Chapter 3 OPERATION CONTROL STRATEGY AND SIMULATION OF PV SYSTEM INTERCONNECTED WITH EU

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Chapter 3

OPERATION CONTROL STRATEGY AND SIMULATION OF PV SYSTEM INTERCONNECTED WITH EU

3-1 INTRODUCTION

The performance of PV power system interconnected with EU can be improved through an application of advanced control method. This chapter introduces an application of an artificial neural network on the operation control of the PV/EU to improve system efficiency and reliability. There are two modes of PV system operation. Stand-alone PV system with battery storage and grid connected PV system without battery storage. This chapter focuses on the operation control of a hybrid system consists of PV system accompanied with or without battery storage interconnected with EU taking into account the variation of solar radiation and load demand during the day. Different feed forward neural network architectures are trained and tested with data containing a variety of operation patterns. A simulation is carried out over one year using the hourly data of the load demand, insolation and temperature at Zafarâna site, Egypt as a case study. It introduces also a complete computer simulation program of PV system interconnected with EU. The proposed computer simulation uses hysteresis current control and instantaneous p-q (real-imaginary) power theory. A computer simulation program has been designed to simulate phase voltage of the inverter leg,
phase-to-phase voltage of the inverter leg, current in each IGBT's, DC input current to the inverter, AC output current of the inverter that injected to the load/grid, load current, grid current, power output of the inverter and finally power factor of the inverter. The DC input current represents the output of PV solar cell array for all sunlight conditions. The computer simulation program is confirmed on a realistic circuit model implemented in the simulink environment of Matlab. Considering the design parameters which have been determined in chapter 2, one subsystem of PV system can be selected to represent the PV system. This subsystem consists of 55 panels connected in parallel. Each panel consists of 32 series modules. The maximum power produced from this subsystem at maximum radiation is about 500kW. Fig. 3-1 represents the proposed configuration of PV system based on subsystem which can feed a part of the load demand of 500kW.

Fig. 3-1 PV/Load/EU System Block Diagram.
3-2 METHODOLOGY OF CONTROL STRATEGY

3-2-1 Control strategy Issue of PV System Connected to EU without BS.

PV system connected to EU is designed to operate in parallel with EU as shown in Fig. 3-2. A bi-directional interface is made between the PV system AC output circuit and the EU, typically at an on-site distribution panel or service entrance. This allows the AC power produced by the PV system to either supply on-site electrical loads, or to back feed the EU when the PV system output is greater than the on-site load demand. At night and during other periods when the electrical loads are greater than the PV system output, the balance of power required by the loads is received from the EU. When the EU is down, this system automatically shut down and disconnected from the grid by using NN.

![Fig. 3-2 Single-Line Diagram for the Control Strategy of the PV/EU System](image-url)
Power flows in Fig. 3-2 must satisfy the following equations.

\[ P_{pv}(t) \pm P_g(t) = P_L(t) \]  \hspace{1cm} (3-1)

\[ P_{pv}(t) = ON_{pv} \times P_{pv, out}(t) \]  \hspace{1cm} (3-2)

Where:

- \( P_{pv}(t) \): The power from PV system, kW.
- \( P_g(t) \): The power to or from EU, kW.
- \( P_L(t) \): The Load demand, kW.
- \( t \): The hourly time over one year.
- \( ON_{pv} \): Optimum number of PV system.
- \( P_{pv, out}(t) \): The output power from one PV module (see chapter 2).

\( P_g(t) \) is positive when the PV power is less than the load demand and negative when PV power greater than the load demand.

The neural network that makes the decision of connecting PV system with electric utility takes its place only when the DC input voltages lay in the allowed range of power conditioning unit, PCU, and disconnecting from electric utility when the DC input voltages are out of range of the PCU. The NN detects the value of the sample DC voltage taken from the voltage produced from PV system, \( V_{dc_{pv}} \). Then, the NN sends an 1 (ON), or 0 (OFF) trip signal to the switches S1, S2, and S3. The NN will send an ON-trip signal to switches only if the following condition is realized:

\[ V_{dc_{pv}} > \min (V_{dc_{pv}}) \]  \hspace{1cm} (3-3)

Where:

- \( \min V_{dc_{pv}} \): The voltage value which is less than the minimum allowable limit PCU voltage.

The three switches shown in Fig. 3-2 are shifted according to the generated power from PV system.

Four modes can be considered as follows:-
Mode 1: If the radiation is low and the PV system can't be connected to the EU, then switch S1 is OFF, S2 is ON and S3 is OFF.

