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ВЪРХУ НЕУТРАЛНИТЕ УРАВНЕНИЯ С ПРЕДАВАТЕЛНИТЕ ЛИНИИ БЕЗ ЗАГУБИ С ТУНЕЛЕН ДИОД И УСПОРЕДНО ВКЛЮЧЕН КАПАЦИТЕТ

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РЕЗЮМЕ: Чрез неподвижна точка е доказана теорема за съществуване на решение на неутрални уравнения, възникващи при предавателните линии.

Настоящата работа продължава нашите изследвания върху уравненията на предавателните линии без загуби с нелинейни резистивни елементи.

В една предишна работа [1] изучавахме неутрални уравнения ([2]-[4]) с нелинейности предизвикани от нелинейните волт-амперни характеристики, които са от полиномен тип. Тук ние разглеждаме една начална задача за неутрални уравнения с експоненциални нелинейности в дясната страна. Такъв проблем е еквивалентен (вж. [2], [5] -[7]) на една начално-гранична задача за линейна хиперболична система с нелинейни гранични условия. Наистина, в някой случай апроксимирането на волт-амперната характеристика на дифузионния ток в полупроводниците ([8], [9]) може да се изглади чрез експоненциална функция. Зависимостта между дифузионния ток и напрежението е от вида $i(u) = (Ae^{\alpha u} - 1)$, където A и α са константи. Известно е, че такъв тип нелинейности имат и други приложения (вж. [10], [11]). Следователно формулирайки началната задача

$$\dot{u}(t) = F(u(\Delta_1,(t)),\dots,u(\Delta_m,(t)),\dot{u}(\gamma_1,(t)),\dots,\dot{u}(\gamma_n(t)), \quad t > 0$$

$$u(t) = \varphi(t),\ t \le 0 \qquad (1)$$

$$\dot{u}(t) = \dot{\varphi}(t),\ t \le 0,$$

ние трябва да наложим такива условия върху дясната страна на (1), $F(u_1,\dots,u_m,v_1,\dots,v_n)$, че да може да се включат експоненциални нелинейности. Например F може да бъде избрана от вида

$$F(u_1,\dots,u_m,v_1,\dots,v_n) = A\sum_{k=1}^{n}(e^{\alpha_k u_k} - 1) + B\sum_{s=1}^{n} v_s .$$

Задача (1) се свежда до следната (след полагане $y(t) = \dot{u}(t)$ for $t > 0$ и $\psi(t) = \dot{\varphi}(t)$ при $t \le 0$, предполагайки $\varphi(0) = 0$):

$$y(t) = F\left(\int_0^{\Delta_1(t)} y(\tau)d\tau,\dots,\int_0^{\Delta_n(t)} y(\tau)d\tau, y(\gamma_1(t)),\dots,y(\gamma_n(t))\right), t \in [0,T_0]$$

$$y(t) = \psi(t),\ t \le 0 . \qquad (2)$$

Правим следните предположения (C) :

(C1) функциите $\Delta_i(t),\gamma_s(t) : R^1_+ \to R^1$

(C1)

$(i = 1,\dots,m; s = 1,\dots,n)$, са непрекъснати,

$\Delta_i(0) \le 0, \gamma_s(0) \le 0$ и $t - \Delta_i(t) \ge \Delta_0 > 0$,
$t - \gamma_s(t) \ge \gamma_0 > 0$ за някакви константи $\Delta_0, \gamma_0 > 0$.

(C2) функциите $\psi(t) : R^1_- \to R^1$ и

$F(u_1,\dots,u_m,v_1,\dots,v_n) : R^{m+n} \to R^1$ и $\psi(.) : R^1_- \to R^1$ са непрекъснати и удовлетворяват условието

$$\psi(0) = F\left(\int_0^{\Delta_1(0)} \psi(s)ds,\dots,\int_0^{\Delta_m(0)} \psi(s)ds, \psi(\gamma_1(0)),\dots,\psi(\gamma_n(0))\right) =$$

$$= F(0,\dots,0,\psi(0),\dots,\psi(0)).$$

(C3) $|F(u_1,\dots,u_m,v_1,\dots,v_n)| \le A\sum_{k=1}^{n} |e^{\alpha_k u_k} - 1| + B\sum_{s=1}^{n} |v_s|$,

където A, B са положителни константи.

