HYBRID EQUIVALENT CIRCUIT GENERATION

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Abstract*: The main objective of this paper is to correctly define the hybrid equivalent circuits. These circuits allow the separation of the linear portions of electronic circuits from the nonlinear ones and in this way the polarization process of electronic devices becomes much more efficient. When linear and/or nonlinear analyzed circuits have a small number of nonlinear circuit elements, their analysis, synthesis, and simulation are performed more efficiently if the nonlinear part of circuit is separated from the linear one. A new modeling technique, called H ~ modeling, is introduced for multi-port networks. It is shown that H ~ models are more dynamic compared to equivalent Thevenin or Norton circuits and have the ability to describe port behavior more accurately. A special type of model H ~ is also introduced, called model H ~ nullified, or simply model H ~ and many properties of H modeling are investigated, including circuit energy management. It is shown that the H models are not limited to single-port networks, but also cover multiport. A major property of H modeling is the local polarization of transistors. It separates the nonlinear components from the linear portion of circuit for faster and more efficient polarization of circuit. Here a designer can take advantage of H-modeling and bias individual transistors (or in combinations) with no need to perform the normal circuit biasing. The proposed strategy separates linear and nonlinear portions of an analog circuit and takes more control of nonlinear portions. This separation of portions (components) of circuit is achieved by introducing a new port model that cancels the ports of nonlinear devices. In turn, this leads to a new technique for polarizing nonlinear components. This separation of portions (components) within the circuit is accomplished by introducing a new port modeling that nullifies the ports of nonlinear devices.*

1. INTRODUCTION

Due to the rapid development of technology, analog and mixed signal integrated circuit technology has an important and decisive role in communications and signal processing. In particular, the rapid development of CMOS technology has made analog circuit designers very interesting, [1–11], for this technology. Other evolutions of technology, such as: low supply voltages, low power consumption, performance complexity and high number of transistors have led to a substantial increase in the demand for new design methodologies and techniques.

A major difficulty in approaching the analog circuits is the DC polarization - obtaining the desired operating points through a fast convergence procedure; and the problem worsens with the advancement of technology, which is due to the increase in the size and complexity of the circuit. The analysis can even lead to multiple DC operating points, or to the instability of these operating points due to positive reactions. In the SPICE circuit simulator [1, 2, 6, 7, 9-22], for example, methods such as Newton-Raphson iteration techniques are used to treat circuit nonlinearities; sometimes the major difficulty is to make the circuit analysis procedure converge in a limited number of iterations. Schemes such as the addition of minimum conductance (GMIN), shunt resistors, changing the tolerance values for results and the feed step are usually adopted in a simulator to make convergence possible.

Usually, a poor selection of the initial conditions or the adoption of large and irregular calculation steps causes the instability of the calculation process or may even lead to this process diverging. Another difficulty may result from a fixed topology of the fixed supply circuit throughout the polarization process. With such a pre-set of conditions, the operating points are found naturally through long and timely iterations. All this adds to the design task and the useful processing time. We need a more guided design procedure; a procedure that helps a designer go through a top-down and piece-by-piece design strategy.

The main objective of this paper is to correctly define the hybrid equivalent circuits. These circuits allow the separation of the linear portions of the electronic circuits from the non-linear ones and in this way the polarization process of the electronic devices becomes much more efficient. In general, H models are used in various analyzes and applications of analog circuits such as: transformation of sources, analysis in DC, analysis in AC (frequency or phasor and s-domain), [1, 2, 4, 9].

Section 2 defines the hybrid equivalent circuits, specifying the necessary and sufficient conditions for a one-port linear circuit to be replaced by an equivalent hybrid circuit. Section 3 sets out the necessary and sufficient conditions for the one-port linear circuit to be replaced by a Nullified Equivalent Hybrid Circuit. Thévenin, Norton and hybrid equivalent circuits are used in the construction of Nullified Hybrid equivalent circuits.

Equivalent Thévenin, Norton, hybrid and null hybrid circuits are used in the local polarization of analog circuits, [1 - 18]. Several illustrative examples are presented that highlights the veracity of the elaborated procedures.