Mode 2: If the radiation is high and the generated power lower than the load demand then the load demand will be supplied from PV system and the deficit power will be taken from the EU. (S1=ON, S2=ON, S3=OFF)

Mode 3: If the radiation is high and the generated power greater than the load demand then the load demand will be supplied from PV system and the surplus power will be sent to the EU. (S1=ON, S2=OFF, S3=ON)

Mode 4: If there is no radiation and there is a problem in EU then the load demand will be not supplied. (S1=OFF, S2=OFF, S3=OFF). The operation of the three switches shown in Fig. 3-2 can be summarized as shown in Table (3-1).

Note:- If the load demand includes a critical load, it must install a battery storage, BS or any other source to supply this critical load in this case.

Table (3-1) Operational modes of PV System Interconnected with EU

<table>
<thead>
<tr>
<th>Mode</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>Generated power vs. Load demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
<td>$P_{pv} \approx 0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PV DC voltage out of operation limits</td>
</tr>
<tr>
<td>2</td>
<td>ON</td>
<td>ON</td>
<td>OFF</td>
<td>$P_{pv} &lt; P_L$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PV DC voltage within operation limits</td>
</tr>
<tr>
<td>3</td>
<td>ON</td>
<td>OFF</td>
<td>ON</td>
<td>$P_{pv} &gt; P_L$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PV DC voltage within operation limits</td>
</tr>
<tr>
<td>4</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>$P_{pv} = 0$ and grid has a problem</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PV DC voltage out of operation limits</td>
</tr>
</tbody>
</table>

3-2-2 Control Strategy Issue of PV/BS System Connected to EU

The design and installation of this system are more complicated and expensive, but it is more reliable than the PV/EU without BS. In this type of intertie system, the load demand has both PV system, EU and BS as shown in Fig. 3-3. Under normal circumstances, the system operates in a grid-connected mode, supplementing the on-site loads or sending excess power back onto the grid while keeping the battery fully charged. If the EU power
fails, power will be drawn instantly from the backup batteries to support the critical loads [101-105]. Control strategy issue of this system has been carried out using NN.

![Diagram of control strategy](image)

Fig. 3-3 Single-line Diagram for the control strategy of the PV/EU/BS System

Power flows from the system must satisfy the following Equations:

\[ P_{pv}(t) \pm P_g(t) \pm P_{bat}(t) = P_L(t) \]  

(3-4)

Where:

- \( P_{bat}(t) \) : The output/input power from/to BS, kW.
- \( P_{bat}(t) \) is positive when the batteries is discharged and negative when charged.

If the generated power from PV array exceeds that of the load demand, the batteries will be charged first with the round-trip efficiency according to the following Equation:

\[ E_{bat}(t) = E_{bat}(t-1) + \left( E_{pv}(t) - E_L(t)/\eta_{inv} \right) * \eta_{bat} \]  

[64] (3-5)

Where:

- \( \eta_{inv} \) : The efficiency of the inverter in percent.
- \( \eta_{bat} \) : The round-trip efficiency of the batteries in percent.
E_{bat}(t) : The energy stored in batteries in hour t.
E_{bat}(t-1) : The energy stored in batteries in previous hour.
E_{L}(t) : The energy of the load demand in hour t.
E_{pv}(t) : The energy generated by PV array in hour.

When there is no solar radiation or there is a failure in EU the batteries will be discharged by the amount that is needed to cover critical loads only by the following equation:

\[
E_{bat}(t) = E_{bat}(t-1) - \frac{E_{L}(t)}{\eta_{inv}}
\]  
\[\text{[64]} \quad (3-6)\]

The energy stored in batteries at any hour t is subject to the following constraint:

\[
E_{bat, min} \leq E_{bat}(t) \leq E_{bat, max}
\]  
\[\text{[64]} \quad (3-7)\]

That means that the batteries should not be over discharged or overcharged at any time. That protects batteries from damage.

- The size of battery bank in a PV system connected to EU accompanied with BS is dependent on three main factors [106], [107]:-
  1- The number of hours that the battery bank should provide the critical load without input from PV system or EU.
  2- The depth of discharge of the battery strongly depends on the applications, and can vary from a few percent to as much as 70%. The fact is that too deep cycling of limited batteries reduces their life expectancy.
  3- The total ampere of the critical loads.

