

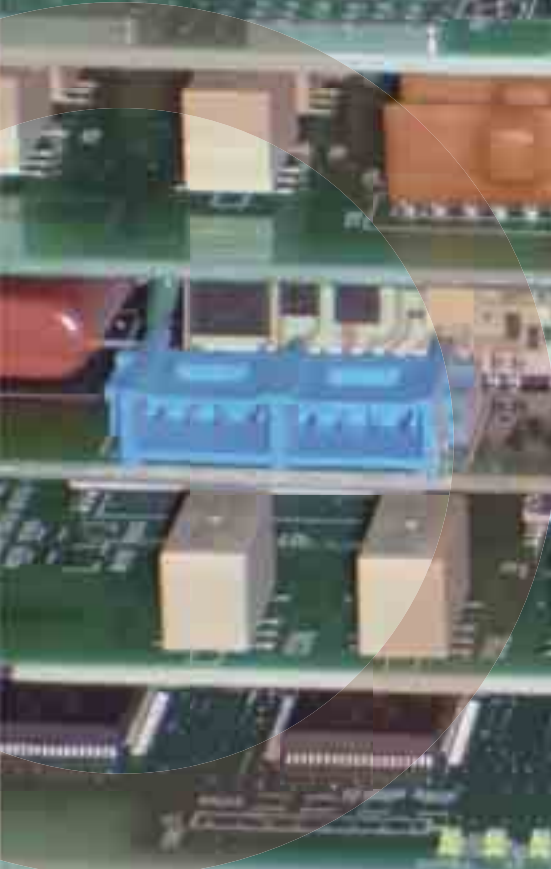
DINAMIČKA SVOJSTVA TIRISTORA DYNAMIC PROPERTIES OF THYRISTORS

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U radu su razmatrana dinamička svojstva tiristora. Ukratko je razmatrano svojstvo p-n barijere i objašnjen princip uključanja tiristora pomoću dvotranzistorskog modela uz zornu grafičku interpretaciju osnovne jednačbe. Zatim su razmatrana dinamička svojstva tiristora s detaljnijim osvrtom na efekte du/dt i di/dt , i na dinamički proces uključanja.

In this work the dynamic properties of thyristors are considered. The property of the p-n barrier is briefly reviewed and the principle of thyristor turn-on by means of a two-transistor model explained, along with an illustrative graphic interpretation of the basic equation. Described next are the dynamic properties of thyristors with a more detailed analysis of the du/dt and di/dt effects and the dynamic turn-on process.

Ključne riječi: dinamička svojstva tiristora; režimi rada tiristora; tiristor
Key words: dynamic properties of thyristors; thyristor; thyristor operating modes



1 UVOD

Pri izboru elemenata nekog strujnog kruga mora se voditi računa o režimu rada svakog elementa. To znači da za svaki element treba utvrditi dopuštene vrijednosti struje, napona i snage te radnu temperaturu. Prekoračenje bilo koje dopuštene vrijednosti obično dovodi do oštećenja elemenata. Posebno treba obratiti pozornost na temperaturu koja, pored ostalog, utječe na radne karakteristike elemenata. Isto tako važno je znati frekvencijsko područje rada kao i dinamička svojstva elemenata. Pri višim frekvencijama mogu doći do izražaja paraziti kapaciteti i induktiviteti, na što valja također paziti.

U strujnom krugu tiristor ima ulogu sklopke zbog čega se javljaju prijelazni procesi. Trajanje prijelaznog procesa uključanja i isključenja tiristora ne ovisi samo o dinamičkim svojstvima tiristora već i o ostalim parametrima kruga. U posljednje vrijeme razvijaju se tiristori za veće snage i više frekvencije, a za primjenu su vrlo važna njihova dinamička svojstva, brzina porasta napona (du/dt) i struje (di/dt).

Prekoračenje kritične vrijednosti du/dt dovodi do prijevremenog uključanja, a prekoračenje di/dt do uništenja tiristora. Budući da tiristor provede struju najprije u uskom kanalu, koji se proširuje određenom brzinom, nastaje njegovo lokalno pregrijavanje. To se sprječava ograničenjem brzine porasta struje. Također pri prijelaznim procesima mogu se javiti nedozvoljena strujna i naponska nadvišenja.

Glavno pitanje razvoja tiristora snage većih frekvencija povezano je s brzinom porasta struje i napona te skraćanjem vremena oslobađanja. Povećanje brzine rada tiristora nemoguće je bez poznavanja prirode prijelaznih procesa u tiristoru.

2 KARAKTERISTIČNE POJAVE I EFEKTI DINAMIČKOG REŽIMA RADA

2.1 Dinamička svojstva uključanja

Velik broj radova, pretežno eksperimentalnih, posvećeno je analizi prijelaznog procesa uključanja tiristora. Stroga analiza prijelaznih procesa u tiristoru nije provedena, a osnovni odnosi provedeni su uz cijeli niz ograničenja. Za analizu prelaznih procesa vrlo često se koristi dvotranzistorski model tiristora. Ovdje će biti razmatrana osnovna svojstva prijelaznog procesa uključanja ti-

1 INTRODUCTION

In selecting the elements of a circuit, the operating mode of each element must be taken into account. This means that permissible current, voltage and power values, as well as operating temperature, should be determined for each element. Excess of any prescribed value will as a rule cause damage to the elements. Special attention should be paid to temperature which, among other things, influences the operating characteristics of the elements. It is also important to know the frequency range and the dynamic properties of the elements. At higher temperatures, stray capacitance and inductance may appear, which should also be taken care of.

In a circuit the thyristor acts as a switch, which results in transient processes. The duration of thyristor on-and-off transient processes does not depend only on the dynamic features of the thyristor, but also on other circuit parameters. Recently, thyristors of greater power and higher frequencies are being developed, whereas very important in application are their dynamic properties, voltage rise rate (du/dt) and current rise rate (di/dt).

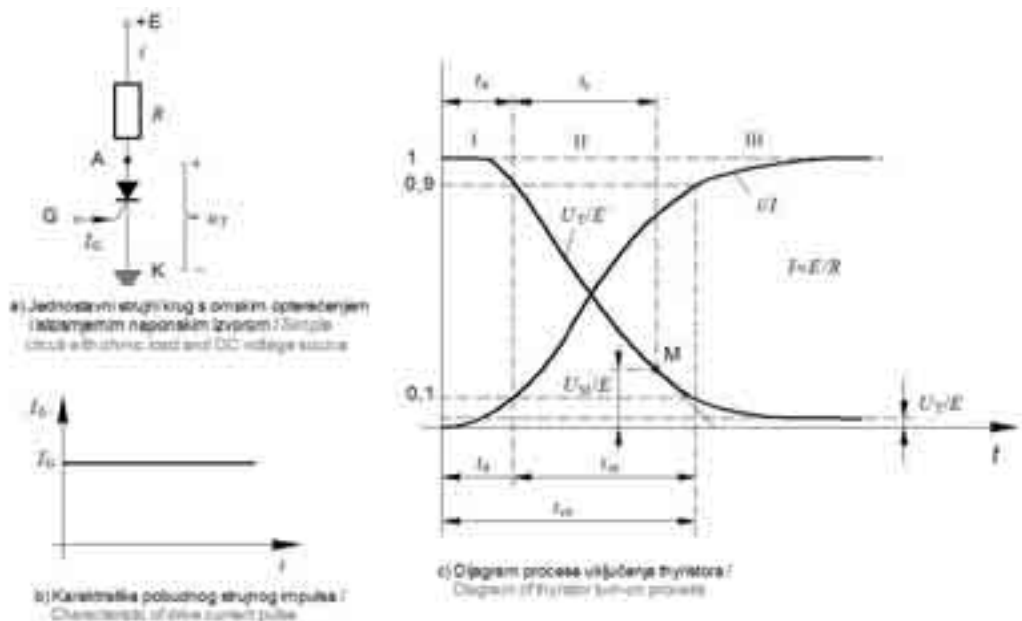
Excess of critical du/dt value will lead to a premature turn-on, excess of di/dt value will lead to the destruction of the thyristor. As the thyristor conducts electricity first in a narrow channel, which expands at a certain rate, it overheats locally. This is prevented by limiting the current rise rate. In transient processes impermissible current and voltage overshoots may also occur.

The main question encountered in developing power thyristors of higher frequencies is linked to the current and voltage rise rate and the disconnection time reduction. Increasing the thyristor's operating speed is impossible without knowing the nature of the transient processes going on in it.

2 CHARACTERISTIC PHENOMENA AND EFFECTS OF THE DYNAMIC OPERATING MODE

2.1 Dynamic turn-on features

Many works, mostly experimental ones, deal with the thyristor's transient turn-on processes. A meticulous analysis of the transient processes in the thyristor has never been made though, whereas the basic relations have been analyzed in the light of a series of restrictions. The two-transistor model of a thyristor is very often used in analyzing the transient processes. We shall discuss here the basic features of the thyristor's transient turn-on



Slika 1 – Analiza prijelaznog procesa u tiristoru
Figure 1 – Analysis of the transient processes in the thyristor

ristora, na način pogodan za inženjersku primjenu.

Prijelazni procesi obično se razmatraju u jednostavnom strujnom krugu s omskim opterećenjem i istosmjernim naponskim izvorom (slika 1a).

Dovođenjem odgovarajućeg pobudnog strujnog impulsa $I_G > 0$ (slika 1a, 1b), tiristor će nakon nekog vremena (vrijeme uključivanja) prijeći u vodljivo stanje. U toku procesa uključivanja struja i napon tiristora mijenjaju se kontinuirano (slika 1c). Radi pojednostavljene analize, proces uključivanja može se rastaviti na više karakterističnih perioda. Međutim, navedeni autori nisu u tome jedinstveni; jedni taj proces dijele u dva perioda [1], [3], [4], [5], [6], [10], [11], [24], [30], [31], a drugi u tri [25], [27] i [53]. Pri tome se jedni služe krivuljom smanjenja napona [1], [5], [6], [10], [11], [30] i [31], a drugi krivuljom porasta struje, dok veza između te dvije krivulje nije nigdje dana. U slučaju čisto omskog opterećenja tiristorskog kruga, sasvim je svejedno koja se krivulja koristi, dok je u slučaju induktivnog opterećenja vrijeme porasta struje duže od vremena smanjenja napona. Neki autori [37], [42] i [52] dijele proces uključivanja na dvije statičke i dvije dinamičke faze. Prva dinamička faza započinje pojavom vodljivog kanala, a druga se završava rasprostriranjem struje po cijelom presjeku tiristora.

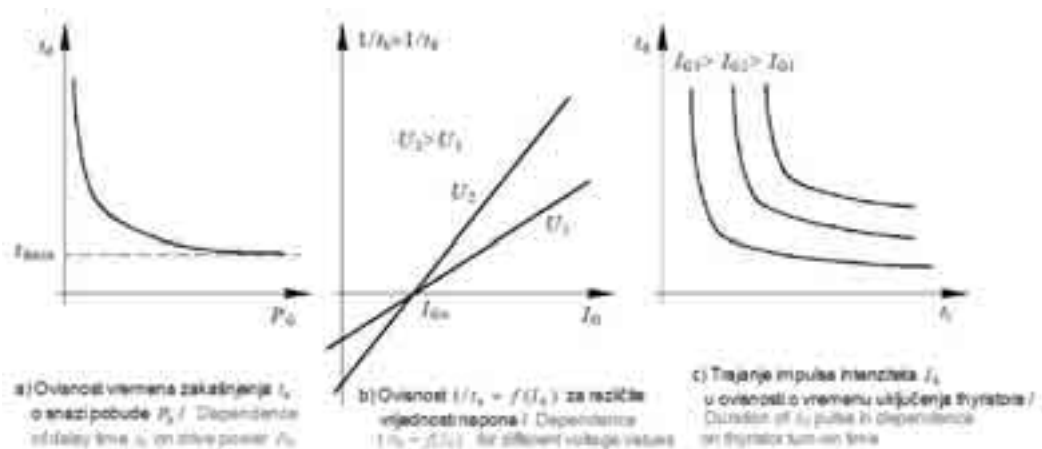
Za našu analizu prijelaznog procesa čini se najprihvatljivija naponska krivulja podijeljena u

process in a way suitable for engineering application.

Transient processes are usually studied in a simple circuit with ohmic load and dc voltage source (Figure 1a).