2. HYBRID EQUIVALENT CIRCUIT

Considering a linear resistive circuit containing resistors, independent voltage and/or current sources and all four types of two-port controlled sources. We extract from the terminals (nodes) A and B of the circuit the resistor with resistance R_{AB}, as in *fig. 1*. The left circuit of nodes A, B in *fig. 1* must satisfy the conditions of equivalence of this circuit with the equivalent Thévenin circuit and respectively with the circuit Norton equivalent. In order for a resistive linear circuit to be substituted, in relation to the terminals A, B, with an equivalent Thévenin circuit, the voltage U_{AB} must exist and be unique for any value J of the current of an ideal independent current source, when the R_{AB} resistor is replaced by such a source. Similarly, if the R_{AB} resistor in *fig. 1* is replaced by an ideal independent voltage source with e.m.f. E, the resistive linear circuit to the left of terminals A, B can be replaced by an equivalent Norton circuit if the I_{AB} current exists and is uniquely determined for any value E of the ideal independent voltage source, [1, 2, 9, 14].
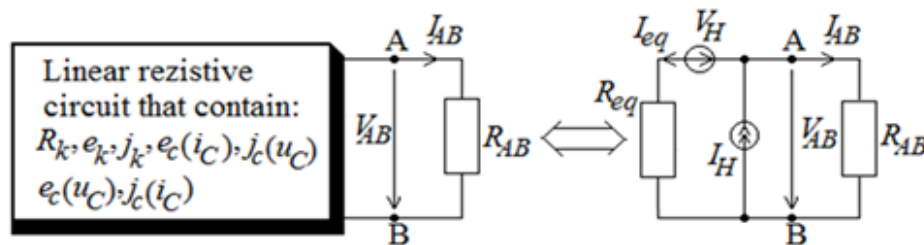

Fig 1. Hybrid equivalent circuit

A Hybrid equivalent circuit, or simply an H~model, of a two-terminal network is a generalized version of Thévenin or Norton equivalent circuit; for resistive circuits it consists of a voltage source V_H, a current source I_H and an equivalent resistance, R_{eq}, which is identical with the Thévenin or Norton model (*fig. 1*). Apparently here one source, V_H or I_H, can be selected arbitrarily and the other source is found through eq. (3).

We assume that the circuit to the left of the R_{AB} resistor in *fig. 1* satisfies the conditions of existence of the equivalent Thévenin and Norton circuits. According to Thévenin's theorem, the I_{AB} current has the expression:

$$I_{AB} = \frac{V_{Th}}{R_{AB}+R_{eq}},$$ (1)

Where is the voltage at terminals A, B of the active circuit, when $I_{AB} = 0$, and   the equivalent resistance of the passivated circuit in relation to terminals A, B ($I_{AB} = 0$). Applying the Kirchhoff's laws to the hybrid equivalent circuit in *figure 1*, it follows:

$$\text{KCL: } I_{eq} = I_H - I_{AB} = I_H - \frac{U_{Th}}{R_{AB}+R_{eq}}$$

(2)

$$\text{KVL: } V_H = R_{AB}I_{AB} - R_{eq}I_{eq} = R_{AB}\frac{U_{Th}}{R_{AB}+R_{eq}} - R_{eq}\left(I_H - \frac{U_{Th}}{R_{AB}+R_{eq}}\right)$$

It follows from equations (2):

$$I_H = I_{sc} - \frac{V_H}{R_{eq}} \text{ or } V_H = V_{Th} - R_{eq} \cdot I_H$$

(3)

where $I_{sc} = I_{ABsc} = \frac{V_{Th}}{R_{eq}}$.

It can be seen that, as with the Thévenin or Norton models, only two measurements are required here to determine all the parameters of the H model. For example, for a selected value of I_H and two measurements of V_{Th} and $I_N = I_{sc}$, eqs. $R_{eq} = U_{Th}/I_{sc}$ and (3) can be used to obtain the R_{eq} and V_H parameters of the model. Now, considering two circuits N_1 and N_2 connected by the gate j (V_j, I_j), as shown in *figure 2*, there are two types of H models for the one-port linear circuit N_1. The 1 H model (1 H ~ model) is shown in *fig. 3. (a)*. To find this model first open the port where $I_j = 0$. Taking into account *fig. 3. (a)* and of equation (3) we have:
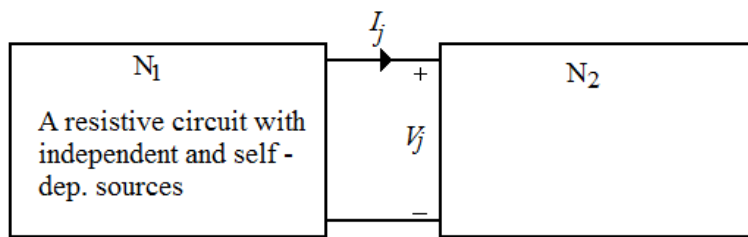
$$V_j = V_H + R_{eq}I_N = V_{Th}.$$

(4)

