<table>
<thead>
<tr>
<th><strong>Title</strong></th>
<th>Realizability of n-port resistive networks with 2n terminals</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Author(s)</strong></td>
<td>Chen, MZ; Wang, K; Yin, M; Li, C; Zuo, Z; Chen, G</td>
</tr>
<tr>
<td><strong>Citation</strong></td>
<td>The 9th Asian Control Conference (ASCC 2013), Istanbul, Turkey, 23-26 June 2013. In Conference Proceedings, 2013, p. 1-6</td>
</tr>
<tr>
<td><strong>Issued Date</strong></td>
<td>2013</td>
</tr>
<tr>
<td><strong>URL</strong></td>
<td><a href="http://hdl.handle.net/10722/189986">http://hdl.handle.net/10722/189986</a></td>
</tr>
<tr>
<td><strong>Rights</strong></td>
<td>Asian Control Conference Proceedings. Copyright © IEEE.; ©2013 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.; This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License.</td>
</tr>
</tbody>
</table>
Realizability of $n$-Port Resistive Networks with $2n$ Terminals

Michael Z. Q. Chen
Department of Mechanical Engineering
The University of Hong Kong
Hong Kong SAR, P. R. China
Email: mzqchen@hku.hk

Kai Wang
School of Automation
Nanjing University of Science and Technology, Nanjing, P. R. China

Minghui Yin
School of Automation
Nanjing University of Science and Technology, Nanjing, P. R. China

Chanying Li
Academy of Mathematics and Systems Science
Chinese Academy of Sciences
Beijing, P. R. China

Zhiqiang Zuo
Tianjin Key Laboratory of Process Measurement and Control, School of Electrical Engineering and Automation
Tianjin University, Tianjin, P. R. China

Guanrong Chen
Department of Electronic Engineering
City University of Hong Kong
Hong Kong SAR, P. R. China

Abstract—In this paper, we consider the realizability problem of $n$-port resistive networks containing $2n$ terminals. A necessary and sufficient condition for any real symmetric matrix to be realizable as the admittance of an $n$-port resistive network containing $2n$ terminals is obtained. The condition is based on the existence of a parameter matrix. We then focus on a three-port resistive network containing six terminals. A necessary and sufficient condition is derived for any real symmetric matrix to be realizable as the admittance of a three-port resistive network containing six terminals and at most five positive elements, whose topological structure is properly restricted.

Keywords: Network synthesis, resistive network, inerter.

I. INTRODUCTION

Passive network synthesis is an important subject in systems theory and experienced a “golden era” in the 1930–1970s [1], [2], [3], [19]. Although there have been many elegant and useful results in this field, there are still many unsolved important problems such as minimal realizations.

Recently, a new mechanical element named “inerter” [13], [26] has been introduced, in which the force applied at its two terminals is proportional to the relative acceleration between them. One of the main motivations for the inerter research is passive mechanical network synthesis. The spring, damper, and inerter are analogous to the inductor, resistor, and capacitor, respectively [26]. The impedance (admittance) of any passive network is positive-real [19] and any positive-real impedance (admittance) is realizable with a finite number of resistors (dampers), inductors (springs), and capacitors (inerters) following the Bott-Duffin procedure [3]. Hence, one can use dampers, springs, and inerters to construct any passive mechanical network in a systematic manner. Since mechanical systems require as few elements as possible, interest in passive network synthesis has been renewed lately [10], [11], [12], [14], [15], [16], [17], [18], [30]. In particular, there was an independent call for a renewed investigation by Kalman [22].

Realization problems of multi-port transformerless networks have not been fully addressed, not even for the $n$-port resistive networks. Noticeably, the investigation on $n$-port resistive networks is the first step of solving realization problems of multi-port transformerless networks and can provide guidance on further investigations. Besides, several results of minimal realizations of one-port networks can be derived based on the results of the $n$-port resistive networks [14], [15]. Therefore, as one of the important topics in passive network synthesis, it is quite essential to have a new endeavor on the realization problem of $n$-port resistive networks. For any $n$-port resistive network, using the generalized star-mesh transformation [29], the number of terminals is ranged from $n+1$ to $2n$. Networks containing $n+1$ terminals have been determined [7], [20], while networks containing $n+p$ terminals with $p > 1$ remain unsolved. Among them, networks containing $2n$ terminals form a particularly important class, which is investigated here.

