REAL-TIME POWER SYSTEM ANALYSIS USING NEURAL COMPUTING

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ABSTRACT

It is common practice for the power system dispatcher before taking any action to precede it with power flow analysis so as to avoid costly experimentation with the real system. Hence speed of power flow solutions is an extremely important factor for real-time implementation of corrective actions. The advantage of fast computation of Artificial Neural Network (ANN) is used for obtaining power flow solutions in real time. The input to the ANN are the real and reactive power generations and demands in the system, and the output data are the complex bus voltages. A few configurations of the neural network are experimented and the best results are achieved with a single-layer feedforward neural network with nonlinear feedback. Using the trained neural network, an approximate solution of power flow can be obtained almost immediately. It is found that the accuracy of solutions is increased by one or two orders of magnitude, when feedback is incorporated in the neural network.

INTRODUCTION

Undoubtedly, the importance of power flow analysis in modern-day power system operation and planning is one of monumental proportions. It provides snapshots in time of the system behavior under both normal and abnormal conditions. Operators depend on it i) for performing security assessment under normal system operation and ii) for applying appropriate corrective strategies under emergency conditions.

A typical power system is modeled by a large set of non-linear equations which are normally solved by using any of the widely acclaimed power flow solution techniques viz., the Gauss-Seidel method, the Newton-Raphson method or the fast-decoupled method. Of these three, the fast-decoupled method provides the fastest solutions. However, all of these methods require significant computational effort and are therefore difficult to use in real time applications. This paper presents arguments that the conventional tedious approach to obtaining solutions of power flow by using numerical methods can be avoided by using simulated neural computing.

In the recent past several attempts have been made to investigate the suitability of artificial neural networks in power system applications [1-3]. All of the authors have reported relative success with their formulations. This paper presents a number of different configurations of the neural network and identifies a particular case which is most suitable for power flow analysis in real-time applications.

THE ONE LAYER NEURAL NETWORK

A one layer neural network is characterized by a layer of input neurons and a layer of output neurons interconnected to one another by weights to be determined by the training process. This process is illustrated in Fig. 1. It should be mentioned here that the weights applied to the interconnections of the neurons make significant differences in the accuracy of the predictions of the output desired. For large networks, the number of weights can become very large. We are working on an approach whereby we can eliminate some of the weights from consideration and still arrive at accurate results. This feature will be enumerated in a later paper.

![One layer neural network](Fig1.png)

For application to power flow, the power system is linearized and then modeled by one layer of the forward neural network as shown in Fig. 2. The input data are the real and reactive power generations and demands in the system, and the output data are the complex bus voltages.

Single layer neural network represents a linear system and it is obvious that results obtained for a nonlinear system such as a power system can not be accurate. One possible solution is to introduce additional input layers to generate second and higher order nonlinear terms. This approach however will result in significant increase of the size of a neural network and it will be impractical for large power systems to be analyzed.
ONE LAYER NEURAL NETWORK WITH NON-LINEAR FEEDBACK

A possible approach to increase accuracy is to use a feedback loop as shown in Fig. 3. Line power vector can be directly computed from bus voltages and line impedances. Using simple summation with complex arithmetic the input vector $\text{INF}$ (bus powers) can be obtained from line powers summation. At initial state, the vector of line powers $\text{SL}$ is zero and there is no feedback - $\text{INF}$ is zero. Therefore in the first step the input vector $\text{IN}$ is applied to the neural network and an approximate initial vector of bus voltages $\text{VB}$ is obtained. In the second step the difference between input vector $\text{IN}$ and feedback vector $\text{INF}$ is computed from line powers $\text{SL}$ and bus voltages $\text{VB}$. Therefore the neural network operates on the difference (error) and the vector of line powers is corrected.

Fig. 2. Linear Neural Network for Power Flow

Fig. 3. Neural Network With feedback for Power Flow Analysis

By adding the non-linear feedback, we can obtain significant improvement over the case with no feedback. Usually a few iterations are enough to obtain convergence as shown in the results section. The results are very much comparable with those from a rigorous mathematical analysis, but the computational effort is negligibly smaller in comparison.

