Analysis of Electrical Circuits with Controlled Sources through the Principle of Superposition

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Abstract— **In the text books, while solving the circuits with controlled sources using Principle of Superposition (POS), controlled sources are not deactivated. Thus POS has not been applied in the 'true sense' to circuits with dependent sources. It is shown here that POS can be applied in the 'true sense' to such circuits also, but with caution. POS is applicable to all those circuits with dependent sources as well, if it is applicable to these circuits when all the dependent sources are treated as independent sources. We have included two such examples: one which cannot be solved only employing series-parallel reduction, current voltage division, and Ohm's law, second which has more than one controlled sources. The method based on POS is compared with that based on Miller equivalents and generalized matrix method. It is shown that the latter one is the most efficient. It is hoped that the teachers will emphasize that POS can be applied, in the true sense, for analysing circuits with controlled sources. The prospective authors would include this theory in their future text books. However, they should motivate the students to use generalized matrix method for better efficiency.**

Keyword-Circuit analysis, controlled sources, matrix method, Miller theorem, superposition

I. INTRODUCTION

AS many as 20 introductory books on circuit analysis [1-20] have been referred to by Leach [21] in order to find out if dependent sources can be suppressed while applying the principle of superposition (POS) to electrical circuits. He finds that these books either state or imply that superposition of dependent sources is not allowed, which, he contends, is a misconception. He finally concludes that POS can be applied to such networks also through a formal proof followed by several examples. Unfortunately, the reviewer of his paper [21] cited a circuit shown in Fig. 1 where the POS cannot be applied. Leach [21] mentions that ***the circuit cannot be solved by any other method. This will be shown in this paper.***

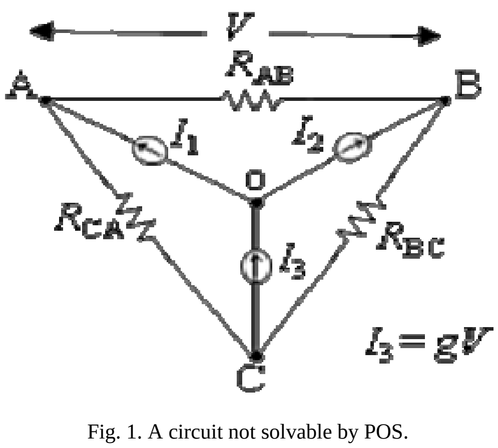


Fig. 1. A circuit not solvable by POS.

The conditions where POS cannot be applied are stated in [21]. In this paper, we give ***a general condition on the circuits to which POS cannot be applied***.

Damper [22] feels there is an error in Leach's proof [21] but agrees to his final conclusion. Without involving Leach's proof and Damper's subsequent correction, we provide ***a simple, but convincing proof***. The results are verified by the matrix method [23].

All the examples in [21] are solved by employing voltage and current division, series-parallel reduction, and Ohm's law. In this paper, it is shown through an example that ***there are circuits which cannot be solved just by using these techniques***. One needs to use star/delta transformation, KCL, KVL, or more general matrix method [23]. Also we have taken one example which has two controlled sources. Finally, we show that the matrix method is more efficient.

II. ANALYSIS OF CIRCUITS WITH CONTROLLED SOURCES USING POS

We prove that POS can be applied in **'true sense'** in solving the circuits with controlled sources. Here 'true sense' means that the response due to all the independent and dependent sources is obtained by superimposing the responses obtained, considering one source at a time. For convenience, without any loss of generality, we take the typical two-node network shown in Fig. 2, with current sources only as it is explained in [21] that voltage sources, if present, can be converted into current sources. Using node analysis, one can write

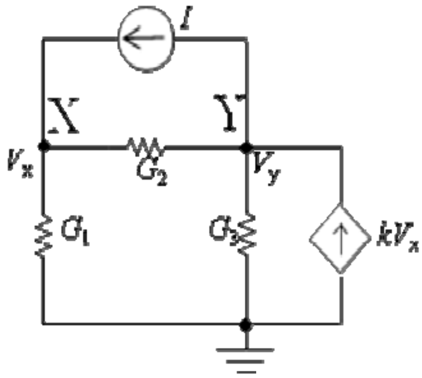


Fig. 2. Typical 2 node network.