The size of battery bank can be expressed by the following equation:

\[
\text{Battery Size} = \frac{P_{L,\text{critical}} \times T_{cri}}{\eta_{bat} \times \xi}
\]  
\[\text{(3-8)}\]

Where:

\( P_{L,\text{critical}} \) : The maximum critical load in the period Tcri.
Tcri : The number of hours that the battery bank should provide the critical load without input from PV system or EU.

ξ : The depth of discharge of the battery in percent.

Total ampere hour required can be calculated by the following equation:

\[ \text{Ampere-Hour} = \frac{\text{battery Size}}{\text{system voltage}}. \quad (3-9) \]

- Advanced system control strategy seeks to reduce depth-of-discharge for the batteries bank, maximize the utilization of PV system, and ensure high reliability of the system. Fig. 3-3 shows the advanced system control of the system connected to the EU accompanied with BS. The following steps describe how the operation control strategy of PV/BS with EU is investigated.

**Mode 1:**

When the solar radiation is low and the generated power from PV system less than the load demand then, this power will be sent to the batteries according to the Eqn. (3-6), i.e., switches S1 and S3 will be OFF, switch S4 will be on state of charge in the position 1 and switch S2 will be ON as shown in Fig. 3-3.

**Mode 2:**

When the solar radiation is high and the generated power greater than the load demand, then the load demand will be supplied from PV system and the surplus power will be sent to the batteries if it is needed to be fully charged according to the Eqn. (3-5). (S1 =ON, S2 =NO/OFF, S3 =OFF, S4 on state of charge)

**Mode 3:** If there is no radiation and there is a failure in EU then the critical load demand will be supplied from batteries. (S1 =ON, S2 =OFF, S3 =OFF, S4 on state of discharge). Operational control modes are shifted according to Table (3-2).
Table (3-2) Operational Modes of PV System Connected to EU Accompanied with BS

<table>
<thead>
<tr>
<th>Mode</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>Generated power vs. Load demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
<td>1</td>
<td>$P_{pv} &lt; P_L$ i.e. radiation is low</td>
</tr>
<tr>
<td>2</td>
<td>ON</td>
<td>OFF</td>
<td>ON/OFF</td>
<td>1</td>
<td>$P_{pv} &gt; P_L$ i.e. radiation is high</td>
</tr>
<tr>
<td>3</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>0</td>
<td>$P_{pv} = 0$</td>
</tr>
</tbody>
</table>

### 3-3 SIMULATION OF PV/EU SYSTEM.

#### 3-3-1 Modeling of PV sub-System

Figure 3-4 shows the modeling of one PV sub-system. This sub-system consists of 55 parallel PV panels. Each PV panel consists of 32 series PV module of ASE-300-DGF/17.

![Fig. 3-4 Modeling Diagram of one Subsystem.](image-url)
3-3-2 Modeling of a DC/AC Inverter

The device for converting DC to AC is called an inverter. There are two power inverters topology for utility interface:-

1- Line Commutated Inverter, LCI.

The Line Commutated Inverter, LCI is composed of 6 thyristors, and a line filter. The LCI is often referred to as a Current-Source Inverter, because it requires an inductor at the input.

The advantages of the LCI are:
- High efficiency
- Low cost

Although these advantages are very interesting for any inverter, the LCI has important drawbacks:
- Generation of high-amplitude/low-frequency current harmonics in the grid
- Uncontrollable power factor, which is lower than unity [15].

2. Voltage Source Inverter, VSI

The so-called Voltage Source Inverter, VSI and its application in PV and wind turbines. This circuit is illustrated in Fig. 3-5. The diodes parallel to the power switches are called freewheeling diodes because they allow the current to continue to flow in the inductance when the power switches (IGBTs) are turned OFF. This circuit can produce different square wave sequence patterns, from a DC-link voltage. The line filter is composed of an inductance, which absorbs the difference in voltage between the grid and the square wave pattern created by the inverter. The line filter smoothens the current generated by the VSI. The advantage of the VSI is, with the use of turn-off devices, the ability to create any kind of square sequences. The most basic type of VSI produces square waves, switching at the grid frequency. They create low frequency harmonic components, with larger requirements on the line filter [15].
There are two broad categories of inverter control techniques, voltage control and current control. Each type of control has a specific use. For a grid-connected inverter the voltage on the output is generally dictated by the grid power source, therefore current control is used to output a predetermined amount of current. With the grid voltage approximately constant this corresponds to a predetermined power level. Voltage control is typically employed for a non-grid connected inverters where voltage level is important. Some devices such as AC motors can be controlled using voltage or current control. It is possible to have controllers that use both current and voltage control, however one of the control loops is usually weakly integrated and its main purpose is to increase the stability and response of the system. Current control inverter scheme uses a bang-bang hysteresis type modulation technique as shown in Fig. 3-6 for phase (A) [85]. Figure 3-6 describes how the inverter current is generated and kept within a tolerance band, by switching the IGBT pairs (G1, G4).
3-3-3 Filter