Training of the Neural Network

For a given power system such a network can be trained using, for example the back propagation algorithm which is very slow and requires hundreds or thousands of iterations depending on the size of the system. However in this case, the projection algorithm based on the least squares approximation technique is found to be more efficient. Since an artificial neural network without hidden layers is used, the projection training algorithm is very stable and efficient.
For supervised training the exact solutions obtained from a conventional power flow program are used. The training procedure was verified on a modified six bus system [4] and the IEEE-24 bus test system[5]. Relevant data for the two systems pertinent to power flow are shown in the appendix. Training sets of 24 input and 24 output vectors were used for the 6-bus power system and 96 input and 96 output vectors were used for the 24-bus system. The input training data for the 6-bus system consists of the eight elements: real bus powers (real power generations minus the real power demands) at all buses except the slack bus and reactive power demands at all load buses. The 24 output vectors consist of the eight elements: bus voltage angles at all buses except the slack bus and voltage magnitudes at all load buses. These correspond to:

Input: \([P_2, P_3, P_4, P_5, Q_6, Q_4, Q_5, Q_6]\)

Output: \([\delta_2, \delta_3, \delta_4, \delta_5, \delta_6, IV_4, IV_5, IV_6]\)

After training is completed, the ANN is tested for validation. A set of new input test pattern is applied to the neural network. Table 1 shows the weights assigned for the interconnections between the inputs and the outputs. Table 2 shows the input test pattern to the ANN and Table 3 shows the corresponding output from the ANN. Comparisons of the performance of the ANN relative to a fast-decoupled solution for the 6-bus system can be made by inspection of Table 4.

### Table 1. Weights used for the 6-Bus System

<table>
<thead>
<tr>
<th>(P_2)</th>
<th>(P_3)</th>
<th>(P_4)</th>
<th>(Q_2)</th>
<th>(Q_3)</th>
<th>(Q_4)</th>
<th>(Q_5)</th>
<th>(Q_6)</th>
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<tr>
<td>0.400</td>
<td>0.600</td>
<td>0.700</td>
<td>0.400</td>
<td>0.500</td>
<td>0.200</td>
<td>0.100</td>
<td>0.010</td>
</tr>
<tr>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
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<td>1.000</td>
<td>1.000</td>
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</tr>
</tbody>
</table>

### Table 2. Input Test Pattern for the 6-Bus Case

<table>
<thead>
<tr>
<th>(d(1))</th>
<th>(d(2))</th>
<th>(d(3))</th>
<th>(d(4))</th>
<th>(d(5))</th>
<th>(d(6))</th>
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</thead>
<tbody>
<tr>
<td>0.000</td>
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<td>1.000</td>
<td>1.000</td>
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<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>1.000</td>
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<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
</tbody>
</table>

### Table 3. Output Test Pattern for the 6-Bus Case

<table>
<thead>
<tr>
<th>(V(1))</th>
<th>(V(2))</th>
<th>(V(3))</th>
<th>(V(4))</th>
<th>(V(5))</th>
<th>(V(6))</th>
</tr>
</thead>
<tbody>
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<td>1.000</td>
<td>1.000</td>
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<td>1.000</td>
<td>1.000</td>
</tr>
</tbody>
</table>

### RESULTS

Figures 4 and 5 show the 6-bus and 24-bus test systems respectively used in the analysis.
Table 5. Results From the ANN Without Feedback for the 24-Bus System

