INFLUENCE OF p–n CAPACITY BARRIER ON OPTIMAL RC PROTECTION OF THYRISTORS

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Safe operation of the thyristor depends strongly on the critical rate of rise of the off-state voltage, the rate of on-state current, as well as on the recovery overvoltage. The snubber or commutation circuits ensure the required protections of the thyristor. Nevertheless, the design of the snubber circuits is not simple, the protective circuit designed to satisfy the requirements of one quantity will not necessarily perform optimally for another quantity, and a compromise solutions have to be sought. The paper deals with the optimal thyristor snubber design assuming the real thyristor parameters characteristic of the turn-on and turn-off switching intervals of the thyristor. For both modes of operation, the thyristor was replaced by a parallel RC equivalent model, unlike in previous studies, which treated the thyristor as an ideal switch. The analysis study was performed in normalize form to provide a generalized approach. The analysis results are presented by diagrams, for simplification of the selection of required RC elements for particular thyristor protection. The objective of the paper was to evaluate to what extent the choice of protective elements is affected by the RC model parameters of the thyristor and to provide optimal snubber protection for the thyristor. It was demonstrated that the thyristor equivalent capacitance together with other parasitic capacitances, significantly influence the choice of protective components.

K e y w o r d s: thyristor, reverse overvoltage, reverse mod, protective circuit, p-n junction, conducting losses, numerical procedures

1 INTRODUCTION

The rate of rise of the off-state voltage, as well as the recovery overvoltage, are usually limited by connecting a RC circuit in parallel to the thyristor, while the rate of current rise in the on-state is limited by adding an inductance in series to the thyristor. As a result, RC and L, or snubber protection of the thyristor is obtained. The issue of thyristor protection has been dealt with in a number of reports, which may be divided into two basic groups with respect to the thyristor equivalent model during junction recovery. The first group of papers treat the thyristor essentially as an ideal switch [1–4], the most comprehensive presentation is provided in [4], while in the second group, where the thyristor is replaced by a current source with an exponential decrease [5–7] , the most detailed approach is outlined in [7]. Since the thyristor turn-on and turn-off processes are significantly affected by the reverse-biased p-n junction, the thyristor may be modelled by equivalent parallel RC elements during the turn-on and turn-off switching intervals. In addition to parallel RC elements, the capacitance between the thyristor anode and cathode is connected in parallel, or in the case of a series connection, a resistor is placed in parallel to the thyristor. The values of the snubber components, RC and L, can be derived using this equivalent switching model of the thyristor. The efficiency of the calculated protective strategies is tested by supplying a direct voltage to the equivalent circuit. All relevant functions were normalized and provided in dependence on rated factors and thyristor parameters. It gives possibility to set up a family of peak overvoltage and control the rise times off first maximum voltage curves for the given initial conditions, which may be used for the choice of an optimal thyristor protection.

2 EQUIVALENT SCHEME AND BASIC FUNCTIONS

The thyristor turn-on and turn-off processes are significantly affected by the biased p-n junction that acts as a parallel connection of nonlinear RC elements. The capacitance of the p-n junction is determined by its dimension and by the reverse supply voltage. Since thyristor dimensions increase with increasing power, the capacitance of the reverse-biased p-n junction increases while its resistance decreases, so that they can no longer be neglected during the turn-on and off periods. For the same reason, the parasitic anode to cathode capacitance also increases. In the event of a thyristor series connection, an additional resistance is introduced between the anode and the cathode. Considering this fact, the thyristor was modelled by parallel R_1 and C_1 elements (Fig. 1). The objective of the current investigation was to evaluate the influence of these elements on the choice of protective elements R_2 and C_2, which are connected in parallel to the thyristor (Fig. 1). To simplify the analysis, the equivalent elements R_1 and C_1 were assumed to be linear. For the same reason, the protective R_2C_2 circuit was assumed to be noninductive and the resistance of the inductive winding L was neglected (Fig. 1). Direct voltage E was supplied to

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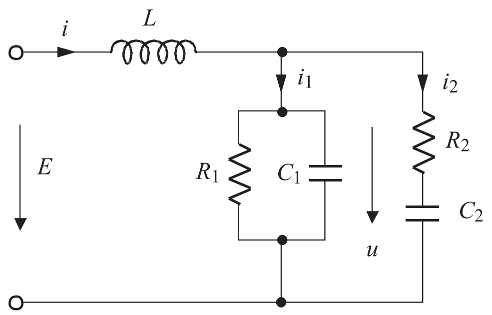

Fig. 1. Equivalent scheme of the thyristor and protective elements.

the thyristor in the experimental setup, while for all other waveforms the values were obtained by computation.

