A UNIFIED APPROACH IN DETERMINING MODES OF CURRENT CONDUCTION IN FULLY PHASE-CONTROLLED AC TO DC CONVERTERS

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ABSTRACT
This paper presents a unified analysis method in the determination of the different modes or aspects of current conduction in fully phase-controlled converters. In this method, continuous load current mode is initially assumed and the unified expressions for the instantaneous load currents for converters with output pulse number greater than one are determined at points of the converter output voltage discontinuities and/or at points of minimum output current values. Modified expression for the instantaneous current value for the converter with one output pulse number is derived. From the signs of these instantaneous current values, the converter output current modes are identified. In the analysis, 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. The reported method has the advantage of giving more information than other reported methods available in the literature about the nature/shape of a given converter output current waveform and the degree of load current continuity or discontinuity from the transition of continuous to discontinuous current conduction modes.
Index terms – ac to dc converters, control delay angle, continuous/discontinuous current conduction mode

1. INTRODUCTION

Studies on current conduction in phase-controlled ac to dc converters have been widely reported, [1, 2 and 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 reduce the harmonic power loss and other disadvantages that may be associated with discontinuous load current conduction.

For the conventional fully phase-controlled converter, Dewan and Straughen [1], used iterative method to plot boundary curves between continuous and discontinuous current modes for switching instants where the ac voltage instantaneous value is greater than the load emf or the load dc voltage. Further work by Dubey and others identified discontinuous current modes for switching instants where the ac voltage instantaneous value is less than the load emf [2, 3]. But, to identify current conduction modes, this further work initially assumes zero converter output current value at the given converter control delay angle.

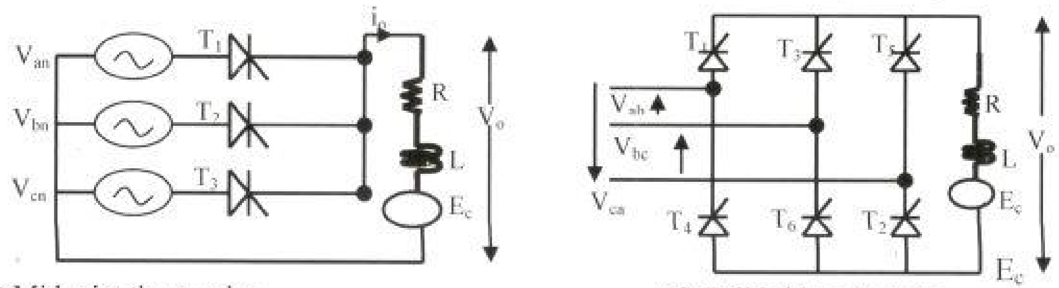
The unified analysis method employed in this paper initially assumes continuous load current, which allows progressive determination of the exact value of the instantaneous converter output current at the instant of output voltage discontinuity or minimum load current. With these known instantaneous 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. A generalized analysis is given for fully phase-controlled converters with an output pulse number greater than one and in modified derived expressions for the one pulse converter obtained.

2. THE AC TO DC CONVERTER

Figures 1(a) to 1(d) are the basic configurations of the one pulse, two-pulse, three-pulse and six-pulse fully phase-controlled thyristor ac to dc converters. The converter ac source (reference) input voltage is designated as $V_m \sin\omega t$. The thyristor 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_c. The assumed turn on signal duration and the range of the control delay angle are 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

(a) one pulse (b) Full bridge two pulse



(c) Midpoint three pulse (d) Full bridge six pulse

Fig 1. Basic configurations of the one pulse, two-pulse, three-pulse and six-pulse ac to dc thyristor converters.

3. Generalised Analysis of the Fully Phase-Controlled N_P-Pulse Converter

3.1 Modes of Discontinuous Load Current

For a general RLE load supplied by a fully phase-controlled N_p-pulse converter with $N_p>1$, there are three modes (Fig, 2: continuous and discontinuous current modes shown for $N_p = 2$) of discontinuous load current conduction. 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)

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

$\omega t_a = 0$ for $N_p = 1$

$= \pi (1/2 - 1/N_p)$ 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 1 discontinuous current conduction can only occur during the converter rectification mode.

