OPTIMALNA RC ZAŠTITA TIRISTORA

OPTIMAL RC PROTECTION OF THYRISTORS

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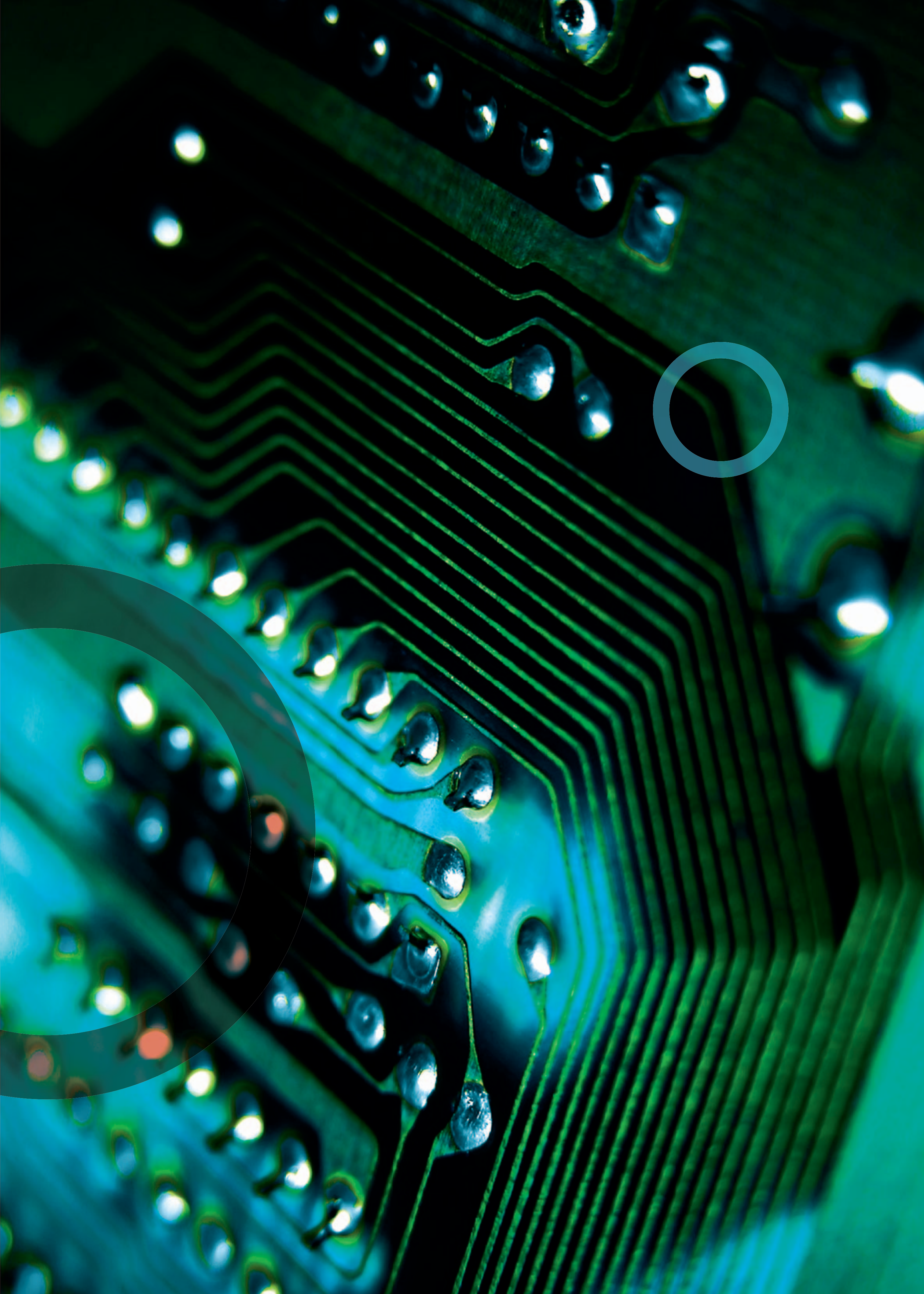
Tiristori su osjetljivi na brzinu porasta anodnog napona, prenapona oporavka i brzinu porasta struje. Zbog toga se tiristori zaštićuju dodatnim sklopovima. Ponekad zaštitni sklop projektiran za prigušenje jednog prijelaznog procesa neće biti optimalan za prigušenje drugog procesa pa je nužno nekakvo kompromisno rješenje. U radu se analiziraju optimalni uvjeti rada zaštite tiristora, s tim da su u obzir uzeti parametri tiristora, koji su karakteristični za period uklapanja i isklapanja. Analiza je provedena u normiranom obliku, što analizi daje općenitost.

Thyristors are susceptible to the increase rate of anode voltage, recovery overvoltage and current increase rate. They are therefore protected by means of supplementary circuits. Sometimes a protection circuit that has been designed to attenuate a certain transient process is not optimal for the attenuation of some other process, therefore a compromise solution is needed. In this paper, the optimal operating conditions of the thyristor protection are analyzed, where the thyristor parameters that are characteristic for the turn-on and turn-off period have been taken into consideration. The analysis has been performed in a normized form, which assures its general applicability.

Ključne riječi: frekvencija, napon, RC zaštita, regulacija, tiristor
Key words: frequency, RC protection, regulation, thyristor, voltage



1 UVOD

Tiristori imaju vrlo široku primjenu na području regulacije u elektrotehnici. Sustavi uzbude sinkronih generatora realizirani su promjenom statičke uzbude, tj. primjenom tiristora, čime se postiže: visoka pogonska preciznost, pouzdanost, potrebna snaga uzbude, te regulacija napona generatora. Također je vrlo velika primjena tiristora u regulaciji brzine vrtnje elektromotora. Posebno je pogodna primjena za velike sporohodne motore, te regulaciju grupnih elektromotornih pogona, gdje su prisutni teški pogonski uvjeti.