$$\begin{bmatrix} y_{11} & -y_{12} \\ -y_{12} & y_{22} \end{bmatrix}\begin{bmatrix} V_x \\ Vy \end{bmatrix} = \begin{bmatrix} \sum I_x \\ \sum Iy \end{bmatrix} = \begin{bmatrix} I \\ -I + kV_x \end{bmatrix}. \tag{1}$$

Note that $\sum I_x$ and $\sum I_y$ may or may not contain the independent and/or dependent sources depending upon the position of the current sources in the circuit. In the circuit shown, node X has the independent current source I only while node Y has both the independent current source I and dependent current source KV_x. Eqn (1) can be rewritten as

$$\begin{bmatrix} y_{11} & -y_{12} \\ -y_{12} & y_{22} \end{bmatrix}\begin{bmatrix} V_x \\ Vy \end{bmatrix} = \begin{bmatrix} I \\ -I \end{bmatrix} + \begin{bmatrix} 0 \\ kV_x \end{bmatrix} \tag{2}$$

$$= R_i + R_d$$

where R_i is the response due to the independent source I and R_d is that due to the dependent source kV_x. It is obvious from eqn (2) that the node voltages can be solved by the POS. For example

$$V_x = V_{x1} + V_{x2}$$

$$V_x = \frac{\begin{bmatrix} I & -y_{12} \\ -I & y_{22} \end{bmatrix}}{\Delta} + \frac{\begin{bmatrix} 0 & -y_{12} \\ kV_x & y_{22} \end{bmatrix}}{\Delta} \tag{3}$$

where $\Delta = y_{11}y_{22} - y_{12}^2$.

Here dependent source kV_x should be treated as an independent source of value kV_x where V_x is the full and final value, i.e., when all the sources (independent and dependent) are present. Hence, it can be deactivated without reducing the controlling variable V_x to zero while determining the response due to the independent source I, like we do not put any current through, or voltage across, any element 0 while deactivating an independent source. Solving for V_x from (3), one gets

$$V_x = \frac{(y_{22} - y_{12})}{\Delta - y_{12}k} I \tag{4}$$

Similarly, from eqn (2), by Cramer's rule, one gets

$$V_y = \frac{\begin{bmatrix} y_{11} & I \\ -y_{12} & -I \end{bmatrix}}{\Delta} + \frac{\begin{bmatrix} y_{11} & 0 \\ -y_{12} & kV_x \end{bmatrix}}{\Delta}$$

$$= \frac{-y_{11} + y_{12}}{\Delta} I + \frac{y_{11}}{\Delta} kV_x.$$

Substituting for V_x from (4), and simplifying

$$V_y = \frac{(-y_{11} + y_{12} + k)}{\Delta - y_{12}k} I. \tag{5}$$

Now we solve the circuit by the matrix method of [23]. Equation (1) can be expressed as

$$\begin{bmatrix} y_{11} & -y_{12} \\ -y_{12} & y_{22} \end{bmatrix}\begin{bmatrix} V_x \\ Vy \end{bmatrix} = \begin{bmatrix} I \\ -I \end{bmatrix} + .\begin{bmatrix} 0 & 0 \\ k & 0 \end{bmatrix}\begin{bmatrix} V_x \\ Vy \end{bmatrix}$$

which yields

$$\begin{bmatrix} y_{11} & -y_{12} \\ -y_{12} - k & y_{22} \end{bmatrix}\begin{bmatrix} V_x \\ Vy \end{bmatrix} = \begin{bmatrix} I \\ -I \end{bmatrix}.$$

On solving one gets

$$V_x = \frac{(y_{22} - y_{12})}{\Delta - y_{12}k} I \tag{6}$$

and

$$V_y = \frac{(-y_{11} + y_{12} + k)}{\Delta - y_{12}k} I \tag{7}$$

Equations (6) and (7) are the same as eqns (4) and (5), respectively. Thus, we conclude that POS can be applied to linear circuits with controlled sources also.