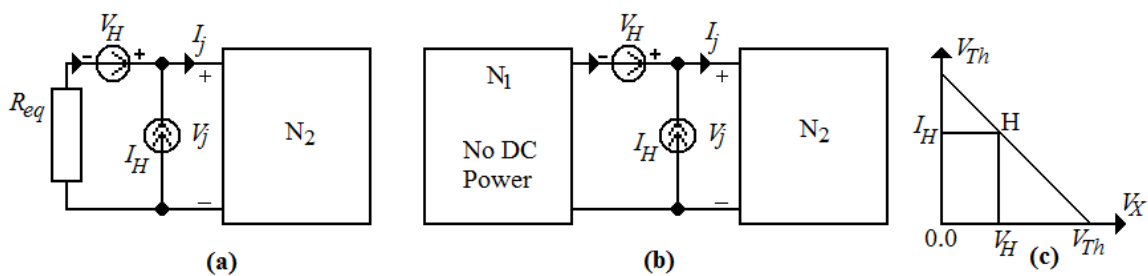Fig. 2. Two networks N_1 and N_2 connected through a port j (V_j, I_j)

Fig. 3. A two-terminal Hybrid equivalent circuit for N_1; (a) Type 1 representation; (b) Type 2 representation; (c) The location on the port's characteristic curve

From eq. (4) it results:

$$V_H = V_{Th} - R_{eq}I_N = V_{Th} - R_{eq}I_{sc} \tag{5}$$

In the Type 2 H ~ model, however, the sources remain the same as in Type 1, but instead of calculating the equivalent resistance R_{eq}, we let N_1 unaltered, except that all its DC power sources are removed, as shown in *figure 3. (b).* The term "DC power removed' means that all DC sources are removed from the N_1, including charges on the capacitors and currents through the inductors. Type 2 H~model is useful in several applications, such as moving the DC sources in a circuit to its port terminals without disturbing the internal structure (topology) of the network.

Note that, because of having two sources instead of one, an H~model represents an axis of freedom that acts as a tool in dynamic modeling of a port. As indicated in *fig. 3. (c),* an H~- model covers a full and continuous range of equivalent circuits for a two-terminal network. It is evident from Eq. (2) and *fig. 3. (c)* that both the Thévenin and Norton models are two special cases of an H~-model.

Example 1: A simplified small signal equivalent circuit of a single stage BJT amplifier with load is represented in *fig. 4. (a),* the X-Y port is connected to a load R_L. Here we would like to have: i) an H~-model for the two-terminal circuit, on the left of X-Y, so that the power consumption on both sides of the port are equal; and ii) modify the H~-model in part i) so that the power consumption in the two terminal circuit (the left of X-Y) becomes zero.
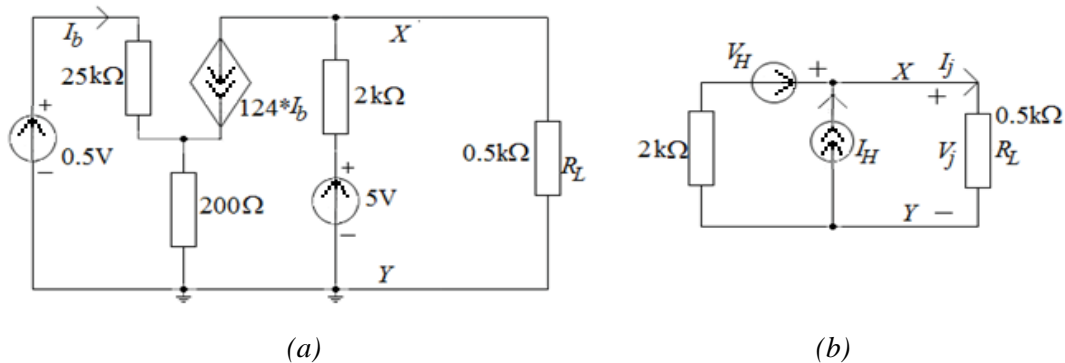

(a)   (b)

Fig. 4. (a) A simplified small signal equivalent circuit of a single stage BJT amplifier with load; (b) An H~-model of the amplifier.

Solution: We first find an H~-model representation for the two-terminal circuit as depicted in *fig. 4. (b),* with the source values, V_H and I_H, unspecified. Second, to make the power consumption on both sides of port j equal we need to have:

$$R_L I^2_j = R_{eq} (I_H - I_j)^2 \tag{6}$$

By using eq. (3) and knowing that $V_{Th} = 2.52$ V and $R_{eq} = 2$ kΩ we get $I_j = 1.008$ mA, $I_H = 1.512$ mA, $V_H = -0.504$ V, and the power consumed for each side is $P_j = R_L*(I_j)2 = 0.508$ mW. For part ii), because the situation for the load R_L is not changed we still have $I_j = 1.008$ mA, $V_j = 0.504$V, and $P_j = 0.508$ mW. Now, to make the power consumption to the left of X – Y zero we must have $R_{eq}(I_H - I_j)^2 = 0$; or simply $I_H = I_j = 1.008$ mA, and as a result $V_H = V_j = 0.504$ V. This concludes the solution with the fact that in the part ii) the total power consumption is reduced to half, i.e., from 1.016 mW to 0.508 mW.