By bringing a certain drive pulse $I_G > 0$ (Figures 1 a, 1 b), the thyristor will after a while (turn-on time) switch over to the conductive state. During the turn-on process the thyristor's current and voltage will be changing continuously (Figure 1c). In order to simplify the analysis, the turn-on process can be broken down into several characteristic periods. However, the listed authors are not of one mind about it; some divide the process into two periods [1], [3], [4], [5], [6], [10], [11], [24], [30], [31], the others into three [25], [27], [53]. Some use the voltage decrement curve, the others use the current rise curve [1], [5], [6], [10], [11], [30], [31], but the link between these two curves is nowhere given. In the case of a purely ohmic load on the thyristor circuit it makes no difference which curve is used, while in the case of an inductive load the time of current rise time is longer than that of voltage drop. Some authors [37], [42], [52] divide the turn-on process into two static and two dynamic phases. The first dynamic phase starts with the appearance of the conductive channel, the second phase ends after the current has spread across the whole thyristor.

For our analysis of the transient process the most convenient seems to be the voltage curve divided into three characteristic periods: the delay period,



Slika 2 – Period zakašnjenja prijelaznog procesa tiristora
Figure 2 – Delay period of thyristor transient process

tri karakteristična perioda: period zakašnjenja, regeneracije i uspostavljanja stacionarnog stanja (slika 1c). Ta podjela se skoro u potpunosti podudara s podjelom prema preporuci IEC.

the regeneration period and the period of establishing stationary state (Figure 1c). Such a division is almost wholly in line with the corresponding IEC recommendation.

2.2 Period zakašnjenja

Period zakašnjenja počinje u trenutku dovođenja pobudnog impulsa I_G , pa do početka lavinskog porasta struje, što praktički odgovara sniženju anodnog napona na 90 % početne vrijednosti (slika 1c). Odgovarajući vremenski interval zove se vrijeme zakašnjenja (t_d), a sastoji se od vlastitog vremena zakašnjenja (t_0) tranzistora T_2 i vremena skupljanja kritičnog naboja (t_k). Vrijeme t_0 je vrlo kratko, koje ne ovisi o veličini strujnog impulsa I_G , već o parametrima i efektivnoj debljini baze p_2 [28]. Po isteku vremena t_0 , započinje skupljanje prostornog naboja u bazama. Tijekom vremena t_k skupi se tzv. kritični naboj (Q_{kr}), koji izaziva lavinski proces u barijeri J_2 , [4]. Eksperimentalno je utvrđeno i teoretski objašnjeno da kritični naboj ovisi o parametrima tiristora, pobudnoj struji i anodnom naponu, a praktički ne ovisi o temperaturi i neznatno je veći u statičkom režimu rada [29].

Ovisnost $1/t_k = f(I_G)$ za različite vrijednosti napona predstavlja pravac (slika 2b), pa se može lako utvrditi eksperimentalnim putem [29]. U katalozima se obično daje zavisnost vremena zakašnjenja o jakosti pobudne struje I_G ili o snazi pobude P_G (slika 2a). Što je veća pobudna struja, odnosno snaga, manje je vrijeme zakašnjenja. Međutim, postoji minimalno vrijeme zakašnjenja ($t_{dmin} = t_0$) ispod kojega se ne može aktivirati tiristor bez obzira na intenzitet impulsa (slika 2a). Ako je trajanje impulsa intenziteta I_G kraće od neke minimalne vrijednosti, također neće doći do uključivanja tiristora (slika 2c)

2.2 Delay period

The delay period starts from the moment of feeding the drive pulse I_G , to the beginning of the avalanche current rise, which practically corresponds to a decrease in anode voltage to 90 % of the starting value (Figure 1c). The corresponding time interval is called time delay (t_d) and consists of the own time delay (t_0) of transistor T_2 and the concentration time of the critical charge (t_k). Time t_0 is very short, does not depend on the quantity of the current pulse I_G , but on the parameters and effective thickness of base p_2 [28]. Upon expiry of time t_0 , the space charge grouping in the bases starts. Over the time t_k the so-called critical charge (Q_{kr}) picks up, triggering the avalanche process in barrier J_2 , [4]. It has been experimentally determined and theoretically explained that the critical charge depends on the thyristor's parameters, drive current and anode voltage, that it practically does not depend on temperature and is slightly higher in the static operating mode [29].

Dependence $1/t_k = f(I_G)$ for various voltage values is represented by a line (Figure 2b), so it is easy to determine experimentally [29]. Usually specified in catalogues is the dependence of delay time on the drive current intensity I_G or the drive power P_G (Figure 2a). The greater the excitation current, or power, the shorter the delay time. There is, however, a minimal delay time ($t_{dmin} = t_0$) below which the thyristor cannot be activated regardless of the pulse intensity (Figure 2a). Neither will the thyristor turn on if the duration of a pulse of intensity I_G is shorter than a minimal value (Figure 2c) [23], or, regardless of the duration of an impulse, if intensity is lower than the limit value I_{G0} (Figure 2b). Delay time is proportional to

[23]. Do aktiviranja tiristora također neće doći, bez obzira na dužinu trajanja impulsa, ako je intenzitet manji od granične vrijednosti I_{G0} (slika 2b). Vrijeme zakašnjenja proporcionalno je efektivnim širinama baza, pa zbog toga opada porastom anodnog napona (slika 2b), a obrnuto proporcionalno s vremenom života, pa raste s temperaturom. Smanjenjem strmine impulsa I_G , povećava se vrijeme zakašnjenja. Ta ovisnost daje se u katalozima.

2.3 Period regeneracije

U periodu regeneracije, nastavlja se punim intenzitetom započeti proces lavinskog porasta struje. Iako velik broj radova analizira proces uključivanja tiristora, vrlo malo autora razmatra prijelaz iz statičkog u dinamičko stanje, koje se karakterizira naglim padom napona. Jedna grupa autora za analizu koristi tranzistorski model [3], [21] i [23], dok drugi razmatraju kritični naboj [29], ali ni u jednom slučaju ne daju informaciju o naponu. Prvi model, koji opisuje nagli pad blokirajućeg napona, ne daje pravu sliku [38]. U radu [37] razmatran je odnos napona i struja samo u prvoj dinamičkoj fazi uključivanja tiristora pomoću jednodimenzionalnog modela, koji daje samo određenu aproksimaciju procesa. Zbog složenosti procesa ne mogu se odjednom teoretski obuhvatiti svi efekti i pojave, već se svaki efekt posebno analizira, kao npr. etapa modulacije vodljivosti baza [27], zatim lavinska injekcija [14], brzina pomicanja granice oblasti prostornog naboja [36] i [41], pad napona na n-bazi [34], proces prepolarizacije emitterskih kapaciteta [40] itd. Rezultati tih istraživanja imaju veliku važnost, prije svega za proizvodnju tiristora.

Lavinski proces započinje kada je $\alpha_1 + \alpha_2 = 1$, a egzaktniji uvjet dobio bi se pomoću dinamičkih faktora pojačanja [3]. U radu [14] pokazano je da se tiristor brže uključuje pri većim gustocama struje i većim početnim naponima. Pri većem naponu vlada jače polje u barijeri J_2 , a osim toga, lavinska injekcija se odvija u većem prostoru, pa je i proces brži.

Period regeneracije se završava u trenutku prepolarizacije barijere J_2 , tj. pri $U_{J2}=0$. Međutim, cijela barijera J_2 nije se odjednom prepolarizirala, već najprije samo na jednom vrlo uskom dijelu prijelaza, u vidu uskog vodljivog kanala, u blizini pobudne elektrode. Vodljivi kanal je najuži u bazi n, koja je ujedno najslabije vodljiva, pa je, gotovo sav pad napona na tom dijelu vodljivog kanala. Zbog toga može odgovarajući pad napona U_M na tiristoru biti znatno veći od 0,1E (slika 1c), što ovisi o početnoj gu-

the effective widths of the bases, which is why it decreases with an increase in anode voltage (Figure 2b), and is inversely proportional to life-time, hence it rises with temperature. A decrease in the I_G impulse rise rate will lead to an increase in delay time. This dependence is given in catalogues.

2.3 Regeneration period

In the regeneration period, the started process of avalanche current rise is continued with full intensity. While the thyristor turn-on process is analyzed in many works, very few authors are studying the transition from static to dynamic state, which is characterized by a rapid voltage drop. One group of authors is using the transistor model [3], [21], [23] in the analysis, the other group is studying the critical charge [29], but neither provides information about voltage. The former model, which describes a rapid drop of the blocking voltage, does not give the true picture [38]. In a work [37] the relation between current and voltage is studied only in the first dynamic phase of the thyristor turn-on process by means of the one-dimensional model, which can give only an approximation of the process. Due to the complexity of the process, it is impossible to theoretically comprise at one stroke all the effects and phenomena, so each effect is instead individually analyzed, for instance, the base conductivity modulation stage [27], then the avalanche injection [14], the shifting speed of the space-charge limit area [36], [41], voltage drop on n-base [34], the pole reversal process of emitter capacities [40] etc. The results of these studies are of great importance, especially for the manufacture of thyristors.

The avalanche process starts when $\alpha_1 + \alpha_2 = 1$, whereas a more exact condition would be obtained by means of dynamic amplification factors [3]. A work [14] shows that the thyristor turns on faster at higher current densities and higher starting voltages. At a higher voltage a stronger field prevails in barrier J_2 and, in addition to it, the avalanche injection develops in a larger space, which in turn makes the process faster.

The regeneration period ends at the moment of pole reversal of barrier J_2 , i.e., at $U_{J2}=0$. However, the whole barrier J_2 has not changed poles at once, but first only on a very narrow transition part, in the form of a narrow conductive channel, close to the excitation electrode. The conductive channel is the narrowest in the n-base which, at the same time, is least conductive, so that nearly the entire voltage drop rests on that part of the conductive channel. That is why the corresponding voltage drop U_M on the thyristor can be much bigger than 0.1E (Figure 1c), which

stoći struje [34]. U tom trenutku krivulje napona i struje imaju točku infleksije. Odgovarajuće vrijeme trajanja perioda regeneracije zove se vrijeme regeneracije (t_r). Ono se skraćuje smanjenjem debljine baza tiristora i povećanjem anodnog napona.

2.4 Period uspostavljanja stacionarnog stanja

Period uspostavljanja stacionarnog stanja započinje u trenutku prepolarizacije središnjeg p-n prijelaza, a završava smanjenjem napona na stacionarnu vrijednosti. Smanjenje napona koje nastaje zbog modulacije vodljivosti n-baze i zbog postupnog širenja vodljivog kanala po cijeloj barijeri J_2 , vrlo je važan efekt širenja vodljivog kanala, osobito kod tiristora velikih snaga, pa će biti detaljnije razmatran. Napon se u tome periodu smanjuje eksponencijalno s vremenskom konstantom (t_{rs}) [3]. Napon U_M ovisi o tipu tiristora, a veći je što je veća struja na kraju prethodnog perioda [27]. Prema tome, što je veći napon U_M , veći su gubici. Za impulsní režim rada važno je da su U_M i vremenska konstanta (t_{rs}) što manji.

Stacionarni napon U_T sastoji se od pada napona na sva tri prijelaza i na n-bazi, koja je najslabije vodljiva. Obično je taj napon mali (do 2 V), dok u nekim slučajevima može biti znatno veći [3] i [43]. To se događa u slučaju kad se u uključenom stanju sačuva u prijelazu J_2 zona tako jakog električnog polja, da driftne brzine elektrona i šupljina dostižu brzinu zasićenja. Ta se zona stvara zbog nedovoljne injekcije emitera, pa je $\alpha_1 + \alpha_2 = 1$ [43].

2.5 Vrijeme uključanja tiristora

Prema preporuci IEC, vrijeme uključanja tiristora (t_{uk}) traje od trenutka pojave pobudne struje I_G , pa sve dok napon na tiristoru ne padne na 10 % početne vrijednosti (slika 1c). To se vrijeme dijeli na vrijeme zakašnjenja (t_d) i vrijeme smanjenja napona (t_{sn}), u kojem napon padne sa 90 % na 10 % početne vrijednosti (slika 1c). Obično je $t_{sn} = t_r$ (slika 1c).

Iznos i oblik napona, kao i vrijeme uključanja, ne ovise o parametrima tiristora, već i o parametrima kruga. Eksperimentalno je utvrđeno da je vrijeme smanjenja napona kraće što je manja propusna struja i brzina porasta struje [31]. Tako npr. pri omskom opterećenju kruga struja brže raste, a napon sporije opada (crtkane linije) u odnosu na induktivno opterećenje (puna linija) (slika 3a). Zatim u omskom krugu

depends on the starting current density [34]. In this juncture the voltage and current curves have a point of inflection. The corresponding time of the regeneration period duration is referred to as regeneration time (t_r). It can be shortened by decreasing the thyristor base thickness and increasing anode voltage.