The initial conditions for the analysis of the voltage rise time rate are $i(0) = 0$ and $u(0) = 0$, and those for the analysis of the recovery overvoltage, $i(0) = I_{2M}$ (maximum reverse current). The voltage on capacitance C_1 was assumed to be $u(0) = U \leq E$ [8, 10, 11].

For the sake of generalization, the analysis is most conveniently performed in a normalized form. Hence, the dimensionless time $\tau = T$ is defined first, while the angular frequency shall be determined later. The equivalent scheme of the thyristor circuit (Fig. 1) can be described by the following equations:

$$\begin{aligned} &\omega L\frac{\mathrm{d}i}{\mathrm{d}\tau} + u = E\,, \quad i = i_1 + i_2\,, \\ &i_1\frac{u}{R_1} + \omega C_1\frac{\mathrm{d}u}{\mathrm{d}\tau}\,, \quad u = R_2 i_2 + \frac{1}{\omega C_2}\int i_2 \mathrm{d}\tau\,. \end{aligned} \tag{1}$$

where: E – direct voltage, u – thyristor voltage.

The rated thyristor voltage is obtained from the Laplace transform of eqns. (1):

$$\frac{U(p)}{E} = \frac{b_3p^3 + b_2p^2 + b_1p + 1}{p(a_3p^3 + a_2p^2 + a_1p + 1)} \tag{2}$$

where:

$$\begin{aligned} a_1 &= \omega\Big(\frac{L}{R_1} + R_2C_2\Big), \quad b_1 = \omega\Big(\frac{Li(0)}{E} + R_2C_2\Big), \\ a_2 &= \omega^2 LC_1\Big(1 + \frac{C_1}{C_2} + \frac{R_1C_1}{R_2C_2}\Big), \\ b_2 &= \omega^2\Big(\frac{Li(0)}{E}R_2C_2 + LC_1\frac{u(0)}{E}\Big), \\ a_3 &= \omega^3 LC_1R_2C_2\,, \qquad b_3 = \omega^3 LC_1R_2C_2\frac{u(0)}{E}\,. \end{aligned} \tag{3}$$

To define the unknown angular frequency ω, it is convenient to select a unity value for the term a_3 ($a_3 = 1$) of the characteristic equation (2), which yields:

$$\omega^3 = \frac{1}{LC_1R_2C_2}\,. \tag{4}$$

To simplify and generalize the computation, the following substitutions are introduced:

$$\begin{aligned} &\omega_0 = \frac{1}{\sqrt{LC_1}}\,, \rho = \sqrt{\frac{L}{C_1}}\,, \quad \delta = \frac{\rho}{R_1}\,, \\ &\alpha = \frac{\omega_0 Li(0)}{E} \text{– initial current factor,} \\ &\beta = \frac{u(0)}{E} \quad \text{– initial voltage factor} \end{aligned} \tag{5}$$

and the unknown protective elements R_2 and C_2 are replaced by the following rated parameters:

$$\lambda_1 = \frac{R_2}{\rho}\,, \qquad \lambda_2 = \frac{C_2}{C_1}\,. \tag{6}$$

The characteristic equation may now be written as:

$$p^3 + a_2p^2 + a_1p + 1 = (p + p_0)(p^2 + 2\zeta\omega_n p + \omega_n^2) = 0 \tag{7}$$

where ζ is the relative damping factor and ω_n is the relative angular frequency of undamped oscillations.