This paper considers the realizability condition for an $n$-port resistive network containing $2n$ terminals. A necessary and sufficient condition is obtained for the realizability of any $n$-port resistive network containing $2n$ terminals, which is based on the existence of a parameter matrix and presented in a unified form. Besides, the values of the elements are also parameterized. Furthermore, an explicit condition is derived for a three-port resistive network containing six terminals and at most five elements in a restricted topological structure.

The remaining part of this paper is organized as follows. Section II formulates the problem to be solved. In Section III, the main results are presented. Section III-A provides some preliminaries; Section III-B derives a necessary and sufficient condition for the realization of an $n$-port resistive network with $2n$ terminals; and Section III-C focuses on the realizability conditions for a three-port resistive network. The conclusion is drawn in Section IV.
II. Problem Formulation

Consider an $n \times n$ real symmetric matrix in the form of

\[
Y = \begin{bmatrix}
y_{11} & y_{12} & y_{13} & \cdots & y_{1,n-1} & y_{1n} \\
y_{12} & y_{22} & y_{23} & \cdots & y_{2,n-1} & y_{2n} \\
y_{13} & y_{23} & y_{33} & \cdots & y_{3,n-1} & y_{3n} \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\
y_{1,n-1} & y_{2,n-1} & y_{3,n-1} & \cdots & y_{n-1,n} & y_{nn}
\end{bmatrix}.
\]  

(1)

It is well known that $Y$ is necessarily paramount [8] for any resistive $n$-port network consisting of only non-negative resistors. Furthermore, it is also known from [28] that paramountcy is a necessary and sufficient condition for realization when $n \leq 3$. From the results in [4], it can be derived that the port graph of a realization must be made part of a tree. The internal vertices (the vertices which are not terminals) can be eliminated by the generalized star-mesh transformation [29]. Therefore, only the networks whose vertices are all terminals need to be investigated. In this setting, the number of vertices (terminals) of the network is from $n + 1$ to $2n$. The realization problem for the $n$-port resistive network with $n + 1$ vertices has been solved [5], [6], [7], [20]. The problem with $n + p$ vertices where $p > 1$ was studied in [21], [23], [24], [25]. However, this problem has not been completely solved.

This paper is concerned with the realization problem of 2n-terminal resistive networks consisting of only non-negative resistors. We first consider the general $n$-port networks, and then investigate the three-port case. In this study, no negative resistors or internal vertices are permitted. The basic notations and theorems in graph theory are referred to [27].

III. Main Results

This section contains the main results of this paper, which is divided into three subsections.

A. Basic Concepts and Results

This subsection presents some definitions and lemmas that will be used in the following discussion.

Definition 3.1: [9] A connected graph in which each pair of vertices has one and only one edge is called a complete graph.

It is noted that complete graph was first defined in [7], which confines the number of vertices to $n + 1$, as [7] only considers the realization of $n$-port resistive networks containing $n + 1$ vertices. In this paper, we generalize this term to one for $n + p$ with $p \geq 1$. If the network graph of any $n$-port resistive network is regarded as a complete graph, then the conductance of the resistor in each edge is non-negative with zero conductance corresponding to an open-circuit element.

Definition 3.2: [9], [28] A real symmetric matrix, with each main-diagonal element not less than the sum of the absolute values of all the other elements in the same row, is called a dominant matrix.

Definition 3.3: [9], [28] A real symmetric matrix, with each principle minor not less than the absolute value of any non-principle minor formed by the same rows, is called a paramount matrix.

It is obvious that when $n = 2$, the dominant matrix and the paramount matrix are equivalent.

Definition 3.4: [9] A real $m \times m$ symmetric matrix $Y$ is called a uniformly tapered matrix if its entries satisfy

\[
\bar{y}_{i,j} - \bar{y}_{i,j+1} \geq \bar{y}_{i-1,j} - \bar{y}_{i-1,j+1}
\]

for $j \geq i$, where $\bar{y}_{0,i} = \bar{y}_{i,m+1} = 0$ for all $i$ and $j = 1, 2, \ldots, m$.

From the above definition, it can be verified that all the entries of a uniformly tapered matrix must be non-negative.