Isto tako je važna primjena tiristora u raznim regulatorima-pretvaračima, namijenjenim za industrijske potrebe, kao što je npr. indukcijsko grijanje i taljenje metala u svrhu daljnje obrade, te praktički svugdje gdje se zahtijeva regulacija napona i frekvencije u vrlo širokom rasponu.

Ograničenje brzine porasta napona [1] i ograničenje prenapona oporavka tiristora [2] postiže se pomoću RC sklopa koji se dodaje paralelno tiristoru, a ograničenje brzine porasta struje [3] i [4] postiže se dodavanjem induktiviteta u seriju s tiristorom. Na taj način se postiže tzv. RC zaštita i L zaštita. Na tu temu napisano je mnogo radova. S obzirom na način nadomještanja tiristora u periodu oporavka barijere svi ti radovi o zaštiti mogu se podijeliti u dvije grupe. U prvoj grupi radova tiristor se tretira kao idealna sklopka [5], a u drugoj grupi tiristor se nadomješta sa strujnim izvorom, čija struja eksponencijalno pada [6]. U radovima [1], [2], [3], [4], [7], [8] i [9] pri analizi navedenih pojava, tiristor je nadomješten paralelnim RC sklopom, ali bez zaštitnog RC sklopa, dok je u radu [3] pri analizi RC zaštite tiristor nadomješten nelinearnim otporom. U ovom radu analizira se naponska i strujna zaštita tiristora, pri čemu je tiristor nadomješten paralelnim RC sklopom.

1 INTRODUCTION

Thyristors are widely applied for regulation purposes in electrical engineering. Excitation systems of synchronous generators are realized by variation of static excitation, i.e. by application of thyristors, which assures: high operating preciseness, reliability, the required excitation power and regulation of the generator voltage. Thyristors are much applied in particular to regulate the rotation speed of an electric motor. They are particularly suitable for large, low speed motors and for regulation of electrical motor drives, where operating conditions are hard.

Also, the application of thyristors is important in various regulators-converters that are used for industrial purposes, e.g. induction heating and melting of metal for further processing, and indeed wherever a wide range regulation of voltage and frequency is required.

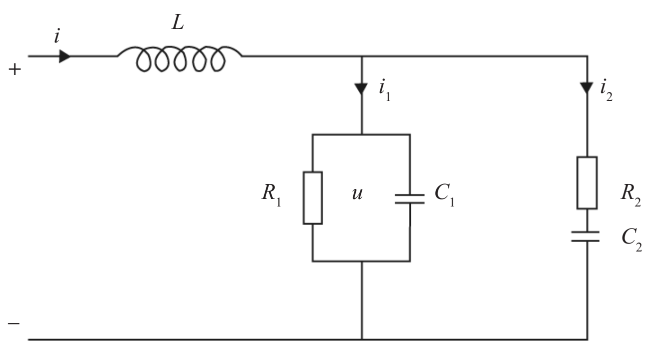
Limitation of the voltage increase rate [1] and of the thyristor recovery overvoltage [2] is achieved by an RC circuit which is added parallel to the thyristor, while limitation of the current increase rate [3] and [4] is performed by adding the inductance serially to the thyristor. In this way, the so called RC protection and L protection are realized. Many papers have been written on this topic. With regard to substitution of the thyristors in a barrier recovery period, all these papers can be grouped into two groups. In the first group, the thyristor is considered an ideal switch [5] and in the second group where the thyristor is replaced with a current source whose current decreases exponentially [6]. In the papers [1], [2], [3], [4], [7], [8] and [9] for analysis of the phenomena mentioned, the thyristor was replaced with a parallel RC circuit, but without a protective RC circuit, while in the paper [3], for analysis of RC protection, the thyristor was replaced with a nonlinear resistance. In this paper, voltage and current protection of the thyristor are analyzed, where the thyristor is replaced with a parallel RC circuit.

2 NADOMJESNA SHEMA I OSNOVNE RELACIJE

Dimenzije tiristora rastu s dopuštenom snagom pa se u nekim režimima rada ne mogu zanemariti parametri tiristora. U ovom se radu tiristor nadomješta paralenim R_1, C_1 linearnim elementima (slika 1) dok se paralelni zaštitni krug R_2, C_2 smatra bezinduktivnim, a u serijskom zaštitnom krugu s induktivitetom L se zanemaruje otpor R, koji je obično malog iznosa u odnosu na otpor tiristora R_1.

2 EQUIVALENT SCHEME AND BASIC RELATIONS

The dimensions of thyristors increase with the increase of the power allowed, and therefore the thyristor parameters in certain operating regimes cannot be disregarded. In this paper, the thyristor is replaced with linear elements R_1, C_1 (Figure 1), the parallel protective circuit R_2, C_2 is considered non-inductive and in a serial protection circuit of inductance L, the resistance R, which is usually low in comparison with the thyristor resistance, R_1, is disregarded.



Slika 1
Nadomjesna shema tiristora i elemenata zaštite
Figure 1
Equivalent scheme of the thyristor and protective elements

Početni uvjeti za analizu brzine porasta napona su $i(0) = 0$ i $u_{C_1}(0) = u(0) = 0$, dok je za analizu prenapona oporavka uzeto da je početni uvjet $i(0) = I_{2M}$ (maksimalna inverzna struja), a napon na kapacitetu je $u(0) = U < E$ [2].

Analizu je pogodno provesti u normiranom obliku, radi poopćenja rezultata pa se kao prvo definira bezdimenziono vrijeme $\tau = \omega t$. Kružna frekvencija ω naknadno će biti određena. Nadomjesna shema (slika 1) može se opisati sljedećim jednadžbama:

Initial conditions for analysis of the voltage increase rate are $i(0) = 0$ and $u_{C_1}(0) = u(0) = 0$, while for analysis of the recovery overvoltage it has been taken that the initial condition is $i(0) = I_{2M}$ (maximal inverse current) and voltage at the capacitance is $u(0) = U < E$ [2].