Comparison of the coefficients in equation (7) yields:

$$p_0 = \frac{1}{\omega_n^2}\,, \quad a_1 = \omega_n^2 + \frac{2\zeta}{\omega_n}\,, \quad a_2 = \frac{1}{\omega_n^2} + 2\zeta\omega_n\,. \tag{8}$$

For further simplification, the following substitutions are introduced:

$$\lambda = \sqrt[3]{\lambda_1\lambda_2}\,, \quad z = \frac{\lambda}{\omega_n}\,, \quad x = \omega_n\tau\,. \tag{9}$$

Considering substitutions (8), (7) and (3), the following two equations are obtained:

$$\begin{aligned} \frac{\delta}{z\omega_n^3} + z^2 &= \frac{2\zeta}{\omega_n^3} + 1\,, \\ \frac{1 + \lambda_2}{z^2\omega_n^3} + \delta z &= 2\zeta + \frac{1}{\omega_n^3}\,. \end{aligned} \tag{10}$$

Equation (10) yields:

$$\omega_n^3 = \frac{2\zeta z - \delta}{z(z^2 - 1)}\,, \quad \lambda_2 = \frac{(2\zeta - \delta z)(2\zeta z - \delta)}{z^2 - 1}z + z^2 - 1\,. \tag{11}$$

By introducing the above substitutions, it was possible to express the angular frequency ω_n explicitly in terms of only two variables, ζ and z. Further, the coefficients b_1, b_2 and b_3 in (3) can now also be expressed in terms of the variables ζ and z:

$$\frac{b_1}{\omega_n^2} = \frac{\alpha}{z\omega_n^3} + z^2\,, \quad \frac{b_2}{\omega_n} = \alpha z + \frac{\beta}{z^2\omega_n^3}\,, \quad b_3 = \beta\,. \tag{12}$$

Consequently, the parameters of the voltage equation (2) appear to be dependent on two variables (ζ and z) and three factors (α, β and δ).

3 DETERMINATION OF PEAK VOLTAGE VALUE

To establish the recovery overvoltage and the rate of thyristor voltage increase, it is necessary to determine the first thyristor voltage peak. This voltage depends on factors a, p and those in (8) and on variables ζ and z, which in turn depend on parameters λ_1 and λ_2. If follows from eqn. (7) that there are four characteristic cases, for each of which the voltage waveform $u(\tau)$ is analyzed.

1. Case $\zeta < 1$

The expression for the rated thyristor voltage is of the following form:

$$\frac{u}{E} = 1 + Ae^{-x\omega_n^3} + e^{-\zeta x}[A_1 \sin mx + A_2 \cos mx] \quad (13)$$

where:

$$m = \sqrt{1-\zeta^2}\,, \qquad A = \frac{\frac{b_3}{\omega_n^6} - \frac{1}{\omega_n^3}\frac{b_2}{\omega_n} + \frac{b_1}{\omega_n^2} - 1}{m_3^2 + m^2}\,,$$

$$A_1 = \frac{m_1 m_3 + m m_2}{m(m_3^2 + m^2)}\,, \quad A_2 = \frac{m_2 m_3 - m m_1}{m(m_3^2 + m^2)}\,,$$

$$m_1 = (\zeta^2 - m^2 b_3 - \zeta\Big(\frac{b_2}{\omega_n} + \frac{1}{\omega_n^3}\Big) + \frac{b_1}{\omega_n^2}\,,$$

$$m_2 = \Big(\frac{b_2}{\omega_n} - 2\zeta b_3 - \frac{1}{\omega_n^3}\Big) + \frac{b_1}{\omega_n^2}\,,$$

$$m_3 = \frac{1}{\omega_n^3} - \zeta\,.$$

The first maximum of function (13) cannot be accurately determined analytically but only numerically.

2. Case $\zeta = 1$

The required rate voltage is of the following form:

$$\frac{u}{E} = 1 + Ae^{-x\omega_n^{-3}} + e^{-x}[A_1 x + A_2] \qquad (14)$$

where:

$$A_1 = \frac{m_1}{m_2}\,, \quad A_2 = \frac{b_3 - \frac{b_1}{\omega_n^2} + \frac{1}{\omega_n^3}\Big[2(1-b_3) + \frac{b_2}{\omega_n} - \frac{1}{\omega_n^3}\Big]}{m_3^2}$$

while the constants A, m_1 and m_0 have the same values as in the previous case, provided that $\zeta = 1$.