(C4) $|F(u_1,\dots,u_m,v_1,\dots,v_n)| - |F(\bar{u}_1,\bar{u}_2\dots,\bar{u}_m,\bar{v}_1,\dots,\bar{v}_n)| \le$

$$\le A_1\sum_{k=1}^{m} |e^{\alpha_k u_k} - e^{\alpha_k \bar{u}_k}) + B_1\sum_{s=1}^{n} |v_s - \bar{v}_s| ,$$

където A_1 и B_1 са положителни константи.

(C5) $A\sum_{k=1}^{m}\frac{2|\alpha_k|T_0}{2-|\alpha_k|P_0T_0}+nB\le 1$, където $P_0>0$ е константа, така че $|\alpha_k|P_0T_0<2$.

Теорема 1. Ако са изпълнени условията (C), то началната задача (2) има единствено непрекъснато решение.

Доказателство: Разглеждаме множеството X, състоящо се от всички непрекъснати функции $f(t):[0,T_0]\to R^1$, $(T_0>0)$, чиито рестрикции върху $(-\infty,0]$ съвпадат с $\psi(t)$. То става равномерно пространство, снабдено с една достатъчна фамилия от псевдометрики (метрики) (вж. [13] – [14]):

$$\mathrm{A}=\left\{\rho_\lambda(f,\tilde f):\lambda\in[0,\infty)\right\},$$

$$\rho(f,\tilde f)=\sup\left\{e^{-\lambda t}|f(t)-\tilde f(t)|:t\in[0,T_0]\right\}.$$

Въвеждаме следното подмножество M на X:

$$M=\{f(.)\in(X,\mathrm{A}):|f(t)|\le P_0,t\in[0,T_0]\},$$

където P_0 е константа, която не зависи от f. Лесно се проверява, че множеството M е ограничено и затворено (вж.[13]). Дефинираме оператора $T:(X,\mathrm{A})\to(X,\mathrm{A})$ чрез дясната страна (2):

$$(Tf)(t)=\begin{cases}F\left(\int_0^{\Delta_1(t)}f(s)ds,\dots,\int_0^{\Delta_m(t)}f(s)ds,f(\gamma_1(t)),\dots,f(\gamma_n(t))\right),t\in[0,T_0]\\ \psi(t),t\le 0.\end{cases}$$

Очевидно $(Tf)(t)$ е непрекъсната функция.

Ще покажем, че T изобразява M в себе си. Наистина нека $f\in M$. Тогава предвид $(C3)$ имаме:

$$|(Tf)(t)|\le A\sum_{k=1}^{m}\left|e^{\alpha_k\int_0^{\Delta_k(t)}f(s)ds}-1\right|+B\sum_{s=1}^{n}|f(\gamma_s(t)|\le$$

$$\le\left[A\sum_{k=1}^{m}(e^{|\alpha_k|P_0|\Delta_k(t)|}-1)+nBP_0\right].$$

Известно е, че за $0<w<2$ имаме:

$$e^w-1=w+\frac{w^2}{2!}+\frac{w^3}{3!}+\dots+<w\left(1+\frac{w}{2}+\left(\frac{w}{2}\right)^2+\dots\right)=\frac{2w}{2-w}.$$

Следователно

$$\left|\alpha_k\int_0^{\Delta_k(t)}f(s)ds\right|\le|\alpha_k|P_0|\Delta_k(t)|\le|\alpha_k|P_0T_0$$

и тогава

$$\left[A\sum_{k=1}^{m}(e^{|\alpha_k|P_0|\Delta_k(t)|}-1)+nBP_0\right]\le A\sum_{k=1}^{m}\frac{2|\alpha_k|P_0T_0}{2-|\alpha_k|P_0T_0}+nBP_0\le P_0,$$

стига само $A\sum_{k=1}^{m}\frac{2|\alpha_k|T_0}{2-|\alpha_k|P_0T_0}+nB\le 1$ което е $(C5)$.