2.4 The period of establishing the stationary state

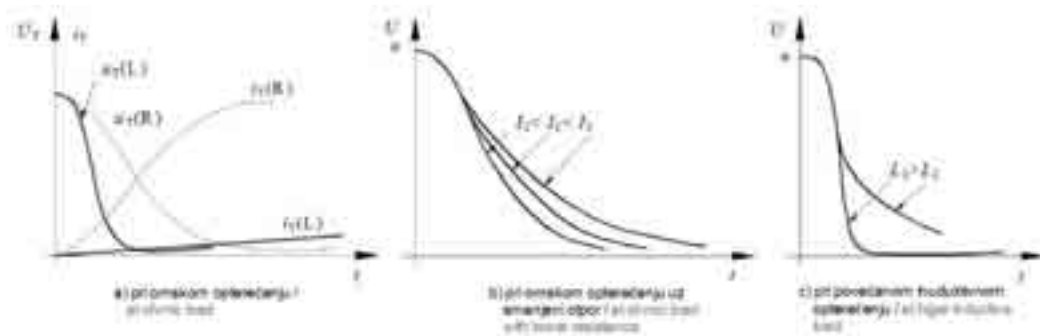
The period of establishing the stationary state starts at the pole reversal moment of the central p-n transition and ends at voltage drop to stationary values. Voltage drop resulting from the n-base conductivity modulation and due to gradual expansion of the conductive channel across the whole barrier J_2 is a very important effect of the expansion of the conductive channel, especially with big power thyristors, so it will be discussed in more detail. Voltage in that period is dropping exponentially with the time constant (t_{rs}) [3]. Voltage U_M depends on the type of thyristor, and is the bigger the bigger the current is at the end of the preceding period [27]. Therefore, the bigger the voltage U_M , the bigger the losses are. For the impulse operation mode it is important that U_M and the time constant (t_{rs}) are as small as possible.

Stationary voltage U_T consists of voltage drop at all three transitions and at the n-base which is the least conductive. That voltage is usually low (up to 2 V), whereas in some cases it may be much higher [3], [43]. This happens if in a turn-on state an area of such a strong electric field is preserved in barrier J_2 that electron drift velocities and hole reach the saturation velocity. That area is formed due to insufficient emitter injection, hence $\alpha_1 + \alpha_2 = 1$ [43].

2.5 Thyristor turn-on time

The IEC-recommended thyristor turn-on time (t_{uk}) lasts from the moment the excitation current I_G appears and until the thyristor voltage drops to 10 % of the starting value (Figure 1c). This time is divided into the delay time (t_d) and the voltage drop time (t_{sn}), within which voltage drops from 90 % to 10 % of the starting value (Figure 1c). Usually $t_{sn} = t_r$ (Figure 1c).

The voltage amount and format, just as the turn-on time, do not depend on thyristor parameters but on circuit parameters. It has been established experimentally that the voltage drop time is the shorter the smaller the forward current and the current rise rate are [31]. Thus in the case of an ohmic circuit load current rise is faster and voltage drop is slower (dotted lines) in relation to an inductive load (full line) (Figure 3a). Then in an ohmic circuit voltage drop is slower at a lower resistance (Figure 3b). An increase in circuit



Slika 3 – Ovisnost napona tiristora o parametrima strujnog kruga
Figure 3 – Dependence of thyristor voltage on current circuit parameters

napon sporije opada pri manjem otporu (slika 3b). Povećavanjem induktiviteta kruga smanjuje se brzina porasta struje, a napon brže opada (slika 3c), ali samo do određene granice.

Ako induktivitet prekorači kritičnu vrijednost, struja će presporo rasti, pa je potrebno duže vrijeme da struja postigne vrijednost struje pridržavanja. Zbog toga vrijeme uključanja znatno poraste. Eksperimentalni rezultati, znatno se razlikuju od teoretskih; vrijeme uključanja je kraće, a pri većim naponima neznatno ovisi o debljini baze. Pri većim naponima kraće je vrijeme uključanja zbog jačeg lavinskog efekta, koji znatno skraćuje vrijeme regeneracije (t_r).

Značajan utjecaj na vrijeme uključanja ima električno polje u n-bazi, koje se javlja u periodu porasta struje. Eksperimentalna istraživanja [36] i [42], pokazala su, da se pri velikoj gustoći struje u n-bazi formira jako električno polje. Pri tome je dominantna driftna komponentna struja, pa je veći pad napona na tiristoru, a vrijeme uključanja duže.

Na kraju treba istaći da se vrijeme uključanja produžuje porastom temperature.

2.6 Rasprostiranje uključelog stanja

2.6.1 Opći pregled

Velika praktična važnost i složenost procesa rasprostiranja uključelog stanja razlog su da je na tu temu napisan velik broj radova, a najznačajniji su [37], [40], [41], [45] do [47] i [52]. Većina navedenih radova temelji se na eksperimentalnim istraživanjima: mjerenju pada napona, mjerenju struje oporavka, mjerenju pomoću sondi, a primjenjuje se elektronsko-optička mjerna tehnika. Većina eksperimentalnih rezultata nema potpunu fizikalnu interpretaciju. Postojeće teorije rasprostiranja uključelog stanja na bazi difuzije [49] i na bazi drifta

inductance will lead to a decrease in the current rise rate, and voltage will be dropping faster (Figure 3c), but only up to a certain point.

If inductance exceeds the critical value, current will grow too slow, so more time will be needed for current to reach the holding current value. For that reason the turn-on time will be considerably longer. The experimental results greatly differ from the theoretical ones; the turn-on time is shorter, and at higher voltages slightly depends on the base thickness. At higher voltages the turn-on time is shorter due to a stronger avalanche effect which significantly shortens the regeneration time (t_r).

A considerable influence on the turn-on time is exerted by the electric field in the n-base which appears in the period of current rise. Experimental research [36], [42] has shown that at a high density of current in the n-base a strong electric field is formed. Dominant in this respect is the drift component current, with a result that voltage drop is greater on the thyristor, and the turn-on time is longer.

Finally, it should be noted that the turn-on time is extended with temperature rise.

2.6 Propagation of turn-on state

2.6.1 A general survey

The great practical importance and complexity of the turn-on state propagation explain why a lot of works have been written on the subject, the most important among them being [37], [40], [41], [45] to [47], [52]. Most of the listed works are based on experimental research: voltage drop measurement, recovery current measurement, measurement by means of probes, as well as optoelectronic measurement technique. Most experimental results lack full physical interpretation. The existing theories of turn-on state propagation, diffusion-based

[54] zasnovane su na grubim modelima iz kojih se ne može ocijeniti relativna uloga tih mehanizama u realnim tiristorima. Maphan [47] i [48], prvi je objasnio da do uništenja tiristora dolazi pri presporom rasprostiranju uključenog stanja po cijeloj barijeri J_2 . Tu pojavu povezao je s brzinom porasta struje i nazvao je efekt di/dt . On je jednostavnim mjerenjem pomoću pomoćne upravljačke priključnice utvrdio da je brzina rasprostiranja uključenog stanja 0,1 mm/ μ s. Kasniji radovi pokazuju da ta brzina nije konstantna, a najkompletnija slika o tome dana je u eksperimentalnim radovima [39] i [40].

2.6.2 Efekt di/dt

Uključenje tiristora nastaje najprije na uskom području u blizini upravljačke elektrode, formirajući u barijeru J_2 uski vodljivi kanal koji se zatim širi određenom brzinom. Početna gustoća struje u uskom kanalu mnogo puta je veća od stacionarne vrijednosti. Ta velika početna gustoća struje izaziva lokalno pregrijavanje tiristora, pa se pojavljuje tzv. vruća točka. Širenjem vodljivog kanala smanjuje se gustoća struje, čija vrijednost ovisi o brzini širenja vodljivog kanala i o brzini porasta struje di/dt . Odgovarajuća zavisnost može se matematički izraziti relacijom

$$\frac{di}{dt} = j \frac{ds}{dt} + \frac{dj}{dt} s, \quad (1)$$

gdje je:

s – trenutni presjek vodljivog kanala.

Vodljivi kanal najsporije se širi u n-bazi u blizini prijelaza J_2 [40], gdje vlada najveća gustoća struje i gotovo sav pad napona, pa na tom mjestu nastaje najveće zagrijavanje.

Smanjenje napona na tiristoru također ovisi o smanjenju gustoće struje, a lokalno zagrijavanje može se odrediti iz analize trenutne snage (slika 4). U promatranom slučaju, trenutna snaga ($p = u \cdot i > 0$, slika 4a) predstavlja brzinu generiranja topline u tiristoru. Za zornu predodžbu generirane topline u tiristoru zgodno je razmatrati odnos trenutne snage (p) i trenutnog presjeka vodljivog kanala (s):

$$\frac{p}{s} = \frac{u \cdot i}{s} = u \cdot j, \quad (2)$$

gdje je j trenutna gustoća struje.

[49] and drift-based [54], rely on rough-and-ready models with which it is not possible to assess the relative role of these mechanisms in real thyristors. Maphan [47], [48] was the first to explain that the destruction of thyristors occurs when the turn-on state propagation throughout the barrier J_2 is too slow. He linked this phenomenon to the current rise rate and called it di/dt effect. Applying a simple method of measuring by means of an auxiliary control clamp, he found that the turn-on state propagation velocity was 0,1 mm/ μ s. Latter-day works show that this velocity is not constant, whereas the fullest picture of it is given in experimental works [39], [40].

2.6.2 di/dt effect

A thyristor turns on first in the narrow area close to the control electrode forming into the barrier J_2 a narrow conductive channel which then expands at a certain rate. The starting current density in the narrow channel is many times higher than the stationary value. This high starting current density causes local overheating of the thyristor and, as a result, a hot spot appears. The expansion of the conductive channel leads a decrease in the density of the current, the value of which depends on the expansion rate of the conductive channel and the rate of current rise di/dt . Appropriate dependence can be mathematically expressed by the following relation

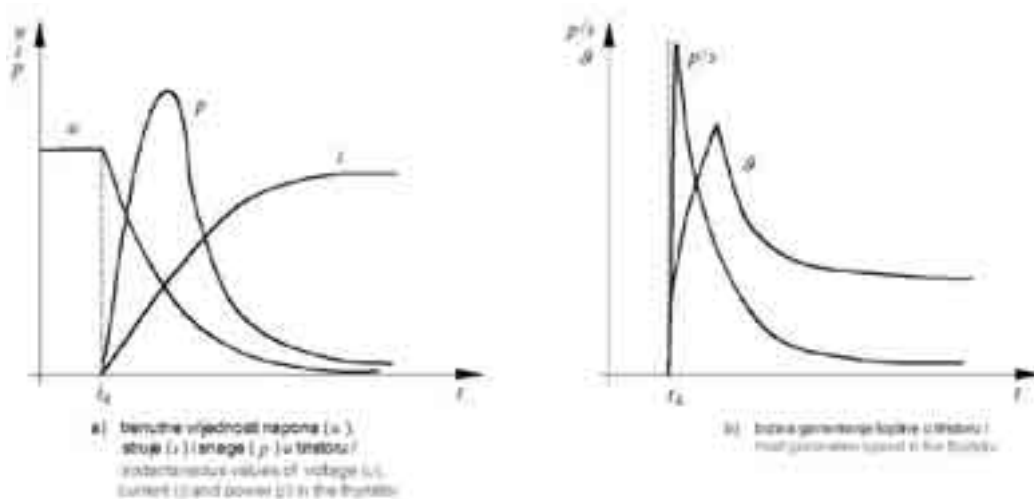
where:

s – instantaneous size of the conductive channel.

The conductive channel is expanding at the lowest rate in the n-base close to barrier J_2 [40], where the highest current density and nearly the whole voltage drop take place, which is why the strongest heating is generated here.

Voltage drop on the thyristor also depends on the decrease in current density, and local heating can be determined from an analysis of the instantaneous power (Figure 4). In the considered case the instantaneous power ($p = u \cdot i > 0$, Figure 4a) represents the rate of heat generation in the thyristor. As an illustration of heat generated in the thyristor it is convenient to study the relation between the instantaneous power (p) and the instantaneous size of the conductive channel (s):

where j is the instantaneous current density.



