REAL-TIME POWER SYSTEM ANALYSIS USING NEURAL COMPUTING

Badrul H. Chowdhury and Bogdan M. Wilamowski
Department of Electrical Engineering
University of Wyoming
Laramie, WY 82071-3295

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 inter-connections 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.

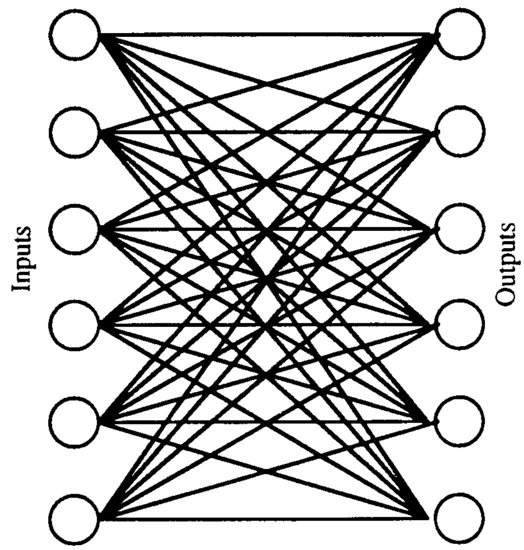

Fig.1. One layer neural network

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 inpractical for large power systems to be analyzed.

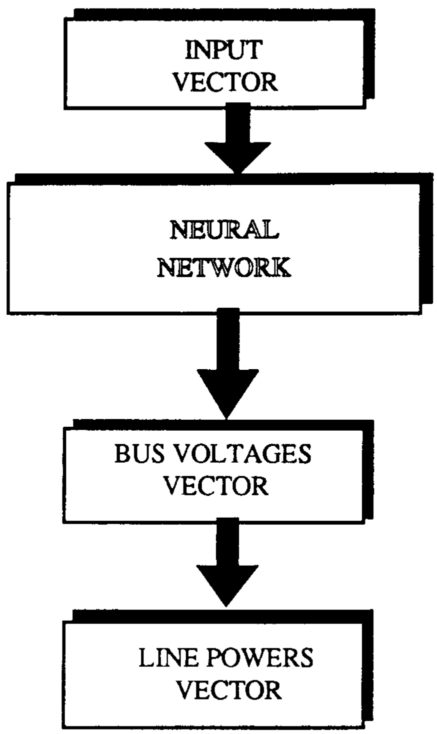

Fig. 2. Linear Neural Network for Power Flow

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 van be directly computed from bus voltages and line impedances. Using simple summation with complex arithmetic the input vector INF (bus powers) can be obtained from line powers summation. At initial state, the vector of line powers SL is zero and there is no feedback - INF is zero. Therefore in the first step the input vector IN is applied to the neural network and an approximate initial vector of bus voltages VB is obtained. In the second step the difference between input vector IN and feedback vector INF is computed from line powers SL and bus voltages VB. Therefore the neural network operates on the difference (error) and the vector of line powers is corrected.