In [21], it is mentioned that POS cannot be applied to networks when all the sources but one are deactivated and the resulting circuit contains a node at which the voltage is indeterminate or a branch in which the current is indeterminate. In such cases POS cannot be used even if all sources are independent. We state this condition in a more general form. POS cannot be applied to circuits with or without independent sources when all the sources but one are deactivated, the activated source should not become open if it is a current source or short if it is a voltage source. Two examples of such circuits are shown in Figs. 1 and 3 where the current source is opened and the voltage source is shorted, respectively. The circuit in Fig. 1 is solvable when one of the current sources, say I_3 is a dependent source such that $I_3 = I_1 + I_2$ (requirement of KCL). If we further make that $I_3 = gV$ [21], the circuit becomes unsolvable because two constraints on I_3 cannot simultaneously be satisfied. Similarly, the circuit shown in Fig. 3 is solvable when one of the voltage sources, say V_{CA}, is a dependent source such that $V_{CA} = -(V_{AB} + V_{BC})$ (requirement of KVL), but becomes unsolvable when V_{CA} is also dependent on some other voltage or current in the circuit.

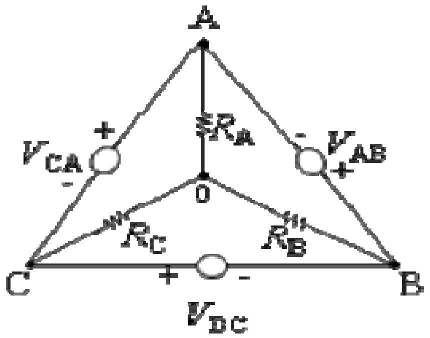


Fig. 3. A circuit to which POS cannot be applied.

Example 1: Determine the output voltage V_o in the circuit shown in Fig. 4 [22].

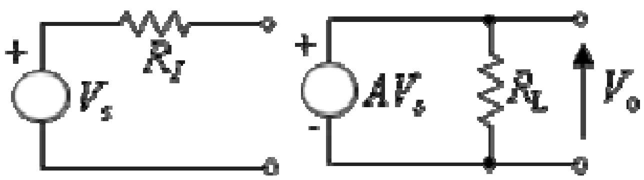


Fig. 4: Circuit for Example 1.

Applying POS

$V_o = V_1$ (due to the source V_s alone) + V_2 (due to the source AV_s alone) = $0 + AV_s = AV_s$.

Example 2: Find the current through G_2 in Fig. 2 when $G_1 = 0.8$ S, $G_2 = 0.2$ S, $G_3 = 0.3$ S, $k = 0.8$ S, $I = 23$ A. Applying POS

$$V_x = I\frac{G_a}{(G_a + G_2)G_1} - kV_x\frac{G_b}{(G_b + G_3)G_1}$$

where

$$G_a = \frac{G_1G_3}{G_1 + G_3}, \quad G_b = \frac{G_1G_2}{G_1 + G_2}$$

Substituting the values, one gets

$$V_x = 15 + (8/23)V_x \quad \to \quad V_x = 23\,\text{V}.$$

By POS for Vy

$$Vy = I\frac{-G_a}{(G_a + G_2)G_3} + kV_x\frac{1}{(G_b + G_3)}$$
$$= -40 + (40/23)V_x = -40 + 40 = 0.$$

Note that it is easier to solve for the controlling variable V_x by POS first and then any other voltage or current, if required, by any other method including using POS.

Example 3: Determine current I in the circuit shown in Fig. 5.