Slika 4 – Analiza trenutne električne snage u tiristoru
Figure 4 – Analysis of instantaneous electric power in the thyristor

Maksimalna vrijednost danog omjera (jednadžba 2) nastaje u trenutku formiranja vodljivog kanala (slika 4b). Nakon kraćeg vremena na tome mjestu stvara se maksimalna temperatura u toku jednog ciklusa (slika 4b), koja može izazvati lokalni toplinski proboj tiristora. Smanjenje lokalne tjemene temperature postiže se smanjenjem gustoće struje u prvoj fazi procesa uključivanja. S većom pobudnom strujom I_G postiže se veća početna površina uključivanja, tj. manja početna gustoća struje [52] i [54], a osim toga sporija je brzina porasta struje i kraće vrijeme uključivanja [52] i [55]. Međutim, pobudna struja ne smije prekoračiti dozvoljenu vrijednost zbog mogućeg oštećenja tiristora.

Tiristor je građen nehomogeno, pa se uvijek lokalno uključi bez obzira na način aktiviranja. Ta lokalna točka također se zadnja isključi u procesu isključenja tiristora [52], zbog čega je u cikličkom režimu rada, di/dt svojstvo lošije.

Poboljšanje di/dt svojstva, može se postići povećanjem početne vodljivosti i brzine rasprostiranja uključenog stanja. Oba ta faktora ovise o pobudnoj struji te o parametrima i geometrijskim odnosima p-n-p-n strukture [55].

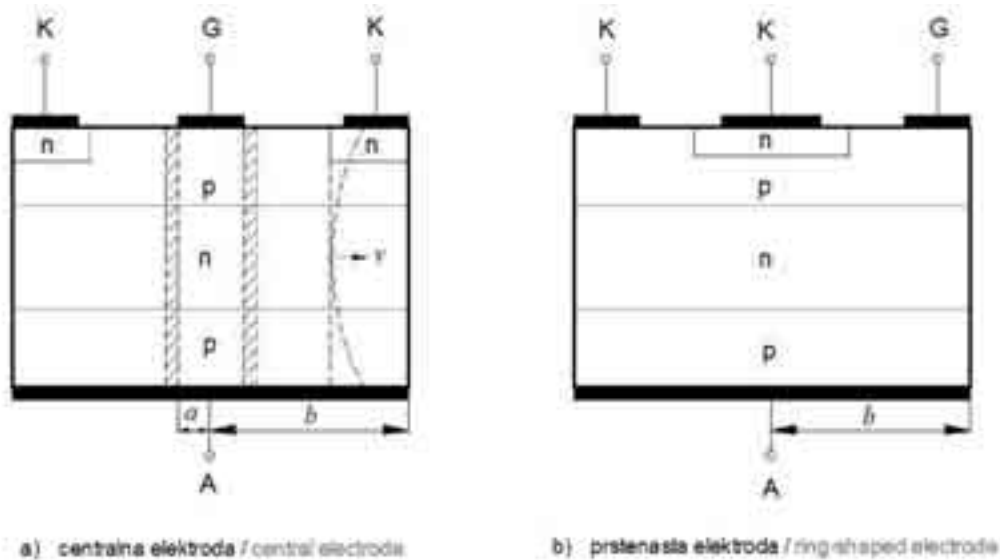
Pokušalo se raznim konstrukcijama pobudne elektrode, a ističu se konstrukcije s centralnom i prstenastom elektrodom (slike 5a i 5b). Poboljšanja su neznatna, jer tiristor i dalje najprije provede na ograničeno malom području uz rub elektrode. Tiristor s prstenastom elektrodom ima nešto veći di/dt , a s centralnom elektrodom ima kraće vrijeme uključivanja cijele površine [55], što je povoljnije za rad na višim frekvencijama.

The maximum value of a given ratio (equation 2) occurs at the moment in which the conductive channel is formed (Figure 4b). After a shorter lapse of time, at that place a maximal temperature develops in the course of a cycle (Figure 4b) which can cause a local thermal breakdown of the thyristor. Decrease in local peak temperature is achieved by lowering the current density in the first turn-on phase. With more drive current I_G a larger starting turn-on surface is attained and thereby a smaller starting current density [52], [54]; besides, the rate of current rise is slower and the turn-on time shorter [52], [55]. However, excitation current may not exceed the permissible value to avoid possible damage on the thyristor.

The thyristor's architecture is inhomogeneous, so it always turns on locally regardless of how it is activated. This local point is also the last to turn off in the thyristor turn-off process [52], which is why in the cyclic operating mode the di/dt property is deteriorated.

The di/dt properties can be improved by increasing the starting conductivity and propagation rate of turn-on state. Both of these factors depend on the excitation current and the parameters and geometrical relations of the p-n-p-n structure [55].

Attempts have been made with various designs of the excitation electrode, with central and ring-shaped electrodes being best known among them (Figures 5a and 5b). Improvements are negligible, however, because the thyristor still stays some while first in a limited small area at the edge of the electrode. The thyristor with a ring-shaped electrode has a little higher di/dt , and with a central electrode it has a shorter turn-on time of the whole surface [55], which is more suitable for operation at higher frequencies [55].



Slika 5 – Vrste konstrukcije pobudne elektrode tiristora
 Figure 5 – Structure types of thyristor excitation electrode

Znatnija poboljšanja svojstva di/dt postižu se pomoću tzv. Querfeld-Emitera [53] i [55]. Znatnija poboljšanja tiristora snage postignuta su ugradnjom pomoćnog tiristora unutar glavnoga [55]. Između glavne katode i pomoćnog tiristora formira se bočno električno polje, koje povećava brzinu širenja vodljivog kanala.

More significant improvements in di/dt properties are achieved by means of the Querfeld-Emitter [53], [55]. Marked improvements have been achieved with power thyristors by installing an auxiliary thyristor into the main thyristor [55]. Between the main cathode and the auxiliary thyristor an electric side field is formed which increases the expansion rate of the conductive channel [55].

2.6.3 Utjecaj temperature i frekvencije na di/dt svojstvo

2.6.3 The influence of temperature and frequency on di/dt property

Dobro poznavanje temperaturnih svojstava tiristora vrlo je važno za praktičnu primjenu. Već je rečeno da se na mjestu početnog uključivanja tiristora razvije maksimalna temperatura, koja u toku procesa opada (slika 4b), u ovisnosti od konstante toplinskog dovoda i gustoće struje. Ako tjemena temperatura prekorači dopuštenu vrijednost, nastaje na tom mjestu trajno oštećenje tiristora. Maksimalno dopuštena lokalna temperatura ovisi o režimu rada. Za pojedinačne impulse kreće se od 900 °C do 1 300 °C [55], dok je maksimalna temperatura elemenata 100 °C do 125 °C. Iz toga proizlazi da je dopuštena vrijednost di/dt , za pojedinačne impulse mnogo veća. U repetitivnom režimu rada, moguće je gomilanje topline u okolici vodljivog kanala, pa se tiristoru dodaju rashladna tijela, ili se smanji di/dt . Porastom radne frekvencije razvija se veća količina topline u jedinici vremena, pa se može poremetiti temperaturna ravnoteža. U tom slučaju se temperaturna ravnoteža može uspostaviti sniženjem radne temperature [53].

Thorough knowledge of the temperature properties of thyristors is very important for their practical use. As already noted, at the place of the thyristor's starting turn-on a maximal temperature develops which falls as the process continues (Figure 4b) in dependence on the thermal feed constant and the current density. If the peak temperature exceeds the permissible value, the thyristor will become permanently damaged at that place. The maximal permissible local temperature depends on the operating mode. For individual impulses it ranges from 9 000 °C to 1 300 °C [55], whereas the maximal temperature of the elements stands at 100 °C to 125 °C. It follows that the permissible value di/dt for individual impulses is much higher. In the repetitive operating mode there is a possibility of heat buildup in the vicinity of the conductive channel, so coolers are added to the thyristor or di/dt is decreased. With the increase in the operating frequency, more heat develops over the unit of time, so that temperature equilibrium can be disrupted. In that case, temperature equilibrium can be established by reducing the operating temperature. [53].

Dakle, dopuštena vrijednost di/dt ovisi o temperaturi kućišta i radnoj frekvenciji. Prekoračenje brzine porasta struje di/dt dovodi do toplinskog uništenja tiristora, pri čemu treba razlikovati dva tipa:

probaj u tzv. vrućoj točki, koji nastaje zbog prevelikog di/dt , a javlja se uvijek u blizini pobudne elektrode u vidu kratera, i to već nakon nekoliko desetaka ciklusa, probaj zbog termičkih zamora, koji nastaje kao posljedica velikih temperaturnih razlika unutar tiristorske strukture. Ta vrsta probaja nastaje nakon nekoliko stotina sati rada blizu pobudne elektrode u vidu kratera.

Međutim, do probaja može također doći zbog prekoračenja vršne vrijednosti struje, iako nije došlo do prekoračenja di/dt [53]. Ta vrsta probaja ne nastaje u blizini pobudne elektrode, već u točki u kojoj dođe do prekoračenja gustoće struje.

Iz dane analize vidi se da je granica opterećenja tiristora usko vezana sa svojstvom di/dt i radnom frekvencijom.

2.6.4 Brzina rasprostiranja i ekvivalentni otpor uključenog stanja

Proces rasprostiranja uključenog stanja istražuje se vrlo intenzivno radi velike praktične važnosti i složenosti pojave. Analitički izrazi za brzinu rasprostiranja [50], [51] i [54], izvedeni na grubim modelima na bazi difuznog, odnosno driftnog mehanizma nemaju praktično značenje za realne tiristore. Razvojem mjernih metoda, prvo s povećanim brojem sondi [50], [51], [52] i [55], a zatim primjenom elektronsko-optičke tehnike, dobiven je bolji uvid u proces rasprostiranja uključenog stanja. Utvrđeno je da se taj proces odvija nejednoliko, dolazi čak do skupljanja vodljivog kanala, obično u početku procesa [50]. Najsporije se širi vodljivi kanal u n-bazi (slika 5a), i to u oblasti maksimalne gustoće struje [55], što je u suprotnosti s teorijskim rezultatima [50], [51] i [54]. Najkompletnija mjerenja rasprostiranja uključenog stanja izvršena su u radovima [52] i [55]. Ti rezultati pokazuju da brzina rasprostiranja uključenog stanja nije monotona, već ima promjenjiv karakter, naročito u početku. Ta je promjenjivost manja pri jačoj pobudi, kao i u kasnijoj fazi. Međutim, srednja brzina rasprostiranja je oko 0,1 mm/ms, kako je još Maphan utvrdio [47] i [48]. Ako je početna gustoća struje manja od neke granične vrijednosti, neće se struja proširiti po cijeloj površini.

Therefore, the permissible value di/dt depends on the temperature of the casing and the operating frequency. Excess rate of current rise di/dt will lead to a thermal destruction of the thyristor, with two types thereof to be distinguished:

breakdown in the hot spot due to excessive di/dt , occurring always in the proximity of the excitation electrode, crater-like, after just several dozens of cycles, breakdown due to thermal fatigue as a result of major temperature differences within the thyristor's structure. This type of breakdown, also crater-like, occurs after several hundred hours of operation close to the excitation electrode.

However, a breakdown can also occur as a result of an excess in peak current value, without any di/dt excess [53]. This type of breakdown does not occur in the proximity of the excitation electrode, but in the point where current density is exceeded.

This analysis shows that the load limit of a thyristor is closely linked to the di/dt property and the operating frequency.

2.6.4 Propagation rate and equivalent resistance of turn-on state

The propagation of the turn-on state process is a subject of intensive research due to a major practical importance and complexity of that phenomenon. Analytical expressions for the rate of propagation [50], [51], [54], derived from approximate models on the basis of a diffuse, drift mechanism, have no practical importance for real thyristors. More advanced measuring methods, first using more probes [50], [51], [52], [55] then optoelectronic techniques [59], [60], [82], have provided a better insight into the propagation of the turn-on state process. It has been found that this process unfolds unevenly, that it may also be accompanied by the grouping of the conductive channel, normally at the start of the process [50]. The conductive channel in the n-base is spreading at the slowest rate (Figure 5a), unexpectedly in the area of maximum current density [55], which contradicts the theoretical results [50], [51], [54]. The most comprehensive measurements of the turn-on state propagation have been performed in works [52], [55]. Their results show that the turn-on state propagation rate is not monotonous, but variable, especially at the start. This variability is less expressed at a stronger excitation, as well as in the later phase. However, the mean propagation rate is approximately 0,1 mm/ μ s, as found by Maphan already [47], [48]. If the starting density of current is lower than some limit value, it will not spread over the whole surface.