Universality is an important characteristic of an H~model. H~models can be accurately applied to all possible cases of linear two-terminal networks, regardless of the port impedances; whereas both Thévenin and Norton equivalent circuits lose their sensitivity in some specific cases when port impedances take extreme low or extreme high values. For example, consider measuring the Thévenin (open circuit) voltage of a two-terminal network N_1 that has the equivalent resistance of $R_{eq} = 2$ MΩ. Suppose the measuring voltmeter has the input impedance of $R_M = 20$ MΩ and the measured open circuit voltage displayed is $V_M = 3$V. Apparently selecting $V_{Th} = V_M = 3$V as the Thévenin voltage for the port carries an error of 10%. Whereas an H~-model with $V_H = V_M = 3$V and $I_H = I_M = 136$ nA represents an exact H~- model for the port. Note that there is no need for any extra measurement to find I_M, because we can simply get it from $I_M = V_M/R_M$.

Example 2: In *figure 5. (a)*, is presented a nonlinear resistive circuit containing a voltage-controlled nonlinear resistor (R_{du12}). The numerical values of the circuit parameters in *fig. 5. (a),* are shown in the figure, and the nonlinear characteristic $I_{Rdu12} = f(U_{Rdu12})$, given by points, is shown in *fig. 5. (c).* The purpose of this example is to show that in the analysis of a nonlinear circuit it is particularly efficient to replace the linear part of the circuit with an equivalent Thévenin, Norton or Hybrid circuit.

(a)   *(b)*
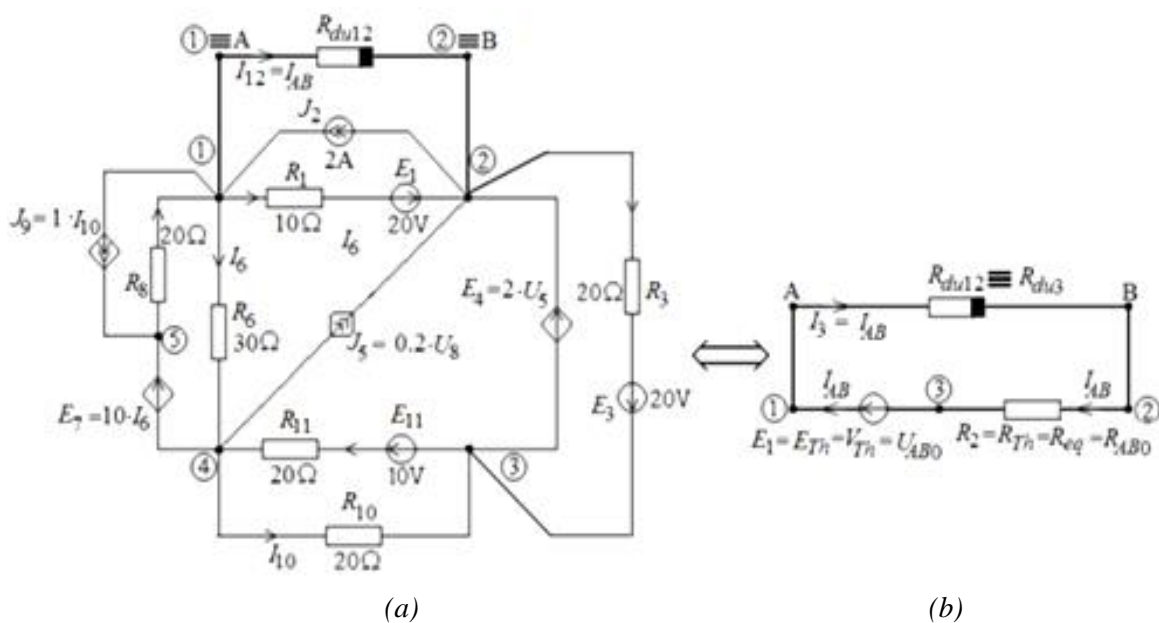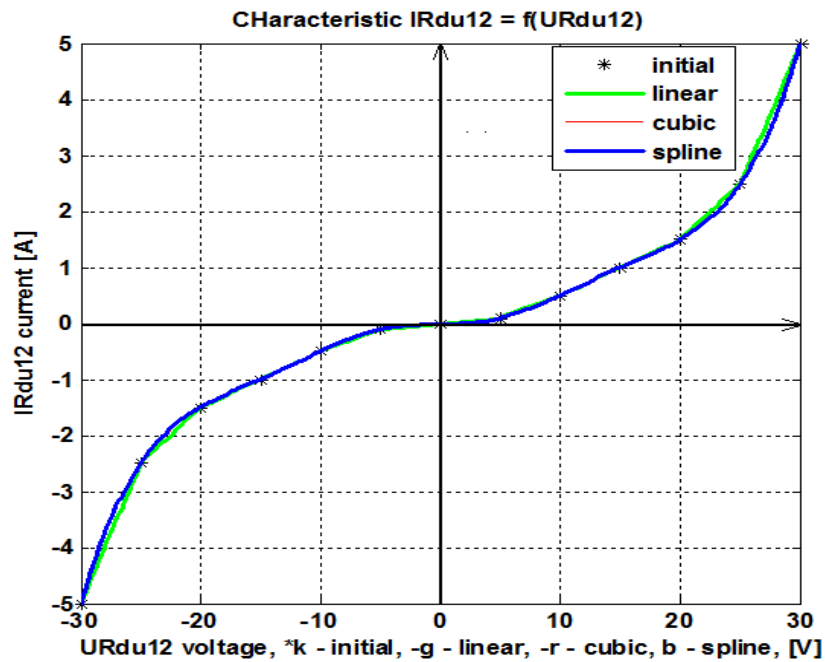
(c)
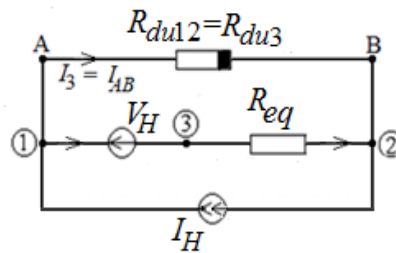
(d)