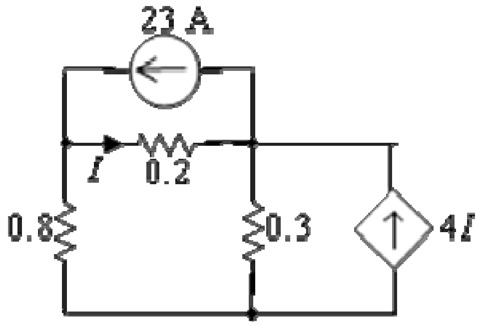


Fig. 5. Circuit for Example 3.

By POS,

$$I = 23\frac{G_a}{(G_a + G_2)} - 4I\frac{G_b}{(G_b + G_3)}$$
$$= 11 - (32/23)I \quad \rightarrow I = 4.6 \text{ A.}$$

Example 4: Consider the circuit shown in Fig. 6.

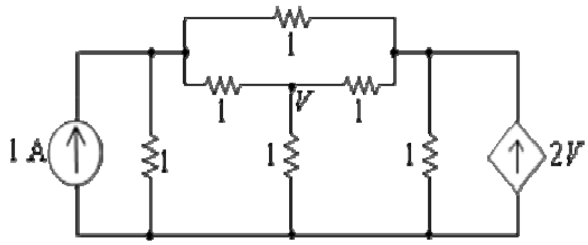


Fig. 6. Circuit for Example 4.

This circuit cannot be solved by series-parallel reduction, current and voltage division and Ohm's law. We solve it by matrix method [23].

By POS and using node analysis, one gets

$$V = \frac{\begin{bmatrix} 3 & 1 & -1 \\ -1 & 0 & -1 \\ -1 & 0 & 3 \end{bmatrix}}{\begin{bmatrix} 3 & -1 & -1 \\ -1 & 3 & -1 \\ -1 & -1 & 3 \end{bmatrix}} + \frac{\begin{bmatrix} 3 & 0 & -1 \\ -1 & 0 & -1 \\ -1 & 2V & 3 \end{bmatrix}}{\begin{bmatrix} 3 & -1 & -1 \\ -1 & 3 & -1 \\ -1 & -1 & 3 \end{bmatrix}} = \frac{1}{4} + \frac{1}{2}V$$

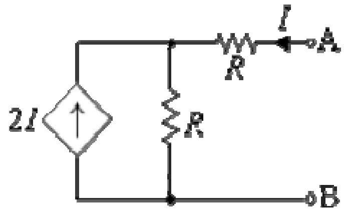
$$\Rightarrow V = \frac{1}{2} \text{ V.}$$

This is the correct answer verified by other method.

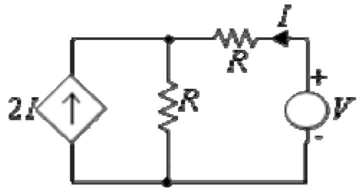
If a network does not have a single independent source, but has dependent sources only, then from eqn (2), we see that $R_i = 0$ and consequently, R_d will also be zero. It means that, in the absence of any independent source, the circuit is dead, i.e., no current through, and voltage across, any element exist, even though the dependent source(s) may be present.

While determining Thevenin equivalent of a circuit without any independent source but with dependent source, both the open circuit voltage and the short circuit current will be zero as explained above. In such a case, Thevenin resistance would be indeterminate using the relation $R_{th} = V_{oc}/I_{sc} = 0/0$. However, if we connect an independent voltage (current) source of value V (I) at the output terminals and find the current I flowing into the voltage source (voltage drop V developed across the current source), then $R_{th} = V/I$ as explained in [24].

Example 5: Find the Thevenin equivalent of the circuit across the terminals AB shown in Fig. 7.



(a)



(b)

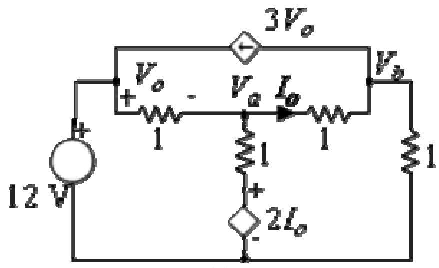
Fig. 7. (a) Circuit for Example 5 and (b) External voltage source connected.