Lemma 3.1: [7], [9] A real symmetric matrix can be realized as the admittance of a resistive network, as shown in Fig. 1, whose port graph is a linear and ordered tree if and only if it is uniformly tapered.
Lemma 3.3: [25] If the \((k+1)\)th row and column of \(Y_{k+1}\) correspond to the new port of \(N_{k+1}\) and the other correspondences are unchanged, then the relationship between \(Y_k\) and \(Y_{k+1}\) is expressed as
\[
Y_{k+1} = (Y_k + 0) + \alpha_k \alpha_k^T,
\]
where \(\alpha_k = [p_1, p_2, \ldots, p_i, p_{k+1}]^T\).

It should be noted that if any other row of \(Y_{k+1}\) is used for the new added port, a similar result can be obtained.

Lemma 3.4: [25] Consider two real symmetric matrices \(Y_k\) and \(Y_{k+1}\), which satisfy the relationship (2). Then \(Y_k\) can be realized as a \(k\)-port resistive network \(N_k\) if and only if \(Y_{k+1}\) is realizable as a \((k+1)\)-port resistive network \(N_{k+1}\).

B. A Necessary and Sufficient Condition for \(n\)-Port Networks

The complete graph of an \(n\)-port resistive network with \(2n\) terminals (vertices) is shown in Fig. 2, where the orientations of the edges of port graph are arbitrary. Theorem 3.1 presents a necessary and sufficient condition for any real symmetric \(n \times n\) matrix \(Y\) in the form of (1) to be realizable as an \(n\)-port resistive network with \(2n\) terminals.

\[
\begin{align*}
\text{Fig. 2. The complete graph of an } n\text{-port resistive network with } 2n \text{ terminals, where the bold line segments correspond to the edges of the port graph.}
\end{align*}
\]

Theorem 3.1: Consider a real symmetric \(n \times n\) matrix \(Y\) in the form of (1). It can be realized as an \(n\)-port resistive network \(N\) with \(2n\) terminals if and only if there exists a real \((2n-1) \times (n-1)\) matrix \(P\) in the form of
\[
P = \begin{bmatrix}
\gamma_1 & \gamma_2 & \cdots & \gamma_{n-1}
\end{bmatrix}
\]
with
\[
\gamma_k := \begin{bmatrix}
p_1^{(k)} & p_{n+1}^{(k)} & \cdots & p_{p+k}^{(k)} & p_{p+k+1}^{(k)} & \cdots & p_{n-1}^{(k)} & p_n^{(k)}
\end{bmatrix}^T
\]
for \(1 \leq k \leq n-1\) such that
\begin{align*}
\max \{- (\alpha_i - \beta_{i-1})^T (\alpha_j - \beta_j), - (\alpha_i - \beta_i)^T (\alpha_j - \beta_{j-1})\} & \leq y_{ij} \\
\min \{- (\alpha_i - \beta_{i-1})^T (\alpha_j - \beta_{j-1}), - (\alpha_i - \beta_i)^T (\alpha_j - \beta_j)\} & \leq y_{ij}
\end{align*}
for \(1 \leq i < j \leq n\) and
\[
y_{ij} \geq - (\alpha_i - \beta_{i-1})^T (\alpha_j - \beta_j), \quad 1 \leq i = j \leq n,
\]
where \(\alpha_i^T\) is the \((2i-1)\)th row of \(P\) with \(1 \leq l \leq n\), \(\beta_n^T\) is the \(2n\)th row of \(P\) with \(1 \leq m \leq n-1\), and \(\beta_0 = \beta_n := 0_{(n-1) \times 1}\).

Proof: Since the network graph can be regarded as a complete graph, the required network can be converted into one whose port graph is a linear ordered tree by adding new ports step by step. Hence, the theorem can be proven by making use of Lemma 3.1, Lemma 3.3, and Lemma 3.4. The details are omitted for brevity.

Furthermore, the element values are presented in Theorem 3.2.

Theorem 3.2: Consider a real symmetric \(n \times n\) matrix \(Y\) in the form of (1). If it can be realized as an \(n\)-port resistive network with \(2n\) terminals as shown in Fig. 2, where the orientations of the ports are from vertex \(A_{2k-1}\) to \(A_{2k}\) with \(1 \leq k \leq n\), that is, \(Y\) satisfies the condition of Theorem 3.1, then the values of the conductance of the resistor of each edge are given by
\begin{align*}
g_{2r-1,2s} & = y_{rs} + (\alpha_r - \beta_{r-1})^T (\alpha_s - \beta_s), \quad 1 \leq r \leq s \leq n, \\
g_{2r-1,2s-1} & = -y_{rs} - (\alpha_r - \beta_{r-1})^T (\alpha_s - \beta_{s-1}), \quad 1 \leq r < s \leq n, \\
g_{2r,2s} & = y_{rs} + (\alpha_r - \beta_s)^T (\alpha_s - \beta_{s-1}), \quad 1 \leq r \leq s \leq n, \\
g_{2r,2s-1} & = -y_{rs} - (\alpha_r - \beta_s)^T (\alpha_s - \beta_{s-1}), \quad 1 \leq r < s \leq n,
\end{align*}
where \(\alpha_r\) and \(\beta_s\) are obtained from the parameter matrix \(P\) as defined in Theorem 3.1, and \(g_{h,l}\) denotes the conductance of the element connecting vertices \(A_h\) and \(A_l\) for \(1 \leq h < l \leq 2n\).