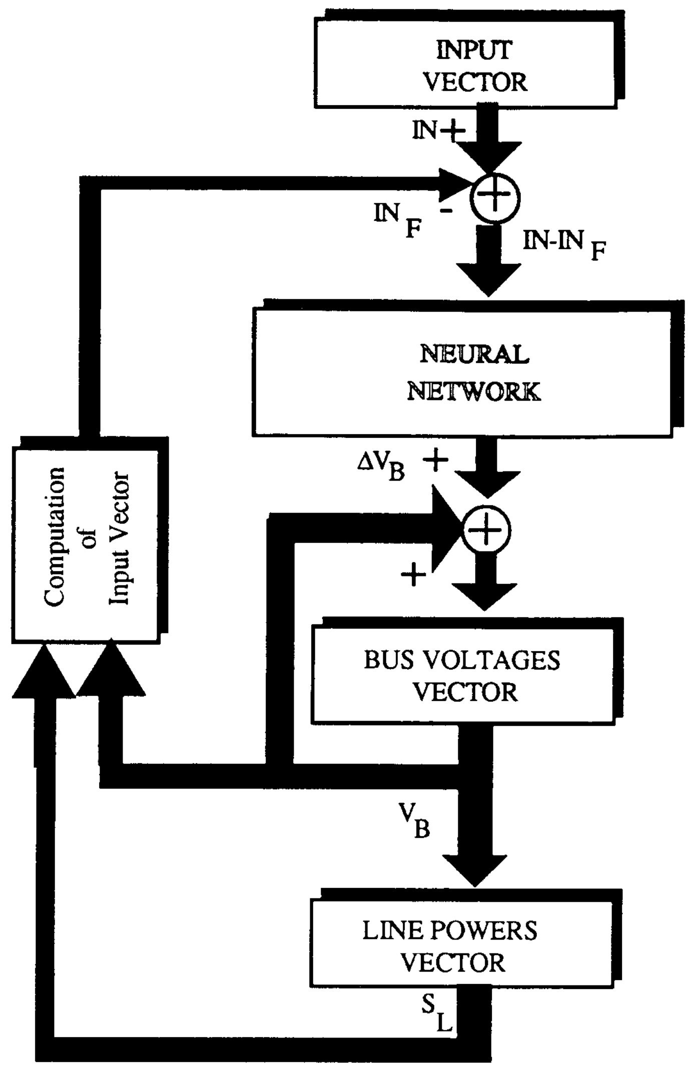

Fig. 3. Neural Network With feedback for Power Flow Analysis

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 is 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: $\{P_2, P_3, P_4, P_5, P_6, Q_{D4}, Q_{D5}, Q_{D6}\}$

Output: $\{\delta_2, \delta_3, \delta_4, \delta_5, \delta_6, |V_4|, |V_5|, |V_6|\}$

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

4.8867	4.8823	3.1830	3.2727	4.3089	-0.1235	-0.1132	-0.1162
4.6942	10.1787	3.0244	5.0325	7.4330	-0.1525	-0.1354	-0.1392
2.8420	3.3386	5.1587	2.4526	2.7060	-0.1232	-0.1298	-0.1315
4.0310	5.4700	2.8121	6.6296	4.8254	-0.1778	-0.1322	-0.1459
4.4969	7.7150	3.0953	4.8059	9.0533	-0.1427	-0.1179	-0.1095
3.6221	1.4848	0.4292	1.7440	2.0758	0.0797	0.0552	0.0439
-0.9412	0.3079	-0.1081	-0.9174	-0.1920	0.1092	0.1390	0.0736
-1.3122	-0.5091	-0.3247	-0.7995	-1.0491	0.0907	0.0735	0.1235
-1.6521	-2.1752	-2.5548	-0.8224	-2.7617	1.0349	1.0378	1.0286

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

P(2),	P(3),	P(4),	P(5),	P(6),	Q(4),	Q(5),	Q(6),
0.400	0.600	-0.700	-0.700	-0.700	-0.700	-0.700	-0.700
0.200	0.433	-0.233	-0.147	-0.324	-0.064	-0.064	-0.049
0.467	0.349	-0.566	-0.076	-0.260	-0.147	-0.017	-0.096
0.556	0.588	-0.579	-0.177	-0.512	-0.206	-0.069	-0.213
0.325	0.492	-0.185	-0.097	-0.619	-0.045	-0.030	-0.154
0.108	0.253	-0.125	-0.109	-0.167	-0.028	-0.037	-0.057
1.063	0.552	-0.431	-0.652	-0.699	-0.175	-0.306	-0.145
0.417	0.952	-0.592	-0.302	-0.621	-0.123	-0.118	-0.155
0.574	0.661	-0.230	-0.584	-0.551	-0.044	-0.203	-0.206
0.455	0.806	-0.665	-0.509	-0.216	-0.315	-0.104	-0.064
0.859	0.592	-0.477	-0.591	-0.533	-0.131	-0.213	-0.174
0.703	0.458	-0.591	-0.485	-0.206	-0.286	-0.236	-0.088
0.601	0.905	-0.640	-0.557	-0.466	-0.312	-0.241	-0.138
0.479	0.346	-0.237	-0.344	-0.332	-0.070	-0.121	-0.114
0.356	0.592	-0.164	-0.425	-0.457	-0.039	-0.070	-0.132
0.882	0.782	-0.693	-0.685	-0.459	-0.333	-0.218	-0.119
0.289	0.324	-0.272	-0.202	-0.210	-0.106	-0.093	-0.068
0.422	0.740	-0.593	-0.589	-0.098	-0.194	-0.262	-0.026
0.579	0.757	-0.484	-0.361	-0.633	-0.130	-0.099	-0.224
0.451	0.482	-0.400	-0.429	-0.201	-0.128	-0.112	-0.089
0.207	0.565	-0.578	-0.120	-0.160	-0.184	-0.052	-0.034
0.427	0.576	-0.148	-0.650	-0.315	-0.063	-0.099	-0.106
0.450	0.658	-0.417	-0.513	-0.293	-0.106	-0.239	-0.108
0.498	0.366	-0.097	-0.321	-0.538	-0.020	-0.103	-0.109

