Optimal Operation of Electric Hybrid WES/BS/DG System By Neural Network

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Abstract

The performance of the Hybrid Wind Energy System/Battery storage/Diesel Generator can be improved through an application of advanced control method. This paper introduces an application of Artificial Neural Network on the operation control of the Wind/Battery/Diesel Hybrid Power Generation System to reduce the fuel consumption. It is generally agreed that using local information such as generated power from Wind Turbine Generator and state of charge for batteries are calculated by new software under known wind speed and load demand. The computer software, which proposed here and applied to carry out these calculations, is based on the minimization of the fuel consumption by diesel generator. Different Feed Forward Neural Network architectures are trained and tested with data containing a variety of operation patterns. The back propagation technique with sigmoid transfer function is used as the training algorithm. A simulation is carried out over one year using the hourly data of the load demand, wind speed at Zafarana site, Egypt. The results show that the selected neural network architecture gives reasonably accurate operation of the system.

Keywords: Wind-Diesel power system, neural networks.

1 INTRODUCTION

Many isolated areas in Egypt are supplied electrical power mainly by diesel generator. However, diesel generator has some problems, e.g. bad maintainability, unreliable fuel supply and high generation cost [1], [2]. Many alternative energy sources have been considered for the solution of that problem. One of them is Wind Energy System / Battery Storage / Diesel Generator Hybrid Power Generation System (WES/BS/DG HPGS), which consists of Wind Turbine Generators (WTGs), Battery Storage (BS) and Diesel Generators (DGs). A WES/BS/DG HPGS are considered economically viable in many cases for supply of electric energy to remote and isolated places where electric utility is not available[3]. In this system, DG is used as supplementary power supply to feed the load during deficit periods and for charging the battery storage, and it is operated near the full output as long as possible to get high efficiency and reduce the fuel consumption. This paper examines the possibility of using an Artificial Neural Network (ANN) for optimal operation control of the WES/BS/DG HPGS. The optimal operation control of WES/BS/DG HPGS should be determined according to the output power of the WES, the stored energy in battery, load demand and capacity of the diesel generators. The optimal operation patterns are calculated by new computer program under the known wind speed and load demand, which minimize fuel consumption. Afterward, the ANN is trained with this optimal operation and then is tested with other patterns that are not used for training processes. Finally, the ANN can operate under new wind speed and new load and send a command signal to operate the diesel generators within deficit periods. “Diesel ON” refers to the state where one or more diesel generators is connected to the bus and loaded. Conversely, “Diesel OFF” refers to the state in which all diesel generators are disconnected from the bus.

2 CHARACTERISTICS OF SYSTEM ELEMENTS

2-1 Modeling of wind turbine

The model used to calculate the output power generated by WTG is shown in Figure 1. Where; P_w is the power in the wind, P_m is the turbine output power, P_t is the generated input power and P_e is the generator power output. C_p is the coefficient of performance of the turbine, K_m is the transmission efficiency and K_g is the generator efficiency. Z_m is the turbine angular velocity.

From the block diagram shown in Figure 1., the electrical power output can be written as follows [4],[5]:

\[ P_e = C_p \cdot \eta_m \cdot \eta_g \cdot 0.5 \cdot \rho \cdot A \cdot v^3 \]  (1)
The characteristic of power output from WTG can be described by the following formula [4-7]:

\[
P_{\text{WTG}}(v) = \begin{cases} 
0 & : v < V_c \\
\frac{C \cdot p^m \cdot \eta \cdot \nu^3}{V_c^m} & : V_c \leq v < V_r \\
\frac{p \cdot \text{rated}}{V_r} & : V_r \leq v < V_f \\
0 & : v > V_f 
\end{cases}
\]  

(2)

Where; \( v \) is the wind speed; m/sec., \( P_{\text{rated}} \) is the rated power; kW, \( A \) is the effective swept area; \( m^2 \), \( V_c \) : The cut-in speed of the WTG, m/sec., \( V_r \) : The rated wind speed of the WTG, m/sec., \( V_f \) : The cut-off speed of the WTG, m/sec.

### 2-2 Battery storage (BS)

Energy from batteries is needed whenever the renewable energy is insufficient to supply the load demand. On the other hand, energy is stored whenever the supply from renewable system exceeds the load demand and when DGs are capable to charge the batteries. The maximum allowable energy taken from or added to the batteries is a percentage of the total capacity, usually taken 10% of capacity/hour. In addition to avoid deep discharge the minimum storage level is limited to 20% of what is available in the batteries before the discharge cycle begins, since we assumed that the battery charge efficiency is set equal to the round-trip efficiency and the discharge efficiency is set equal to 0.9. Two cases are considered in expressing the energy stored in the batteries for hour, \( t \).