Proof: This theorem can be proven by using Lemma 3.2 and Theorem 3.1. The details are omitted for brevity.

C. Realizability Conditions for Three-Port Networks

In the previous subsection, a necessary and sufficient condition is given, which is based on the existence of a parameter matrix. In this subsection, we discuss the three-port resistive networks such that the realizability condition is given directly based on the entries of the admittance matrix. It is known in [31, pg. 372] that any \(3 \times 3\) paramount admittance can be realized by a canonical network containing six elements and five terminals. Hence, this subsection consider the realization problem of a six-terminal network with at most five elements, for which the topological structure is properly restricted.

For a \(2 \times 2\) symmetric matrix, the next lemma can be deduced from [28].

Lemma 3.5: A real symmetric \(2 \times 2\) matrix \(Y\) can be realized as a two-port resistive network with four terminals if and only if it is paramount. Furthermore, at most four elements are required.

A third-order symmetric matrix is expressed in the form of
\[
Y = \begin{bmatrix}
y_{11} & y_{12} & y_{13} \\
y_{12} & y_{22} & y_{23} \\
y_{13} & y_{23} & y_{33}
\end{bmatrix}.
\]

Since we discuss the realizability problem of a special class of this kind of networks, where no internal vertices are permitted,
to better describe the restriction on this kind of networks, the following definition is introduced.

Definition 3.5: For the complete graph of a resistive network, an edge whose corresponding resistor has positive conductance is called a positive edge.

The positive edge is defined to distinguish the one corresponding to an open-circuit element.

Definition 3.6: Consider an n-port network whose port graph contains p ports, where p > 1. If any two parts of the port graph are directly connected with each other by a positive edge, then the network is a called terminal well-connected network.

In what follows, we discuss the realization problem of a three-port resistive network containing six terminals and at most five positive elements that is not terminal well-connected.

Lemma 3.6: Consider a third-order real symmetric matrix $Y$ in the form of (8). If $Y$ is a dominant matrix with at least two of $y_{12}, y_{13},$ and $y_{23}$ being zero, then it can be realizable as the admittance matrix of a three-port resistive network with six terminals and at most five positive elements, which is not terminal well-connected.

Proof: After a proper rearrangement of rows and corresponding columns, $Y$ in (8) can be written in the form of $Y_1 + y$ with $Y_1$ being a $2 \times 2$ paramount matrix and $y \geq 0$. Thus, this lemma follows immediately from Definition 3.5.

Lemma 3.7: Consider a third-order real symmetric matrix $Y$ in the form of (8) that does not satisfy the condition of Lemma 3.6. If it can be realized as the admittance matrix of a three-port resistive network with six terminals, which is not terminal well-connected, then it can be realized by a network from the one shown in Fig. 3 by judiciously swapping the ports and switching the polarities of them, where all the elements denoted by the bold lines always have positive conductance.

$\begin{align*}
L_1 &\leq y_{11}, \quad L_2 \leq y_{22}, \quad L_3 \leq y_{33}, \\
\max \{N_{12}^{(1)}, N_{12}^{(2)}\} &\leq y_{12} \leq \min \{M_{12}^{(1)}, M_{12}^{(2)}\}, \\
\max \{N_{13}^{(1)}, N_{13}^{(2)}\} &\leq y_{13} \leq \min \{M_{13}^{(1)}, M_{13}^{(2)}\}, \\
\max \{N_{23}^{(1)}, N_{23}^{(2)}\} &\leq y_{23} \leq \min \{M_{23}^{(1)}, M_{23}^{(2)}\}, 
\end{align*}$