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

d(2),	d(3),	d(4),	d(5),	d(6),	V(4),	V(5),	V(6),
-5.798	-6.580	-7.211	-6.234	-8.772	1.009	0.990	1.001
-1.461	-0.963	-3.232	-1.106	-3.024	1.029	1.028	1.019
-1.206	-0.829	-3.981	-0.843	-2.609	1.022	1.034	1.020
-1.238	-0.546	-4.088	-1.223	-3.242	1.009	1.018	1.000
-1.387	-1.502	-3.142	-1.282	-4.203	1.027	1.026	1.005
-1.474	-1.399	-2.904	-0.997	-2.783	1.030	1.031	1.020
-1.018	-2.045	-3.717	-3.213	-4.871	1.028	1.005	1.009
-0.969	0.991	-4.163	-1.088	-2.640	1.017	1.017	1.004
-0.928	-0.881	-3.193	-2.427	-3.640	1.030	1.010	1.003
-1.517	1.112	-4.303	-1.723	-1.588	1.017	1.020	1.020
-0.856	-1.064	-3.779	-2.575	-3.676	1.029	1.014	1.011
-1.326	-0.749	-4.051	-2.084	-2.589	1.010	1.006	1.013
-1.349	0.725	-4.278	-2.016	-2.540	1.003	0.998	1.001
-1.230	-1.632	-3.181	-1.891	-3.435	1.032	1.023	1.016
-1.270	-0.822	-3.053	-1.992	-3.388	1.039	1.027	1.015
-1.311	-0.012	-4.385	-2.733	-3.009	1.018	1.009	1.013
-1.458	-1.251	-3.290	-1.307	-2.851	1.024	1.024	1.018
-1.038	1.104	-4.039	-1.625	-1.102	1.015	1.007	1.020
-1.030	-0.227	-3.866	-1.697	-3.438	1.021	1.018	1.001
-1.197	-0.479	-3.567	-1.761	-2.359	1.029	1.025	1.021
-1.407	0.494	-4.064	-0.530	-1.598	1.015	1.028	1.021
-1.315	-0.777	-3.002	-2.647	-3.030	1.048	1.029	1.025
-0.952	0.085	-3.618	-1.749	-2.249	1.019	1.007	1.011
-1.322	-2.255	-2.893	-2.156	-4.485	1.041	1.027	1.016

Table 4. Output from a Fast-Decoupled Power Flow for the 6-Bus Case

d(2),	d(3),	d(4),	d(5),	d(6),	V(4),	V(5),	V(6),
-5.812	-6.589	-7.215	-6.242	-8.781	1.009	0.990	1.001
-1.295	-0.958	-3.162	-1.041	-2.966	1.032	1.034	1.025
-1.509	-0.822	-4.046	-0.936	-2.672	1.035	1.042	1.026
-1.283	-0.430	-4.145	-1.226	-3.229	0.996	1.002	0.983
-2.305	-1.818	-3.411	-1.674	-4.630	1.039	1.029	1.010
-1.288	-1.533	-2.860	-1.004	-2.829	1.023	1.029	1.021
-1.286	-2.406	-3.829	-3.450	-5.184	1.018	0.997	1.006
-0.413	1.063	-4.009	-0.880	-2.453	1.010	1.018	1.006
-0.552	-0.470	-3.055	-2.153	-3.281	1.037	1.015	1.003
-1.700	0.762	-4.378	-1.910	-1.855	1.013	1.019	1.023
-1.211	-1.200	-3.889	-2.738	-3.855	1.029	1.011	1.009
-1.114	-0.838	-3.967	-1.997	-2.551	1.019	1.020	1.029
-1.636	0.749	-4.358	-2.109	-2.603	1.010	1.000	1.001
-0.678	-1.691	-3.031	-1.743	-3.330	1.023	1.025	1.021
-1.808	-1.353	-3.228	-2.360	-3.859	1.034	1.024	1.019
-0.742	0.459	-4.190	-2.394	-2.569	1.016	1.008	1.007
-1.096	-1.005	-3.176	-1.112	-2.606	1.016	1.017	1.009
-1.388	1.050	-4.137	-1.741	-1.230	1.023	1.010	1.022
-0.689	-0.290	-3.727	-1.578	-3.346	1.027	1.030	1.015
-1.751	-0.735	-3.748	-2.032	-2.670	1.032	1.023	1.022
-1.206	0.796	-4.008	-0.364	-1.363	1.011	1.022	1.012
-1.175	-0.538	-2.962	-2.516	-2.851	1.048	1.027	1.020
-1.136	0.024	-3.687	-1.856	-2.342	1.012	0.999	1.004
-0.985	-1.728	-2.781	-1.843	-4.067	1.048	1.030	1.012

RESULTS

Figures 4 and 5 show the 6-bus and 24-bus test systems respectively used in the analysis.

