Generalized hyperbolic model for *I-V* characteristic of semiconductor devices

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Abstract - It is proposed to use the models of volt-ampere characteristics of semiconductor devices such as transistors and photovoltaic cells as a physically reasonable hyperbolic characteristic of the active two-pole with self-limitation of current. In this case, analytical calculation load regime is possible, which is important for the calculations in real time. This approach also allows determining the point of the characteristic regimes, comparing the effectiveness of current regimes.
Keywords: transistor, photovoltaic cell, volt-ampere characteristic, regimes of active two-pole.

I. INTRODUCTION

The traditional exponential model or volt - ampere I - V characteristic of the $p-n$ junction of semiconductor devices requires iterative numerical methods of calculation [1], [2]. This model leads to an increase in calculation time, the problems of convergence. These features are essential in the use of simple and low-cost microcontrollers for the calculation of electronic equipments. The calculations in real-time of the systems direct digital control of the power supplies might be as an example.

It is therefore useful to use more simple models that allow performing direct or analytical calculations.

In this paper, it is proposed to use a physically reasonable hyperbolic characteristic of the active two-pole with self-limitation of current [3]. This characteristic represents fractional - quadratic expression and allows obtaining an appropriate convenient analytical expression for a particular semiconductor device. This approach also allows determining the point of the characteristic regimes, comparing the effectiveness of current regimes.

II. THE HYPERBOLIC VOLT-AMPERE CHARACTERISTIC OF THE ACTIVE TWO-POLE WITH SELF-LIMITATION OF CURRENT

In the theory of the electric circuits idea of the ideal and the real voltage and current sources is developed. Such active two-poles have a linear external or $I-V$ characteristic. In turn, the author examines the active two-pole with self-limitation of the current, which is characterized by a non-linear $I-V$ characteristic. An example of such two-pole is the quasi-resonant voltage converter DC-DC, which has the property of self-limitation of the load current. The $I-V$ characteristic of such active two-pole $i(u)$ has a characteristic species - curve 1 in Fig.1.

In the first quadrant, the active two-pole delivers energy to a load, and its characteristic is already convex species as compared with the linear characteristic 2. The regime is changed from the short-circuit SC, when load current is $i(0)$, to the open-circuit OC , when the load voltage is E. In turn, the rectangular characteristic 3 corresponds to an ideal current source with the limiting maximum load voltage. Thus, depending on the degree of convexity, the curve 1 can move from the line 3 to the line 2.

In the second and fourth quadrants, the active two-pole consumes energy already, but there is a limitation of the current, even for the load voltage is greater voltage E.

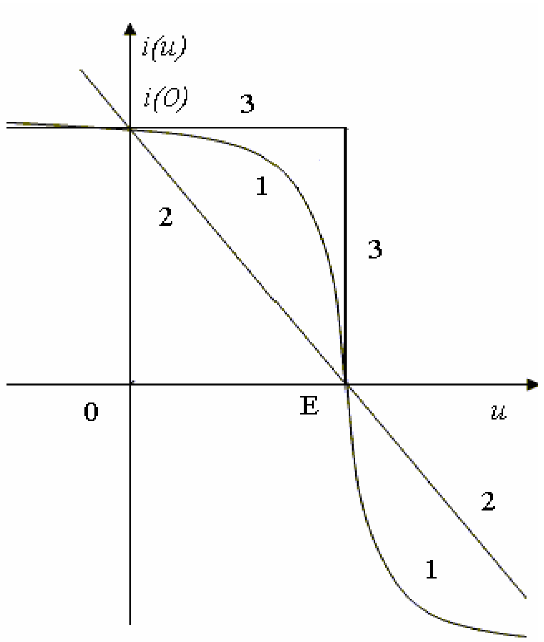

Fig.1. The typical external or $I-V$ characteristics of the active two-poles: 1 – a convex characteristic of the active two-pole with self-limitation of the current, 2 – a linear characteristic of the real voltage or current source, 3 – a rectangular characteristic of an ideal current source with the limiting maximum load voltage

The specific family of the characteristics for the first quadrant with different periods of switching T_K is represented in Fig 2.

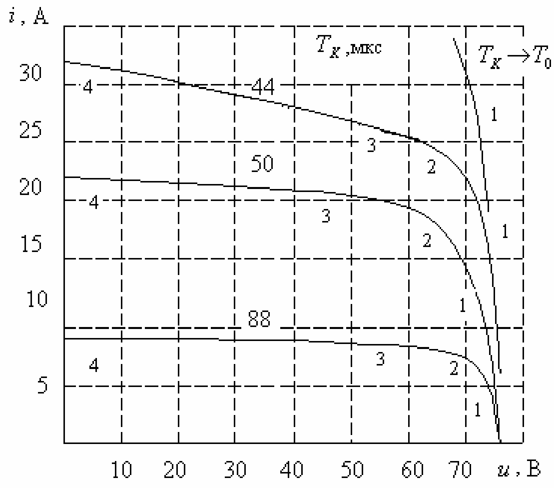

Fig.2.The typical parts of the quasi-resonant voltage converter DC-DC with different period of switching T_K : 1- the characteristic of the voltage source, 2- the start of the current limitation and the maximum load power, 3 - the characteristic of the current source, 4- the SC point

For example, the natural oscillations period is $T_0 = 43.4ms$. The switching period $T_K = 44ms$ is the minimal working and $T_K = 88ms$ is the twice period.