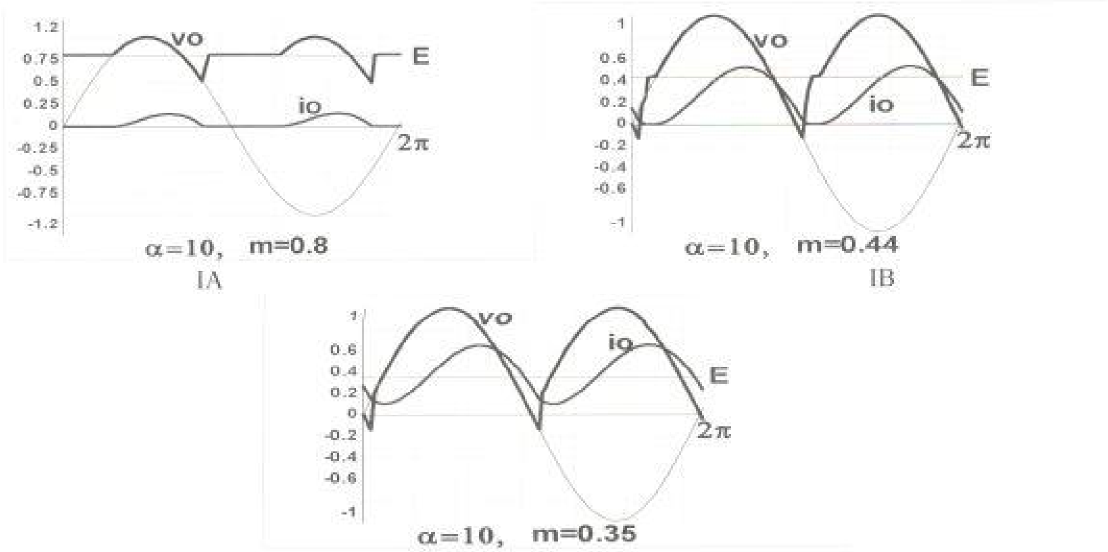
Mode II: *Mode II discontinuous load current operation occurs in the α control delay angle range given by*

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

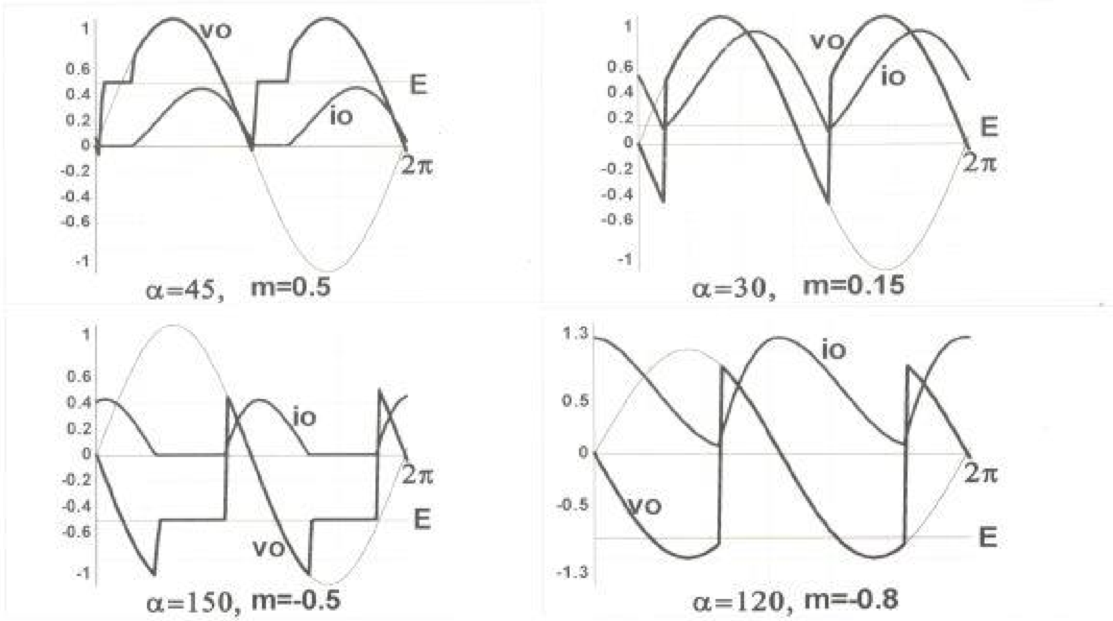
In this mode of operation, the k[th] load current pulse starts from zero value at the switching instant $\omega t = \alpha+\omega t_a + (k-1)2\pi/N_p$ and goes to zero again before the $(k+1)^{th}$ phase of the converter input voltage is switched across the load at $\omega t = \alpha + \omega t_a + 2k\pi/N_p$. 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