U periodu rasprostiranja uključenog stanja nije utvrđena adekvatna veza između napona i struje tiristora. Tiristor bi se mogao za taj period nadomjestiti dinamičkim otporom R_d , pa imamo da je:

$$u = U_0 + i \cdot R_d. \quad (3)$$

Dinamički otpor R_d praktički je jednak otporu uključenog kanala. Najveći dio pada napona u vodljivom kanalu otpada na n-bazu. Radi jednostavnosti, uzima se da je uključen kanal cilindričnog oblika, a brzina jednaka brzini širenja kanala kroz n-bazu. Također se uzima da je otpor vodljivog kanala po jedinici površine jednak statičkom otporu po jedinici površine, a početna površina vođenja se zanemaruje. Iz toga slijedi da je otpor vodljivog kanala:

$$R_d = R_0 \frac{S}{\int_s ds}, \quad (4)$$

gdje je: R_0 – otpor u trenutku uključanja

Pomoću te relacije dobije se dinamički otpor tiristora s centralnom pobudom (slika 5a):

$$R_d = R_0 \frac{b^2 - a^2}{2avt + v^{-2} t^2}, \quad (5)$$

gdje je:

t – vrijeme,
 \bar{v} – srednja brzina širenja vodljivog kanala.

Za prstenastu pobudu (slika 5b) je:

$$R_d = R_0 \frac{b^2}{2bv\bar{t} - v^{-2} t^2}. \quad (6)$$

Dinamički otpor u oba slučaja opada hiperbolički s vremenom, kako je utvrđeno i eksperimentalno [31] i [32]. Eksperimentalno je također utvrđeno, da je utjecaj jakosti struje na dinamički otpor zanemariv [31], te da dinamički otpor tiristora s prstenastom pobudom, brže opada [32] (slika 6a). Ta se činjenica također očituje i u izvedenim relacijama (5) i (6), što je vidljivo iz grafičkog prikaza nazivnika tih jednažbi (slika 6b).

In the turn-on state propagation period, no adequate link has been found between the thyristor's voltage and current. For that period, the thyristor may be substituted by a dynamic resistance R_d , so we get:

The dynamic resistance R_d practically equals the resistance of a turn-on channel. The bulk of voltage drop in the conductive channel goes to the n-base. For the sake of simplicity it will be assumed that the turned on channel is cylinder-shaped and that velocity equals the velocity of channel propagation across the n-base. It will also be assumed that the conductive channel resistance per unit of surface equals the static resistance per unit of surface, whereas the starting conductance surface is ignored. What follows from this is the conductive channel resistance:

where R_0 is resistance at the turn-on moment

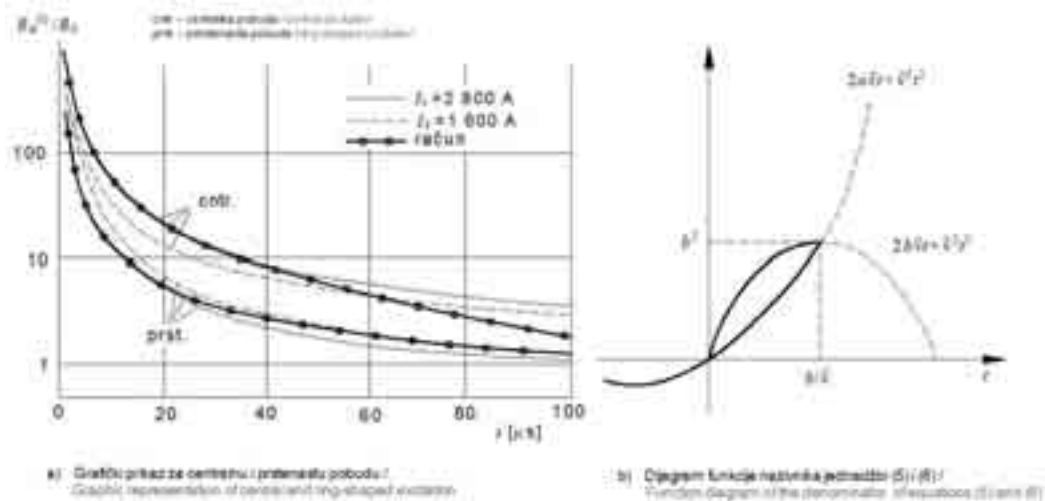
By means of this relation the dynamic resistance of the thyristor with central excitation is obtained (Figure 5a):

where:

t – time,
 \bar{v} – mean propagation speed of the conductive channel.

For the ring-shaped excitation (Figure 5b) it is:

Dynamic resistance in both cases falls hyperbolically with time, as experimentally confirmed [31], [32]. It has also been experimentally determined that the influence of current intensity on dynamic resistance is negligible [31] and that the dynamic resistance of a thyristor with ring-shaped excitation falls faster [32] (Figure 6a). This fact is also reflected on the derived relations (5), (6), as shown in the graphic representation of the denominator of these equations (Figure 6b).



Slika 6 – Ovisnost dinamičkog otpora tiristora s vremenom
 Figure 6 – Time dependence of thyristor's dynamic resistance

Eksperimentalno je utvrđeno [32] da je brzina širenja vodljivog kanala kod prstenaste pobude manja, a u početku procesa u oba je slučaja ta brzina dosta mala [32]. Na slici 6a prikazani su rezultati mjerenja dinamičkog otpora u [32] i ucrtane su odgovarajuće numeričke vrijednosti dobivene pomoću jednadžbi 5 i 6. Pri tome su uzete prosječne vrijednosti mjernih brzina u [32], i to: za centralnu pobudu $v=0,09$ mm/ms, za prstenastu pobudnu $v=0,07$ mm/ μs , a potrebne dimenzije su: $a = 1,6$ mm i $b = 16$ mm [32]. Numeričke vrijednosti pokazuju zadovoljavajuću točnost, a osnovni problem je u određivanju srednje brzine. Početak procesa je osobito važan, pa treba odrediti prosječnu brzinu u tom periodu, jer o njoj ovisi točnost jednadžbe (5) i (6). Međutim, proizvođači tiristora ne daju taj podatak, kao ni dimenzije a i b . Srednja brzina, \bar{v} , mogla bi se procijeniti pomoću relacije (1). Uz poznate vrijednosti v , a i b , izrazi za dinamički otpor jednadžba (5) i (6) mogu se primijeniti pri analizi brzine porasta struje (di/dt) i pri analizi raspodjele temperature.

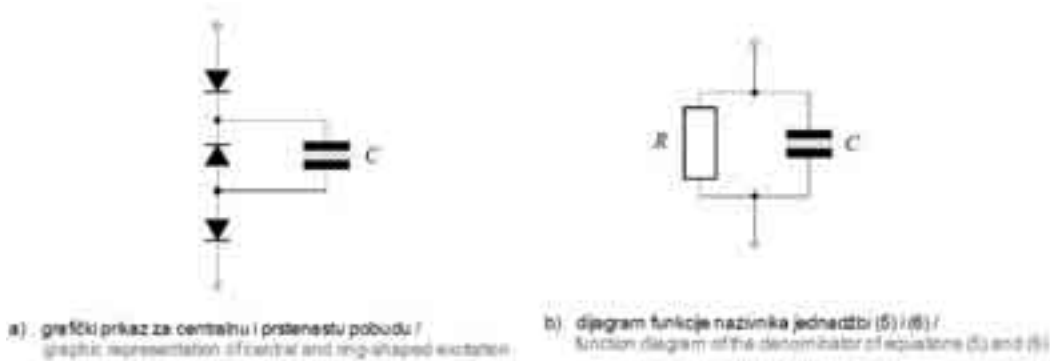
2.7 Efekt du / dt

Do uključivanja tiristora, obično neželjenog, dolazi pri prebrzom porastu anodnog napona. Ta pojava poznata je pod imenom efekt du/dt , o kojem je napisano mnogo radova, a značajniji su [1], [3], [11], [19] i [55]. U trenutku dovođenja napona, tiristor praktički djeluje kao kapacitet sastavljen od serijskog spoja kapaciteta barijera C_1 , C_2 , C_3 . Naime, otpor centralne inverzno polarizirane barijere vrlo je velik, kao i otpor vanjskih p-n prijelaza J_1 i J_3 , sve dok na njima napon ne preskoči vrijednost tzv. napo-

It has been experimentally determined [82] that the propagation rate of the conductive channel with ring-shaped excitation is smaller, that at the start of the process that rate is rather small in both cases [32]. Figure 6a shows the results of measuring dynamic resistance in [32] and appropriate numerical values obtained by means of equations (5) and (6) are entered therein. In this procedure the average values of measuring speeds in [32] are taken, viz.: for central excitation $v=0,09$ mm/ms, for ring-shaped excitation $v=0,07$ mm/ μs , whereas the required dimensions are: $a = 1,6$ mm and $b = 16$ mm [32]. Numerical values show a satisfactory degree of accuracy, whereas the main problem is to determine the mean velocity. The start of the process is particularly important, so the average speed ought to be determined in that period, because the accuracy of equations (5) and (6) depends on it. However, thyristor manufacturers do not disclose this information, nor the above mentioned dimensions a and b . The mean velocity \bar{v} could be assessed by means of relation (1). Given the known values v , a and b , expressions for dynamic resistance (equations 5 and 6) can be applied in analyzing the rate of current rise (di/dt) and the distribution of temperature.

2.7 The du / dt effect

A thyristor turn-on, usually undesired, occurs when anode voltage rises too fast. This phenomenon is termed du/dt effect, which is a subject of many works, the most important among them being [1], [3], [11], [19], [55]. At the moment of voltage feed, the thyristor practically acts as a capacity composed of the series connection of the capacities of barriers C_1 , C_2 , C_3 . Namely, the resistance of the central inversely poled barrier is very strong, as is the resistance of the external p-n transitions J_1 i J_3 , as long as voltage on them does not exceed the knee voltage



Slika 7 – Ekvivalentne sheme za otpor vanjskih p-n prijelaza, za brzi porast napona
Figure 7 – Equivalent diagrams for the resistance of external p-n transitions, for a voltage jump

na koljena. Napon koljena za silicij je oko 0,5 V, nakon čega se otpor vanjskih p-n prijelaza naglo smanjuje, pa se za brzi porast napona može nadomjestiti približnom ekvivalentnom shemom (slika 7).

Detaljnija ekeivalentna shema može se dobiti pomoću prikaza tiristora s dva tranzistora [50]. Međutim, takva je shema suviše komplicirana i nepraktična za postavljeni zadatak.

U centralnom prijelazu J_2 teče kapacitivna struja.

value. The knee voltage for silicon is around 0,5 V, after which the resistance of external p-n transitions steeply drops, and for a voltage jump can thus be substituted by an approximate equivalent diagram (Figure 7).

A more detailed equivalent diagram can be obtained by means of a two-transistor thyristor diagram [50]. However, such a diagram is too complicated and impractical for the task at hand. Detaljnija ekeivalentna shema može se dobiti pomoću prikaza thyristora s dva tranzistora [50].

Capacitive current flows in the central barrier J_2

$$i_c = \frac{d}{dt}[q_2(u)] = \frac{dq_2}{du} \cdot \frac{du}{dt} = C_{J_2}(u) \frac{du}{dt}, \quad (7)$$

čiji iznos i oblik ovisi o brzini porasta napona i kapaciteta barijere J_2 .

Kada se u bazama skupi tzv. kritični naboj, započinje proces uključivanja tiristora. Naboj se brže prikuplja što je veća brzina porasta napona du/dt , dok uključivanje nastupi pri manjem naponu (slika 8a). Nadalje, kritična vrijednost du/dt opada s porastom temperature (slika 8a), a raste s početnim anodnim naponom (slika 8b).

U slučaju pozitivnog početnog napona, kapacitet barijere J_2 je manji, pa je, prema jednačbi (7), dopuštena veća vrijednost du/dt (slika 8b). Isto tako se, u slučaju negativnog početnog napona, moraju najprije sve barijere prepolarizirati, a za to je potrebno vrijeme i određena količina naboja.