Остава да покажем, че T е свиващ оператор. Наистина за всеки $f,\bar f\in M$ предвид неравенствата

$t-\Delta_0\ge\Delta_k(t)\ge\frac{|\alpha_k|P_0\Delta_k(t)}{\lambda}$ (за достатъчно големи $\lambda>0$) $\Rightarrow -\lambda t+|\alpha_k|P_0\Delta_k(t)\le-\lambda\Delta_0$

имаме за $t\in[0,T_0]$, за които $\Delta_k(t)>0$:

$$|(Tf)(t)-(T\bar f(t)|\le A_1\sum_{k=1}^{m}\left|e^{\alpha_k\int_0^{\Delta_k(t)}f(s)ds}-e^{\alpha_k\int_0^{\Delta_k(t)}\bar f(s)ds}\right|+$$

$$+B_1\sum_{s=1}^{n}|f(\gamma_s(t))-\bar f(\gamma_s(t))|\le$$

$$\le A_1\sum_{k=1}^{m}|\alpha_k|e^{\alpha_k\int_0^{\Delta_k(t)}\hat f(s)ds}\left|\int_0^{\Delta_k(t)}f(s)ds-\int_0^{\Delta_k(t)}\bar f(s)ds\right|+$$

$$+B_1\sum_{s=1}^{n}e^{-\lambda\gamma_s(t)}\left|f(\gamma_s(t))-\bar f(\gamma_s(t))\right|e^{\lambda\gamma_s(t)}\le$$

$$\le A_1\sum_{k=1}^{m}|\alpha_k|e^{\alpha_kP_0\Delta_k(t)}\left|\int_0^{\Delta_k(t)}e^{\lambda s}ds\right|\rho_\lambda(f,\bar f)+$$

$$+B_1\sum_{s=1}^{n}e^{\lambda\gamma_s(t)}\rho_\lambda(f,\bar f)\le$$

$$\le e^{\lambda t}\left[A_1\sum_{k=1}^{m}|\alpha_k|e^{-\lambda t+\alpha_kP_0\Delta_k(t)}\left|\frac{e^{\lambda\Delta_k(t)}-1}{\lambda}\right|+\right.$$

$$\left.+B_1\sum_{s=1}^{n}e^{-\lambda t+\lambda\gamma_s(t)}\right]\rho_\lambda(f,\bar f)\le$$

$$\le e^{\lambda t}\rho_\lambda(f,\bar f)\left[A_1\sum_{k=1}^{m}|\alpha_k|\frac{e^{-\lambda\Delta_0}e^{\lambda t}}{\lambda}+B_1ne^{-\lambda\gamma_0}\right]\le$$

$$\le e^{\lambda t}\rho_\lambda(f,\bar f)\left[\frac{A_1e^{-\lambda\Delta_0}e^{\lambda T_0}\sum_{k=1}^{m}|\alpha_k|}{\lambda}+B_1ne^{-\lambda\gamma_0}\right].$$

Следователно

$$\rho_\lambda(Tf,T\bar f)\le\left[A_1\sum_{k=1}^{m}|\alpha_k|\frac{e^{\lambda T_0-\lambda\Delta_0}}{\lambda}+nB_1e^{-\lambda\gamma_0}\right]\rho_\lambda(f,\bar f)\cdot$$

Изразът в последните скоби е по-малък от 1 (ако $T_0-\Delta_0\le 0$) при достатъчно големи стойности на λ, което означава, че T е свиващ оператор.

Трябва накрая да изберем началното приближение. Наистина нека

$$x_0(t) = \begin{cases} \psi(t), t \le 0 \\ \psi(0), t > 0 \end{cases}.$$

Тогава

$$|(Tx_0)(t) - x_0(t)| = \begin{cases} 0, t \le 0 \\ |F(0,...,0,\psi(0),...,\psi(0))|, t > 0 \end{cases}$$

Изображението $j : A \to A$ в този случай е $j(\lambda) = \lambda \Rightarrow$

$\Rightarrow \ j^k(\lambda) = \lambda$, т.е.

$$\rho_{j^k(\lambda)}(x_0, Tx_0) \le |F(0,...,0,\psi(0),...,\psi(0))| < \infty \ (k = 1,2,...) .$$

Следователно T има единствена неподвижна точка, която е решение на (2).