Fig. 5. (a) Diagram of the nonlinear resistive circuit containing a voltage-controlled (v.c.) nonlinear resistor (Rdu12); (b) Linear part of the circuit in Fig. 5. (a) is substituted by a Thévenin equivalent circuit; (c) Characteristic $I_{Rdu12} = f(U_{Rdu12})$; (d) Hybrid equivalent circuit.

Solution: First we analyze with ACAP - Analogue Circuit Analysis Program, [3, 18], the nonlinear resistive circuit in *fig. 5. (a)* and obtain, for the nonlinear resistor R_{du12}, the solution U_{Rdu12} = -0.50813 V and I_{Rdu12} = -0.010163 A. Then, replace the nonlinear resistor with an ideal independent current source with the intensity of the current jo (oriented from node n_2 to node n_1) and simulate, using the CSAP program - Circuit Symbolic Analysis Program, [3], in the full-symbolic form the circuit thus obtained. In this way the expression of the Thévenin voltage $U_{Th} = U_{AB0} = -U_{Jo}$ and the expression of the equivalent resistance R_{eq} = $R_{Th} = R_{AB0} = U_{Th\_cir\_passive} / j_o$ are determined, where $U_{Th\_cir\_passive}$ is the Thévenin voltage of the passivated circuit (all independent sources in the analyzed circuit are canceled, except for current source j_o).

Finally, the circuit parameters are replaced with their numerical values and the numerical values of the Thévenin equivalent circuit parameters $R_{Th} = R_{eq}$ = 4.6667 Ω and U_{Th}

$= E_{eq} = $ -0.5556 V and those corresponding to the equivalent circuit Norton $G_{eq} = 1 / R_{eq} = $ 0.2143 S and $I_{sc} = U_{Th} / R_{Th} = $ -0.11905 A and thus the circuit of *fig. 5.(a)* is equivalent to that of *fig. 5. (b)*. Analyzing, with the program ACAP, [3], the circuit of *fig 5. (b)* the same solution is obtained for the nonlinear resistor R_{du12}, $U_{Rdu12} = $ -0.50813 V and $I_{Rdu12} = $ -0.010163 A. Obviously, the nonlinear circuit in *fig. 5. (b)* is much simpler than the one in *fig. 5. (a)*. *Figure 5. (d)* shows the equivalent hybrid circuit in which the parameters have the values: $R_{eq} = $ 4.6667 Ω, $I_{sc} = $ -0.11905 A, $V_H = 1$ V (value considered arbitrary) and $I_H = I_{sc} - V_H / R_{eq} = $ -0.333334 A. Obviously, for the nonlinear resistor R_{du3} we consider the *characteristic I_{Rdu3} - U_{Rdu3}* from *fig. 5. (c)*.