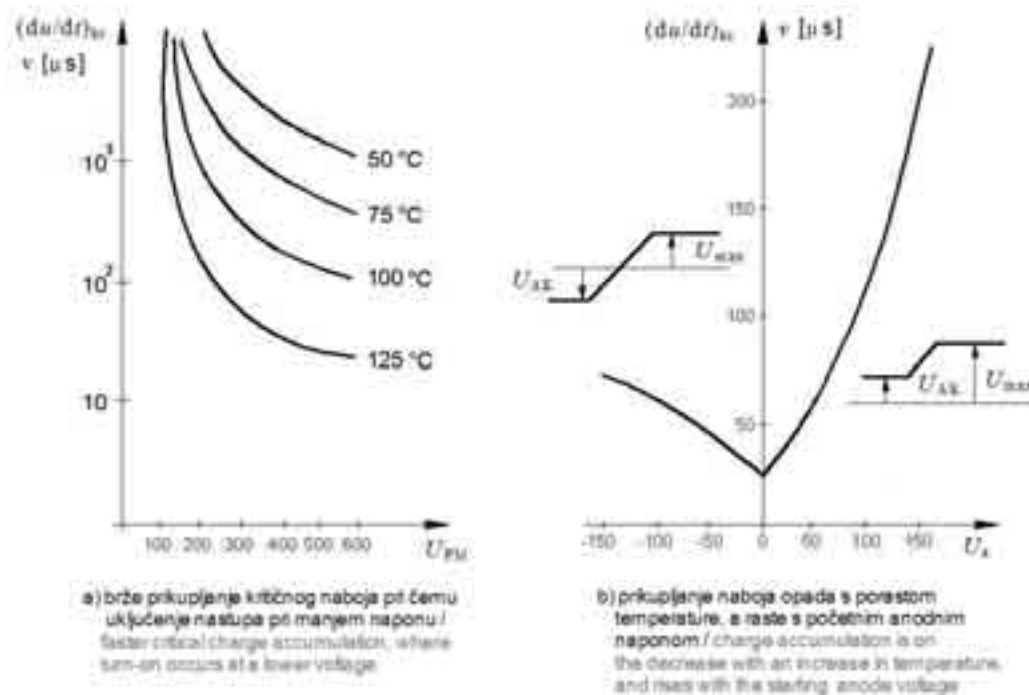
Povećanje kritične vrijednosti du/dt , može se postići povećanjem struje pridržavanja I_L i smanjenjem faktora strujnog pojačanja α_2 . Prva mogućnost je dosta ograničena, a druga se sa-

and its amount and shape depend on the rate of voltage rise and J_2 barrier capacity.

The thyristor turn-on process starts once a critical charge is reached in the bases. The charge accumulates the faster the faster is the rate of voltage rise du/dt , until the turn-on occurs at a lower voltage (Figure 8a). Furthermore, the critical value du/dt is on the decrease with an increase in temperature (Figure 8a), and rises with the starting anode voltage (Figure 8b).

In the case of a positive starting voltage, the capacity of barrier J_2 is smaller, so, according to equation (7), a higher value du/dt is allowed (Figure 8b). Likewise, in the case of a negative starting voltage all the barriers must first reverse their poles, and that requires time as well as a certain amount of charge.

The critical value of du/dt can be increased by increasing the holding current I_L and decreasing the current gain factor α_2 . The first possibility is rather limited, the second possibility is that



Slika 8 – Proces uključanja tiristora u ovisnosti o prikupljenom kritičnom naboju u bazama
Figure 8 – Thyristor turn-on process in dependence on the accumulated critical charge in the bases

stoji u tome da samo dio anodne struje prolazi kroz prijelaz J_3 . Kod manjih tiristora to se postiže stavljanjem otpora između pobudne elektrode i katode [51], a kod većih konstruktivno, pomoću tzv. kratkospojenog emitera [11]. Time je smanjena efektivna površina p-n prijelaza, a osim toga teže se aktivira tiristor strujom I_G .

Pri projektiranju tiristorskog sklopa treba obratiti posebnu pozornost na du/dt . Kod nepoželjnog preranog uključanja, može doći do uništenja tiristora, jer su u tom slučaju lošija di/dt svojstva. Kod projektiranja tiristorskih sklopova može se umjesto nelinearne sheme (slika 7a) koristiti odgovarajuća nelinearizirana nadomjesna shema (slika 7b).

U promatranom slučaju dominantni su otpor i kapacitet inverzno polarizirane barijere J_2 . Volt-tamperska karakteristika inverzno polarizirane barijere je, osim na samom početku, u čitavom radnom području praktički linearna, pa se može uzeti da je otpor R u nadomjesnoj shemi (slika 7b) linearan. Isto tako, kapacitet inverzno polarizirane barijere naglo se smanjuje samo kod malih napona, a u najvećem dijelu radnog područja neznatno se mijenja. Zbog toga se ekvivalentni kapacitet može također linearizirati sa srednjom vrijednošću kapaciteta barijere unutar radnog područja. Kod većine energetske dioda i tiristora, u većem dijelu radnog napona, otpor i kapacitet se neznatno mijenjaju.

only a part of anode current flows across barrier J_3 . With smaller thyristors this is attained by putting resistance between the excitation electrode and the cathode [51], with larger thyristors by way of design, with the shorted emitter [11]. This reduces the effective surface of p-n barrier and, in addition, the thyristor is harder to activate with I_G current.

In designing a thyristor unit special attention should be paid to du/dt . Apart from undesired premature turn-on, the thyristor may be destroyed, because in that case the di/dt properties are inferior. In designing a thyristor unit, an appropriate nonlinearized equivalent diagram (Figure 7b) could be used instead of a nonlinear diagram (Figure 7a).

Dominant in the considered case are the resistance and capacity of the inversely poled barrier J_2 . The volt-ampere characteristic of the inversely poled barrier is practically linear in the whole operating area, except for the very start, so it can be assumed that resistance R in the equivalent diagram (Figure 7b) is linear. Also, the capacity of the inversely poled barrier rapidly drops only at small voltages, whereas slightly varies in the most part of the operating area. For that reason the equivalent capacity can also be linearized with the mean value of the barrier capacity within the operating area. With most energy diodes and thyristors, in a greater part of the operating voltage, resistance and capacity are slightly varying.

2.8 Dinamička svojstva isključenja

2.8.1 Prijelazni proces isključenja

Tijekom procesa isključenja tiristora dolazi do odstranjivanja suvišnog naboja iz p-n-p-n strukture, koji se nagomilao u propusnom režimu rada. Tiristori se najbrže i najčešće isključuju invertiranim naponom, a isto se može postići postupnim smanjenjem struje ispod vrijednosti I_H [4], kao i negativnom pobudnom strujom, ali samo za tiristore manje snage. O tome je objavljen velik broj radova, uglavnom eksperimentalnih.

Za analizu procesa isključenja najprikladniji je tiristorski krug s čisto omskim opterećenjem (slika 1a). Invertiranjem napona započinje odstranjivanje suvišnih nosilaca, koji iz baza prelaze u vanjske slojeve; šupljine prijelaza iz baze n_1 u sloj p_1 , a elektroni iz baze p_2 u sloj n_2 . Najprije se odstranjuju sporedni nosioci uz same prelaze J_1 i J_3 , gdje se formira gradijent koncentracije manjinskih nosilaca, a prijelaz J_2 je propusno polariziran i kroz njega teku struje elektrona i šupljina. Struja šupljina je dominantna, jer je p-baza jače dopirana. Budući da je vrijeme života manjinskih nosilaca u p-bazi kraće, zatim da je ta baza uža i da sadrži manju količinu manjinskih nosilaca, koji se osim toga slabije obnavljaju preko J_2 prijelaza, najprije će iščeznuti gradijent koncentracije uz prijelaz J_3 . Pri tome započinje prepolarizacija barijere J_3 ; njen napon raste, a struja tiristora opada.

Obično je probojni napon barijere J_3 mali, pa brzo dolazi do proboja u trenutku t_2 (slika 9a). Međutim, kako na prijelazu J_1 još uvijek postoji gradijent koncentracije manjinskih nosilaca, i dalje će teći konstantna struja do trenutka t_3 kada nestaje gradijent koncentracije na prijelazu J_1 i pojavljuje se početni zaporni sloj. Barijera J_1 započinje inverznom polarizacijom, pri čemu povećava svoju debljinu i preuzima gotovo sav vanjski napon. U tom periodu (t_3 , t_5) debljina zapornog sloja povećava se toliko da otpor tiristora poraste do nekoliko stotina k Ω , što dovodi do smanjenja struje na vrijednosti struje inverzne polarizacije. U slučaju induktivnog opterećenja kruga, može doći do značajnih naponskih nadvišenja i oscilacija, kako je eksperimentalno utvrđeno [32] (slika 9b). Ta naponska nadvišenja mogu izazvati trajno oštećenje tiristora [32].

Pri induktivnom opterećenju kruga, struja u intervalu (t_0 , t_1) i (t_2 , t_3) raste, jer tiristor predstavlja zanemarivo mali otpor, dok u intervalima (t_1 , t_2) i (t_3 , t_5) struja opada zbog prepolarizacije, najprije barijere J_3 , a zatim J_1 .

2.8 Dynamic turn-off properties

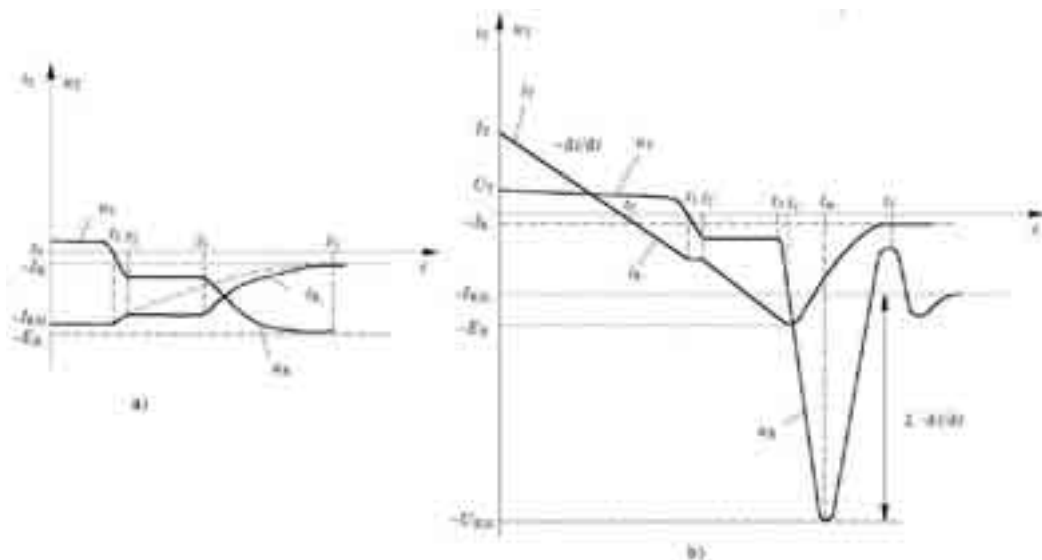
2.8.1 The transient turn-off process

The thyristor turn-off process is accompanied by the removal of the excess charge from the p-n-p-n structure, accumulated in the forward operating mode. The fastest and typical way of turning thyristors off is by voltage inversion, and the same can be done by gradually bringing current down below I_H value [4], as well as by a negative excitation current, but only with lower-powered thyristors. The subject is addressed in many works, mostly experimental ones.

For an analysis of the turn-off process the most convenient is a thyristor circuit with a purely ohmic load (Figure 1a). With voltage inversion starts the removal of excess carriers which from the bases move to external layers; transition holes from base n_1 to layer p_1 , electrons from base p_2 to layer n_2 . First removed are secondary carriers at barriers J_1 and J_3 , where a concentration gradient of secondary carriers is formed and barrier J_2 is forwardly poled, letting electron and hole currents flow through it. Hole current is dominant, because the p-base doping is stronger. Considering the fact that the lifetime of secondary carriers in p-base is shorter, that that base is narrower and that it contains a smaller quantity of secondary carriers, which, in addition to it, regenerate rather weakly across barrier J_2 , first to disappear will be the concentration gradient at barrier J_3 . At the same time, pole reversal of barrier J_3 starts; its voltage rises, thyristor current drops.

The breakdown voltage of barrier J_3 is usually low, so the breakdown occurs quickly at the moment t_2 (Figure 9a). However, as the concentration gradient of secondary carriers still exists on barrier J_1 , the constant current will go on flowing up to the moment t_3 when the concentration gradient at barrier J_1 disappears and the starting barrier layer emerges. Barrier J_1 starts with inverse polarization, gaining on thickness in the process, taking over nearly the whole external voltage. Over that period (t_3 , t_5) the thickness of the barrier layer goes up so much that thyristor resistance rises to reach several hundred k Ω , which causes current drop down to the current values of inverse polarization. In the case of an inductive circuit load, as experimentally found, this may lead to significant voltage overshoots and oscillations [32] (Figure 9b). Such voltage overshoots can cause permanent damage to thyristors [32].