**Case 1:** If the generated energy from WES exceeds that of the load demand, the batteries will be charged with round-trip efficiency according to the following equation [8]:

\[
E_{\text{bat}}(t) = E_{\text{bat}}(t-1) + (E_{\text{WTG}}(t) + E_{\text{dg}}(t) - E_{\text{L}}(t)) \eta_{\text{inv}} \eta_{\text{bat, in}}
\]  

(3)

Where;
- \( \eta_{\text{inv}} \) : The efficiency of the inverter in percent.
- \( \eta_{\text{bat, in}} \) : The round-trip efficiency of the batteries in percent.
- \( E_{\text{bat}}(t) \) : The energy stored in batteries in hour \( t \).
- \( E_{\text{bat}}(t-1) \) : The energy stored in batteries in previous hour.
- \( E_{\text{WTG}}(t) \) : The energy generated by WTG in hour.
- \( E_{\text{dg}}(t) \) : The energy from DG in hour.

**Case 2:** When the energy of the load demand is greater than the available energy generated, the batteries will be discharged by the amount that is needed to cover the deficit. It can be expressed as follows [8]:

\[
E_{\text{bat}}(t) = E_{\text{bat}}(t-1) - (E_{\text{L}}(t) / \eta_{\text{inv}} - E_{\text{WTG}}(t))
\]  

(4)

The energy stored in the batteries at any hour \( t \) is subjected to the following constraint [8]:

\[
E_{\text{bat, min}} \leq E_{\text{bat}}(t) \leq E_{\text{bat, max}}
\]  

(5)

This constraint means that the batteries should not be over discharged or over charged at any time and protects the batteries against damage. When the available energy generated and stored in batteries is insufficient to satisfy the energy of the load demand for any hour \( t \) a command signal should be sent from ANN to operate DGs to supply the load demand.

### 3 LOAD CHARACTERISTICS

It is assumed here that the load demand varies monthly. This means that each month has daily load curve different from other months. Therefore, there are twelve daily load curves through the year. Figure 2. shows the load demand for January, June and October. Table 1 shows the Characteristics and Parameters of WES/BS/DG HPGS under study.

![Figure 2. The Hourly Load Demand for January, June and October](image)

#### Table (1)

<table>
<thead>
<tr>
<th>Characteristics of the system parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average yearly energy demand</td>
<td>5368.16 MWh</td>
</tr>
<tr>
<td>Average yearly energy generated from WTG</td>
<td>3827.66 MWh</td>
</tr>
<tr>
<td>Average yearly energy generated from DG</td>
<td>1499.36 MWh</td>
</tr>
<tr>
<td>Maximum load demand</td>
<td>1.1875 MW</td>
</tr>
<tr>
<td>No. of WTG needed</td>
<td>11</td>
</tr>
<tr>
<td>Battery size</td>
<td>34.469 MWh</td>
</tr>
</tbody>
</table>

#### Characteristics of the selected WTG Nordex N27/150

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power, ( P_{\text{wtg, max}} )</td>
<td>150 kW</td>
</tr>
<tr>
<td>Rated wind speed, m/sec.</td>
<td>10.5</td>
</tr>
<tr>
<td>Cut-in wind speed, m/sec.</td>
<td>3.5</td>
</tr>
<tr>
<td>Cut-off wind speed, m/sec.</td>
<td>25</td>
</tr>
<tr>
<td>Rotor diameter, m</td>
<td>27</td>
</tr>
<tr>
<td>Hub height, m</td>
<td>31.5</td>
</tr>
</tbody>
</table>

### 4 PROBLEM FORMULATION

The major concern in the operation of an electrical power system that utilizes renewable energy sources is the accurate selection of components that can economically satisfy the load demand. The energy generated by WES is utilized for
minimizing the cost of operating diesel generator. Figure 3, represents an example for a WES/BS/DG HPGS. Energy flows from the system, in which \( P_{\text{wtg}}(t) \) is the output power of WES, \( P_{\text{bat}}(t) \) is the output power of the batteries, \( P_{\text{dg}}(t) \) is the output power of diesel generator, \( P_{L}(t) \) is the hourly load demand and \( t \) is the hourly time over one year. These flows must satisfy Eqn. (6). \( P_{\text{bat}}(t) \) is positive when the batteries is discharged and negative when charged.

\[
P_{\text{wtg}}(t) + P_{\text{dg}}(t) + P_{\text{bat}}(t) = P_{L}(t) \quad (6)
\]

The system components are found to achieve the following items:
1. Minimizing the electrical production cost $/kWh
2. Ensuring that the load is served according to a certain reliability criteria [10].
3. Minimizing the operation of DGs.