We connect a voltage source at the terminals AB. By POS

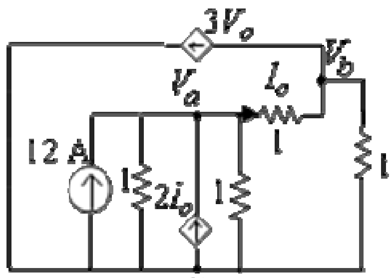
$$I = \left(\frac{1}{2R}\right)V - \left(\frac{R}{R+R}\right)2I \;\rightarrow\; \frac{V}{I} = R_{Th} = 4R.$$

Example 6: Determine the node voltages V_a and V_b in the circuit shown in Fig. 8(a).

There are two dependent sources; one is controlled by a voltage V_o and the other by current I_o which require the evaluation of corresponding difference of two node voltages. Such controlling variables almost double the complexity of the solution by POS. Such a problem has not been considered in [21-22].



(a)



(b)

Fig. 8. (a) Circuit for Example 6 and (b) reduced circuit.

We apply the node analysis. By POS, one gets

$$V_a = \frac{\begin{vmatrix} 12 & -1 \\ 0 & 2 \end{vmatrix}}{\begin{vmatrix} 3 & -1 \\ -1 & 2 \end{vmatrix}} + \frac{\begin{vmatrix} 2I_o & -1 \\ 0 & 2 \end{vmatrix}}{\begin{vmatrix} 3 & -1 \\ -1 & 2 \end{vmatrix}} + \frac{\begin{vmatrix} 0 & -1 \\ -3V_o & 2 \end{vmatrix}}{\begin{vmatrix} 3 & -1 \\ -1 & 2 \end{vmatrix}}$$

$$= \frac{24 + 4I_o - 3V_o}{5} \tag{8}$$

$$V_b = \frac{\begin{vmatrix} 3 & 12 \\ -1 & 0 \end{vmatrix}}{\begin{vmatrix} 3 & -1 \\ -1 & 2 \end{vmatrix}} + \frac{\begin{vmatrix} 3 & 2I_o \\ -1 & 0 \end{vmatrix}}{\begin{vmatrix} 3 & -1 \\ -1 & 2 \end{vmatrix}} + \frac{\begin{vmatrix} 3 & 0 \\ -1 & -3V_o \end{vmatrix}}{\begin{vmatrix} 3 & -1 \\ -1 & 2 \end{vmatrix}}$$

$$= \frac{12 + 2I_o - 9V_o}{5} \tag{9}$$

$$\text{Now} \quad I_o = \left(V_a - V_b\right)/1 \tag{10}$$

$$= \frac{24 + 4I_o - 3V_o}{5} - \frac{12 + 2I_o - 9V_o}{5}$$

$$\Rightarrow 2V_o - I_o = -4 \tag{11}$$

$$\text{Now} \quad V_o = 12 - V_a \tag{12}$$

$$= 12 - \frac{24 + 4I_o - 3V_o}{5}$$

$$\Rightarrow V_o + 2I_o = 18 \tag{13}$$

From eqns (11) and (13), by Cramer’s rule

$$V_o = \frac{\begin{vmatrix} -4 & -1 \\ 18 & 2 \end{vmatrix}}{\begin{vmatrix} 2 & -1 \\ 1 & 2 \end{vmatrix}} = 2 \text{ V}, \quad I_o = \frac{\begin{vmatrix} 2 & -4 \\ 1 & 18 \end{vmatrix}}{\begin{vmatrix} 2 & -1 \\ 1 & 2 \end{vmatrix}} = 8 \text{ A}.$$