<table>
<thead>
<tr>
<th>Bus</th>
<th>slack</th>
<th>voltage (MVAR)</th>
<th>power generated (MW)</th>
<th>power demand (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUS 1</td>
<td>1.00000</td>
<td>0.00000</td>
<td>52.22</td>
<td>70.67</td>
</tr>
<tr>
<td>BUS 2</td>
<td>0.00000</td>
<td>-64.65</td>
<td>115.00</td>
<td>32.00</td>
</tr>
<tr>
<td>BUS 3</td>
<td>0.93111</td>
<td>0.3729</td>
<td>0.00</td>
<td>6.54</td>
</tr>
<tr>
<td>BUS 4</td>
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<td>0.0121</td>
<td>0.00</td>
<td>808.00</td>
</tr>
<tr>
<td>BUS 5</td>
<td>0.97315</td>
<td>-2.4885</td>
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<td>60.60</td>
</tr>
<tr>
<td>BUS 6</td>
<td>0.96663</td>
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<td>0.00</td>
<td>3.36</td>
</tr>
<tr>
<td>BUS 7</td>
<td>0.96600</td>
<td>1.0768</td>
<td>300.00</td>
<td>53.07</td>
</tr>
<tr>
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<td>0.0183</td>
<td>0.00</td>
<td>44.14</td>
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<tr>
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<td>0.94200</td>
<td>2.2245</td>
<td>284.00</td>
<td>53.07</td>
</tr>
<tr>
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<td>0.96685</td>
<td>-1.0000</td>
<td>0.00</td>
<td>3.29</td>
</tr>
<tr>
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<td>0.97516</td>
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<tr>
<td>BUS 12</td>
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<td>9.5677</td>
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</tr>
<tr>
<td>BUS 13</td>
<td>0.99000</td>
<td>14.6287</td>
<td>591.00</td>
<td>177.46</td>
</tr>
<tr>
<td>BUS 14</td>
<td>1.00000</td>
<td>10.7915</td>
<td>215.00</td>
<td>100.69</td>
</tr>
<tr>
<td>BUS 15</td>
<td>0.91000</td>
<td>0.3473</td>
<td>155.00</td>
<td>44.00</td>
</tr>
<tr>
<td>BUS 16</td>
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<td>21.7430</td>
<td>0.00</td>
<td>55.20</td>
</tr>
<tr>
<td>BUS 17</td>
<td>0.15100</td>
<td>29.1588</td>
<td>0.00</td>
<td>52.00</td>
</tr>
<tr>
<td>BUS 18</td>
<td>0.30736</td>
<td>17.3551</td>
<td>0.00</td>
<td>28.40</td>
</tr>
<tr>
<td>BUS 19</td>
<td>0.0825</td>
<td>19.3239</td>
<td>0.00</td>
<td>61.89</td>
</tr>
<tr>
<td>BUS 20</td>
<td>0.05000</td>
<td>20.0000</td>
<td>0.00</td>
<td>151.00</td>
</tr>
<tr>
<td>BUS 21</td>
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<td>29.6516</td>
<td>296.09</td>
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</tr>
<tr>
<td>BUS 22</td>
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<td>0.00</td>
<td>202.00</td>
</tr>
<tr>
<td>BUS 23</td>
<td>0.08753</td>
<td>12.0467</td>
<td>0.00</td>
<td>20.79</td>
</tr>
</tbody>
</table>

Table 6. Results From the ANN With Non-Linear Feedback for the 24-Bus System After One Iteration