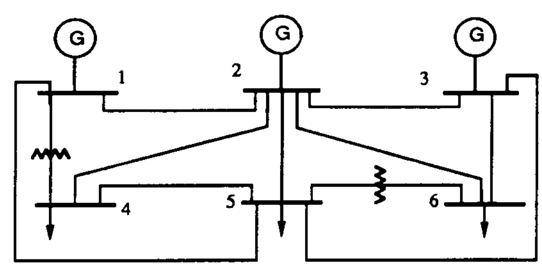

Fig. 4. The 6-Bus Test System

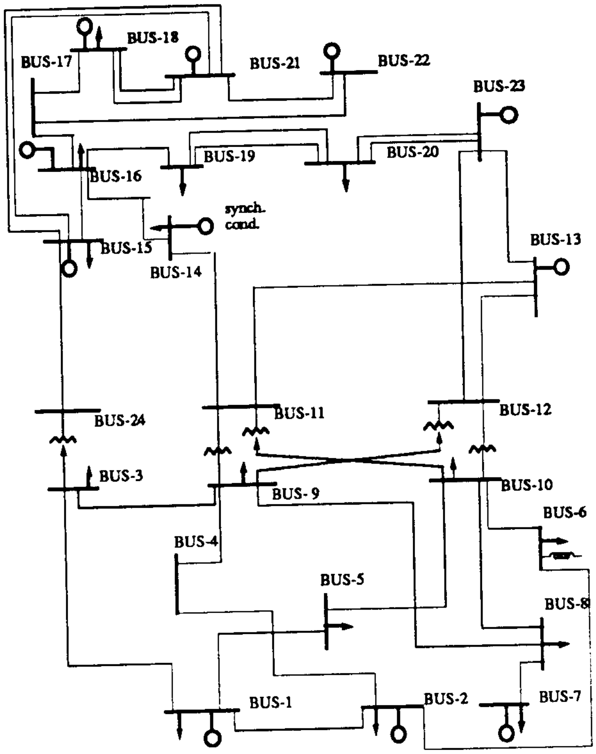

Fig. 5. The 24-Bus Test System

Table 5 shows results of using the one-layer neural network without the feedback for predicting power flow results for the 24-bus test system. The table shows bus voltage magnitudes and angles and real and reactive power generations after the first iteration. Before the next iteration, a non-linear feedback as mentioned in an earlier section, is employed and results after the first iteration following the application of the feedback are shown in Table 6. The instant increase in accuracy due to the feedback is obvious from the data. Table 7 shows the same after the second iteration following feedback. This table should be compared with Table 8 which shows results of applying the fast-decoupled method on the test system. It can be observed from these tables that the ANN solution approaches the numerically found accurate values within only two iterations.

Table 5. Results From the ANN Without Feedback for the 24-Bus System

	type	voltage [P.U.]	voltage [deg]	power generated [MW]	power generated [MVAR]	power demand [MW]	power demand [MVAR]
BUS 1	slack	1.00000	0.0000	52.22	70.67	115.00	32.00
BUS 2	|V|-cont	1.00000	-0.0039	192.00	64.05	117.00	35.00
BUS 3	load	0.93111	1.5279	0.00	6.54	208.00	38.00
BUS 4	load	0.94321	-2.3291	0.00	5.01	90.00	23.00
BUS 5	load	0.97315	-2.4885	0.00	20.60	85.00	22.00
BUS 6	load	0.96663	-5.0386	0.00	3.16	151.00	35.00
BUS 7	|V|-cont	0.96000	1.6768	300.00	53.07	155.00	45.00
BUS 8	load	0.93704	-3.1830	0.00	44.14	202.00	45.00
BUS 9	load	0.94240	1.2245	0.00	1.08	218.00	52.00
BUS 10	load	0.96485	-1.0000	0.00	3.29	250.00	65.00
BUS 11	load	0.97516	8.5366	0.00	36.58	0.00	0.00
BUS 12	load	0.96463	9.9677	0.00	28.54	0.00	0.00
BUS 13	|V|-cont	0.99000	14.8287	591.00	117.46	305.00	74.00
BUS 14	|V|-cont	1.00000	10.7915	0.00	126.67	215.00	49.00
BUS 15	|V|-cont	1.01000	18.2637	215.00	100.69	349.00	78.00
BUS 16	|V|-cont	1.01000	17.7543	155.00	77.13	128.00	38.00
BUS 17	load	1.01897	21.7430	0.00	55.20	0.00	0.00
BUS 18	|V|-cont	1.01500	22.8606	387.89	-27.39	380.00	79.00
BUS 19	load	1.00376	17.3551	0.00	28.40	212.00	53.00
BUS 20	load	1.00825	19.3239	0.00	61.89	145.00	36.00
BUS 21	|V|-cont	1.02500	23.8085	386.42	78.47	0.00	0.00
BUS 22	|V|-cont	1.04500	29.6516	296.09	30.94	0.00	0.00
BUS 23	|V|-cont	1.01000	21.2384	660.00	23.71	0.00	0.00
BUS 24	load	0.98753	12.0867	0.00	20.79	0.00	0.00