The EU interface contains filters to reduce the harmonics generated by the inverter and to neutralize spikes coming from the EU and protections to prevent overload and islanding as shown in Fig. 3-7. In order to maintain a constant DC bus voltage, the average power $P_{pv}$ being supplied by the PV array must equal to the average output power $P_{inv}$ being drawn by the inverter and injected into the EU. The DC side controller will adjust the PV array voltage to operate at the maximum power point by using neural network.
3-3-4 Modeling of EU

The three-phase AC source represents the three-phase generator, a power plant or output from a transformer. It consists of three single phase voltage sources, which have a common neutral. Each of the voltage levels can be arbitrarily set to create unbalanced, sags or swells voltage conditions. According to theory, the voltages from these lines are usually $120^\circ$ out of phase from each other and the frequency for the AC voltage is usually 50 Hz. The lines that come out from the three-phase source represent the lines on the EU. The detailed block diagram of the three-phase AC voltage source is shown in Fig. 3-8.

![Block Diagram of Three-phase AC Voltage Source](image)

Fig. 3-8 Block Diagram of Three-phase AC Voltage Source.

3-3-5 Simulation Methodology of PV/EU.

The system shown in Fig. 3-1 demonstrates PV solar cells array connected to EU through a DC/DC boost converter and DC/AC inverter. The DC voltage obtained from PV solar cells array is applied to an IGBT's inverter. The task of the boost DC/DC converter drains the power from the PV solar cells array and feeds the DC link capacitor with a MPPs control by using a NN. Fig. 3-9 shows simulink block diagram for the simulated of PV solar cells array interfaced with EU through PWM voltage source inverter and its control.
Fig. 3-9 Schematic Diagram of the PV System Connected with EU.
The variables which will be sensed by the controller are solar cells array current $I_{pv}$, solar cells array voltage, $V_{dcpv}$, inverter filter output currents $I_{fa}$, $I_{fb}$, $I_{fc}$, load phase currents $I_{la}$, $I_{lb}$, $I_{lc}$ and EU phase voltages $V_a$, $V_b$, $V_c$. The DC link voltage, $V_{dcpv}$ must be controlled to be higher than the peak phase to phase voltage of the EU. To provide the active filtering function, the filter output currents $I_{fa}$, $I_{fb}$, and $I_{fc}$ are controlled to ensure that the utility line currents are sinusoidal and in phase with the phase voltage. The filter output currents are also controlled to pass power from the PV solar cells array to the load and/or EU. The proposed system control scheme for the system under study usually uses the instantaneous reactive power theory, IRPT. The load currents and load voltages are sampled and transformed into the two-axis $\alpha\beta$-coordinate system and then into the rotating $dq$-coordinate system. IRPT uses the park transformation which given in Eq. (3-10) to generate two orthogonal rotating vectors $\alpha$ and $\beta$ from the three-phase vectors a, b and c. This transformation is applied to the voltages and currents and so the symbol $x$ is used to represent voltage or current. IRPT assumes balanced three-phase loads and does not use the $x_0$ term [108].

$$
\begin{bmatrix}
    x_0 \\
    x_\alpha \\
    x_\beta
\end{bmatrix} =
\begin{bmatrix}
    \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\
    1 & -\frac{1}{2} & -\frac{1}{2} \\
    0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}
\end{bmatrix}
\begin{bmatrix}
    x_a \\
    x_b \\
    x_c
\end{bmatrix}
$$

[108] (3-10)

The supply voltage and load current are transformed into $\alpha\beta$ quantities. The instantaneous active and reactive powers ($p$) and ($q$) are calculated from the transformed voltage and current as given in Eqn. (3-11).

$$
\begin{bmatrix}
    p \\
    q
\end{bmatrix} =
\begin{bmatrix}
    V_\alpha & V_\beta \\
    -V_\beta & V_\alpha
\end{bmatrix}
\begin{bmatrix}
    i_\alpha \\
    i_\beta
\end{bmatrix}
$$

[108] (3-11)
Where;

\( p \) : The converter instantaneous real power, W.