In the case of an inductive circuit load, current grows linearly in intervals (t_0 , t_1) and (t_2 , t_3), because the thyristor poses a negligibly small resistance, whereas in intervals (t_1 , t_2) and (t_3 , t_5) current drops because of pole reversal, first of barrier J_3 , then of bar-



Slika 9 - Odstranjivanje suvišnog naboja iz baze tiristora
Figure 9 - Removal of excess charge from the thyristor base

U trenutku t_3 nastupa prepolarizacija barijere J_1 , struja usporava svoj rast i u t_4 postiže svoj maksimum, a napon na tiristoru poraste do vrijednosti napona izvora. Time još nije odstranjen sav suvišan naboj iz baze n, struja je još znatna, ali postupno opada do vrijednosti inverzne struje zasićenja, dok napon raste da bi u trenutku t_m poprimio svoj maksimum (slika 9b). Odgovarajuće naponsko nadvišenje jednako je padu napona na induktivitetu. Tijekom prepolarizacije barijera J_1 naglo povećava svoju debljinu, a napon brzo raste, pa pri tome u barijeri teče znatna kapacitivna struja.

Odstranjivanje suvišnog naboja iz baza ne vrši se samo inverznom strujom već i rekombinacijom, koja postaje značajnija u periodu smanjenja inverzne struje (slika 9).

2.8.2 Vrijeme oporavka

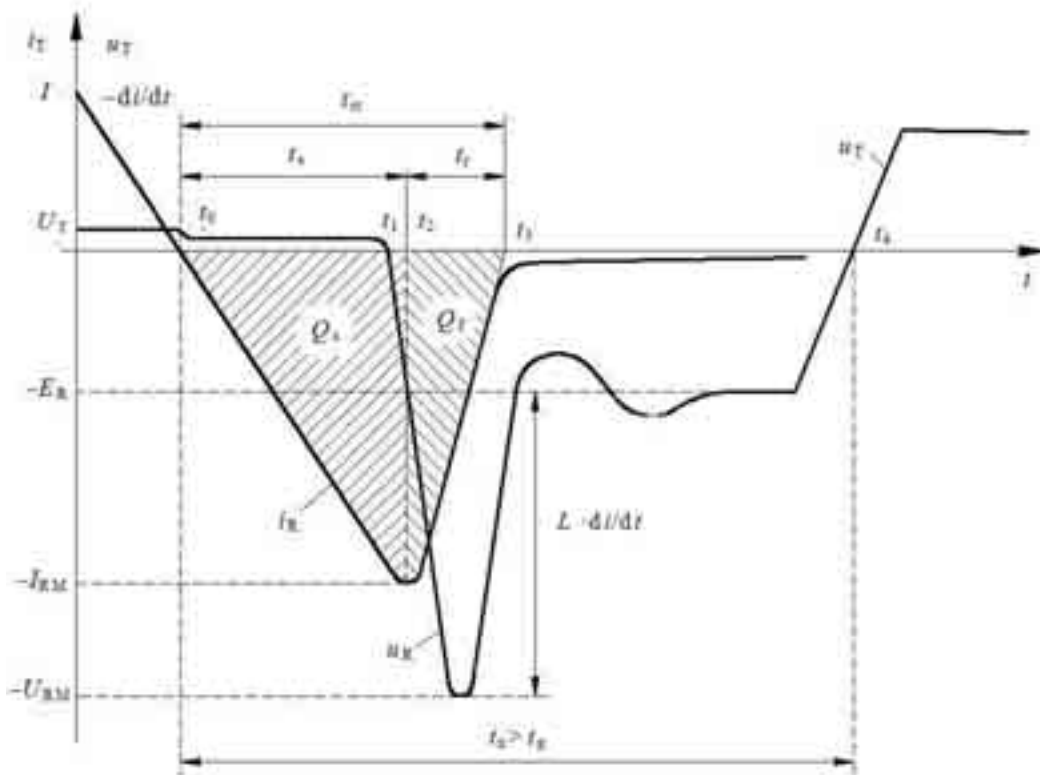
Većina tiristora građena je tako da je probojni napon barijere J_3 zanemarivo mali, pa je dinamička karakteristika isključenja tiristora praktički ista kao p-n diode (slika 10). U slučaju induktivnog opterećenja struja se linearno mijenja do trenutka t_1 , kada započinje prepolarizacija barijere J_1 (slika 10). U vremenskom intervalu t_0 do t_1 napon je pozitivan, a struja negativna, pa se tiristor može nadomjestiti naponskim izvorom čija je EMS jednaka zatečenom radnom naponu na tiristoru, a unutarnji otpor je vrlo mali. Nakon t_1 , struja još neznatno raste i u t_2 postiže svoj maksimum (slika 10). Protekli vremenski interval zove se vrijeme oporavka barijere (t_s). Zatim dolazi

rier J_1 . At the moment t_3 the pole reversal of barrier J_1 takes over, current decelerates its rise and at t_4 reaches its maximum, whereas voltage on the thyristor rises to the source voltage value. This still has not removed complete excess charge from base n, current is still significant, but gradually falling to the value of inverse saturation current, while voltage rises to reach its maximum at the moment t_m (Figure 9b). A certain voltage overshoot equals a voltage drop on inductance. In the course of pole reversal barrier J_1 rapidly increases in thickness, voltage rises quickly, and a significant capacitive current flows in the barrier.

Excess charge is removed from the bases not only by inverse current, but also by recombination which in the period of decreasing inverse current becomes more significant (Figure 9).

2.8.2 Recovery time

Most thyristors are so structured that the breakdown voltage of barrier J_3 is negligibly small, so the dynamic characteristic of thyristor turn-off is practically the same as it is with p-n diode (Figure 10). In the case of inductive load, current linearly changes up to the moment t_1 , when the pole reversal of barrier J_1 takes over (Figure 10). In the time interval t_0 to t_1 voltage is positive, current is negative, so the thyristor can be substituted for a voltage source whose EMF equals the found operating voltage on the thyristor, and the internal resistance is very small. After t_1 , current still rises slightly and at t_2 reaches its maximum (Figure 10). The passed time interval is the recovery time of barrier (t_s). Next comes n-base cleaning, where current gradually drops to the value



Slika 10 – Dinamička karakteristika isključenja tiristora
Figure 10 – The dynamic characteristic of thyristor turn-off

do čišćenja n-baze, pri čemu struja postupno opada do vrijednosti inverzne struje zasićenja. Proteklo vrijeme zove se vrijeme oporavka baze (t_f), a neki ga zovu vrijeme pada struje. Ukupno vrijeme zove se vrijeme oporavka tiristora $t_r = t_s + t_f$, dok je sa t_x označeno vrijeme odmaranja (slika 10).

Zatečena količina naboja Q_0 u n-bazi mnogo puta je veća u trenutku kad struja prelazi kroz nulu (t_0) od zatečenog naboja u p-bazi, a ovisi o parametrima tiristora, amplitudi propusne struje I i brzini smanjenja struje ($-di/dt$) (slika 10). Dio zatečenog naboja odstranjuje se rekombinacijom, a tzv. prijelazni naboj $Q_{\pi} = Q_s + Q_f$ putem prisile struje. Prijelazni naboj ovisi o tipu tiristora i režimu rada, a raste s temperaturom za 0,4 %/°C.

Proizvođači obično daju podatke o naboju Q_s u zavisnosti od propusne struje I , temperature i od brzine inverzne struje di_R/dt . Pomoću tih podataka može se izračunati:

$$t_s = \sqrt{\frac{2Q_0}{\frac{di_R}{dt}}}, \quad (8)$$

vrijeme oporavka barijere [t_s]:
tjemena vrijednost inverzne struje (slika 10):

of inverse saturation current. The passed time is the recovery time of barrier (t_f), some refer to it as current drop time. The total time is the thyristor's recovery time $t_r = t_s + t_f$ (Figure 10), whereas t_x signifies rest time (Figure 10).

The amount of charge Q_0 found in n-base is many time greater at the moment when current is passing through null (t_0) than the amount of charge found in p-base, depending on thyristor parameters, forward current amplitude I and current drop rate ($-di/dt$) (Figure 10). A part of the found charge is removed by recombination and the transition charge $Q_{\pi} = Q_s + Q_f$ due to influence exerted by current. The transition charge depends on the type of the thyristor and its operating mode, and grows with temperature at the rate of 0,4 %/°C.

Manufacturers usually disclose data on charge Q_s in dependence on forward current I , temperature and the velocity of inverse current di_R/dt . By means of these data it is possible to compute:

barrier recovery time [t_s]:
inverse current peak value (Figure 10):

$$I_{RM} = \sqrt{2Q_s \frac{di_R}{dt}} \quad (9)$$

Opadajući dio struje oporavka nije dovoljno teoretski obrađen, a eksperimentalno je utvrđeno da struja oporavka u većini slučajeva ima trokutast oblik i da je $t_s = 0,6 \cdot t_r$ [2].

U eksperimentalnim radovima [32], [34] i [50] izvršena su opširna istraživanja destruktivnih oscilacija u krugovima s diodom. Utvrđeno je da prekoračenje kritične vrijednosti di_R/dt (krug s malim otporom i relativno velikim induktivitetom) stvara nagli pad struje oporavka, pri čemu nastanu prigušene oscilacije s visokim naponskim šiljcima. Također je utvrđeno da i pri vrlo malim induktivitetima (nekoliko mikrohenrija) mogu nastati oscilacije, pa treba obratiti pozornost i na induktivitet sabirnice. Kritična brzina porasta inverzne struje tiristora proporcionalna je s debljinom n-baze.

Sprječavanje mogućih naponskih udara na tiristoru i diodi postiže se ugradnjom zaštitnog kruga.

2.8.3 Vrijeme odmaranja i ekvivalentna shema tiristora za period isključenja

Sposobnost blokiranja ponovo dovedenog pozitivnog napona tiristor postiže kad se iz n-baze odstrani sav suvišni naboj. Tijekom vremena oporavka t_{rr} odstranjen je iz n-baze samo dio suvišnog naboja, a daljnje odstranjenje odvija se pretežno rekombinacijom. Vremenski interval od prolaska struje kroz nulu pa do trenutka kada je tiristor sposoban blokirati pozitivni napon maksimalno dopuštene brzine porasta zove se vrijeme odmaranja t_x (slika 10). To vrijeme ovisi o više faktora.

Ono je proporcionalno s dužinom vremena života manjinskih nosilaca u n-bazi, koja raste s temperaturom. Zbog toga treba paziti da se pravodobno ohladi i najkraće mjesto u tiristoru, a to je početni kanal vođenja. Iz toga slijedi da vrijeme odmaranja raste s brzinom porasta struje, kao i s porastom propusne struje i dužinom njenog trajanja. Vrijeme odmaranja se skraćuje s porastom inverznog napona do određene granice, te sa smanjenjem pozitivnog napona i brzinom porasta toga napona.

Za praksu je vrlo važan proces isključenja tiristora, osobito nakon početka prepolarizacije barijere J_1 , tj. za $t > t_2$ (slika 10). U dostupnoj literaturi nije dan analitički izraz odnosa napona i struje za inverzni režim rada tiristora. Me-

The evanescent part of recovery current has not been sufficiently theoretically explored, whereas it has been experimentally found that recovery current is in most cases triangularly shaped and that $t_s = 0,6 \cdot t_r$ [2].

In experimental works [32], [34] and [50] destructive oscillations in diode circuits have been extensively explored. It has been found that excess critical value di_R/dt (a circuit with small resistance and relatively big inductance) will cause a sharp drop of recovery current, accompanied by damped oscillations with pronounced voltage spikes. It has also been found that oscillations may occur at very small inductances (several μH), so attention should also be paid to busbar inductance. The critical growth rate of thyristor inverse current is proportional to the thickness of n-base.

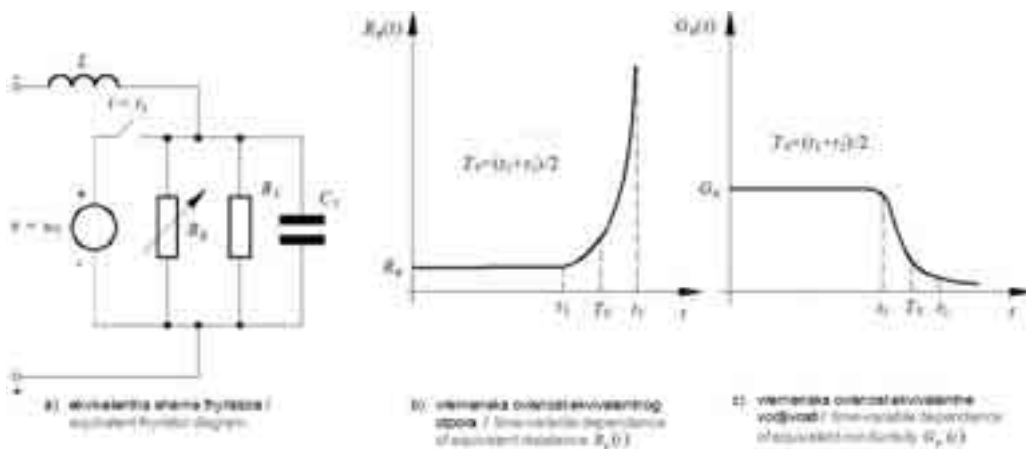
Possible voltage shocks on thyristors and diodes are prevented by installing a protection circuit.