3. Case $\zeta = \omega_n = 1$

$$\frac{u}{E} = 1 + a^{-\tau} + e^{-x}\Big[\frac{A_1\tau^2}{2} + A_2\tau + A_3\Big] \qquad (15)$$

where: $A_1 = b_1 - b_2 + b_3 + 1$, $A_2 = b_2 - 2b_3 - 1$, $A_3 = b_3 - 1$. The first maximum can be determined accurately from eqn. (15) using an analytical procedure.

4 Case $\zeta > 1$

The required rate voltage is:

$$\frac{u}{E} = 1 + Ae^{-x\omega_n^{-3}} + A_1 e^{s_1 x} + A_2 e^{s_2 x}\,, \qquad (16)$$

where:

$$s_1 = \zeta - \sqrt{\zeta^2 - 1}\,, \quad s_2 = \zeta + \sqrt{\zeta^2 + 1}\,,$$

$$A_1 = \frac{s_1^2 b_3 - a_1\frac{b_2}{\omega_n} + \frac{b_1}{\omega_n^2} - \frac{s_2}{\omega_n^3}}{\big(\frac{1}{\omega_n^3} - s_1\big)(s_2 - s_1)}\,,$$

$$A_2 = \frac{s_2^2 b_3 - s_2\frac{b_2}{\omega_n} + \frac{b_1}{\omega_n^2} - \frac{s_1}{\omega_n^3}}{\big(\frac{1}{\omega_n^3} - s_1\big)(s_2 - s_1)}$$

while constant A has the same value as in the previous case.

The first maximum of function (16) can only be accurately determined by a numerical procedure. For this purpose, eqn. (16) is first differntiated and then its maximum calculated.

4 TURN–OFF PEAK VOLTAGE AND TURN–OFF RISE TIME VALUES DIAGRAMS

When designing a thyristor protection strategy, current protection with inductance L should be defined first using relation $L = E : (\mathrm{d}i/\mathrm{d}t)$ to the turn-on current rise $\mathrm{d}i/\mathrm{d}t$. Whereupon voltage protection is defined by selecting protective elements R_2 and C_2. The purpose of this voltage protection is to prevent an increasing of the turn-off recovery overvoltage and turn-off voltage rise values in excess of certain critical or borderline values. There are a number of pairs of R_2–C_2 values which satisfy particular criteria, but there are less number of values which satisfying both voltage criteria. For general practical purposes, the following rated functions must be defined:

1. Rated overvoltage

$$M_n = \frac{U_m}{E} = f(\alpha, \beta, \delta, \zeta, z)\,. \qquad (17)$$

2. Rated time of maximum voltage increase

$$T_n = \omega_n t_1 = z x_1 = g(\alpha, \beta, \delta, \zeta, z)\,. \qquad (18)$$

Both functions depend on factors α, β and δ and variables ζ, and z, which in turn depend on parameters λ_2 and λ_2. With these factors, parameters λ_1 and λ_2 satisfy the rated values of M_n and T_n. Accordingly, for different values of M_n, function f can be represented by a family of curves in the field of the λ_1 ?and λ_2. Function g can be represented in a similar manner. Similarly, it was possible to set up a series curve families M_n and T_n in dependence on parameters λ_1 and λ_2 for different values of factors α, β and δ. The curve families M_n and T_n for $\alpha = 0.01$ and $\alpha = \beta = 0$ are shown in Fig. 2.

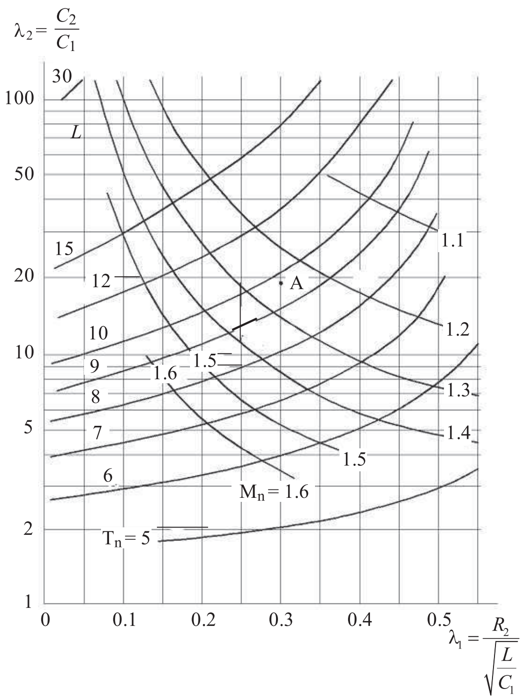

Fig. 2. Normalized overvoltage M_n and time T_n diagrams ($d = 0.01$; $a = b = 0$).