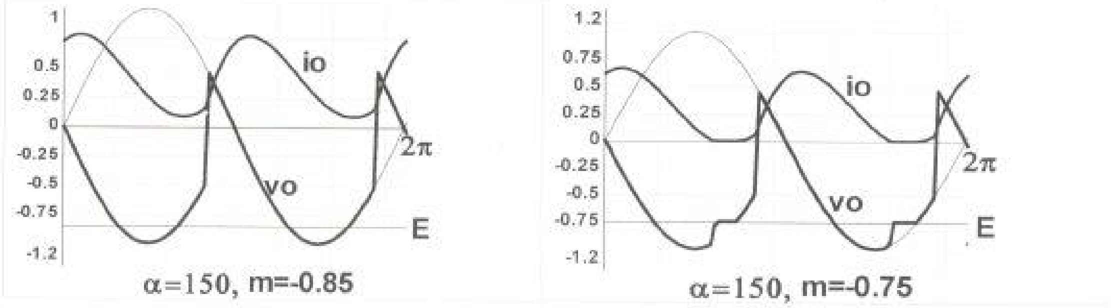
$$(N_p - 1)2\pi/N_p - \psi \le \alpha+\omega t_a \le \omega t_a + \pi \text{ for } m< 0 \text{ and } N_p>1 \quad (4)$$



(a) Mode I $0 \le \alpha \le \mu$



(b) Mode II $\mu \le \alpha \le \pi-\mu$



(c) Mode III $\pi-\mu \le \alpha \le \pi$

Fig.2: **Conduction modes for the 2-pulse full bridge thyristor ac to dc converter**

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. 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, [4] – [8], 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

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

where t_q is the thyristor turn off time.

3.2 *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 impedance angle ϕ. Then the instantaneous value of the load current is determined at the angular distance where, at the boundary between continuous and discontinuous load current operation, the load current is zero. 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 as in equations (6), (7) and (8) below.

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

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

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

where:

$$x_1 = (\alpha+\omega ta-\psi)/\tan\phi \quad (9)$$

$$x_2 = (\alpha+\omega ta-2\pi+\psi)/\tan\phi \quad (10)$$

$$\psi' = 2\pi(N_p-1)/N_p - \psi \quad (11)$$

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 value $I_{0\alpha}$ at $\omega t = \alpha + \omega t_a$ for $I_{0\psi} = 0$.

$$I_{0\alpha} = -m/\cos\phi - \sin(\alpha-\omega t_a-\phi) + \{m/\cos\phi - \sin(\psi-\phi)\}e^{x_3}, \quad \alpha+\omega t_a \le \psi \quad (12)$$

where $x_3 = \psi-\alpha+\omega t_a-\pi$

(13)

Load current conduction is mode 1A or 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 at $\omega t = \alpha+\omega t_a$ is zero. Under this condition, $I_{0\psi}^{//}$ can be shown to be

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

If $I_{0\psi}^{//} \geq 0$, load current is continuous.
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 be unbounded for $\phi = 0$, while, for pure inductive load, the term $(1/\cos\phi)$ will also be unbounded $\phi = \pi/2$. 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.