The analysis must be performed in a normized form, for generalization of results, therefore non-dimensional time $\tau = \omega t$ is initially defined. Circular frequency ω will be determined later. An equivalent scheme (Figure 1) can be described by the following equations:

$$\omega L \frac{\mathrm{d}\, i}{\mathrm{d}\, \tau} + u = E, \qquad (1)$$

$$i = i_1 + i_2, \qquad (2)$$

$$i_1 = \frac{u}{R_1} + \omega C_1 \frac{\mathrm{d}u}{\mathrm{d}\tau}, \tag{3}$$

$$u = R_2 i_2 + \frac{1}{\omega C_2} \int i_2 \,\mathrm{d}\tau, \tag{4}$$

gdje je:

E – istosmjerni napon,
u – napon na tiristoru.

Primjenom Laplaceove transformacije na relacije (1) do (4) dobiva se da je normirani napon na tiristoru:

where:

E – direct voltage,
u – voltage at thyristor.

If the Laplace transformation is applied to the relation (1) to (4), the following normized voltage is obtained at the thyristor:

$$\frac{U}{E} = \frac{b_3 p^3 + b_2 p^2 + b_1 p + 1}{p(a_3 p^3 + a_2 p^2 + a_1 p + 1)}, \tag{5}$$

gdje je:

where:

$$a_1 = \omega \left(\frac{L}{R_1} + R_2 C_2 \right), \tag{5a}$$

$$b_1 = \omega \left(\frac{L i(0)}{E} + R_2 C_2 \right), \tag{5b}$$

$$a_2 = \omega^2 L C_1 \left(1 + \frac{C_1}{C_2} + \frac{R_1 C_1}{R_2 C_2} \right), \tag{5c}$$

$$b_2 = \omega^2 \left(\frac{L i(0)}{E} R_2 C_2 + L C_1 \frac{u(0)}{E} \right), \tag{5d}$$

$$a_3 = \omega^3 L C_1 R_2 C_2, \tag{5e}$$

$$b_3 = \omega^3 L C_1 R_2 C_2 \frac{u(0)}{E}. \tag{5f}$$

Za definiranje nepoznate frekvencije ω pogodno je odabrati da član a_3 karakteristične jednadžbe (5) bude jednak jedinici ($a_3 = 1$) pa slijedi:

For defining the unknown frequency ω it is suitable to establish that the value of the member a_3 of the characteristic equation is equal to one ($a_3 = 1$), from which follows:

$$\omega^3 = \frac{1}{LC_1R_2C_2} \cdot \tag{6}$$

Zbog pojednostavljenja i poopćavanja proračuna uvode se sljedeće supstitucije:

For simplification and generalization of the calculation, the following substitutions are introduced:

$$\omega_0 = \frac{1}{\sqrt{LC_1}}, \tag{7}$$

$$\rho = \sqrt{\frac{L}{C_1}}, \tag{8}$$

$$\delta = \frac{\rho}{R_1}, \tag{9}$$

$$\alpha = \frac{\omega_0 Li(0)}{E} \tag{10}$$

– faktor početne struje / initial current factor,

$$\beta = \frac{u(0)}{E} \tag{11}$$

– faktor početnog napona / initial voltage factor,

a umjesto nepoznatih elemenata R_2 i C_2 sljedeći normirani parametri:

and, instead of the unknown elements R_2 and C_2, the following normized parameters are introduced:

$$\lambda_1 = \frac{R_2}{\rho}, \tag{12}$$

$$\lambda_2 = \frac{C_2}{C_1}. \tag{13}$$

Karakteristična jednadžba može se prikazati na sljedeći način:

The characteristic equation can be presented as follows:

$$p^3 + a_2 p^2 + a_1 p + 1 = (p + p_0)(p^2 + 2\zeta\,\omega_n p + \omega_n^2) = 0, \tag{14}$$

gdje je:

ζ – relativno prigušenje, a
ω_n – relativna kružna frekvencija.

Usporedbom koeficijenata relacije (14) slijedi da je:

where:

ζ – relative attenuation,
ω_n – relative circular frequency.

From comparison of the coefficients in the relation (14) it follows:

$$p_0 = \frac{1}{\omega_n^2}, \tag{15}$$

$$a_1 = \omega_n^2 + \frac{2\zeta}{\omega_n}, \tag{16}$$

$$a_2 = \frac{1}{\omega_n^2} + 2\zeta\omega_n . \tag{17}$$

Relativno prigušenje ζ i relativna kružna frekvencija ω_n ne mogu se jednostavno izraziti u ovisnosti o koeficijentima a_1 i a_2. Radi daljnjeg pojednostavljenja proračuna uvode se sljedeće supstitucije:

Relative attenuation ζ and relative circular frequency ω_n cannot be unambiguously expressed in dependence on the coefficients a_1 and a_2. For further simplification of the calculation, the following substitutions are introduced:

$$\lambda = \sqrt[3]{\lambda_1 \lambda_2}, \tag{18}$$

$$z = \frac{\lambda}{\omega_n}, \tag{19}$$

$$x = \omega_n \tau . \tag{20}$$

Uzimajući u obzir dane supstitucije i izraze a_1 i a_2, jednadžbe (5), (15), (16) i (17), dobiju se sljedeće dvije jednadžbe:

If the substitutions and expressions a_1 and a_2, the equations (5), (15), (16) and (17), are taken into consideration, the following two equations are obtained:

$$\frac{\delta}{z\omega_n^3} + z^2 = \frac{2\zeta}{\omega_n^3} + 1, \tag{21}$$

$$\frac{1+\lambda_2}{z^2\omega_n^3}+\delta z=2\zeta+\frac{1}{\omega_n^3}. \qquad (22)$$