5 SELECTION OF THYRISTOR AND ITS RC PROTECTION FOR PARTICULAR APPLICATION

5.1 Thyristor selection and basic data

Thyristor selection basically depends on a particular circuit operating conditions which define the requirements at thyristor characteristics, such as rated and permitted voltage and current, latching and holding current, turn-on and turn-off recovery time, permitted $\mathrm{d}u/\mathrm{d}t$ and $\mathrm{d}i/\mathrm{d}t$ values, *etc.*

Similar difficulties are encountered in design of the high frequency converters. The operating frequency increase is limited by the following values: critical values of the rate of turn-on rise time of the blocking voltage ($\mathrm{d}u/\mathrm{d}t$) and the rate of the turn-on current rise ($\mathrm{d}i/\mathrm{d}t$), switching time (turn-on, recovery time) and power dissipation of the thyristor.

The power rating of the thyristor is significantly affected by its operating frequency. Higher frequencies cause increasing of the switching losses, losses. For reliable thyristor operation, it is essential to balance switching and conducting losses in order to avoid excessive temperature oscillations, which may lead to fatigue of thyristor materials. Fatigue resulting from different temperature coefficients of thyristor components eventually leads to thyristor breakdown after a given number of heating and cooling cycles. This process is significantly affected by the rate of turn- on current increase ($\mathrm{d}i/\mathrm{d}t$). A proper selection of thyristor protection may substantially reduce the switching losses occurring during thyristor turn-on.

The power rating of the thyristor also depends on the current waveform. Thus with decreasing the leading angle the ratio of maximum to average power increases, leading to an increase ratio of the peak to virtual average temperature values. Likewise, it is important to consider that the RC protection may influence the efficiency factor and affect the switching times.

Of course, the above thyristor parameters will not all assume a critical value at the same time and this will largely depend on the operating conditions. Different types of thyristors have therefore been designed to meet the requirements of different types of converters.

The 501PBQ110 thyristor was selected to illustrate the computation of RC protection. The RC protection was defined for the following operating conditions without going into a detailed analysis of the operation of a given converter:

$$\frac{\mathrm{d}u}{\mathrm{d}t} = 300\frac{\mathrm{V}}{\mu\mathrm{s}}\,,\ \frac{\mathrm{d}i}{\mathrm{d}t} = 25\frac{\mathrm{A}}{\mu\mathrm{s}}\,,\ I_T = 250\,\mathrm{A},\ E = 600\,\mathrm{V}\ (\text{direct}).$$

The required inductance may be easily computed from the following equation:

$$L = E\big(\mathrm{d}i/\mathrm{d}t\big) = 24\,\mu\mathrm{H}\,.$$

The values of resistance R_1 and C_1 cannot be determined uniquely. The capacitance of the P–N junction is nonlinear and it ranges between 1 nF and 10 nF for the thyristor in question. Since resistance R is added in parallel to each thyristor in a series connection, the value of resistance R_1 is set between 4.9 and 50 kΩ.

5.2 Computation of RC protection for $\mathrm{d}u/\mathrm{d}t$

The rate of critical charge generation in the bases also depends on the anode voltage waveform. The critical or borderline value of du/dt is that value at which the thyristor is still capable of blocking the voltage of a given linear increase amplitude. This value is usually obtained experimentally. Since under real-time conditions the voltage waveform differs from the test voltage waveform, it is essential to determine the functional correlation between the experimentally obtained critical value of $\mathrm{d}u/\mathrm{d}t$ and the actual voltage waveform. The critical value of $\mathrm{d}u/\mathrm{d}t$ is defined as follows:

$$\left(\frac{\mathrm{d}u}{\mathrm{d}t}\right)_{kr} = k\frac{U_m}{t_1} \tag{19}$$

where:

U_m –peak value of increasing voltage,
T_1 –time of the first maximum, peak, voltage,
K –voltage waveform correction factor.