The part 1 for all curves corresponds to the characteristic of the voltage source when the load voltage is depended little from its current in view of the high efficiency. Point 2 corresponds to the start of the current limitation and the maximum load power. The part 3 in the form of an inclined line corresponds to further current limitation up to the SC point 4. The represented specific characteristics allow carrying out the analysis and justifying equivalent generator for such active two-pole. Such points of the characteristic regimes as SC and OC are suggesting the possibility of using the equivalent generator (circuit) with the nonlinear internal resistance R_{i1} in Fig.3.

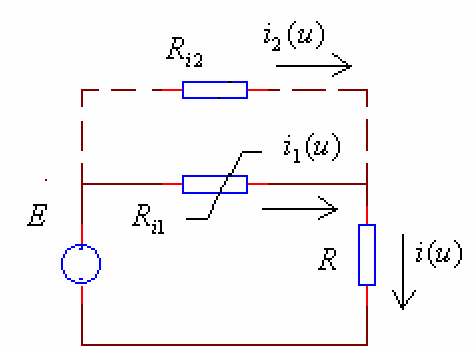

Fig.3. The equivalent generator of the active two-pole with self-limitation of the current with the nonlinear and linear internal resistances

The OC voltage determines the voltage source E and the SC current - the value of the internal resistance for this regime:

$$R_{i1}(0) = \frac{E}{i_1(0)} = \frac{E}{I_1}.$$

To establish the dependence of the internal resistance on the voltage, we define the resistance value $R_{i1}(u)$ for actual data for the current and voltage and we build a plot of the linear relationship (Fig.4, line 1).
The minimum value of the resistance $R_{i1}(E)$ corresponds to the voltage E. If the resistance $R_{i1}(u)$ is not dependent on the voltage (line 2), we get a voltage source with the internal resistance and the linear characteristic (Fig.1, line 2). If the resistance $R_{i1}(u)$ goes through the point $(E,0)$ - straight line 3, then we get a current source (Fig.1, lines 3). The given case presents then an interim version where the straight line 1 passes through the point $(AE,0)$.

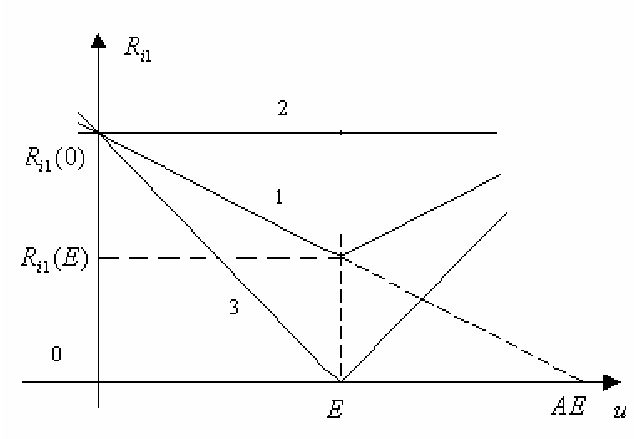

Fig.4. The dependence of the internal resistance on the load voltage of the typical active two-poles: 1-an active two-pole with self-limitation of the current, 2- the real voltage source, 3- an ideal current source with the limiting maximum load voltage

Line 1 equation has the appearance for the work area $u \le E$:

$$R_{i1} = \frac{1}{I_1}\left(E - \frac{u}{A}\right).$$

On the other hand, we receive from the equivalent generator circuit:

$$R_{i1} = \frac{E-u}{i_1(u)}. \quad (1)$$

Eliminating value R_{i1}, we get the equation:

$$i_1(u) = I_1 A \frac{1-u}{A-u}. \quad (2)$$

Here and further the voltage u is normalized by the E. This expression defines a hyperbole. The parameter A determines the degree of convexity. If $A \to \infty$, then curve is degenerated into a straight line (Fig. 1, line 2). If $A = 1$, then we get a rectangular characteristic – the hyperbole is merged with the asymptotes (Fig.1, lines 3).

In the characteristics at the parts 3 a linear part is shown increasingly, which is tended to a vertical line when $T_K \to T_0$. Therefore, the characteristics are a linear hyperbolic. Then we can make an assumption about the introduction of the equivalent generator scheme in Fig.3 of another, but a linear resistor R_{i2} with a value that is specified the period T_K. Let us obtain the expression of the characteristic for this case.