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

	type	voltage [P.U.]	voltage [deg]	power generated [MW]	power generated [MVAR]	power demand [MW]	power demand [MVAR]
BUS 1	slack	1.00000	0.0000	254.14	40.72	115.00	32.00
BUS 2	|V|-cont	1.00000	-0.1558	192.00	26.83	117.00	35.00
BUS 3	load	0.95837	-0.2835	0.00	0.00	208.00	38.00
BUS 4	load	0.96995	-1.8450	0.00	0.00	90.00	23.00
BUS 5	load	0.98891	-1.8256	0.00	0.00	85.00	22.00
BUS 6	load	1.00920	-3.5718	0.00	0.00	151.00	35.00
BUS 7	|V|-cont	0.96000	0.4373	300.00	37.07	155.00	45.00
BUS 8	load	0.95182	-2.3122	0.00	0.00	202.00	45.00
BUS 9	load	0.96951	-0.5304	0.00	0.00	218.00	52.00
BUS 10	load	0.99624	-1.5948	0.00	0.00	250.00	65.00
BUS 11	load	0.98755	2.7948	0.00	0.00	0.00	0.00
BUS 12	load	0.98508	3.6223	0.00	0.00	0.00	0.00
BUS 13	|V|-cont	0.99000	6.1452	591.00	18.95	305.00	74.00
BUS 14	|V|-cont	1.00000	3.7534	0.00	88.03	215.00	49.00
BUS 15	|V|-cont	1.01000	7.3503	215.00	-2.25	349.00	78.00
BUS 16	|V|-cont	1.01000	7.1286	155.00	104.51	128.00	38.00
BUS 17	load	1.01559	9.0756	0.00	0.00	0.00	0.00
BUS 18	|V|-cont	1.01500	9.6873	387.89	-84.52	380.00	79.00
BUS 19	load	1.00413	7.0270	0.00	0.00	212.00	53.00
BUS 20	load	1.00631	8.1231	0.00	0.00	145.00	36.00
BUS 21	|V|-cont	1.02500	10.1649	386.42	170.04	0.00	0.00
BUS 22	|V|-cont	1.04500	12.9786	296.09	81.94	0.00	0.00
BUS 23	|V|-cont	1.01000	9.2032	660.00	78.28	0.00	0.00
BUS 24	load	1.00422	4.5016	0.00	0.00	0.00	0.00

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

	type	voltage [P.U.]	voltage [deg]	power generated [MW]	power generated [MVAR]	power demand [MW]	power demand [MVAR]
BUS 1	slack	1.00000	0.0000	194.31	51.59	115.00	32.00
BUS 2	|V|-cont	1.00000	-0.0627	192.00	25.88	117.00	35.00
BUS 3	load	0.95868	0.5812	0.00	0.00	208.00	38.00
BUS 4	load	0.97035	-1.2976	0.00	0.00	90.00	23.00
BUS 5	load	0.98903	-1.4075	0.00	0.00	85.00	22.00
BUS 6	load	1.00951	-2.9111	0.00	0.00	151.00	35.00
BUS 7	|V|-cont	0.96000	1.4201	300.00	35.76	155.00	45.00
BUS 8	load	0.95199	-1.3848	0.00	0.00	202.00	45.00
BUS 9	load	0.96985	0.3613	0.00	0.00	218.00	52.00
BUS 10	load	0.99652	-0.8065	0.00	0.00	250.00	65.00
BUS 11	load	0.98731	3.8174	0.00	0.00	0.00	0.00
BUS 12	load	0.98486	4.5582	0.00	0.00	0.00	0.00
BUS 13	|V|-cont	0.99000	7.1105	591.00	20.08	305.00	74.00
BUS 14	|V|-cont	1.00000	4.9288	0.00	88.54	215.00	49.00
BUS 15	|V|-cont	1.01000	8.6599	215.00	-4.82	349.00	78.00
BUS 16	|V|-cont	1.01000	8.4001	155.00	100.26	128.00	38.00
BUS 17	load	1.01562	10.3777	0.00	0.00	0.00	0.00
BUS 18	|V|-cont	1.01500	10.9673	387.89	-90.48	380.00	79.00
BUS 19	load	[illegible].00419	8.2201	0.00	0.00	212.00	53.00
BUS 20	load	[illegible]00635	9.2323	0.00	0.00	145.00	36.00
BUS 21	|V|-con[illegible]	[illegible]02500	11.4018	386.42	165.48	0.00	0.00
BUS 22	|V|-cont	[illegible]04500	14.1829	296.09	81.30	0.00	0.00
BUS 23	|V|-cont	1.01000	10.2304	660.00	75.71	0.00	0.00
BUS 24	load	1.00386	5.5917	0.00	0.00	0.00	0.00