Iz jednadžbi (21) i (22) dobije se da je:

From the equations (21) and (22) it is obtained as follows:

$$\omega_n^3=\frac{2\zeta z-\delta}{z\left(z^2-1\right)}, \qquad (23)$$

$$\lambda_2=\frac{\left(2\zeta-\delta z\right)\left(2\zeta z-\delta\right)}{z^2-1}z+z^2-1. \qquad (24)$$

Danim supstitucijama nije izgubljeno ni jedno rješenje, a postiglo se da je relativna kružna frekvencija ω_n izražena eksplicitno u ovisnosti o samo dvije varijable ζ i z. Koeficijenti b_1, b_2 i b_3 u relaciji (5) mogu se također izraziti u ovisnosti o ζ i z na sljedeći način:

None of the solutions has been lost due to the substitutions, whereas the relative circular frequency ω_n is explicitly expressed in dependence of only two variables, ζ and z. The coefficients b_1, b_2 and b_3 in the equation (5) can be also expressed in dependence of ζ and z as follows:

$$\frac{b_1}{\omega_n^2}=\frac{\alpha}{z\omega_n^3}+z^2, \qquad (25)$$

$$\frac{b_2}{\omega_n}=\alpha z+\frac{\beta}{z^2\omega_n^3}, \qquad (26)$$

$$b_3=\beta. \qquad (27)$$

Na taj način parametri jednadžbe (5) ovise o dvije varijable ζ i z i tri faktora α, β i δ.

The parameters of the equation (5) depend at the end on two variables ζ and z and on three factors α, β and δ.

3 ODREĐIVANJE PRVOG MAKSIMUMA NAPONA

Za određivanje prenapona oporavka kao i brzine porasta na tiristoru potrebno je odrediti prvi maksimum napona na tiristoru. Taj napon ovisi o faktorima α, β i δ i varijablama ζ i z, koje ovise o parametrima λ_1 i λ_2. Iz karakteristične jednadžbe (14) proizlazi da postoje četiri karakteristična slučaja. Za svaki slučaj se razmatra oblik napona $u(\tau)$.

1) Slučaj ($\zeta < 1$)

Izraz za normirani napon na tiristoru ima sljedeći oblik:

3 DETERMINING OF THE FIRST VOLTAGE MAXIMUM

In order to determine the recovery overvoltage and increase rate at the thyristor, the first voltage maximum at the thyristor must be determined. This voltage depends on factors α, β and δ and variables ζ and z, which depend on the parameters λ_1 and λ_2. It is to be concluded, based on the characteristic equation (14), that there are four characteristic cases. For each case, the voltage form $u(\tau)$ is considered.

1) Case ($\zeta < 1$)

The equation for the normized voltage on the thyristor is as follows:

$$\frac{u}{E} = 1 + A\mathrm{e}^{-x\omega_n^3} + \mathrm{e}^{-\zeta x}\left[A_1 \sin mx + A_2 \cos mx\right]. \tag{28}$$

Izrazi za konstante A, A_1 i A_2 su vrlo složeni pa ovdje nisu navedeni. Prvi maksimum se može približno odrediti iz drugog dijela jednadžbe (28), a numeričkim postupkom se može točno odrediti taj maksimum.

2) Slučaj ($\zeta = 1$)

Traženi normirani napon ima oblik:

The expressions for the constants A, A_1 and A_2 are very complex, and therefore they are not presented here. The first maximum can be approximately determined from the second part of the equation (28), this maximum can be exactly determined by means of a numerical method.

2) Case ($\zeta = 1$)

The subject normized voltage has the following form:

$$\frac{u}{E} = 1 + A\mathrm{e}^{-x\omega_n^{-3}} + \mathrm{e}^{-x}\left[A_1 x + A_2\right], \tag{29}$$

čiji se prvi maksimum može približno odrediti iz drugog dijela jednadžbe, a točno numeričkim postupkom.

3) Slučaj ($\zeta = \omega_n = 1$)

Traženi normirani napon je oblika:

whose first maximum can be approximately determined from the second part of the equation, this maximum can be exactly determined by means of a numerical method.

3) Case ($\zeta = \omega_n = 1$)

The subject normized voltage has the following form:

$$\frac{u}{E} = 1 + \mathrm{e}^{-\tau} + \mathrm{e}^{-x}\left[\frac{A_1\tau^2}{2} + A_2\tau + A_3\right]. \tag{30}$$

Prvi maksimum se može točno odrediti iz relacije (30).

4) Slučaj ($\zeta > 1$)

The first maximum can be exactly determined from the equation (30).

4) Case ($\zeta > 1$)

Traženi normirani napon je:

The subject normized voltage is:

$$\frac{u}{E} = 1 + A\,\mathrm{e}^{-x\omega_n^{-3}} + A_1\,\mathrm{e}^{s_1 x} + A_2\,\mathrm{e}^{s_2 x}, \quad (31)$$

gdje je:

where:

$$s_1 = \zeta - \sqrt{\zeta^2 - 1}, \quad (31a)$$

$$s_2 = \zeta + \sqrt{\zeta^2 + 1}. \quad (31b)$$

Prvi maksimum se može približno odrediti iz drugog dijela relacije (31), a točnu vrijednost numeričkim putem. Navedene konstante A, A_1 i A_2 za pojedine slučajeve dane su u [9], kao i odgovarajući numerički postupak za određivanje prvog maksimuma.

The first maximum can be approximately determined from the second part of the equation (31), the exact value can be determined by means of a numerical method. The mentioned constants A, A_1 and A_2 for particular cases are given in [9], as well as a numerical method for determining the first maximum.