\( q \) : The converter instantaneous imaginary power, VAR.

\( V_\alpha, V_\beta \): Supply voltage in vector \( \alpha \) and \( \beta \).

\( i_\alpha, i_\beta \) : Load current in vector \( \alpha \) and \( \beta \).

Then, the reference compensating currents are determined by taking the inverse of Eqn. (3-11) as given in Eqn. (3-12).

\[
\begin{bmatrix}
i_\alpha^* \\
i_\beta^*
\end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix}
\]  \[ (3-12) \]

The inverse park transformation is applied to reference current \( i_\alpha^* \) and \( i_\beta^* \) and this gives the harmonic currents in standard three-phase form as shown in Eqn. (3-13).

\[
\begin{bmatrix}
i_\alpha^* \\
i_\beta^* \\
i_\gamma^*
\end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix}
\]  \[ (3-13) \]

In a balanced three-phase system with linear loads, the instantaneous real power, \( p \), and imaginary power, \( q \), are constant and equal to the three-phase conventional active power, \( p_{3\Phi} \), and reactive power, \( q_{3\Phi} \), respectively. Then, for a given real and imaginary instantaneous power, the inverter control strategy consists in synthesizing output currents that the references in \( \alpha\beta \) coordinates are given by:

\[
\begin{bmatrix}
i_\alpha^* \\
i_\beta^*
\end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} p_{pv} \\ q_{pv} \end{bmatrix}
\]  \[ (3-14) \]
The value of $P_{pv}$ should be equal to the real power supplied by the PV array. On the other hand the value of $Q_{pv}$ equal to zero in order to maintain constant output power factor (often unity). The full decoupling of the active and reactive power regulation loops can be easily achieved as shown in Fig. 3-10. From Eqn. (3-13) and Eqn. (3-14), $P_{pv}$, $Q_{pv}$, and the measured terminal voltages, the desired phase currents, $i_a^*$, $i_b^*$ and $i_c^*$ are found. The desired phase currents, $i_a^*$, $i_b^*$ and $i_c^*$ and the load phase currents, $i_a$, $i_b$, $i_c$ are inputs to the comparator tolerance band controller to generate PWM control signals. The PWM control signals are the gating signals to the inverter bridge switches. This technique, which is shown in Fig. 3-6 for a sinusoidal reference current $i_a^*$, where the actual current $i_a$ is compared with tolerance band around the reference current associated with that phase. If the actual current in Fig. 3-6 tries to go beyond the upper tolerance band, G4 is turned on i.e. G1 is turned off. The opposite switching occurs if the actual current tries to go below the lower tolerance band. Similar actions take place in the other two phases [85]. This technique has the advantage of yielding instantaneous current control, resulting in a fast response. However, the switching frequency depends on how fast the current changes form the upper limit to the lower limit and vice versa. This, in turn, depends in $V_{dc pv}$ in Eqn. (3-3) i.e. solar radiation and the load demand. Moreover, the switching frequency is not constant but varies along the current waveform.

Fig. 3-10 Active and Reactive Power Regulation
There are two modes of operation:

- **Mode 1**: When the generated power from PV solar cells array is lower than the load demand then the deficit power will be supplied from the EU. i.e. $S_1=ON$, $S_2=ON$, $S_3=OFF$ as shown in Fig. 3-2.

- **Mode 2**: When the generated power from PV solar cells array is greater than the load demand then the surplus power will be transmitted to the EU. i.e. $S_1=ON$, $S_2=OFF$, $S_3=ON$ as shown in Fig. 3-2.

### 3-4 APPLICATION AND RESULTS

#### 3-4-1 Operation control strategy of PV System Connected to EU.

Figure 3-11 shows the structure of the proposed three layers NN. $X_1$, $X_2$ and $t$ are the three-input training matrix which represent electrical power generated from PV, load demand, and time respectively. $W^{(1)}$ and $W^{(2)}$ are the weight matrices. The network consists of four-input layers, six nodes in hidden layer and three nodes in output layer which sigmoid transfer function. The network has been found after a series of tests and modifications. Table (3-3) shows the weights and bias for the NN.