Simulating, by the ACAP program, the circuit from *figure 5. (d)*, we obtain the same solution for the nonlinear resistor $R_{du3} = Rd_{u12}$, $U_{Rdu3} = U_{Rdu12} = $ -0.50813 V and $I_{Rdu3} = I_{Rdu12} = $ -0.010163 A. Obviously, even in this case, the nonlinear circuit in *figure 5. (d)* is much simpler than the one in *figure 5. (a)*.

Example 3: Consider the circuit of *fig. 6. (a)*, where two sections of a circuit are connected through a port $j(V_j, I_j)$. Let the MOS diode be characterized by $i = K (V-1)^2$ mA for $V > 1$ V and let $K = 0.5$ mA/V^2. The analysis shows that port j is not a null port because $I_j = 1$ mA and $V_j = 3$ V. Next, we increase port j of N_2 by two current and voltage sources $I_j = 1$ mA and $V_j = 3$ V and then remove the supply sources of 5 V and 1 mA from N_1. As a result a new null port $k(V_k, I_k)$ is created, as shown in *fig. 6. (b)*.
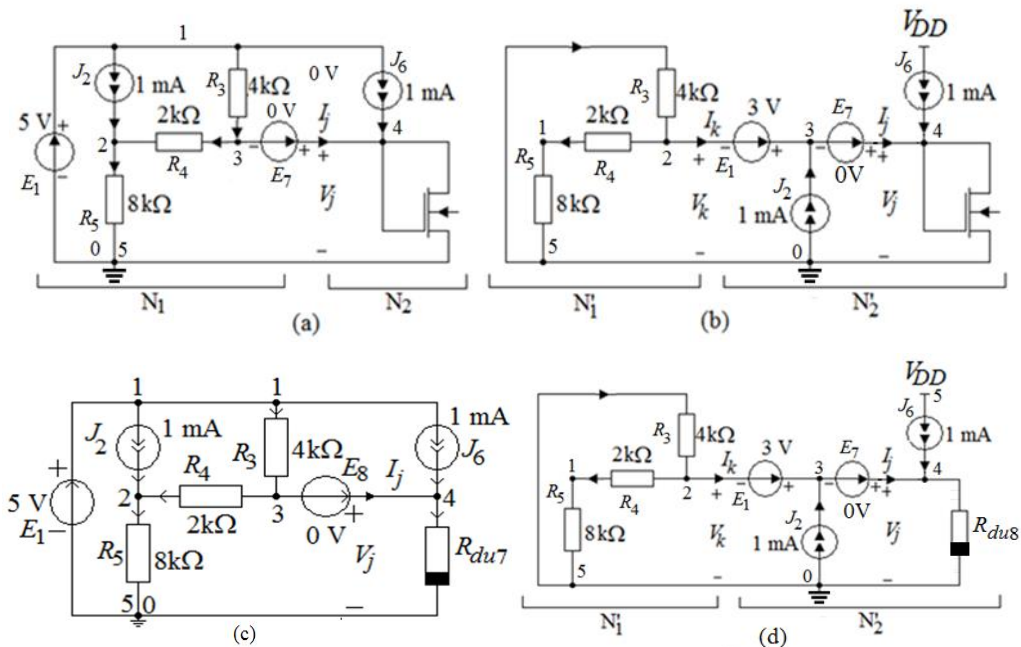
Fig. 6. (a) Example of two networks N1 and N2 separated by a port j; (b) Creation of a null port k in an H-modeling representation; (c) The MOS diode from Fig. 6. (a) was replaced by the voltage-controlled nonlinear resistor R_{du7} with the characteristic $I_7 = k \cdot (V_7 - 1.0)^2$ with $k = 0.5$ mA/V^2 and $V_7 > 1$; (d) The MOS diode from fig. 6. (b) was replaced by the voltage-controlled nonlinear resistor $Rdu8$ with the characteristic $I_8 = k \cdot (V_8 - 1.0)^2$ with $k = 0.5$ mA/V^2 and $V_8 > 1$.

The numerical values of the Thévenin equivalent circuit parameters in respect of the n_2 - n_0 nodes of the circuit in *fig. 6. (a)* are: $R_{Th} = R_{eq} = 2.8572$ kΩ and $U_{Th} = E_{eq} = 8.7143$ V, and those corresponding to the Norton equivalent circuit $G_{eq} = 1 / R_{eq} = 0.35$ S and $I_{sc} = U_{Th} / R_{Th} = 3.05$ mA. The equivalent hybrid circuit of the circuit in *fig. 6. (b)* in respect of the n_2 - n_0 nodes, as one of the two quantities V_H and I_H can be considered arbitrary, the parameters of this circuit can take the values: $V_H = 3.0$ (value considered arbitrary), current, according to relation (2), has the value $I_H = I_{sc} - V_H / R_{eq} = 2.0$ mA and if the current $I_H = 1$m A is considered arbitrary, the voltage, according to relation (2), results $V_H = V_{Th} - R_{eq} \cdot I_H = 5.8572$ V. If at the circuit terminals in *figs. 6. (a)* and *(b)*, we connect, instead of the transistor, a nonlinear voltage-controlled resistor R_{dvc}, with current-voltage characteristic $I_{dvc} = K (V_{dvc}-1)^2$ mA for $V_{dvc} > 1$ V, and let $K = 0.5$ mA/V^2, we obtain the circuits shown *in figs. 6. (c)* and *(d)*.