Така теоремата е доказана.

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ON THE NEUTRAL LOSSLESS TRANSMISSION LINE EQUATIONS WITH TUNNEL DIODE AND A LUMPED PARALLEL CAPACITANCE

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ABSTRACT
By means of a fixed point approach an existence theorem for neutral equations arising in transmission lines is proved.

THE PRESENT PAPER CONTINUOUS INVESTIGATIONS ON LOSLESS TRANSMISSION LINES EQUATIONS WITH NONLINEAR RESISTIVE ELEMENTS.

In a previous paper [1] we have studied neutral equations ([2]-[4]) with nonlinearities caused by a nonlinear $V-I$ characteristic which is of polynomial type. Here we consider an initial value problem for neutral equations with an exponential nonlinearity in the right-hand side. Such a problem is equivalent (cf. [5]-[7], [2]) to an initial-boundary value problem for linear hyperbolic system with a nonlinear boundary conditions. Indeed in some cases the approximation of the $V-I$ characteristic curve generated by the diffusion current in semiconductors [8]-[9] can be fitted by an exponential function. The relation between the diffusion current and the voltage is of the type $i(u)=(Ae^{\alpha u}-1)$, where A and α are constants. It is known that such type nonlinearities have also another applications (cf. [10], [11]).

Therefore formulating the initial value problem

$$\dot{u}(t)=F(u(\Delta_1,(t)),\dots,u(\Delta_m,(t)),\dot{u}(\gamma_1,(t)),\dots,\dot{u}(\gamma_n(t))),\quad t>0$$

$$u(t)=\varphi(t),\ t\le 0 \qquad (1)$$

$$\dot{u}(t)=\dot{\varphi}(t),\ t\le 0,$$

we have to impose such conditions on the right-hand side of (1), $F(u_1,\dots,u_m,v_1,\dots,v_n)$, in order to include exponential nonlinearities. For instance F can be chosen of the type

$$F(u_1,\dots,u_m,v_1,\dots,v_n)=A\sum_{k=1}^{n}(e^{\alpha_k u_k}-1)+B\sum_{s=1}^{n}v_s\ .$$

We reduce the problem (1) to the following one (putting $y(t)=\dot{u}(t)$ for $t>0$ and $\psi(t)=\dot{\varphi}(t)$ for $t\le 0$ assuming $\varphi(0)=0$):

$$y(t)=F\left(\int_0^{\Delta_1(t)}y(\tau)d\tau,\dots,\int_0^{\Delta_n(t)}y(\tau)d\tau,y(\gamma_1(t)),\dots,y(\gamma_n(t))\right),t\in[0,T_0]$$

$$y(t)=\psi(t),\ t\le 0\ . \qquad (2)$$

We make the following assumptions (C):

(C1) functions $\Delta_i(t),\gamma_s(t):R^1_+\to R^1$

$(i=1,\dots,m;s=1,\dots,n)$ are continuous and $t-\Delta_i(t)\ge\Delta_0>0$, $t-\gamma_s(t)\ge\gamma_0>0$ for some constants Δ_0,γ_0.

(C2) the functions $F(u_1,\dots,u_m,v_1,\dots,v_n):R^{m+n}\to R^1$ and $\psi(.):R^1_-\to R^1$ are continuous and satisfies the condition

$$\psi(0)=F\left(\int_0^{\Delta_1(0)}\psi(s)ds,\dots,\int_0^{\Delta_m(0)}\psi(s)ds,\psi(\gamma_1(0)),\dots,\psi(\gamma_n(0))\right)=$$
$$=F(0,\dots,0,\psi(0),\dots,\psi(0)).$$

(C3) $|F(u_1,\dots,u_m,v_1,\dots,v_n)|\le A\sum_{k=1}^{n}|e^{\alpha_k u_k}-1|+B\sum_{s=1}^{n}|v_s|$

where A,B are positive constants.