4 DIJAGRAMI MAKSIMALNOG NAPONA I ODGOVARAJUĆEG VREMENA PORASTA NAPONA

Pri određivanju zaštite tiristora, prvo se definira strujna zaštita s induktivitetom L, a zatim se definira naponska zaštita preko R_2 i C_2. Ta naponska zaštita ne smije dopustiti prekoračenje graničnog prenapona oporavka i granične brzine porasta napona na tiristoru. Postoji veliki broj parova R_2 i C_2 koji zadovoljavaju samo jednu vrijednost, a manji broj i drugu naponsku vrijednost. Za praktičnu primjenu potrebno je odrediti sljedeće normirane funkcije:

– Normirani prenapon (prvi maksimum):

4 DIAGRAMS OF MAXIMAL VOLTAGE AND RELATED VOLTAGE INCREASE TIME

In determining the protection of the thyristor, the current protection with an inductance L must be determined first, afterwards the voltage protection is defined using R_2 and C_2. The voltage protection will prevent the thyristor critical recovery voltage and critical voltage increase rate being exceeded. There are numerous pairs of values R_2 and C_2 that fulfil one value only, while fewer of them fulfil another value as well. The following normized functions will be determined for practical application:

– Normized overvoltage (the first maximum):

$$M_\mathrm{n} = \frac{U_\mathrm{m}}{E} = f(\alpha, \beta, \delta, \zeta, z). \quad (32)$$

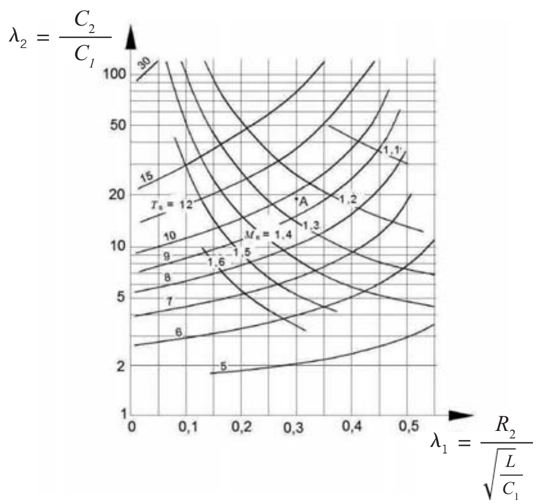
– Normirano vrijeme porasta prvog maksimuma:

– Normized increase time of the first maximum:

$$T_\mathrm{n} = \omega_0 t_1 = z x_1 = g(\alpha, \beta, \delta, \zeta, z). \quad (33)$$

Obje definirane funkcije ovise o faktorima α, β i δ i varijablama ζ i z, koje ovise o parametrima λ_1 i λ_2. Treba odrediti takav par λ_1 i λ_2 koji uz zadane faktore α, β i δ zadovoljavaju normirane vrijednosti M_n i T_n. Tako se npr. funkcija *f* za razne vrijednosti M_n može prikazati u ravnini λ_1 i λ_2 kao familija krivulja. Na isti način može se prikazati i g funkcija. Na osnovu toga nacrtano je niz familija krivulja M_n i T_n u ovisnosti o parametrima λ_1 i λ_2 te različitim faktorima α, β i δ. Na slici 2 prikazane su familije krivulja M_n i T_n za $\delta = 0{,}01$, $\alpha = \beta = 0$.

Both defined functions depend on the factors α, β and δ and on the variables ζ and z, which depend on the parameters λ_1 and λ_2. The pair of values λ_1 and λ_2 must be so determined that along with the specified factors α, β and δ they meet the normized values M_n and T_n. For example, the function *f* for various values M_n can be presented in the plane λ_1 and λ_2 as a family of curves. The function g can be presented the same way. Based on this, a group of curves M_n and T_n has been plotted, dependent on the parameters λ_1 and λ_2 and on various factors α, β and δ. The family of curves M_n and T_n for $\delta = 0{,}01$, $\alpha = \beta = 0$ is presented in Figure 2.



Slika 2
Normirani dijagrami prenapona oporavka M_n i vremena T_n za ($\delta = 0{,}01$; $\alpha = \beta = 0$)

Figure 2
Normized diagrams of the recovery overvoltage M_n and time T_n for ($\delta = 0{,}01$; $\alpha = \beta = 0$)

5 IZBOR TIRISTORA I RC ZAŠTITE

5.1 Izbor tiristora i osnovni podaci

Izbor tiristora vezan je uz dobro poznavanje dinamike rada sklopa. Pri tome je potrebno uzeti u obzir niz navedenih specifičnih osobina tiristora kao što su: nominalna i dozvoljena vrijednost napona i struje, struja pridržavanja, vrijeme uključenja i odmaranja, $\mathrm{d}u/\mathrm{d}t$, $\mathrm{d}i/\mathrm{d}t$ itd.

Obično se poteškoće javljaju kod projektiranja pretvarača s višim frekvencijama. Povećanje radne frekvencije ograničeno je sljedećim faktorima: kritičnim vrijednostima brzine porasta direktnog napona ($\mathrm{d}u/\mathrm{d}t$) i struje uključenja ($\mathrm{d}i/\mathrm{d}t$), vremenom komutacije (uključenja i odmaranja) i gubitcima snage u tiristoru.

Opteretivost tiristora u značajnoj mjeri ovisi o frekvenciji. Pri povišenim frekvencijama rastu komutacijski gubici, osobito gubici uključenja tiristora. Za pouzdan rad tiristora nužno je uskladiti gubitke u periodu komutacije s gubi-

5 SELECTION OF THYRISTOR AND RC PROTECTION

5.1 Selection of thyristor and basic data

The selection of the thyristor demands a thorough knowledge of the circuit operating dynamics. Many of the specified thyristor properties need to be taken into consideration here: nominal and allowed current and voltage, holding current, turn-on time and resting time, $\mathrm{d}u/\mathrm{d}t$, $\mathrm{d}i/\mathrm{d}t$ etc.