<table>
<thead>
<tr>
<th>Bus</th>
<th>slack</th>
<th>voltage (MVAR)</th>
<th>power generated (MW)</th>
<th>power demand (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUS 1</td>
<td>1.00000</td>
<td>0.00000</td>
<td>52.22</td>
<td>70.67</td>
</tr>
<tr>
<td>BUS 2</td>
<td>0.00000</td>
<td>-64.65</td>
<td>115.00</td>
<td>32.00</td>
</tr>
<tr>
<td>BUS 3</td>
<td>0.95837</td>
<td>0.2835</td>
<td>0.00</td>
<td>208.00</td>
</tr>
<tr>
<td>BUS 4</td>
<td>0.96995</td>
<td>-2.4850</td>
<td>0.00</td>
<td>90.00</td>
</tr>
<tr>
<td>BUS 5</td>
<td>0.98891</td>
<td>-1.8256</td>
<td>0.00</td>
<td>85.00</td>
</tr>
<tr>
<td>BUS 6</td>
<td>0.92002</td>
<td>3.5738</td>
<td>300.00</td>
<td>53.07</td>
</tr>
<tr>
<td>BUS 7</td>
<td>0.96000</td>
<td>0.4733</td>
<td>300.00</td>
<td>37.07</td>
</tr>
<tr>
<td>BUS 8</td>
<td>0.96951</td>
<td>-5.5036</td>
<td>0.00</td>
<td>218.00</td>
</tr>
<tr>
<td>BUS 9</td>
<td>0.96624</td>
<td>-1.5048</td>
<td>0.00</td>
<td>252.00</td>
</tr>
<tr>
<td>BUS 10</td>
<td>0.96755</td>
<td>2.4898</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>BUS 11</td>
<td>0.98508</td>
<td>3.6233</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>BUS 12</td>
<td>0.99000</td>
<td>10.7915</td>
<td>591.00</td>
<td>126.97</td>
</tr>
<tr>
<td>BUS 13</td>
<td>0.94000</td>
<td>3.7334</td>
<td>0.00</td>
<td>88.03</td>
</tr>
<tr>
<td>BUS 14</td>
<td>0.91000</td>
<td>7.1286</td>
<td>215.00</td>
<td>100.51</td>
</tr>
<tr>
<td>BUS 15</td>
<td>0.10500</td>
<td>9.6873</td>
<td>387.89</td>
<td>84.52</td>
</tr>
<tr>
<td>BUS 16</td>
<td>0.04413</td>
<td>0.0720</td>
<td>0.00</td>
<td>212.00</td>
</tr>
<tr>
<td>BUS 17</td>
<td>0.00631</td>
<td>8.1231</td>
<td>386.42</td>
<td>70.09</td>
</tr>
<tr>
<td>BUS 18</td>
<td>0.02550</td>
<td>10.1649</td>
<td>386.42</td>
<td>170.04</td>
</tr>
<tr>
<td>BUS 19</td>
<td>0.01000</td>
<td>22.9786</td>
<td>296.09</td>
<td>81.94</td>
</tr>
<tr>
<td>BUS 20</td>
<td>0.00422</td>
<td>4.5016</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 7. Results From the ANN With Non-Linear Feedback for the 24-Bus System After Two Iterations

<table>
<thead>
<tr>
<th>Bus</th>
<th>slack</th>
<th>voltage (MVAR)</th>
<th>power generated (MW)</th>
<th>power demand (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUS 1</td>
<td>1.00000</td>
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<td>154.14</td>
<td>54.72</td>
</tr>
<tr>
<td>BUS 2</td>
<td>0.00000</td>
<td>-64.65</td>
<td>215.00</td>
<td>32.00</td>
</tr>
<tr>
<td>BUS 3</td>
<td>0.95837</td>
<td>-0.2835</td>
<td>0.00</td>
<td>208.00</td>
</tr>
<tr>
<td>BUS 4</td>
<td>0.96995</td>
<td>-2.4850</td>
<td>0.00</td>
<td>90.00</td>
</tr>
<tr>
<td>BUS 5</td>
<td>0.98891</td>
<td>-1.8256</td>
<td>0.00</td>
<td>85.00</td>
</tr>
<tr>
<td>BUS 6</td>
<td>0.92002</td>
<td>3.5738</td>
<td>300.00</td>
<td>53.07</td>
</tr>
<tr>
<td>BUS 7</td>
<td>0.96000</td>
<td>0.4733</td>
<td>300.00</td>
<td>37.07</td>
</tr>
<tr>
<td>BUS 8</td>
<td>0.96951</td>
<td>-5.5036</td>
<td>0.00</td>
<td>218.00</td>
</tr>
<tr>
<td>BUS 9</td>
<td>0.96624</td>
<td>-1.5048</td>
<td>0.00</td>
<td>252.00</td>
</tr>
<tr>
<td>BUS 10</td>
<td>0.96755</td>
<td>2.4898</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>BUS 11</td>
<td>0.98508</td>
<td>3.6233</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>BUS 12</td>
<td>0.99000</td>
<td>10.7915</td>
<td>591.00</td>
<td>126.97</td>
</tr>
<tr>
<td>BUS 13</td>
<td>0.94000</td>
<td>3.7334</td>
<td>0.00</td>
<td>88.03</td>
</tr>
<tr>
<td>BUS 14</td>
<td>0.91000</td>
<td>7.1286</td>
<td>215.00</td>
<td>100.51</td>
</tr>
<tr>
<td>BUS 15</td>
<td>0.10500</td>
<td>9.6873</td>
<td>387.89</td>
<td>84.52</td>
</tr>
<tr>
<td>BUS 16</td>
<td>0.04413</td>
<td>0.0720</td>
<td>0.00</td>
<td>212.00</td>
</tr>
<tr>
<td>BUS 17</td>
<td>0.00631</td>
<td>8.1231</td>
<td>386.42</td>
<td>70.09</td>
</tr>
<tr>
<td>BUS 18</td>
<td>0.02550</td>
<td>10.1649</td>
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<tr>
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<td>22.9786</td>
<td>296.09</td>
<td>81.94</td>
</tr>
<tr>
<td>BUS 20</td>
<td>0.00422</td>
<td>4.5016</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Table 8. Results From the Fast-Decoupled Power Flow for the 24-Bus System