Table 8. Results From the Fast-Decoupled Power Flow for the 24-Bus System

	type	voltage [P.U.]	[deg]	power generated [MW]	[MVAR]	power demand [MW]	[MVAR]
BUS 1	slack	1.00000	0.0000	166.76	57.24	115.00	32.00
BUS 2	|V|-cont	1.00000	-0.0173	192.00	25.81	117.00	35.00
BUS 3	load	0.95883	0.9976	0.00	0.00	208.00	38.00
BUS 4	load	0.97041	-1.0363	0.00	0.00	90.00	23.00
BUS 5	load	0.98914	-1.2155	0.00	0.00	85.00	22.00
BUS 6	load	1.00972	-2.6025	0.00	0.00	151.00	35.00
BUS 7	|V|-cont	0.96000	1.8815	300.00	35.12	155.00	45.00
BUS 8	load	0.95207	-0.9556	0.00	0.00	202.00	45.00
BUS 9	load	0.96997	0.7806	0.00	0.00	218.00	52.00
BUS 10	load	0.99671	-0.4394	0.00	0.00	250.00	65.00
BUS 11	load	0.98721	4.3018	0.00	0.00	0.00	0.00
BUS 12	load	0.98477	5.0025	0.00	0.00	0.00	0.00
BUS 13	|V|-cont	0.99000	7.5685	591.00	20.52	305.00	74.00
BUS 14	|V|-cont	1.00000	5.4819	0.00	88.65	215.00	49.00
BUS 15	|V|-cont	1.01000	9.2781	215.00	-6.27	349.00	78.00
BUS 16	|V|-cont	1.01000	8.9984	155.00	97.81	128.00	38.00
BUS 17	load	1.01561	10.9951	0.00	0.00	0.00	0.00
BUS 18	|V|-cont	1.01500	11.5735	387.89	-93.03	380.00	79.00
BUS 19	load	1.00420	8.7829	0.00	0.00	212.00	53.00
BUS 20	load	1.00635	9.7558	0.00	0.00	145.00	36.00
BUS 21	|V|-cont	1.02500	11.9861	386.42	163.28	0.00	0.00
BUS 22	|V|-cont	1.04500	14.7520	296.09	81.04	0.00	0.00
BUS 23	|V|-cont	1.01000	10.7158	660.00	74.61	0.00	0.00
BUS 24	load	1.00369	6.1056	0.00	0.00	0.00	0.00

It was felt that a good indicator of relative speeds of solution would be the time it took for solutions to sonverge for both the ANN and the conventional methods viz., the Gauss-seidel and the fast-decoupled methods. Fig. 6 shows a comparison of these factors. Two cases for the fast-decoupled method are shown in the figures. These are:

FD-I: Solution by the fast decoupled method with the Jacobian matrix already calculated and inverted.

FD-II: Solution by the fast decoupled method before the Jacobian matrix has been calculated and inverted.

The time shown is that on an "80286" IBM-compatible machine running at 12 MHz. From the figure it is obvious that the Gauss-Seidel method is not appropriate for real-time applications. The ANN solutions compare very well with the fast-decoupled method. In fact, the ANN solution approaches the actual solution faster. However, no significant improvement in the iteration errors are observed in the ANN case after the initial iterations.

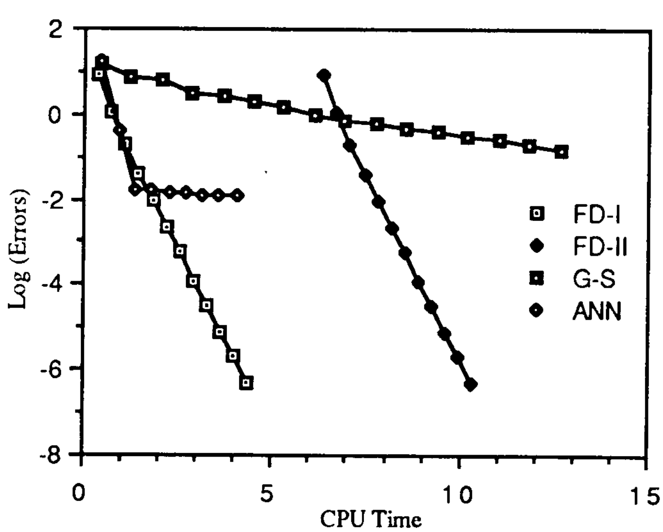

Fig. 6. Comparison of Errors Vs. CPU Time on "80286" IBM Machine at 12 MHz.