Under the equivalent generator circuit, taking into account (1), (2) the load current is given:

$$i(u) = i_1(u) + i_2(u) = I_1 A \frac{1-u}{A-u} + I_2(1-u), \quad (3)$$

where the linear component of the current in the SC regime is:

$$I_2 = i_2(0) = \frac{E}{R_{i2}}.$$

III. APPLICATION OF HYPERBOLIC VOLT – AMPERE CHARACTERISTIC

The calculation for resistive load. In this case, the load voltage $u = i \cdot R_H$. Then expression (3) leads to a quadratic equation which is solved analytically.

In general, the circuit of the equivalent generator can be complemented by capacitances and inductances for calculations of the transient or steady-state regimes. In particular, in the small signal the traditional methods of calculation as well as the developing methods that are targeted at simplifying the computational model of the circuit can be used [4], [5].

Deviation of the regime from the point of maximum power.

The I-V characteristic according to (3) is presented in Fig.5 for the current $I_1 = 1$, which represents the hyperbola with center S and asymptotes X, Y. Since the extreme points of the regime change are SC and OC, we turn to the projective coordinate system, given by the center F from the intersection of the tangents (as asymptotes) in these locations. Therefore, the point of hyperbola is given by rotating of the radius vector $R_F F$. We accept the point of maximum power P_M^- as an initial position. Non-Euclidean distance $R_1, R(P_M^-)$ is determined by the hyperbolic length of the hyperbola arc. We use the concept of pole and polar of second order curve, which is given I-V characteristic, to justify the definition of the regimes change.

The point F is a pole, and the line passing through the points SC and OC (hereinafter referred to as line SC- OC), is called polar. The mapping or symmetry of points $+P \to -P$ is performed regarding to this polar. Mapping of points R_1, R_2, regarding to the point of maximum power leads to the complementary system of pole and polar. To do this, we pass tangent through the point P_M^-, which crosses the line SC- OC in the point T. This point T will be a pole, and line FP_M^- - polar. Regarding to this polar this mapping is received. Thus, we obtained the associatively picture or «kinematics» of regimes change regarding to the chosen initial point and the extreme points. This helps justify the comparison of the effectiveness of the regimes of various energy sources.

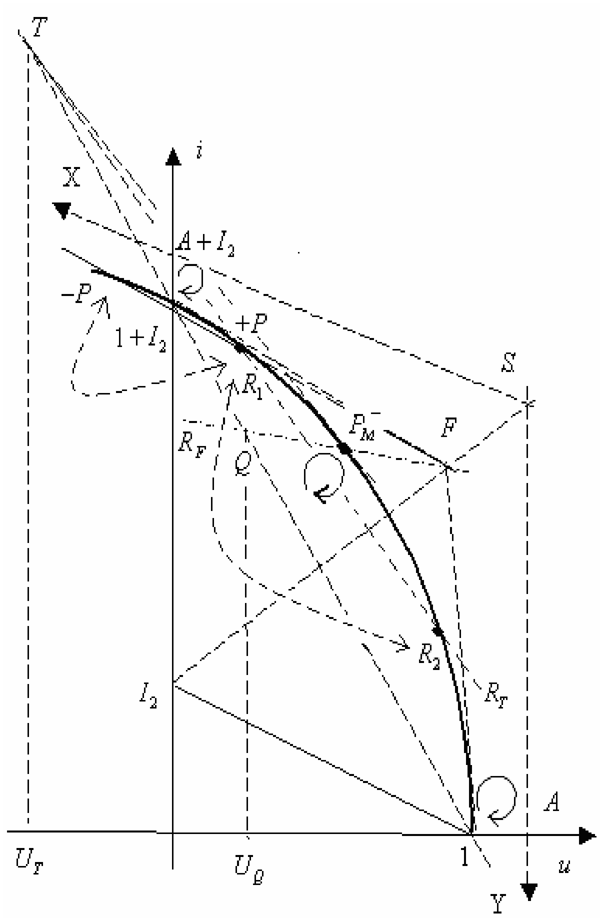

Fig.5. Studied convex I-V characteristic

Similarity I-V characteristics of various electronic and semiconductor devices. Such devices as bipolar and field-effect transistors, photovoltaic cells, nonlinear resistors, electron tubes, based on different physical principles, and the corresponding I-V characteristics are described as various dependencies. However, the typical I-V characteristics are qualitatively similar to each other. Hence it is interesting to use the proposed hyperbolic characteristics as a possible generalized model. Then, for the specific characteristic of the device it is necessary to find the coefficients of the approximation A, I_1, I_2.

To do this, we set three matching points $i^1(u^1), i^2(u^2), i^3(u^3)$ of actual and approximating curve in a given area of work. Then, the expression (3) defines the system of three equations. From this system we find the value A, I_1, I_2.

IV. CONCLUSION

Calculations show a good agreement of the proposed expression and the traditional exponential model for the photovoltaic cells. This hyperbolic model allows calculating the load regime analytically. The model of characteristic can be developed further through the introduction of the required elements in the equivalent generator circuit.

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