To meet the above objectives, the five switches as shown in Figure 3. are shifted according to the generated power from WES and diesel generators. When the wind speed is high, the load will be supplied from WES, i.e., switches S1 and S5 will be ON and the surplus power will be stored in the batteries, switch S2 will be on state of charge in the position 1, switch S3 and switch S4 will be OFF. If the wind speed becomes low, the battery supplies the load, i.e., S1 and S5 will be ON and switch S2 will be on state of discharge; S2 will be in the position 0 and switch S3 and switch S4 will be OFF. If the wind speed becomes very low and power from the battery becomes lower than the limit value then S5 will be ON and switch S2 will be ON state of charge in the position 1, switch S1 will be OFF, switch S3 will be ON and switch S4 will be OFF. Finally, if the power from diesel is greater than the load demand then S4 will be ON, S5 will be ON, and the surplus power will be sent to the batteries.

**Mode 1:** If the total electrical power generated by WES is less than the load demand, batteries will be charged. (S1=ON, S2=OFF, S3=OFF, S4=OFF, S5=ON)

**Mode 2:** If the total electrical power generated by WES and batteries is not sufficient, the load demand the ANN will send a command signal to operate diesel generator in order to feed this load demand. (S1=OFF, S2=on position 0, S3=ON, S4=OFF, S5=ON)

**Mode 3:** If the total electrical power generated by WES and batteries is not sufficient, the load demand the ANN will send a command signal to operate diesel generator in order to feed this load demand. (S1=OFF, S2=on position 0, S3=ON, S4=OFF, S5=ON)

**Mode 4:** If the power generated from diesel generator is higher than the load demand, the batteries will be charged. (S1=OFF, S2=on position 0, S3=ON, S4=ON, S5=ON/OFF). Operational modes are shifted according to Table 2.

### Table 2

<table>
<thead>
<tr>
<th>Mode</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>Generated power vs. Load demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>( P_{\text{wtg}} &gt; P_{L} )</td>
</tr>
<tr>
<td>2</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>( P_{\text{wtg}} &lt; P_{L} )</td>
</tr>
<tr>
<td>3</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>( P_{\text{wtg}} + P_{\text{bat}} &lt; P_{L} )</td>
</tr>
<tr>
<td>4</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td>( P_{\text{dg}} &gt; P_{L} )</td>
</tr>
</tbody>
</table>

### 5 SYSTEM SIMULATION

A new computer program has been proposed and written using Matlab software to simulate the system shown in Figure 3. The power flow management algorithm is presented in flowchart in Figure 4. Each decision block represents one of the modes described above. Note that each branch loops back to the beginning of the algorithm, since any of the mode can change at any moment.

The inputs of this program are:
1. Wind speed m/sec,
2. Characteristic of WTGs,
3. Hourly load demand; Watt.

The output of this program are number of WTG used, Number and capacity of DG, BS size and finally the optimal operation patterns that are used to be the input of ANN. The outputs of ANN are five command signals that sent to switches S1, S2, S3, S4 and S5.

### 6 PROPOSED NETWORK

Figure 5 shows the structure of the proposed three layers ANN. \( X_1, X_2, X_3 \) and \( t \) are the four-input training matrix and represent state of charge, electrical power generated from WTGs, load demand and time respectively. \( W^{(1)} \) and \( W^{(2)} \) are the weight matrices. The network consists of 4 input layers, 10 nodes in hidden layers and five nodes in output layer which sigmoid transfer function. The network has been found after a series of tests and modifications. We have used the ANN to make optimal operation of the WES/BS/DG HPGS and make optimal control for power flow between wind power, batteries and diesel generator. Figure 6 shows the difference between output from ANN and the desired output for the test data of 120 examples (5 months).
Batteries are charged
System Mode 1

IF Pwtg(t) > PL(t)
Batteries are discharged
System Mode 2

No
Yes

Signal from ANN to make System Mode 4
IF Pwtg(t) + Pbatt(t) > PL(t)
BS >= 0.2 * size of BS

Yes
No

For i=1 : 12
For t=1 : 24

Battery state of charge which corresponding to the optimal operation of the WES/BS/DG/HPGS through the months of January and October respectively. From Figure 7 and Figure 9, it can be seen that the power produced from WES and diesel generator accompanied with BS equal exactly the power of the load demand through the day, which represents the month. On the other hand, the diesel generator is setting to operate at its maximum efficiency to save the fuel consumption. These procedures reduce the price of the kWh produces from WES/BS/DG HPGS.

Figure 4. Flowchart of the Operational Modes of WTG/BS/DG HPGS.

Figure 5. Structure of the Proposed Three Layers ANN.