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

1. Chowdhury, B.H. and B. M. Wilamowski, 1991. "Security Assessment using neural computing." In *Proceeding of First Intern. Forum on Application of Neural Networks to Power Systems*, (Seattle July 23-26), 54-58.

2. Sobajic, D.J. and Y. H. Pao, 1989. "Artificial Neural Net Based Dynamic Security Assessment for Electric Power Systems," *IEEE Transaction on Power Systems*, Vol. 4: 220-228.

3. Sobajic, D.J.; Y. H. Pao; W. Njo; and J. Dolce, 1990. "Real-time Security Monitoring of Electric Power Systems," *In Proc of the 1990 ISCAS*, vol 3. (New Orleans, LA, May), 2929-2932.

4. Wood, A.J. and B. F. Wollenberg, 1984. *Power Generation, Operation and Control.* John Wiley & Sons, Inc.

5. IEEE Committee Report, 1979. "IEEE Reliability Test System", *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-98(3): 2047-2054.

APPENDIX

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

BUS DATA

		voltage [PU]	[deg]	power gen. [MW]	[MVAR]	power dem. [MW]	[MVAR]
BUS- 1	slack	1.05	0.0	0.0	0.0	0.0	0.0
BUS- 2	|V|-cont	1.05	0.0	50.0	54.4	10.0	12.0
BUS- 3	load	1.07	0.0	60.0	0.0	0.0	0.0
BUS- 4	load	1.0	0.0	0.0	0.0	70.0	70.0
BUS- 5	load	1.0	0.0	0.0	0.0	70.0	70.0
BUS- 6	load	1.0	0.0	0.0	0.0	70.0	70.0

LINE DATA

	from	to	R	X	B	MVA Rat.	
1	BUS- 1	BUS- 2	.100	.200	.040	175.0	1
3	BUS- 1	BUS- 5	.080	.300	.060	175.0	1
4	BUS- 2	BUS- 3	.050	.250	.060	175.0	1
5	BUS- 2	BUS- 4	.050	.100	.020	175.0	1
6	BUS- 2	BUS- 5	.100	.300	.040	175.0	1
7	BUS- 2	BUS- 6	.070	.200	.050	175.0	1
8	BUS- 3	BUS- 5	.120	.260	.050	175.0	1
9	BUS- 3	BUS- 6	.020	.100	.020	175.0	1
10	BUS- 4	BUS- 5	.200	.400	.080	175.0	1

TRANSFORMER DATA

	from	to	tap	phase	X	MVA Rat.	
2	BUS- 1	BUS- 4	0.95	4.00000	.200	175.0	2
11	BUS- 5	BUS- 6	1.00	5.00000	.300	175.0	2

The power flow data for the IEEE-24 bus test system follows:

BUS DATA

		voltage [PU]	[deg]	power gen. [MW]	[MVAR]	power dem. [MW]	[MVAR]
BUS- 1	slack	1.0	0.0	185.91	97.28	115.0	32.0
BUS- 2	|V|-cont	1.0	0.0	192.0	-14.91	117.0	35.0
BUS- 3	load	1.0	0.0	0.0	0.0	208.0	38.0
BUS- 4	load	1.0	0.0	0.0	0.0	90.0	23.0
BUS- 5	load	1.0	0.0	0.0	0.0	85.0	22.0
BUS- 6	load	1.0	0.0	0.0	0.0	151.0	35.0
BUS- 7	|V|-cont	0.96	0.0	300.0	0.0	155.0	45.0
BUS- 8	load	1.0	0.0	0.0	0.0	202.0	45.0
BUS- 9	load	1.0	0.0	0.0	0.0	218.0	52.0
BUS-10	load	1.0	0.0	0.0	0.0	250.0	65.0
BUS-11	load	1.0	0.0	0.0	0.0	0.0	0.0
BUS-12	load	1.0	0.0	0.0	0.0	0.0	0.0
BUS-13	|V|-cont	0.99	0.0	591.0	0.0	305.0	74.0
BUS-14	|V|-cont	1.0	0.0	0.0	0.0	215.0	49.0
BUS-15	|V|-cont	1.010	0.0	215.0	0.0	349.0	78.0
BUS-16	|V|-cont	1.010	0.0	155.0	0.0	128.0	38.0
BUS-17	load	1.0	0.0	0.0	0.0	0.0	0.0
BUS-18	|V|-cont	1.015	0.0	387.89	0.0	380.0	79.0
BUS-19	load	1.0	0.0	0.0	0.0	212.0	53.0
BUS-20	load	1.0	0.0	0.0	0.0	145.0	36.0
BUS-21	|V|-cont	1.025	0.0	386.42	0.0	0.0	0.0
BUS-22	|V|-cont	1.045	0.0	296.09	0.0	0.0	0.0
BUS-23	|V|-cont	1.01	0.0	660.0	0.0	0.0	0.0
BUS-24	load	1.0	0.0	0.0	0.0	0.0	0.0