Some manufacturers test the rate of voltage increase by supplying voltage of the waveform $u = U_m(1 - e^{-t/\tau})$. The critical rate of voltage increase is defined by the slope of the straight line through a point, the value of which is $0.632\,U_m$. It is assumed that after three time constants

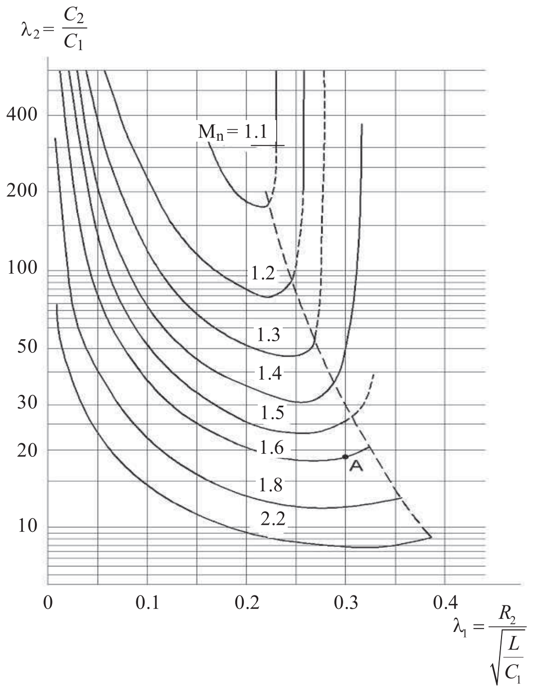

Fig. 3. Rated diagram of reverse overvoltage M_n ($\delta = 0.01$, $\alpha = 4.49$, $\beta = 0$).

τ the exponential function attains its maximum value, yielding in this case $t_1 = 3\tau$?and $k_1 = 1.9$.

It is assumed that in the case of a sine voltage waveform the slope is defined by a straight line through point 0.5 Um, in which case $t_1 = \pi/2$ and $k_3 = 1.5$. This definition appears to approximate a linear voltage increase most closely because there is only a slight deviation.

When voltage E is supplied to a thyristor circuit (Fig. 1), the thyristor voltage increases from an initial value of $u(0)$ to its first peak U_m over time t_1. Based on eqns. (17), (18) and (19), the rated value of thyristor voltage increase is obtained as follows:

$$\left(\frac{\mathrm{d}u}{\mathrm{d}t}\right)_n = \frac{1}{k\omega_0 E}\frac{\mathrm{d}u}{\mathrm{d}t} = \frac{M_n}{T_n}\,. \qquad (20)$$

Thus, if $R_1 = 4.9\,\mathrm{k}\Omega$ and $C_1 = 10\,\mathrm{nF}$, it follows from eqn. (5) that $\delta = 0.01$ with initial voltage and current equaling zero, so that $\alpha = \beta = 0$. The corresponding family of curves T_n and M_n is shown in Fig. 2. With given values of E, $\mathrm{d}u/\mathrm{d}t$ and $k = 1.9$, the rated voltage obtained from eqn. (20) is $(\mathrm{d}u/\mathrm{d}t)_n = 0.129$. Assuming that the overvoltage is 26 % of E, then the rated overvoltage is $M_n = 1.26$ and eqn. (20) yields $T_n = 9.77\,s$ for the rated time of increase. As this corresponds to point A in Fig. 2, it follows that the optimal RC protection is defined by $R_2 = 14.7\,\mathrm{k}\Omega$ and $C_2 = 0.185\,\mu\mathrm{F}$.

Based on the numerical analysis outlined in [11], it may be concluded that the selection of RC protection appears to be unaffected by $R_1 > 4.9\,\mathrm{k}\Omega$, while the influence of capacitance C_1 is obvious. Namely, at a 10-fold increase in capacitance C_1, the value of protective resistance R_2 increased by about 11 % and that of capacitance C_2 by about 7 %. It should be noted that the capacitance of the reverse-biased junction decreases with increasing voltage.