Difficulties usually occur when converters of higher frequencies are designed. Increase of operating frequency is limited by the following values: critical values of the direct voltage increase rate ($\mathrm{d}u/\mathrm{d}t$) and of the turn-on current increase rate ($\mathrm{d}i/\mathrm{d}t$), commutation time (turn-on and resting) and power losses in the thyristor.

The loadability of the thyristor depends on frequency to a significant degree. At higher frequencies commutation losses increase, particularly turn-on losses of the thyristor. For reliable operation of the thyristor, losses in the commutation period must cima u periodu vođenja da ne dođe do većih temperaturnih oscilacija, zbog čega brže dolazi do umora materijala tiristora. Pojava umora, uvjetovana različitim temperaturnim koeficijentom širenja sastavnih dijelova tiristora, dovodi do uništenja tiristora nakon određenog broja ciklusa zagrijavanja i hlađenja. Pri tome svemu značajnu ulogu ima brzina porasta struje uključenja ($\mathrm{d}i/\mathrm{d}t$). Pravilnim izborom zaštite tiristora mogu se znatno smanjiti komutacijski gubici uključenja.

Svi navedeni parametri tiristora neće istodobno biti jednako kritični, a to ovisi o režimu rada. U tu svrhu izgrađeni su razni tipovi tiristora koji odgovaraju zahtjevima pojedinih vrsta pretvarača.

Tiristor 501PBQ110 proizvod IR izabran je za prikaz proračuna RC zaštite. Ne ulazeći u kompletnu analizu rada određenog pretvarača, treba odrediti RC zaštitu tiristora za sljedeće uvjete rada:

$$\frac{\mathrm{d}u}{\mathrm{d}t} = 300 \frac{V}{\mu s},$$

$$\frac{\mathrm{d}i}{\mathrm{d}t} = 25 \frac{A}{\mu s},$$

$I_T = 250\mathrm{A}$ – istosmjerna struja provođenja tiristora,

$E = 600\mathrm{V}$ – istosmjerno.

Iz danih podataka lako se izračuna potrebni induktivitet $L = E/(\mathrm{d}i/\mathrm{d}t) = 24\ \mu\mathrm{H}$.

Vrijednosti otpora R_1 i C_1 nije moguće jednoznačno odrediti jer se u nekim slučajevima, kao npr. kod serijskog spajanja tiristora, tiristoru dodaje paralelno otpor, a u kapacitet C_1 treba uključiti i parazitni kapacitet spojnih vodova. Iz dimenzija tiristora procijenjeno je da je R_1, u oba smjera oko 50 Ω, a odgovarajući kapacitet C_1 oko 1nF.

5.2 Proračun RC zaštite za $\mathrm{d}u/\mathrm{d}t$

Brzina skupljanja kritičnog napona u bazama ovisi i o obliku anodnog napona. Kritična ili granična vrijednost $\mathrm{d}u/\mathrm{d}t$ je ona vrijednost kod koje je tiristor još sposoban da blokira napon određene amplitude linearnog porasta. Ta se vrijednost određuje eksperimentalno. U realnim uvjetima valni oblik napona razlikuje se od ispitnog napona pa je potrebno utvrditi funkcionalnu vezu između eksperimentalno utvrđene kritične vrijednosti

be aligned with losses in the conducting period, in order to prevent significant temperature oscillations that speed up fatigue of the thyristor material. The fatigue, caused by different thermal expansion coefficients of the thyristor components, will after a certain number of warming-up and cooling-down cycles destroy the thyristor. In this, the turn-on current increase rate ($\mathrm{d}i/\mathrm{d}t$) plays an important role. Proper selection of the thyristor protection can contribute to a significant decrease of the commutation turn-on losses.

All the thyristor parameters mentioned will not be equally critical at the same time, it depends on the operating regime. For this purpose, many various types of thyristors meeting the demands of particular types of converters have been designed and produced.

The thyristor 501PBQ110 product IR has been selected for calculation of the RC protection. Without performing an overall analysis of operation for a certain converter, RC protection of the thyristor must be determined for the following operating conditions:

$$\frac{\mathrm{d}u}{\mathrm{d}t} = 300 \frac{V}{\mu s},$$

$$\frac{\mathrm{d}i}{\mathrm{d}t} = 25 \frac{A}{\mu s},$$

$I_T = 250\mathrm{A}$ – direct conducting current of the thyristor

$E = 600\mathrm{V}$ – direct.

From the above data, the inductance $L = E/(\mathrm{d}i/\mathrm{d}t) = 24\ \mu\mathrm{H}$ is calculated.

The resistance values of R_1 and C_1 cannot be unambiguously determined, as in certain cases, e.g. when the thyristors are serially connected, the resistance is added in parallel to the thyristor and a parasitic capacitance of the connecting lines must be included in the capacitance C_1. From the thyristor dimensions, it is estimated that R_1, in both directions is about 50 Ω, the referring capacitance C_1 is approximately 1nF.

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

The collection rate of the critical voltage in bases depends on the anode voltage form. A critical or boundary value $\mathrm{d}u/\mathrm{d}t$ is the value at which the thyristor is still capable of blocking the voltage of the specific linear increase amplitude. This value

$\mathrm{d}u/\mathrm{d}t$ i $\mathrm{d}u/\mathrm{d}t$ kod stvarnog valnog oblika. Kritična vrijednost $\mathrm{d}u/\mathrm{d}t$ može se definirati kao:

is experimentally determined. In real conditions, the voltage waveform differs from the test voltage, therefore functional relationship between the experimentally determined critical value $\mathrm{d}u/\mathrm{d}t$ and $\mathrm{d}u/\mathrm{d}t$ under the realistic waveform shall be found out. The critical value $\mathrm{d}u/\mathrm{d}t$ can be defined as follows:

$$\left(\frac{\mathrm{d}u}{\mathrm{d}t}\right)_{\mathrm{kr}} = k\frac{U_{\mathrm{m}}}{t_1}\,, \tag{34}$$

gdje je:

U_{m} – vršna vrijednost rastućeg napona,
t – vrijeme kroz koje se postigne taj maksimalni napon,
k – faktor korekcije.