(C4) $|F(u_1,\dots,u_m,v_1,\dots,v_n)|-|F(\bar{u}_1,\bar{u}_2\dots,\bar{u}_m,\bar{v}_1,\dots,\bar{v}_n)|\le$

$$\le A_1\sum_{k=1}^{m}|e^{\alpha_k u_k}-e^{\alpha_k\bar{u}_k}|+B_1\sum_{s=1}^{n}|v_s-\bar{v}_s|\ .$$

where A_1 and B_1 are positive constants.

(C5) $A\sum_{k=1}^{m}\frac{2|\alpha_k|T_0}{2-|\alpha_k|P_0T_0}+nB\le 1$, where $P_0>0$ is chosen such that $|\alpha_k|P_0T_0<2$.

Theorem 1. Under assumption (C) the initial value problem (2) has a unique continuous solution.

Proof. Consider the set X consisting of all continuous functions $f(t):[0,T_0]\to R^1$, $(T_0>0)$ whose restrictions on

$(-\infty,0]$ coincide with $\psi(t)$. It becomes a uniform space endowed with the following saturated family of pseudometrics (metrics) (cf. [13]-[14]):

$$A=\left\{\rho_\lambda(f,\tilde{f}):\lambda\in[0,\infty)\right\},$$

$$\rho(f,\tilde{f})=\sup\left\{e^{-\lambda t}\,|f(t)-\tilde{f}(t)|:t\in[0,T_0]\right\}.$$

Introduce the following subset M of X:

$M=\{f(.)\in(X,A):|f(t)|\le P_0,\ t\in[0,T_0]\}$,
where P_0 is a constant which does not depend on f. It is easy to see that M is bounded and closed set. Define the operator $T:(X,A)\to(X,A)$ by right-hand side of (2):

$$(Tf)(t)=\begin{cases}F\left(\int_0^{\Delta_1(t)}f(s)ds,\ldots,\int_0^{\Delta_m(t)}f(s)ds,f(\gamma_1(t)),\ldots,f(\gamma_n(t))\right), & t\in[0,T_0]\\ \psi(t), & t\le 0.\end{cases}$$

Obviously $(Tf)(t)$ is a continuous function.

In what follows we show that T maps the set M into itself. Indeed let $f\in M$. Then in view of $(C3)$ we have

$$|(Tf)(t)|\le A\sum_{k=1}^m\left|e^{\alpha_k\int_0^{\Delta_k(t)}f(s)ds}-1\right|+B\sum_{s=1}^n|f(\gamma_s(t))|\le$$

$$\le\left[A\sum_{k=1}^m\left(e^{|\alpha_k|P_0|\Delta_k(t)|}-1\right)+nBP_0\right].$$

It is know that for $0<w<2$ we have:

$$e^w-1=w+\frac{w^2}{2!}+\frac{w^3}{3!}+\ldots+<w\left(1+\frac{w}{2}+\left(\frac{w}{2}\right)^2+\ldots\right)=\frac{2w}{2-w}.$$

Therefore

$$\left|\alpha_k\int_0^{\Delta_k(t)}f(s)ds\right|\le|\alpha_k|P_0|\Delta_k(t)|\le|\alpha_k|P_0T_0$$

and then

$$\left[A\sum_{k=1}^m\left(e^{|\alpha_k|P_0|\Delta_k(t)|}-1\right)+nBP_0\right]\le A\sum_{k=1}^m\frac{2|\alpha_k|P_0T_0}{2-|\alpha_k|P_0T_0}+nBP_0\le P_0,$$

provided $A\sum_{k=1}^m\frac{2|\alpha_k|T_0}{2-|\alpha_k|T_0}+nB\le 1$ which is $(C5)$.