3.3 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 between continuous and discontinuous current modes can be obtained by setting the appropriate expression equations (6), (7), (8) or (14) of the instantaneous current equal to zero. For the one-pulse, two-pulse, three-pulse and six pulse fully phase converters of Fig. 1, Figures 3 to 6 show plots of the boundary curves between continuous and discontinuous load current modes of m versus α with the load impedance angle ϕ as the parameter.

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

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

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

$$m_b(0<\phi<\pi/2) = \cos\phi\{\cos(\alpha-\phi)\sin\omega t_a - \sin(\alpha-\phi)\cos\omega t_a(1+e^{-2\pi/(Np\tan\phi)})/(1-e^{-2\pi/(Np\tan\phi)})\}, \quad \psi \leq \alpha+\omega t_a \leq \psi^{/} \qquad (18)$$

On the other hand, iterative method has to be used to determine $m_b(0<\phi<\pi/2)$ in the delay angle ranges of $0\leq \alpha+\omega t_a \leq \psi$ and $\psi^{/} \leq \alpha+\omega t_a \leq \pi+\omega t_a$. 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.

Illustrative Performance Graphs from Analysis Equations

From equations 6 to 18, a general program is developed to obtain the boundary curves (Figs. 3-6) of the normalized load emf m versus the control delay angle α^{o} with the load impedance angle ϕ as the parameter for converter output pulse number N_p of one, two, three and six respectively. For a given boundary curve corresponding to a given load impedance angle, ϕ, a given operating point (α, m) under the given load angle has continuous or discontinuous load current according as the given operating point is below or above the boundary curve. For a discontinuous load current operation so identified, the nature of the discontinuity can be determined from (12) to (14).

4. CONCLUSION

In this paper, a unified and an improved method for the identification of continuous and discontinuous load current modes in fully 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 information on how far the continuous current operation is from being discontinuous. The reverse is the case if the 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.

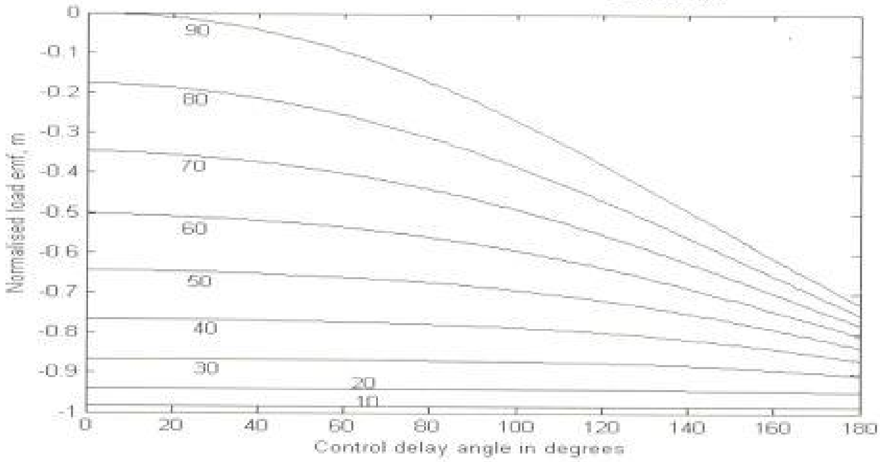


Fig. 3: Boundary between continuous and discontinuous load current modes in the m versus α plane with ϕ as parameter for one-pulse ac to dc thyristor converter