![Fig. 3-11 Structure of the Proposed Three Layers NN used for Control Strategy of PV/EU.](image-url)
Table (3-3a) Weights $W^{(1)}$ and Biases for 3+6+3 NN for PV Interconnected with EU

<table>
<thead>
<tr>
<th>$W^{(1)}$</th>
<th>bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.9174</td>
<td>-7.1051</td>
</tr>
<tr>
<td>-0.4595</td>
<td>0.1757</td>
</tr>
<tr>
<td>-0.1753</td>
<td>-3.0308</td>
</tr>
<tr>
<td>4.7950</td>
<td>-1.3670</td>
</tr>
<tr>
<td>0.9331</td>
<td>3.3055</td>
</tr>
<tr>
<td>-1.0232</td>
<td>-1.4380</td>
</tr>
</tbody>
</table>

Table (3-3b) Weights $W^{(2)}$ and Biases for 3+6+3 NN for PV interconnected with EU

<table>
<thead>
<tr>
<th>$W^{(2)}$</th>
<th>bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>-17.480</td>
<td>2.9759</td>
</tr>
<tr>
<td>17.3487</td>
<td>0.4277</td>
</tr>
</tbody>
</table>

Figure 3-12 shows the evaluation of the 3+6+3 NN errors. Figures 3-13 and 3-14 display the optimal operation of the PV/EU hour by hour through the day which represents the months of January and July respectively.
Fig. 3-13 Optimal Operation of the PV/EU to Feed the Load Demand during January (winter).

Fig. 3-14 Optimal Operation of the PV/EU to Feed the Load Demand during July (summer).
From Figs. 3-13 and 3-14 it can be seen that the deficit energy has been taken from EU (i.e. the NN send a trip signal to switches S1 to turn ON, S2 to turn ON and S3 to turn OFF). On the other hand, the surplus energy has been injected to EU through the day (i.e. the NN send a trip signal to switches S1 to turn ON, S2 to turn OFF and S3 to turn ON). Figure 3-15 shows the difference between output from NN and the desired output for the test data of 120 examples (Five months). These differences are displayed for switches S1, S2 and S3. From this Figure it can be seen that the ANN of 3+6+3 operates with a high accuracy.

Fig. 3-15 Relation Between Outputs and Target for Five Months

Figures 3-16 and 3-17 display the output of the proposed NN of 3+6+3 for month of January and July respectively using test data. This output may be 1 or 0 for each switch. From Figures 3-13 and 3-16 (January) it can be noticed that the trip signal which produced from NN send to switch S1 at hours 8, 9, 10, 11, 12, 13, 14, 15, 16 and 17. This means that the PV system feed the load demand at these hours. On the other hand, switch S2 (for example) equal
to 1 at hours 1, 2, 3, 4, 5, 6, 7, 8, 9, 18, 19, 20, 21, 22, 23 and 24. This means that the EU should supply the load demand at these hours. On the other hand, the power injected to EU through switch S3 at hours 10, 11, 12, 13, 14, 15, 16 and 17. From switch S1 and S2 it can be noticed that the PV system with EU feed the load demand at hours 8 and 9.

Fig. 3-16 Outputs of Neural Network for Month of January.

Fig. 3-17 Outputs of Neural Network for Month of July.
From Figures 3-14 and 3-17 (July) it can be noticed that the trip signal which produced from NN send to switch S1 at hours 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18 and 19. This means that the PV system fed the load demand at these hours. On the other hand, switch S2 (for example) equal to 1 at hours 1, 2, 3, 4, 5, 6, 7, 8, 9, 19, 20, 21, 22, 23 and 24. This means that the EU should supply the load demand at these hours. On the other hand, the energy injected to EU through switch S3 at hours 10, 11, 12, 13, 14, 15, 16, 17 and 18. From Fig. 3-17 it can be noticed that the PV system with EU feed the load demand at hours 8, 9 and 19. This is clear from switches S1 and S2.

3-4-2 Operation control strategy of PV/BS System Connected to EU

From Fig. 2-9 in chapter 2 it can be seen that the maximum load is 95 Mwh. According to Ref. [73], [109] the critical load equal to 18% of a maximum load demand, so the battery sizes necessary to maintain a critical load during one hour can be calculated according to Eqn. (3-8) as follows:

\[
\eta_{ba} = 80\%, \quad \xi = 80\%
\]

Battery Size = \(0.18 \times 95 / (0.8 \times 0.8) = 26.7 \text{ Mwh}\)

A new subroutine computer program has been proposed and written using Matlab software to simulate the PV/BS system. The flowchart of this program is shown in Fig. 3-18. This subroutine program has been branched from the flowchart of the computer program shown in Fig. 2-7. The output of this program has been used to be the input of NN. The outputs of NN are four trip signals that send to switches S1, S2, S3 and S4 as shown in Fig. 3-3. Through a series of tests and modifications it has been found that the network consists of five input layer, nine nodes in hidden layer and four nodes in output layer which sigmoid transfer function.
Fig. 3-18 Flowchart of the Proposed Computer Program for PV/EU Accompanied with BS.