The left side of the circuits in *fig. 6. (c),* respectively *fig. 6. (d),* are replaced in turn, with respect to terminals n_2 - n_0, by: the equivalent circuit Thévenin (*fig. 6. (c)*) and the two variants of the Hybrid equivalent circuit (see *fig. 6. (b)*). Analyzing all five types of circuits, thus generated, by the ACAP program, [3, 18], it is obtained the same operating point for the voltage-controlled nonlinear resistor R_{dvc} ($V_{Rdvc} = 5.0833$ V, $I_{Rdvc} = 1.2708$ mA).

Obviously, the structure of the circuits in *figs. 6. (c)* and *(d)* are much simpler.

3. NULLIFIED HYBRID EQUIVALENT CIRCUIT

An equivalent canceled hybrid circuit, called model H, is a special case of a model H ~; where, the values of the voltage and current sources in the model are identical to the voltage and current values corresponding to the port, which means that the sources in a model H represent the polarization situation of the corresponding port. For example, taking the case of *fig. 2*, where the network N_1 supplies the voltage V_j and the current I_j to polarize the network N_2. The two models for this example are shown in *figs. 7. (a),* and *(b)*.
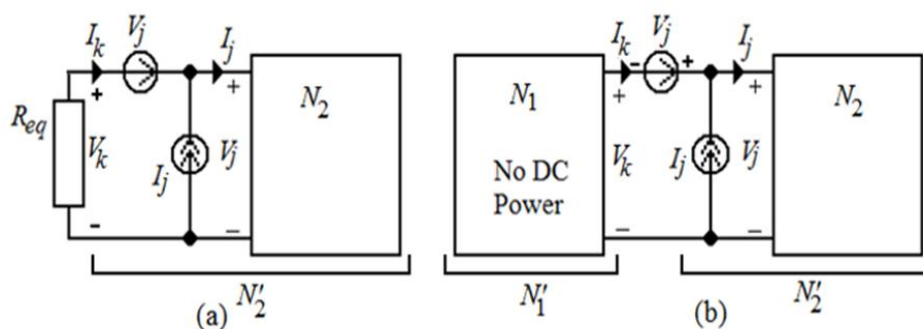

Fig. 7. An H-model for a two terminal N1: (a) Type 1 representation; (b) Type 2 representation.

Note that *Figs. 7. (a)* and *(b)* are identical to *Figs. 3. (a),* and *3. (b),* except that here, the model sources represent the port values. Note also from *figs. 7* that, as a result of modeling H, another port, k (V_k, I_k) (see *fig. 7*) is created in N_1, where both V_k and I_k are zero. Port k(V_k, I_k) is called "null" port, and the process of creating it is called "port cancellation", as will be discussed shortly.

Theorem 1 introduces an important property of a model H that deals with the distribution of electricity in a network [13]. It adds an extra dimension to power analysis and segmentation of power in a network.

Theorem 1: Considering an N_2 network connected to another N_1 network through a port (through a gate) j (V_j, I_j), as shown in *fig. 2*. Replacing N_1 with type H or type 2 models reduces the energy consumption in N'_1 to zero, while the energy consumption in N_2 remains unchanged.

Proof: Consider the model H ~ in *fig. 3. (a)* or *3. (b)*. Both sources, I_H and V_H, supply power to the N_1 and N_2 networks. The power delivered to N_2 is fixed and is calculated with the relation $P_2 = V_j \cdot I_j$; whereas in model 1 of type H ~ the power consumed by the network N_1 (*fig. 3. (a)*) is $P_1 = R_{eq} \cdot (I_H - I_j)^2$. Therefore, the power P_1 in N_1 becomes zero if $I_H = I_j$ which results in $V_H = V_j$. However, for model H type 2, we observe from *fig. 3. (b)* that N'_1 does not have a direct current source from which to obtain energy, plus its port is also canceled. Therefore, all currents and voltages inside N'_1 must be zero, resulting in zero power consumption.

Port cancellation (Nullification): Consider an N_2 network connected to another N_1 network through a port j (V_j, I_j), as shown in *fig. 2*. One way to cancel Port j is to enlarge the port on both sides (N_1 and N_2) by power sources: the current I_j and the voltage source V_j. The result is the creation of another port k (V_k, I_k) which, by definition, is a null port, meaning both I_k and V_k are zero.