These differences are displayed for switches S1, S2, S3, S4 and S5. From this Figure it can be seen that the ANN of 4+10+5 operates with a high accuracy. Figures 7, 8 display the optimal operation of the WES/BS/DG/HPGS hour by hour through the days, which represent the months of January and October respectively. Figure 9 reveals the

Figure 6. Relation between outputs and target for Five months

Figure 7. Optimal operation of the WTG/BS/DG/HPGS to feed the load demand at Zafarâna site during January

Figure 8. Optimal operation of the WTG/BS/DG/HPGS to feed the load demand at Zafarâna site during October
Figure 9. State of charge of WTG/BS/DG/HPGS (Zafarâna site) during January and October

Figure 10 displays the output of the proposed ANN of 4+10+5 for month of January as an example using test data. This output may be 1 or 0 for each switch. From this Figure it can be noticed that the command signal which produced from ANN and sent to switch S1 (for example) equal to 1 at hours 2, 8, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22 and 24. This means that the WES accompanied with BS feed the load demand on these hours. On the other hand, ANN send a signal to switch S3 to operate the DGs on hours 1, 3, 4, 5, 6, 7, 9, 10 and 23. The load demand on these hours feed from DGs and S1 on these hours is OFF. The output of DGs are higher than the load demand on hours 1, 3, 4, 5 and 23. The surplus energy at these periods send to the batteries as shown in Figure 10, for switch S4. Considering Figure 8. and Figure 11, for October, it is found that the DG operates exactly to feed the load demand at the hours of 4, 6, 7, 8, 9, 10, 11, 12, 15 and 16 through signal send to switch S3. In addition, battery storage will be charged through hours of 4, 6, 7, 10, 11, 12, 13, 15, 17, 19 and 21 from DG and from WES as corresponding to switch S2. On the other hand, the battery storage feeds the load demand sharing with WES through the hours of 1, 2, 3, 5, 8, 9 14, 16, 18, 20, 22, 23 and 24. Considering Figures 12, 13 and 14. For the generation and load curve for June, it is found that in some periods the batteries in state of discharge through hours from 2 to 16 so that the DG does not operate to feed the load demand. In addition, battery storage will be charged again through WES at hours of 1, 17, 18, 19, 20, 21, 22, 23 and 24 from DG and from WES as corresponding to switch S2. Figure 15 shows the state of charge for the batteries storage through year.

Figure 12. Optimal operation of the WTG/BS/DG/HPGS to feed the load demand at Zafarâna site during June

Figure 13. State of charge of WTG/BS/DG/HPGS (Zafarâna site) during June

Figure 14. Outputs of the Neural Network for June
The present paper presents one possible application of intelligent systems. For the cases here studied, ANN has been applied to the operation of electric WES/BS/DG/HPGS, using the learning capacity of neural networks, applied to the parameters of hybrid systems. The NN proposed shows the importance of establishing an optimized control, both in terms of the selection of the best strategy, and of the relationship between the power generated by the wind system, DGs and load profile.

From the results obtained above the following conclusions can be drawn from this paper:

- A novel technique based on ANN is proposed to achieve the optimal operation control of WES/BS/DG/HPGS. This ANN operates the WES/BS/DG/HPGS to feed the load demand. On the other hand, the DG is setting to operate at its maximum efficiency to save the fuel consumption. Thus the price of kWh produces on WES/BS/DG/HPGS will be reduced.
- The 4+10+5 ANN is the suitable neural network for optimal operation of WES/BS/DG/HPGS at Zafarâna site.
- The ANN has a very high accuracy and achieve the optimal hour by hour operation for WES/BS/DG/HPGS as shown in Figures 6, 10 and 14.

7 CONCLUSIONS

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REFERENCES


BIOGRAPHIES

Adel A. Elbaset (PhD 2006) was born in Nag Hamadi, Qena - Egypt, on Oct. 24. 1971. He received the B. S., M.Sc., and Ph. D. from Faculty of Eng., Electrical Eng. Dept., Minia University, Egypt, in 1995, 2000, and 2006, respectively. He is a member of the Faculty of the College of engineering, Minia University, Egypt since 1996 till now. Dr. A. Elbaset is currently a Postdoctoral Fellow at the University of Kumamoto, Japan. His research interests are in the area of power electronics, power system protection and control, power Quality and Harmonics, neural network, a fuzzy system and renewable energy, where he co-supervised a number of M. Sc. thesis and published about 22 papers and number of technical projects.

Takashi Hiyama (M’86, SM’93) received his B.Eng., M.Eng. and Ph.D. degrees in electrical engineering from Kyoto University in 1969, 1971 and 1980 respectively. Since 1989, he has been a professor at the Department of Computer Science and Electrical Engineering, Kumamoto University, Japan. His current research interests include the intelligent systems applications to power systems operation, control and management. He is a senior member of IEEE, a member of IEE of Japan and Japan Solar Energy Society.