Figure 3-19 shows the structure of the proposed three layers NN. $X_1, X_2, X_3, X_4$ and $t$ are the five-input training matrix and represent state of charge,
electrical power generated from PV, electrical power for EU, load demand and time respectively. $W^{(1)}$ and $W^{(2)}$ are the weight matrices. Table (3-4) shows the weights and bias for this NN. Figure 3-20 shows the evaluation of the 5+9+4 NN errors. Figures 3-21 and 3-22 display the optimal operation of the PV/EU accompanied with BS hour by hour through the day which represents the months of January and July respectively.

Fig. 3-19 Structure of the Proposed Three Layers NN used for Control Strategy of PV/EU Accompanied with BS.
Table (3-4a) Weights $W^{(1)}$ and Biases for 5+9+4 NN for PV Interconnected with EU Accompanied with BS

<table>
<thead>
<tr>
<th></th>
<th>$W^{(1)}$</th>
<th>b1</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>-4.40</td>
<td>3.29</td>
</tr>
<tr>
<td></td>
<td>-4.83</td>
<td>-2.70</td>
</tr>
<tr>
<td></td>
<td>-0.29</td>
<td>-2.89</td>
</tr>
<tr>
<td></td>
<td>6.44</td>
<td>2.75</td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
<td>-0.02</td>
<td>2.06</td>
</tr>
<tr>
<td></td>
<td>2.60</td>
<td>-2.59</td>
</tr>
<tr>
<td></td>
<td>1.36</td>
<td>4.19</td>
</tr>
<tr>
<td></td>
<td>1.96</td>
<td>-0.14</td>
</tr>
</tbody>
</table>

Table (3-4b) Weights $W^{(2)}$ and Biases for 5+9+4 NN for PV Interconnected with EU Accompanied with BS

<table>
<thead>
<tr>
<th></th>
<th>$W^{(2)}$</th>
<th>b1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.21</td>
<td>-0.46</td>
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<td></td>
<td>-6.38</td>
<td>-4.94</td>
</tr>
<tr>
<td></td>
<td>-10.50</td>
<td>5.03</td>
</tr>
<tr>
<td></td>
<td>-5.06</td>
<td>-12.97</td>
</tr>
</tbody>
</table>

Fig. 3-20 Relation Between Error and Epoch For 5+9+4 ANN
Fig. 3-21 Optimal Operation of the PV/BS with EU to Feed the Load Demand during January (winter).

Fig. 3-22 Optimal Operation of the PV/BS with EU to Feed the Load Demand during July (summer).
Figure 3-23 reveals state of charge for BS which corresponding to the optimal operation of the PV/EU accompanied with BS through the months of January and July respectively. From Fig. 3-21, Fig. 3-22 and Fig. 3-23 it can be seen that the energy produced from PV system and EU accompanied with BS equal to the energy of the load demand through the day which represents the month of January and July respectively. Figure 3-24 shows the difference between output from NN and the desired output for the test data of 120 examples (Five months). These differences are displayed for switches S1, S2, S3 and S4. From this Figure it can be seen that the NN of 5+9+4 operates with a high accuracy.

![Figure 3-23 State of Charge of PV/BS with EU during January (winter) and July (summer)](image-url)
Figures 3-25 and 3-26 display the output of the proposed NN of 5+9+4 for the month of January and July respectively using test data. This output may be 1 or 0 for each switch. From Figures 3-21, Fig. 3-23 and Fig. 3-25 (January) it can be noticed that the trip signal which produced from NN send to switch S1 at hours 8, 9, 10, 11, 12, 13, 14, 15, 16, 17 and 19. This means that the PV system with battery storage feed the load demand at these hours. The storage batteries supplied the load demand at hours 19. On the other hand, switch S2 (for example) equal to 1 at hours 1, 2, 4, 5, 6, 7, 8, 9, 18, 19, 21, 22, 23 and 24. This means that the EU should supply the load demand at these hours. On the other hand, the energy injected to EU through switch S3 at hours 10, 11, 12, 13, 14, 15, 16 and 17. Finally, battery storage will be on state of charge through switch S4 at hours of 1, 2, 4, 5, 6, 7, 8, 9, 10, 18, 20, 21, 22, 23 and 24. On the other hand, the BS will be discharged through the hours of 12, 13, 14, 15, 16, 17 and 19. Then the BS can feed the load demand only during these hours.
Fig. 3-25 Outputs of Neural Network for January