However, there is an alternative method of creating a null port when two networks N_1 and N_2 are connected through a port j (V_j, I_j), shown in *fig. 2*. Here we can simply replace N_1 with its model H (type 1 or type 2) and create the null port k (V_k, I_k), as shown in *fig. 7*. As a result of the port cancellation procedure, N'_2, is created, which contains the N_2 circuit plus the sources belonging to the H model. Similarly, another N'_1 network is created, on the left side, when the H model loses its sources. As will be seen later, these extended networks have a particular importance in polarizing the circuit. It is observed that the characteristic curves of ports j and k are identical, except for the displacements of *v* and *i*, the coordinate axes, from the origin to the point $Q_j(V_j, I_j)$. This causes the operating point $Q_j(V_j, I_j)$ to fall on the origin, creating a new operating point $Q_k(0, 0)$ for the port k, shown in *fig.8*. This simply means that for any pair of networks, N_1 and N_2, connected via a port j, it is always possible to cancel the port and change N_1 and N_2 to N'_1 and N'_2, where N'_1 and N'_2 are identical to N_1 and N_2, except for the *v* and *i* coordinate axes which move at the port operating point. This is mentioned in Characteristic 1.

Characteristic 1: Consider two networks N_1 and N_2 connected through a port j, as in *fig.3*. If port j is null, then the characteristic curve *i-v* of the port, searching (looking at us) through any network, passes through the origin and the origin is the operating point of that port. If port j is not null, it is always possible to cancel the port to obtain the corresponding networks N'1 and N'2 with a null port k, as shown in *figure 8*.
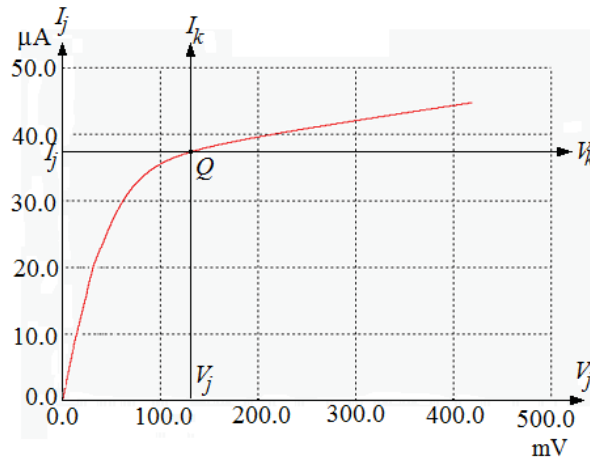
Fig. 8. The i-v coordinate axis moved from (0, 0) for the j port to a new position, $Q_j(V_j, I_j)$, for the k port.

4. CONCLUSIONS

The paper presents the necessary and sufficient conditions to be met by one-port or multi-port linear circuits to be replaced by equivalent Hybrid circuits. These circuits are widely used in the analysis of analog circuits.

A new modeling technique, called H ~ -modeling, is introduced for multi-port networks. It is shown that H ~ models are more dynamic compared to equivalent Thevenin or Norton circuits and have the ability to describe port behavior more accurately. A special type of model H ~ is also introduced, called model H ~ nullified, or simply model H ~; and many properties of H modeling are investigated, including circuit energy management. It is shown that the H models are not limited to single-port networks, but also cover multiports. A major feature of H modeling is the local polarization of the transistors. It separates the nonlinear components from the linear portion of the circuit for faster and more efficient polarization of the circuit. Here a designer can take advantage of H-modeling and bias individual transistors (or in combinations) with no need to perform the normal circuit biasing. The proposed strategy separates linear and nonlinear portions of an analog circuit and takes more control of nonlinear portions. This separation of the portions (components) of the circuit is achieved by introducing a new port model that cancels the ports of nonlinear devices. In turn, this leads to a new technique for polarizing nonlinear components.

The paper presents the necessary and sufficient conditions to be met by one-port or multi-port linear circuits to be replaced by equivalent Hybrid circuits. These circuits are widely used in the analysis of analog circuits.

The main advantage of Hybrid's theorem is that it allows us to replace any part a circuit which forms a linear resistive one-port (but which is of no interest in a given situation) by only two circuit elements without affecting the solution of the solution of the remainder of the circuit.

Thévenin, Norton and Hybrid equivalent circuits are used in the construction of Nullified Hybrid equivalent circuits. Equivalent Thévenin, Norton, hybrid and null hybrid circuits are used in the local polarization of analog circuits.

Based on the paper can introduce a guided design procedure for biasing of the electronic circuits.

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