Neki proizvođači ispituju brzinu porasta s eksponencijalnom funkcijom. Kritična brzina porasta napona definira se nagibom pravca koji prolazi kroz točku čija je vrijednost 0,632 U_{m}. Može se smatrati da nakon tri vremenske konstante τ eksponencijalna funkcija poprimi maksimalnu vrijednost pa je u ovom slučaju k_1 = 1,9.

U slučaju sinusnog ispitnog napona uzima se da je nagib određen pravcem koji prolazi kroz 0,5 U_{m} pa je u tom slučaju k_2 = 1,5. Takva definicija najbliža je slučaju linearnog porasta napona jer postoji neznatno odstupanje.

Prilikom priključenja tiristorskog sklopa (slika 1) na napon E, napon na tiristoru raste od neke početne vrijednosti $u(0)$ do prvog maksimuma U_{m} tokom vremena t_1. Na osnovi toga može se odrediti normirana brzina porasta napona na tiristoru:

where:

U_{m} – peak value of the increasing voltage,
t – time for obtaining the maximal voltage,
k – correction factor.

Some manufacturers test the increase rate with an exponential function. The critical voltage increase rate is defined by the slope of the line passing through the point whose value is 0,632 U_{m}. It can be considered that after the three time constants τ the exponential function reaches the maximal value, therefore k_1 = 1,9.

In the case of the sine testing voltage, it is considered that the slope is determined by a line passing through 0,5 U_{m}, therefore k_2 = 1,5. This definition is closest to the linear increase of voltage, as the deviation is insignificant.

When the thyristor circuit (Figure 1) is connected to the voltage E, the voltage at the thyristor increases from the initial value $u(0)$ to the first maximum U_{m} during the time t_1. Based on this, the normized voltage increase rate at the thyristor is:

$$\left(\frac{\mathrm{d}u}{\mathrm{d}t}\right)_{\mathrm{n}} = \frac{1}{k\omega_0 E}\,\frac{\mathrm{d}u}{\mathrm{d}t} = \frac{M_{\mathrm{n}}}{T_{\mathrm{n}}} \tag{35}$$

Tako npr., ako je R_1 = 4,9 kΩ i C_1 = 10 nF slijedi iz jednadžbi (7), (8) i (9) da je δ = 0,01, a početni napon i struja su nula, pa je $\alpha = \beta = 0$. Odgovarajuća familija krivulja T_{n} i M_{n} za navedene podatke prikazana je na slici 2. Uz dane podatke za E i $\mathrm{d}u/\mathrm{d}t$ i k = 1,9 dobije se da je normirani napon $(\mathrm{d}u/\mathrm{d}t)_{\mathrm{n}}$ = 0,129.

Ako se izabere da je normirani prenapon M_{n} = 1,26 dobije se normirano vrijeme porasta T_{n} = 9,77 s. Na slici 2 to je točka A iz čega proizlazi da je optimalna RC zaštita određena s R_2 = 14,7 Ω i C_2 = 0,185 μF.

For example, if R_1 = 4,9 kΩ and C_1 = 10 nF, from equation (7), (8) and (9) it follows that δ = 0,01, while the initial voltage and current are equal to zero, therefore $\alpha = \beta = 0$. The referring curve family T_{n} and M_{n} for the specified data is presented on Figure 2. With the given values for E and $\mathrm{d}u/\mathrm{d}t$ and k = 1,9, the normized voltage $(\mathrm{d}u/\mathrm{d}t)_{\mathrm{n}}$ = 0,129 is obtained.

If the normized overvoltage M_{n} = 1,26 is selected, the normized increase time T_{n} = 9,77 s is obtained. In Figure 2 it is the point A, which implies that the optimal RC protection is defined by R_2 = 14,7 Ω and C_2 = 0,185 μF.

Na temelju numeričke analize u [9] došlo se do zaključka da na izbor elemenata RC zaštite ne utječe otpor $R_1 \geq 4{,}9$ kΩ, dok je utjecaj kapaciteta C_1 očit.Treba imati na umu da kapacitet inverzno polarizirane barijere opada s porastom napona.

Proizvođač za promatrani tiristor daje slje-deće vrijednosti za RC zaštitu: R_2 = 15 Ω, C_2 = 0,2 μF, dok prema [5] slijedi da je: R_2 = 11,8 Ω i C_2 = 0,175 μF. Treba istaći da je dobra podudarnost rezultata provedene analize i rezultata dobivenih iz [5] samo u području najmanje osjetljivosti na parazitni kapacitet C_1, koji nije uzet u obzir u [5].

5.3 Prenapon u inverznom režimu rada tiristora

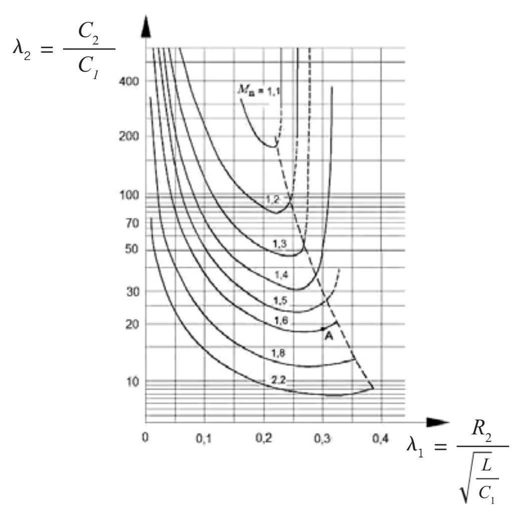
Analiza u inverznom režimu rada provedena je na istoj shemi (slika 1). Budući da oscilacije u inverznom režimu rada započnu u trenutku kada inverzna struja dosegne svoj maksimum I_{RM} [1], za navedeni tiristor ta struja je I_{RM} = 55 A, tako da faktor početne struje α u ovom slučaju nije jednak nuli. U [9] je numerički prikazano da faktor početne struje α ima dominantan utjecaj na iznos prenapona, dok je faktor početnog napona β zanemariv, jer se dobivaju gotovo iste vrijednosti za β = 0 i β = 1. Također je pokazano da otpor $R_1 \geq 4{,}9$ kΩ nema utjecaja, dok kapacitet C_1 znatno utječe jer s porastom kapaciteta C_1 raste inverzni prenapon. Zbog toga radnu točku treba izabrati tako da je RC zaštita što manje osjetljiva na promjena kapaciteta C_1.