For the RC protection of the experimental thyristor the manufacturer provided the following values: $R_2 = 15\,\Omega$ and $C_2 = 0.2\,\mu\mathrm{F}$, whereas eqn. (4) yielded $R_2 = 11.8\,\Omega$ and $C_2 = 0.175\,\mu\mathrm{F}$. It should be noted that the correlation between the results obtained in the current analysis and those outlined in [4] is satisfactory only in the range of least susceptibility to parasitic capacitance C1, which was no considered in [4].

5.3 Overvoltage in the reverse mode of thyristor operation

The reverse mode of operation is analyzed using the expressions for peak voltage determination (17) assuming appropriate initial conditions α and β. Oscillations in the reverse mode commence at the instant when the reverse current attains its peak value I_{RM} [9]. For the thyristor in our experimental setup, the peak reverse current value is $I_{RM} = 55$ A, so that the initial current factor α does not equal zero in this case. It was demonstrated numerically [11] that the initial current factor α exerts a dominant influence on the magnitude of overvoltage, while the initial voltage factor β is practically negligible since almost the same values are obtained for both $\beta = 0$ and $\beta = 1$. Similarly, it was demonstrated that resistance $R_1 > 4.9\,\mathrm{k}\Omega$ has practically no influence, while the effect of capacitance C_1 appears to be substantial, because reverse voltage tends to increase with increasing capacitance C_1. Therefore it is obvious that the operating point should be selected so as to minimize the influence of changing capacitance C_1 on protective circuit operation.

Using eqn. (17), a family of curves was obtained for the rated overvoltage Mn assuming the following factors: $\delta = 0.01$, $\alpha = 4.49$, $\beta = 0$ (Fig. 3). For the previously selected protection parameters, the rated overvoltage is $M_n = 1.6$ (point A in Fig. 3), the corresponding maximum permitted value for the experimental thyristor being $M_n = 2$. Assuming this overvoltage and using the method described in [4], the following values were obtained: $R_2 = 13.2\,\Omega$ and $C_2 = 0.2\,\mu\mathrm{F}$. However, it should be noted that the above analysis was performed assuming instantaneous decrease of recovery current to zero (snap-off) and step waveform of reverse voltage, which actually was not the case.

6 CONCLUSION

Thyristors are sensitive to excessive increases over permitted critical values of the voltage increase rate, current increase rate during thyristor turn-on and recovery overvoltage during turn-off. Recovery overvoltage and the rate of voltage increase are limited by introducing a RC protective circuit, while the rate of current increase is limited with the aid of inductance. Since the thyristor turn-on and turn-off processes are significantly affected by the reverse-biased p-n junction, the thyristor may be replaced by a parallel RC circuit during the turn-on and off periods. Assuming such an equivalent scheme of the thyristor with appropriate RC and L protective elements, the rated responses to direct voltage supply and change of direct voltage bias were tested. Because the characteristic equation was of the third order, it was necessary to introduce a number or rated parameters. Thus it was possible to simplify and generalize the numerical procedure, by presenting the results in dependence on these parameters. The characteristic equation provides four characteristic cases.

For the purposes of analysis, it was necessary to determine the first rated thyristor voltage peak and the time to peak voltage for each of the four characteristic cases. The required numerical procedure was very complex but eventually it was possible to set up a series of diagrams of peak voltage increase and time to peak voltage in dependence on different initial conditions and protective RC elements. For the analysis of the rate of voltage increase, it was necessary to obtain two families of curves for peak voltage and time to peak voltage, respectively, while the analysis of recovery overvoltage required only one family of curves for peak voltage with appropriate initial conditions.

Since the resistance and capacitance of the p-n junction are nonlinear, the capacitance of the equivalent scheme was assumed to range between 1 and 10 nF and its resistance between 4, 9 and $50\,\mathrm{k}\Omega$, while taking care that resistance is added to each thyristor connected in series. While it was demonstrated that for the selected values the capacitance of the equivalent scheme significantly affected the choice of protective RC elements, the influence of resistance was found to be negligible. Therefore it is recommended that the operating point should be selected so as to ensure negligible changes of equivalent scheme capacitance. Optimal choice of protective elements implies that the values of RC parameters are selected with the aid of voltage increase rate and recovery voltage diagrams so as to ensure satisfactory performance during thyristor turn-on and off.

The required numerical procedure was complex but it was possible to set a series of diagrams for various factors α, β and δ, which greatly facilitate the choice of the optimal values of protective elements.

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