LINE DATA

	from	to	R	X	B	MVA Rat.
1	BUS- 1	BUS- 2	.0026	.0139	.23055	140.0
2	BUS- 1	BUS- 3	.0546	.2112	.02860	140.0
3	BUS- 1	BUS- 5	.0218	.0845	.01145	140.0
4	BUS- 2	BUS- 4	.0328	.1267	.01715	140.0
5	BUS- 2	BUS- 6	.0497	.1920	.02600	140.0
6	BUS- 3	BUS- 9	.0308	.1190	.01610	140.0
8	BUS- 4	BUS- 9	.0268	.1037	.01405	140.0
9	BUS- 5	BUS-10	.0228	.0883	.01195	140.0
10	BUS- 6	BUS-10	.0139	.0605	1.2295	140.0
11	BUS- 7	BUS- 8	.0159	.0614	.00830	140.0
12	BUS- 8	BUS- 9	.0427	.1651	.02235	140.0
13	BUS- 8	BUS-10	.0427	.1651	.02235	140.0
18	BUS-11	BUS-13	.0061	.0476	.04995	240.0
19	BUS-11	BUS-14	.0054	.0418	.04395	240.0
20	BUS-12	BUS-13	.0061	.0476	.04995	240.0
21	BUS-12	BUS-23	.0124	.0966	.10150	240.0
22	BUS-13	BUS-23	.0111	.0865	.09090	240.0
23	BUS-14	BUS-16	.0050	.0389	.04090	240.0
24	BUS-15	BUS-16	.0022	.0173	.01820	240.0
25	BUS-15	BUS-21	.0063	.0490	.05150	240.0
26	BUS-15	BUS-21	.0063	.0490	.05150	240.0
27	BUS-15	BUS-24	.0067	.0519	.05455	240.0
28	BUS-16	BUS-17	.0033	.0259	.02725	240.0
29	BUS-16	BUS-19	.0030	.0231	.01155	240.0
30	BUS-17	BUS-18	.0018	.0144	.01515	240.0
31	BUS-17	BUS-22	.0135	.1053	.01106	240.0
32	BUS-18	BUS-21	.0033	.0259	.02725	240.0
33	BUS-18	BUS-21	.0033	.0259	.02725	240.0
34	BUS-19	BUS-20	.0051	.0396	.04165	240.0
35	BUS-19	BUS-20	.0051	.0396	.04165	240.0
36	BUS-20	BUS-23	.0028	.0216	.02275	240.0
37	BUS-20	BUS-23	.0028	.0216	.02275	240.0
38	BUS-21	BUS-22	.0087	.0678	.07120	240.0

TRANSFORMER DATA

	from	to	tap	phase	X	MVA Rat.
7	BUS- 3	BUS-24	0.95	0.00000	.0839	400.0
14	BUS- 9	BUS-11	1.00	0.00000	.0839	400.0
15	BUS- 9	BUS-12	1.00	0.00000	.0839	400.0
16	BUS-10	BUS-11	1.00	0.00000	.0839	400.0
17	BUS-10	BUS-12	1.00	0.00000	.0839	400.0

PROCEEDINGS

Third Workshop on

Neural Networks:
Academic/Industrial/NASA/Defense

WNN 92

10-12 February 1992
Auburn University, Alabama

4-6 November 1992
South Shore Harbour, Texas

Cosponsored by
Auburn University Space Power Institute
Center for Commercial Development of Space Power and Advanced Electronics
NASA Headquarters

In cooperation with
SCS — The Society for Computer Simulation
SPIE — The International Society for Optical Engineering
INNS — The International Neural Networks Society
INNSIGS: Electronics / VLSI, Expert Networks and Standards

Participating
IEEE Neural Networks Council

NASA HEADQUARTERS COSPONSORED

SCS