<table>
<thead>
<tr>
<th>Bus</th>
<th>Slack</th>
<th>Voltage (P.U.)</th>
<th>Power Generated (MW)</th>
<th>Power Demand (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUS 1</td>
<td>slack</td>
<td>1.00000</td>
<td>0.00000</td>
<td>166.76</td>
</tr>
<tr>
<td>BUS 2</td>
<td>V1-cont</td>
<td>1.00000</td>
<td>-0.0173</td>
<td>152.00</td>
</tr>
<tr>
<td>BUS 3</td>
<td>load</td>
<td>0.95883</td>
<td>0.9876</td>
<td>0.00</td>
</tr>
<tr>
<td>BUS 4</td>
<td>load</td>
<td>0.97041</td>
<td>-1.0383</td>
<td>0.00</td>
</tr>
<tr>
<td>BUS 5</td>
<td>load</td>
<td>0.98914</td>
<td>-1.3155</td>
<td>0.00</td>
</tr>
<tr>
<td>BUS 6</td>
<td>load</td>
<td>1.00972</td>
<td>-2.4625</td>
<td>0.00</td>
</tr>
<tr>
<td>BUS 7</td>
<td>V1-cont</td>
<td>0.96000</td>
<td>1.4815</td>
<td>300.00</td>
</tr>
<tr>
<td>BUS 8</td>
<td>load</td>
<td>0.95207</td>
<td>-0.9556</td>
<td>0.00</td>
</tr>
<tr>
<td>BUS 9</td>
<td>load</td>
<td>0.95097</td>
<td>0.7806</td>
<td>0.00</td>
</tr>
<tr>
<td>BUS 10</td>
<td>load</td>
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<tr>
<td>BUS 11</td>
<td>load</td>
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<td>0.00</td>
</tr>
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<td>0.00</td>
</tr>
<tr>
<td>BUS 13</td>
<td>V1-cont</td>
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<td>7.5685</td>
<td>591.00</td>
</tr>
<tr>
<td>BUS 14</td>
<td>V1-cont</td>
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<td>0.00</td>
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<tr>
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CONCLUSION

The advantage of fast analog computing is taken for power system analyses. Such analog neural network with single layer performs linear operation and therefore limited accuracy can be obtained for a nonlinear system such as a power system. To increase accuracy, the nonlinear feedback to evaluate an error can be applied. Although the method was applied to a power system only, it is obvious that the approach is quite general and can be used for fast analysis of any other nonlinear system.

It should be noted that in order to obtain an fast approximate solution using neural net (without nonlinear feedback) no information about power system parameters is required such as line impedances, transformer tap ratios etc. The neural network can be trained using operating data such as bus powers and bus voltages. This approximate solution should be adequate for security assessment and for taking proper control decisions.

REFERENCE

# APPENDIX

The power flow data for the 6-bus test system follows:

<table>
<thead>
<tr>
<th>BUS DATA</th>
<th>voltage [PU]</th>
<th>power gen. [MW]</th>
<th>power dem. [MVAR]</th>
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<th>B</th>
<th>MVA Rat.</th>
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The power flow data for the IEEE-24 bus test system follows:

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<th>B</th>
<th>MVA Rat.</th>
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Third Workshop on

Neural Networks:
Academic/Industrial/NASA/Defense

WN 92

10-12 February 1992
Auburn University, Alabama

4-6 November 1992
South Shore Harbour, Texas

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Center for Commercial Development of Space Power and Advanced Electronics
NASA Headquarters

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INNS — The International Neural Networks Society
INNSIGS: Electronics/VLSI, Expert Networks and Standards

Participating
IEEE Neural Networks Council