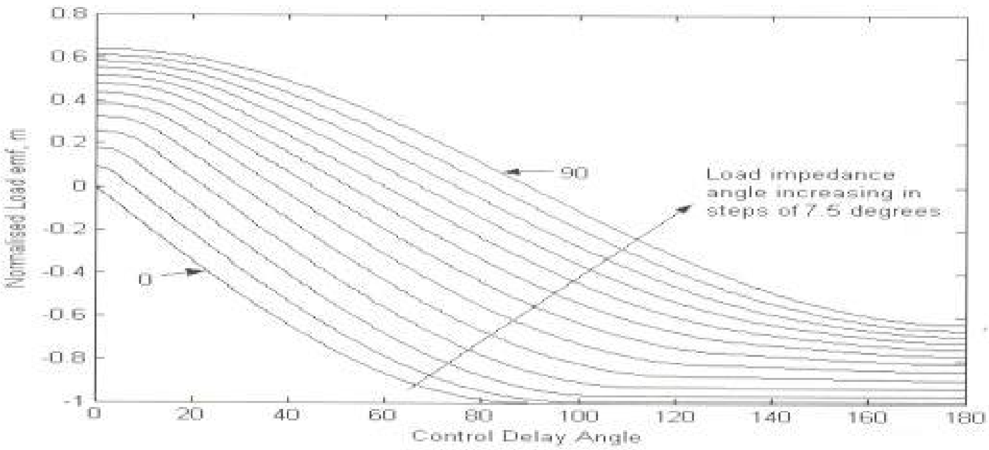


Fig.4 Boundary between continuous and discontinuous load current modes in the m versus α plane with ϕ as parameter for a 2-pulse ac to dc thyristor converter

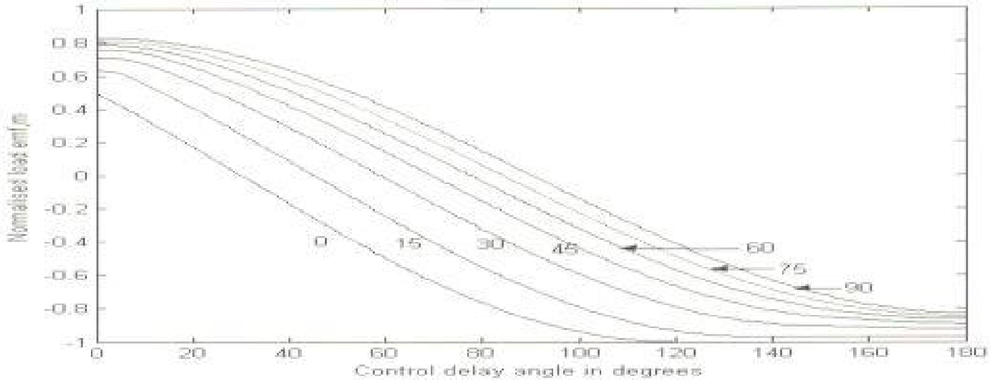


Fig.5 Boundary between continuous and discontinuous current modes in the m versus α plane with ϕ as parameter for a 3-pulse ac to dc thyristor converter

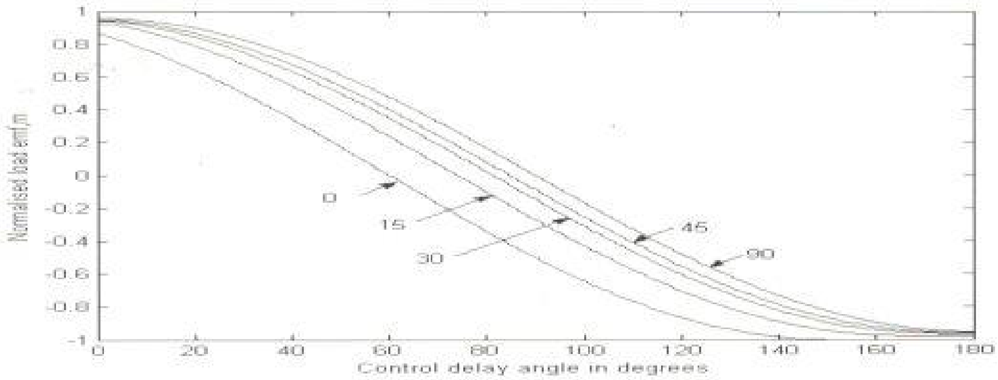


Fig.6 Boundary between continuous and discontinuous current modes in the m versus α plane with ϕ as parameter for a 6-pulse ac to dc thyristor converter

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