2.8.3 The thyristor's rest time and equivalent diagram for the turn-off period

The capability of blocking a re-fed positive voltage is achieved by a thyristor when complete excess charge is removed from n-base. During the recovery time t_{rr} only a part of excess charge is removed from n-base, whereas further removal takes place largely by recombination. The time interval from the passage of current through null to the moment when the thyristor is capable of blocking the positive voltage of maximal permissible growth rate is referred to as rest time t_x (Figure 10). That time depends on a number of factors.

It is proportional to the length of the life-times of secondary carriers in n-base, which grows with temperature. Hence the need to make sure that the hottest place in the thyristor cools off in time, and that is the starting conductance channel. Therefore, the rest time grows with the growth rate of current, as well as the growth and duration of forward current. The rest time is shortened with the rise in inverse voltage up to a certain limit, as well as with the decrease in positive voltage and the rise rate of that voltage.

What matters much in practice is the thyristor turn-off process, especially after the start of the pole reversal of barrier J_1 , i.e., for $t > t_2$ (Figure 10). The available literature does not provide an analytical expression of voltage-current relation for the thy-



Slika 11 – Vrijeme odmaranja i ekvivalentna shema tiristora
 Figure 11 – Rest time and equivalent thyristor diagram

đutim, na temelju danog opisa procesa može se približno napraviti odgovarajuća nadomjesna shema.

Radi toga poslužit će pojednostavljena karakteristika prijelaznog procesa u inverznom režimu rada (slika 10). Od trenutka obrtanja napona izvora, pa do početka prepolarizacije barijere J_1 ($t = t_1$) tiristor se može nadomjestiti naponskim izvorom konstantne EMS i malog unutarnjeg otpora, ili jednostavno samo idealnim naponskim izvorom čija je EMS jednaka padu napona u tom intervalu [$e(t) = u_T$, slika 11]. Međutim, za prijelazni proces osobito je zanimljiv period od početka prepolarizacije barijere J_1 ($t \geq t_1$). Napon u vrlo kratkom vremenskom intervalu ($t_1 + t_2$) naraste na vrijednost $U \leq E_R$, a barijera se prepolarizira.

Taj period može se nadomjestiti vremenski promjenjivim otporom $R_p(t)$ (slika 11a) čija vrijednost u vrlo kratkom vremenskom intervalu (t_1, t_2) poraste od vrijednosti R_p do beskonačnosti, odnosno vodljivost se smanji od vrijednosti G_p do nule. Odgovarajući matematički model otpora $R_p(t)$ može se prikazati eksponencijalnom funkcijom:

$$R_p(t) = R_p \left(1 + e^{\frac{t-T_0}{t_2-t_1}} \right), \quad (10)$$

(slika 11a), a odgovarajuća vodljivost je (slika 11c):

$$G_p(t) = G_p \frac{1}{1 + e^{\frac{t-T_0}{t_2-t_1}}}, \quad (11)$$

Otpor $R_p(t)$ u trenutku t_2 postane reda veličine otpora R_1 inverzno polarizirane barijere J_1 . Interval (t_1, t_2) može se također nadomjestiti

ristor's inverse operating mode. However, based on the given description of the process, it is possible to approximately make an appropriate equivalent diagram.

What can serve this purpose is a simplified characteristic of the transient process in the inverse operating mode (Figure 10). From the moment of the source voltage reversal to the start of the pole reversal of barrier J_1 ($t = t_1$) the thyristor can be substituted by a voltage source of constant EMF and small internal resistance, or just by an ideal voltage source whose EMF equals the voltage drop in that interval [$e(t) = u_T$, Figure 11]. However, of special interest for the transient process is the period from the start of the pole reversal of barrier J_1 ($t \geq t_1$). In a very short time interval ($t_1 + t_2$) voltage rises to $U \leq E_R$, and the barrier reverses the poles.

That period can be substituted by time-variable resistance $R_p(t)$ (Figure 11a) the value of which increases from R_p to infinity over a very short time interval (t_1, t_2), or conductivity decreases from G_p to null. Appropriate mathematical model of resistance $R_p(t)$ can be presented by the exponential function:

(Figure 11a), whereas the corresponding conductivity is (Figure 11c):

Resistance $R_p(t)$ at the moment t_2 becomes of the order of resistance R_1 of inversely poled barrier J_1 . The interval (t_1, t_2) can also be substituted by lin-

EMS $e(t)$ linearnog porasta kao na slici 10, koja se u trenutku t_2 isključuje. U periodu $t > t_2$ glavnu ulogu ima inverzno polarizirana barijera, čija je debljina znatno porasla do trenutka t_2 . Taj period rada može se nadomjestiti paralelnim spojem otpora i kapaciteta inverzno polarizirane barijere J_1 (slika 11a). Dok je otpor $R_p(t)$ u tom intervalu naglo poprimio neizmjerenu vrijednost. Na isti način kao u točki 2.4, otpor i kapacitet barijere J_1 može se linearizirati.

3 ZAKLJUČAK

Analizirana su dinamička svojstva tiristora. Prvo su razmatrana dinamička svojstva i karakteristike uključivanja, a zatim je detaljnije analiziran efekt di/dt . Na temelju proučenih svojstava širenja uključenog kanala predložena je, za taj režim rada, nadomjesna shema tiristora u vidu vremenski promjenjivog otpora. Na temelju općeg izraza za računanje toga otpora određen je odgovarajući izraz za tiristor s prstenastom i centralnom pobudom. Zatim je analiziran efekt du/dt i predložena adekvatna nadomjesna shema za taj period rada. Na kraju su analizirana dinamička svojstva isključenja tiristora i također predložena odgovarajuća nadomjesna shema.

early rising EMF $e(t)$, as in Figure 10, which turns off at the moment t_2 . In the period $t > t_2$ the main role is played by the inversely poled barrier, the thickness of which has considerably increased up to the moment t_2 . That period of operation can be substituted by a parallel connection of the resistance and capacity of the inversely poled barrier J_1 (Figure 11a), while resistance $R_p(t)$ in that interval rapidly rose to infinity. The resistance and capacity of barrier J_1 can be linearized in the same way as in section 2.4 above.

3 CONCLUSION

In this work the dynamic properties of thyristors are analyzed. Considered first were the dynamic turn-on properties and characteristics, which was followed by a more detailed account of the di/dt effect. Based on the studied propagation properties of a turned-on channel, the thyristor's substitution diagram was proposed for this operating mode in the form of time-variable resistance. On the basis of the general expression for the calculation of this resistance, an appropriate expression for the thyristor with ring-shaped and central excitation was defined. Then the du/dt effect was analyzed and an appropriate substitution diagram proposed for that operating period. Finally, the thyristor's dynamic turn-off properties were analyzed and an appropriate substitution diagram likewise proposed.

LITERATURA / REFERENCES

- [1] GENTRY, . et al., Semiconductor Controlled Rectifiers, by Prentice-Hall, 1964
- [2] Тиристоры (справочник), Энергия, 1971
- [3] КУЗЬМИН, ., Тиристоры малой и средней мощности, Советско радио, Москва, 1970
- [4] JUZBAŠIĆ, ., Elektronički elementi, Tehn. knjiga, Zagreb, 1970.
- [5] MEYR, ., Thyristoren in der technischen Anwendung, Band 1, Berlin, 1967
- [6] ДЗЮБИН, ., Тиристоры в электрических схемах, Энергия, Москва, 1972
- [7] ИСАКОВ, . et al., Тиристорные преобразователи повышенной частоты, Техника, Киев, 1976
- [8] STUMPE, ., ETZ-A 83 4, 1962
- [9] GERLACH, ., AEG – Mitteilungen 51, 11/12, 1961
- [10] GERLACH, S., ETZ-A 83, 8, 1962
- [11] ANWANDER, B.B., Mitteilungen 53, 10, 1966
- [12] BORCHERT, ., STUMPE, A.C., AEG-Mitteilungen 54, 5/6, 1964
- [13] FUKSA, ., Elektrotech. Obzor 63, 11, 1974
- [14] КАРДО-СЫСОЕВ, . et al, Ф.Т.П. 8, 6, 1974
- [15] GIBBONS, ., IEEE Trans. E D-11., 8, 1964
- [16] GENTRY, ., IEEE Trans. E D-11, 2, 1964
- [17] YANG, ., SKALNIK, ., IEEE Trans. E D-14, 8, 1967
- [18] GIBBONS, ., Proc. IEEE 55, 8, 1967
- [19] КУЗЬМИН, . et al, Радиот. и электр., 7, 1963
- [20] НАУМОВ, . et al, Радиот. и электр. , 9, 1965
- [21] ЛЕБЕДЕВ, ., Радиотех и электр. , 8, 1966
- [22] BURTSCHER, ., SPENKE, ., Siemens Forsch. u. Entwickl. Ber., 3, 4, 1974
- [23] ЧЕЛНКОВ, . et al, Радиот. и электр. , 12, 1966
- [24] КУЗЬМИН, . et al, Радиот. и электр., 1, 1967
- [25] ЛЕБЕДЕВ, ., Радиот. и электр., 4, 1967
- [26] КУЗЬМИН, . et al, Радиот. и электр., 4, 1968
- [27] КУЗЬМИН, . et al, Радиот. и электр., 9, 1968
- [28] ГОМОНОВА, . et al, Радиоэлектр., XIV, 1, 1961
- [29] ДУМАНЕВИЧ, ., Радиот. и электр., 11, 1972
- [30] КӦНЛ, ., Scientia electr. ,11, 7, 1965
- [31] SOMOS, ., Communications and Electronics 4, 7, 1961
- [32] 31/1 ДЕРМЕНХИ, . et al, Радиот. и электр., 18, 4, 1973
- [33] СИТНИК, . et al, Электромеханика 8, 1966
- [34] STUMPE, ., ETZ-A 83, 9, 1962
- [35] ДЕРМЕНЖИ, . et al, Радиот. и электр., 15, 9, 1970
- [36] КОЦЮБА, ., Тр. Лит. пол. инст., No 327, 1972
- [37] КУЗЬМИН, . et al, Радиот. и электр., 20, 8, 1975
- [38] JAESKLIN, ., IEEE Tr., ED-23, 8, 1976
- [39] DISKOPP, ., ETZ-A 89, 6, 1968
- [40] КАРДО-СЫСОЕВ, ., Радиот. и электр., 15, 1, 1970
- [41] МОЛИБОГ, . et al, Радиот. и электр., 18, 4, 1973
- [42] МОЛИБОГ, . et al, Радиот. и электр., 16, 6, 1971
- [43] КУЗЬМИН, . et al, Радиот. и электр., 18, 1, 1973
- [44] ПАВЛИК, . et al, Радиот. и электр., 18, 7, 1973
- [45] КАРДО-СЫСОЕВ, ., Ф.Т.П. , 5, 12, 1971
- [46] ДЕРМЕНЖИ, . et al, Радиот. и электр., 7, 1970
- [47] ГРЕХОВ, . et al, Ф.Т.П., 4, 11, 1970
- [48] МАРНАН, ., Electronics 35, Au 17, 1962
- [49] МАРНАН, ., IEEE Trans. Comm. a. Electr., 83, Sep. 1964
- [50] LONGINI, ., IEEE Trans. ED-10, May, 1963
- [51] KUZMANOVIĆ, B., Analiza prenapona oporavka energetskih ventila u omskoinduktivnom krugu, Automatika 1/2, Zagreb, 1989.
- [52] KUZMANOVIĆ, B., Uključenje tiristora i period širenja vodljivog kanala, „Elektrotehnika“, 2, Zagreb, 1988.
- [53] KUZMANOVIĆ, B., Analiza brzine porasta napona na inverzno polariziranoj poluvodičkoj barijeri u omsko-induktivnom krugu, „Elektrotehnika“ 32, 2, Zagreb, 1989.
- [54] KUZMANOVIĆ, B., Destruktivne oscilacije na poluvodičkoj diodi u krugu malog induktiviteta, „Elektrotehnika“ 32, 6, Zagreb, 1989

- [55] KUZMANOVIĆ, B., Statička i dinamička svojstva tiristora, Radovi TVA br. 20, monografija, Zagreb, 1978.
[56] KUZMANOVIĆ, B., Destructive Oscillations in Low Inductance Diode Circuit, Proceedings of the IEEE Industry Applications Society Annual Conference, San Diego, USA, 1989

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