where

$L_1 = p_{11}p_{41} + p_{12}p_{42} - (p_{11}p_{11} + p_{12}p_{12}),$
$L_2 = p_{21}p_{41} + p_{22}p_{42} + p_{22}p_{52} - (p_{21}p_{21} + p_{22}p_{22} + p_{42}p_{52}),$
$L_3 = p_{32}p_{52} - (p_{31}p_{31} + p_{32}p_{32}),$
$M_{12}^{(1)} = p_{11}p_{41} + p_{12}p_{42} - (p_{11}p_{21} + p_{12}p_{22}),$
$M_{12}^{(2)} = p_{21}p_{41} + p_{22}p_{42} - (p_{11}p_{21} + p_{12}p_{22} + p_{42}p_{52}),$
$N_{13}^{(1)} = (p_{11}p_{31} + p_{12}p_{32}),$
$N_{13}^{(2)} = p_{31}p_{41} + p_{32}p_{42} - (p_{11}p_{31} + p_{12}p_{32} + p_{42}p_{52}),$
$M_{13}^{(1)} = p_{11}p_{31} + p_{12}p_{32} - (p_{11}p_{31} + p_{12}p_{32}),$
$M_{13}^{(2)} = p_{31}p_{41} + p_{32}p_{42} - (p_{11}p_{31} + p_{12}p_{32}),$
$N_{23}^{(1)} = p_{21}p_{41} + p_{22}p_{42} - (p_{21}p_{31} + p_{22}p_{32}),$
$N_{23}^{(2)} = p_{22}p_{52} + p_{32}p_{52} - (p_{21}p_{31} + p_{22}p_{32} + p_{52}p_{52}),$
$M_{23}^{(1)} = p_{31}p_{41} + p_{32}p_{42} - (p_{21}p_{31} + p_{22}p_{32} + p_{52}p_{52}),$
and $M_{23}^{(2)} = p_{32}p_{52} - (p_{21}p_{31} + p_{22}p_{32}).$

By Theorem 3.2, the values of the conductances $g_{i,j}$ can be calculated as

$\begin{align*}
g_{1,2} &= y_{11} - L_1, \quad g_{3,4} = y_{22} - L_2, \quad g_{5,6} = y_{33} - L_3, \\
g_{1,3} &= M_{12}^{(1)} - y_{12}, \quad g_{2,4} = M_{12}^{(2)} - y_{12}, \quad g_{1,4} = y_{12} - N_{12}^{(1)}, \\
g_{2,3} &= y_{12} - N_{12}^{(2)}, \quad g_{1,5} = M_{13}^{(1)} - y_{13}, \quad g_{2,6} = M_{13}^{(2)} - y_{13}, \\
g_{1,6} &= y_{13} - N_{13}^{(1)}, \quad g_{2,5} = y_{13} - N_{13}^{(2)}, \quad g_{3,5} = M_{23}^{(1)} - y_{23}, \\
g_{4,6} &= M_{23}^{(2)} - y_{23}, \quad g_{5,6} = y_{23} - N_{23}^{(1)}, \quad g_{4,5} = y_{23} - N_{23}^{(2)}.
\end{align*}$

Definition 3.7: A row of a matrix $Y$ is marginally dominant if the elements of the row satisfy $y_{i} = \sum_{j=1, j\neq i}^{n} |y_{ij}|.$

Theorem 3.3: A real symmetric matrix $Y$ in the form of (8) can be realized as the admittance matrix of a three-port resistive network with six terminals and at most five positive elements, which is not terminal well-connected, if and only if $Y$ is dominant and one of the following three conditions holds:

1. at least two of $y_{12}, y_{13},$ and $y_{23}$ are zero;
2. one of $y_{12}, y_{13},$ and $y_{23}$ is zero, and at least two of the three rows are marginally dominant;
3. one of $y_{12}, y_{13},$ and $y_{23}$ is zero, denoted by $y_{ij} = 0$, and only one of the three rows is marginally dominant, which is either the $i$th row or the $j$th row.

Proof: Necessity. Consider a real symmetric matrix $Y$ in the form of (8). If $Y$ does not satisfy the condition of Lemma 3.6, then by Lemma 3.7 it can be realized by the
network shown in Fig. 3 via judiciously swapping the ports and switching the polarities of them, where all the elements denoted by the bold lines have positive conductance, and there is at most one positive element among the edges denoted by the solid lines. In this figure, $A_1$ and $A_3$ are at higher potentials; $A_2$, $A_4$, and $A_6$ are at lower ones. It suffices to consider the network shown in Fig. 3 because the admittances of other cases can be obtained from the network in this figure by proper arrangement of rows and corresponding columns and multiplication of the rows and columns with $-1$, which does not violate the condition.