Based on the results of the numerical analysis in [9] it has been concluded that the resistance $R_1 \geq 4{,}9$ kΩ does not affect the selection of elements of RC protection, whereas the influence of the capacitance C_1 is evident. It must be taken into consideration that the capacitance of the inversely polarized barrier decreases with the increase of voltage.

For the observed thyristor, the manufacturer gives the following values for RC protection: R_2 = 15 Ω, C_2 = 0,2 μF, while in accordance with [5] the values are as follows: R_2 = 11,8 Ω and C_2 = 0,175 μF. It is to be emphasized that the compliance of the results of the performed analysis and the results obtained from [5] is good only in the range where susceptibility to the parasitic capacitance C_1, which has not been taken into account in [5], is lowest.

5.3 Overvoltage in the thyristor inverse operating regime

The analysis in an inverse operating regime was performed in line with the same scheme (Figure 1). As the oscillations in an inverse operating regime start at the moment when the inverse current reaches its maximum value I_{RM} [1], the current value for the subject thyristor is I_{RM} = 55 A, therefore the initial current factor α in this case is not equal to zero. In [9] it is numerically presented that the initial current factor α has a predominant influence on the overvoltage value, whereas the initial voltage factor β is negligible, as almost the same values are obtained for β = 0 and β = 1. It is also shown that the resistance $R_1 \geq 4{,}9$ kΩ has no influence, whereas the influence of capacitance C_1 is significant, as an increase of the capacitance C_1 affects an increase of the inverse overvoltage. Therefore the operating point needs to be chosen so that RC protection is susceptible to a change of the capacitance C_1 as little as possible.



Slika 3
Normirani dijagram inverznog prenapona M_n (δ = 0,01, α = 4,49 i β = 0)

Figure 3
Normized diagram of the inverse overvoltage M_n (δ = 0,01, α = 4,49 and β = 0)

Na slici 3 dana je familija krivulja normiranog prenapona M_n za sljedeće faktore δ = 0,01, α = 4,49 i β = 0. Za već izabrane parametre zaštite slijedi da je u ovom slučaju normirani prenapon M_n = 1,6 (točka A), dok je za izabrani tiristor dopuštena vrijednost M_n = 2. Pomoću metode dane u [1] dobije se za dati prenapon da je R_2 = 13,2 Ω, C_2 = 0,2 μF. Treba istaći da je ta analiza provedena pod pretpostavkom da struja oporavka trenutno pada na nulu, a da napon prepolarizacije ima skok, što ne odgovara stvarnosti.

The curve family of the normized overvoltage M_n for the following factors δ = 0,01, α = 4,49 i β = 0 is provided on Figure 3. For the selected parameters of protection, the normized overvoltage in this case is M_n = 1,6 (point A), whereas the allowed value for the chosen thyristor is M_n = 2. Using the method provided in [1], for the given overvoltage, the following values are obtained R_2 = 13,2 Ω, C_2 = 0,2 μF. It is to emphasize that this analysis has been performed under the assumption that the recovery current falls to zero momentarily, whereas there is a jump of the repolarization voltage, which is not in accordance with the actual situation.

6 ZAKLJUČAK

Posebno je važna primjena zaštite tiristora pri pretvaranju istosmjerne struje u izmjeničnu, visoke frekvencije i velike snage, npr. kod pretvarača za indukcijsko grijanje, vjetroelektrane i dr.

Prigušenje prenapona oporavka i brzine porasta napona na tiristoru postiže se RC zaštitom, a ograničenje brzine porasta struje ograničuje se induktivitetom. U radu je pokazano da izbor zaštite tiristora ovisi i o parametrima tiristora. Posebno je ukazano da na optimalni izbor RC zaštite u znatnoj mjeri utječe kapacitet inverzno polarizirane barijere kao i paralelni parazitni kapacitet spojnih vodova. To se može izbjeći tako da se bira radna točka u kojoj je osjetljivost na promjenu parazitnih kapaciteta zanemariva. Numerički postupak je složen, ali se može napraviti niz dijagrama za karakteristične faktore α, β i δ čime se postupak izbora optimalnih parametara RC zaštite pojednostavljuje.

6 CONCLUSION

Application of thyristor protection is particularly important for conversion of direct current into alternating current, for high frequencies and high powers, e.g. for the induction heating converters, wind power plants, etc.

Attenuation of the recovery voltage and of the voltage increase rate at the thyristor is achieved by RC protection, whereas the current increase rate is limited by inductance. It is presented in the paper that the thyristor parameters affect the selection of the thyristor protection. It is particularly emphasized that capacitance of the inversely polarized barrier, as well as parasitic capacitance of the connecting lines, have a significant impact on optimal selection of RC protection. It can be avoided by selection of the operating point where sensitivity to change of the parasitic capacities is negligible. The numerical procedure is complex, but referring diagrams for characteristic factors α, β and δ can be made, which significantly simplifies the selection procedure for the optimal parameters of RC protection.

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Uredništvo primilo rukopis:
2006-11-29

Prihvaćeno:
2006-12-12

Manuscript received on:
2006-11-29

Accepted on:
2006-12-12