Substituting the values of V_o and I_o in eqns (8) and (9) one gets

$$V_a = 10 \text{ V}, \; V_b = 2 \text{ V}.$$

Now let us solve the same problem by Matrix method [23]. Node analysis gives

$$\begin{bmatrix} 3 & -1 \\ -1 & 2 \end{bmatrix}\begin{bmatrix} V_a \\ V_b \end{bmatrix} = \begin{bmatrix} 12 + 2I_o \\ -3V_o \end{bmatrix}$$

$$= \begin{bmatrix} 12 + 2(V_a - V_b) \\ -3(12 - V_a) \end{bmatrix}$$

$$= \begin{bmatrix} 12 + 2V_a - 2V_b \\ -36 + 3V_a \end{bmatrix}$$

$$= \begin{bmatrix} 12 \\ -36 \end{bmatrix} + \begin{bmatrix} 2 & -2 \\ 3 & 0 \end{bmatrix}\begin{bmatrix} V_a \\ V_b \end{bmatrix}$$

$$\Rightarrow \begin{bmatrix} 1 & 1 \\ -4 & 2 \end{bmatrix}\begin{bmatrix} V_a \\ V_b \end{bmatrix} = \begin{bmatrix} 12 \\ -36 \end{bmatrix}$$

By Cramer's rule

$$V_a = \frac{\begin{vmatrix} 12 & 1 \\ -36 & 2 \end{vmatrix}}{\begin{vmatrix} 1 & 1 \\ -4 & 2 \end{vmatrix}} = 10\text{ V}, \quad V_b = \frac{\begin{vmatrix} 1 & 12 \\ -4 & -36 \end{vmatrix}}{\begin{vmatrix} 1 & 1 \\ -4 & 2 \end{vmatrix}} = 2\text{ V}$$

These are the same as obtained above, but with considerably less effort in solving.

III. **COMPARISON WITH OTHER METHODS**

There is a similarity between the methods based on POS and Miller equivalents [25]. In the former method, the sources are dependent while in the latter method, the elements are dependent on some parameter. However, in both the methods, one has to determine the controlling variables first and then any other desired voltage or current. As proved in [23], matrix method is more efficient than the Miller equivalent approach. It is also more efficient than the method based on POS. This is proved below.

Let there be N number of unknown nodes and S_i and S_d be the number of independent and dependent sources, respectively, in a circuit. We shall compare the number of determinants to be solved by the POS method and the matrix method for determining the voltages of N nodes. In POS method, N equations for N node voltages in terms of controlling variables are to be written invoking POS. These relations require $N(S_i + S_d) + 1$ determinants of the order $N \times N$ to be solved. After this S_d relations among the controlling variables will be determined. Then evaluation of the controlling variables from these relations requires $S_d + 1$ determinants of order $S_d \times S_d$ to be solved. After this the voltages of N unknown nodes are evaluated. Thus in the above example, since N = 2, $S_i = 1$ and $S_d = 2$, it requires 10 determinants of order 2×2 to be solved.

Matrix method requires only $N + 1$ determinants of order $N \times N$ to be solved. Thus, it requires only 3 determinants as against 10 by POS for the circuit of example 6. There is no need to determine the controlling variables explicitly. Thus the matrix method is more efficient, easier and straight forward.

IV. CONCLUSION

In the text books [1]-[20], while solving the circuits with controlled source using POS, controlled sources are not deactivated. Thus POS has not been applied in 'true sense' to circuits with dependent sources. It has been shown here that POS can be applied in the 'true sense' to such circuits also, but with the following caution: (i) All the dependent sources should also be treated as independent sources with their full value (contribution from all the sources). (ii) When the dependent source is deactivated, its controlling variable should not be zeroed. POS is applicable to all those circuits with dependent sources as well if it is applicable to these circuits when all the dependent sources are treated as independent sources. An example which is not solvable by series parallel reduction technique, current voltage division, and Ohm's law alone has been given. Also an example is included that has more than one controlled sources. It is hoped that the teachers will emphasize that POS can be applied in true sense for analysing circuits with controlled sources. The prospective authors would include this theory in their future text books. However, they should motivate the students to use generalized matrix method for better efficiency.

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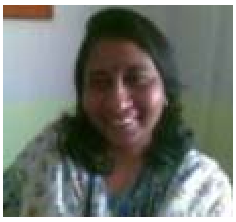

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