Since $Y$ can be realized by the network in the form of Fig. 3, there must exist a parameter matrix $P$ in the form of (9) such that (10)–(13) hold. It is noted that $g_{3,5} = g_{3,6} = g_{4,5} = g_{4,6} = 0$, which is equivalent to

\[
N_{23}^{(1)} - y_{23} = 0, \
N_{23}^{(2)} - y_{23} = 0, \
M_{23}^{(2)} - y_{23} = 0, \
M_{23}^{(1)} - y_{23} = 0.
\]

This implies that

\[p_{22} = p_{42} = p_{52} \neq 0, \quad p_{31}p_{41} = 0, \quad y_{23} = -p_{21}p_{31}.
\]

For the edges represented by the lighter lines in Fig. 3, it suffices to discuss the following two cases.

**Case 1**: $g_{1,3} = g_{2,4} = g_{1,5} = g_{2,6} = 0$. In this case,

\[
M_{12}^{(1)} - y_{12} = 0, \
M_{12}^{(2)} - y_{12} = 0, \
M_{13}^{(1)} - y_{13} = 0, \
M_{13}^{(2)} - y_{13} = 0.
\]

Together with $g_{1,6}; g_{2,5}; g_{1,4}; g_{2,3} > 0$, it can be derived that $Y$ is dominant and at least two of the three rows are marginally dominant.

**Case 2**: One of $g_{1,3}, g_{2,4}, g_{1,5}$, and $g_{2,6}$ is positive. It can be derived that $Y$ is dominant, one of $y_{12}, y_{13}$, and $y_{23}$ is zero, denoted by $y_{i,j} = 0$, and only one of the three rows is marginally dominant, which is either the $i$th row or the $j$th row.

**Sufficiency**: Suppose that $Y$ in the form of (8) satisfies the given condition. If it is dominant and satisfies Condition 1, then it must be realizable as the admittance of the required network by Lemma 3.6.

If it is dominant and satisfies Condition 2, then after proper arrangement of the rows and the corresponding columns, and multiplication of the rows and the corresponding columns with $-1$, the matrix satisfies $y_{23} = 0, y_{12} > 0$, and $y_{13} > 0$. Choose the parameter matrix $P$ such that its elements satisfy

\[p_{31} = 0, \quad p_{11} = p_{21}, \quad 0 < p_{11}p_{41} < p_{41}p_{41}, \quad p_{12} = p_{32}, \quad p_{22} = p_{42} = p_{52}, \quad 0 < p_{12}p_{22} < p_{22}p_{22}, \quad p_{11}p_{41} - p_{11}p_{11} = y_{12}, \quad p_{12}p_{22} - p_{12}p_{12} = y_{13}.
\]

It is obvious that this choice is always possible. It can be verified that (10)–(13) hold. Furthermore, $g_{1,3} = g_{2,4} = g_{1,5} = g_{2,6} = g_{3,5} = g_{3,6} = g_{4,5} = 0, \quad g_{1,4} = p_{11}p_{41} > 0, \quad g_{2,3} = -p_{11}p_{41} + p_{41}p_{41} > 0, \quad g_{1,6} = p_{12}p_{22} > 0, \quad g_{2,5} = -p_{12}p_{22} + p_{22}p_{22} > 0$.

**IV. Conclusion**

This paper has investigated the realizability problem of an $n$-port resistive network containing $2n$ terminals. A general result was derived, which is a necessary and sufficient condition for any real symmetric matrix to be realizable as an $n$-port resistive network containing $2n$ terminals. The condition is in a unified form, obtained based on the existence of a parameter matrix. To make the condition be directly dependent on the entries of the given matrix, the case of $n = 3$ was discussed in detail. A new concept named the terminal well-connected network was introduced. Consequently, a necessary and sufficient condition for any real symmetric matrix to be realizable as the admittance of a three-port six-terminal resistive network, which is not terminal well-connected and contains at most five positive elements, was derived.

**ACKNOWLEDGMENT**

This work is supported by NNSFC 61004093, NNSFC 61203129, NNSFC 61203067, and the “Innovative research projects for graduate students in universities of Jiangsu province” CXLX12_0200.
REFERENCES