It remains to show that T is contractive operator. Indeed for every f and $\bar{f}\in M$ and in view of the inequalities $t-\Delta_0\ge\Delta_k(t)\ge\frac{|\alpha_k|P_0\Delta_k(t)}{\lambda}$ (for sufficiently large $\lambda>0$) $\Rightarrow -\lambda t+|\alpha_k|P_0\Delta_k(t)\le-\lambda\Delta_0$

we have for $t\in[0,T_0]$ for which $\Delta_k(t)>0$:

$$|(Tf)(t)-(T\bar{f}(t)|\le A_1\sum_{k=1}^m\left|e^{\alpha_k\int_0^{\Delta_k(t)}f(s)ds}-e^{\alpha_k\int_0^{\Delta_k(t)}\bar{f}(s)ds}\right|+$$

$$+B_1\sum_{s=1}^n|f(\gamma_s(t))-\bar{f}(\gamma_s(t))|\le$$

$$\le A_1\sum_{k=1}^m|\alpha_k|e^{\alpha_k\int_0^{\Delta_k(t)}\hat{f}(s)ds}\left|\int_0^{\Delta_k(t)}f(s)ds-\int_0^{\Delta_k(t)}\bar{f}(s)ds\right|+$$

$$+B_1\sum_{s=1}^n e^{-\lambda\gamma_s(t)}\left|f(\gamma_s(t))-\bar{f}(\gamma_s(t))\right|e^{\lambda\gamma_s(t)}\le$$

$$\le A_1\sum_{k=1}^m|\alpha_k|e^{\alpha_kP_0\Delta_k(t)}\left|\int_0^{\Delta_k(t)}e^{\lambda s}ds\right|\rho_\lambda(f,\bar{f})+$$

$$+B_1\sum_{s=1}^n e^{\lambda\gamma_s(t)}\rho_\lambda(f,\bar{f})\le$$

$$\le e^{\lambda t}\left[A_1\sum_{k=1}^m|\alpha_k|e^{-\lambda t+\alpha_kP_0\Delta_k(t)}\left|\frac{e^{\lambda\Delta_k(t)}-1}{\lambda}\right|+\right.$$

$$\left.+B_1\sum_{s=1}^n e^{-\lambda t+\lambda\gamma_s(t)}\right]\rho_\lambda(f,\bar{f})\le$$

$$\le e^{\lambda t}\rho_\lambda(f,\bar{f})\left[A_1\sum_{k=1}^m|\alpha_k|\frac{e^{-\lambda\Delta_0}e^{\lambda t}}{\lambda}+B_1ne^{-\lambda\gamma_0}\right]\le$$

$$\le e^{\lambda t}\rho_\lambda(f,\bar{f})\left[\frac{A_1e^{-\lambda\Delta_0}e^{\lambda T_0}\sum_{k=1}^m|\alpha_k|}{\lambda}+B_1ne^{-\lambda\gamma_0}\right].$$

Consequently

$$\rho_\lambda(Tf,T\bar{f})\le\left[A_1\sum_{k=1}^m|\alpha_k|\frac{e^{\lambda T_0-\lambda\Delta_0}}{\lambda}+nB_1e^{-\lambda\gamma_0}\right]\rho_\lambda(f,\bar{f})\cdot$$

But for sufficiently large λ the expression in the bracket is smaller than 1 (if $T_0 - \Delta_0 \le 0$) and therefore T is contractive operator.

Finally we have to choose an initial approximation. Indeed let

$$x_0(t) = \begin{cases} \psi(t), t \le 0 \\ \psi(0), t > 0 \end{cases}.$$

Then

$$|(Tx_0)(t) - x_0(t)| = \begin{cases} 0, t \le 0 \\ |F(0,...,0,\psi(0),...,\psi(0))|, t > 0 \end{cases}$$

The map $j : A \to A$ in this case is $j(\lambda) = \lambda \Rightarrow$

$\Rightarrow j^k(\lambda) = \lambda$, i.e.

$$\rho_{j^k(\lambda)}(x_0, Tx_0) \le |F(0,...,0,\psi(0),...,\psi(0))| < \infty \quad (k = 1,2,...).$$

Therefore T has a unique fixed point which a solution of (2). Theorem is thus proved.

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