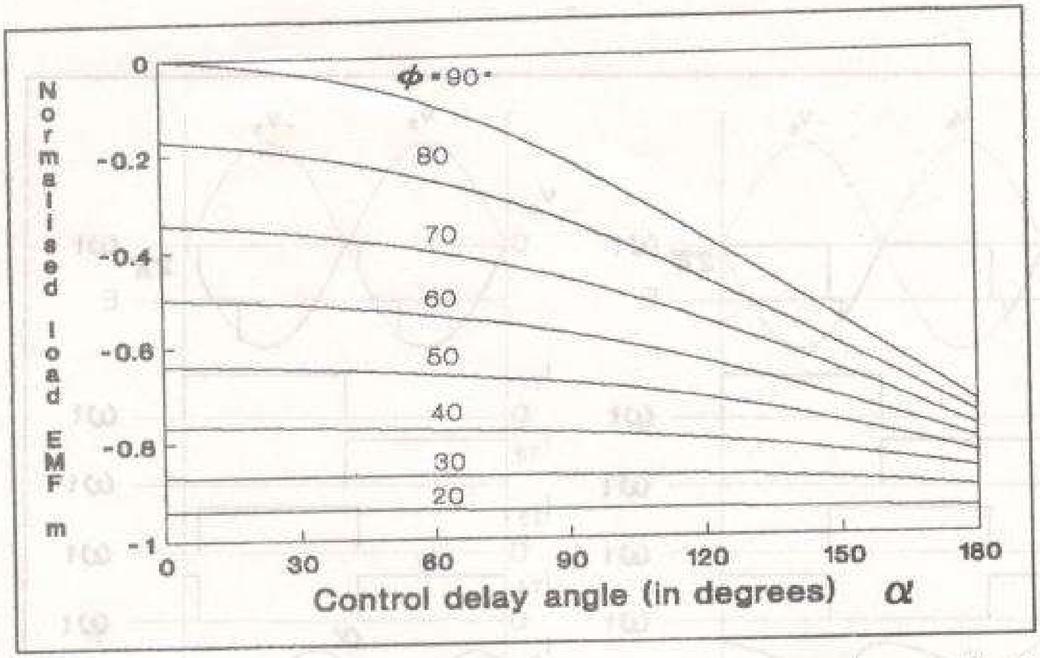

Fig. 3 Boundary between continuous and discontinuous load current modes for phase controlled 1-pulse converter(Np=1)

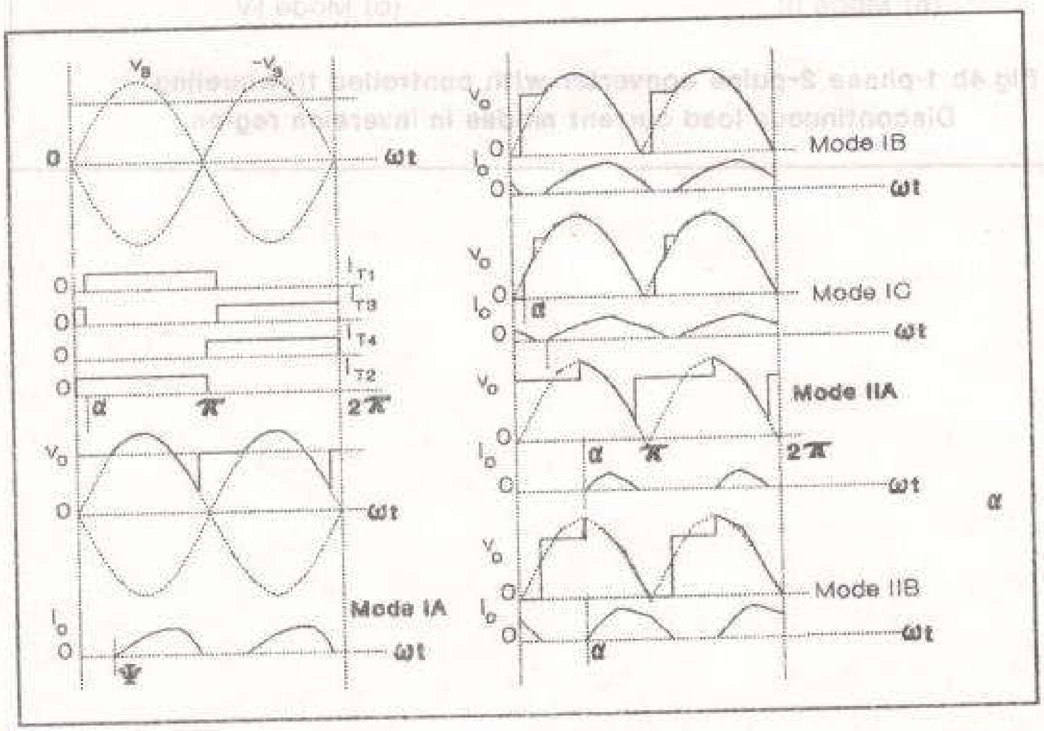

Fig. 4a Discontinuous load current modes of the 2-pulse phase controlled converter with controlled flywheeling and operating in the rectification region

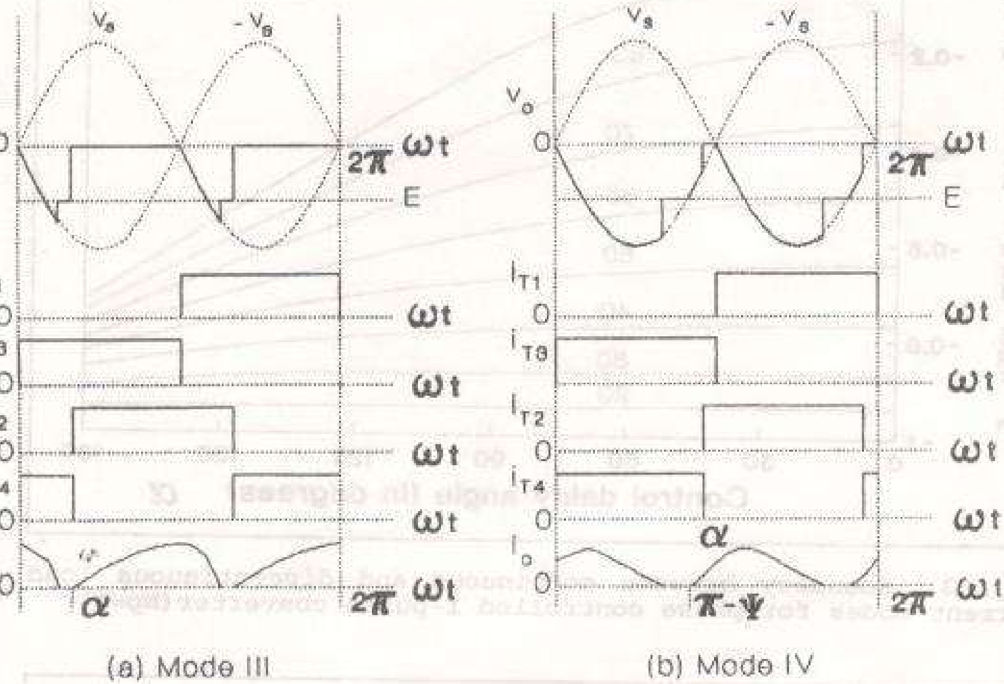

Fig.4b 1-phase 2-pulse converter with controlled flywheeling Discontinuous load current modes in inversion region