Fig. 3-26 Outputs of Neural Network for July
3-5 SIMULATION RESULTS OF PV/EU

There are many software packages have designed for circuit simulation such as Electro-Magnetic Transients Program, EMTP Electronics Workbench, Circuit Maker, PSPICE and other Spice Variations. These are all good programs but they all lack the ability to easily model control systems. Matlab/Simulink version 6 Math Work Inc [110] with power system Blockset, PSB [111] provides a relatively simple method to build power electrical circuits using a library of user defined blocks and concentrate on dynamic/control aspects of the overall system. Power system blockset is a supplementary toolbox that runs on the simulink environment. It provides libraries containing models of typical power equipment such as transformer, machines and power electronics. By using this tool, the power electronic devices and its sophisticated control system can be easily modeled and simulated. The Simulink is a software package for modeling, simulating and analyzing dynamic systems. After a model is defined, it can be simulated using various choice of numerical integration methods such as 4th order Rung-Kutta, etc.

The circuit of Fig. 3-9 is simulated using Matlab/simulink version 6. The system parameters for all radiation condition used in these simulation studies are given in Table (3-5). The output power from PV solar cells array as shown in Fig. 3-27 have been applied to the inverter to feed the load with the EU. The total power load level is 300 kW with load current 455.8 Ampere for duration 0.3 Sec. After 0.3 Sec., the load has changed from 300 kW to 100 kW with load current 151.93 Ampere for duration from 0.3 Sec. to 0.5 Sec. as shown in Fig. 3-27. The following figures show simulation results of the proposed control system. Figure 3-28 displays the simulated phase voltage of the inverter leg, while Fig 3-29 shows the phase-to-phase of the inverter leg. Due to the small width of the hysteresis band, the voltage generated by the
proposed model is nearly sinusoidal when seen at this bus. Fig. 3-30 shows the waveform of the current following in each branch of IGBTs.

Table (3-5) System Parameters

<table>
<thead>
<tr>
<th>SPECIFICATION</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Input DC voltage</td>
<td>600V ± 5%</td>
</tr>
<tr>
<td>Nominal AC output</td>
<td>380 V, 50 HZ, Three-phase</td>
</tr>
<tr>
<td>Maximum output power</td>
<td>500 kW</td>
</tr>
<tr>
<td>Filter inductor, L&lt;sub&gt;f&lt;/sub&gt;</td>
<td>5 mH, 0.82mH, 0.25 mH</td>
</tr>
<tr>
<td>Filter capacitance, C&lt;sub&gt;f&lt;/sub&gt;</td>
<td>800 μF</td>
</tr>
</tbody>
</table>

Fig. 3-27 Simulated of Generated Power from PV, Load Demand and EU Power from/to EU.
Fig. 3-28 Simulated Phase Voltage of the Inverter Leg

Fig. 3-29 Simulated Phase-to-Phase Voltage of the Inverter Leg, \( V_{ab} \)
Fig. 3-30a Simulated Switch Current in IGBT's

Fig. 3-30b Simulated Switch Current in IGBT's
On the other hand, Fig. 3-31 shows the line current injected by the PV solar cells array with total harmonic distortion 1.3 %. The line current of the load demand is shown in Fig. 3-32. From Fig. 3-27 it can be seen that there is a surplus energy in the period from 0.2 Sec. to 0.4 Sec. So the surplus energy will be injected to the EU for these periods. This, in turn, NN sent a trip signal to switches S1 to turn ON, S2 to turn OFF and S3 to turn ON. On the other hand there is deficit energy in the period of 0.2 sec and in the period from 0.4 sec to 0.5. So, the EU will supply the load demand in cooperated with PV solar cells array for these periods. i.e NN sent a trip signal to switches S1 to turn ON, S2 to turn ON and S3 to turn OFF. These can be seen in Fig. 3-33 and Fig. 3-34, where Fig. 3-33 shows the simulated of grid line current with total harmonic distortion of 0.9% that injected to or drawn from grid and Fig. 3-34 displays the simulated power factor of the grid.
Fig. 3-31 Simulated of Inverter Current Injected to the Load/EU.

Fig. 3-32 Simulated of Load Current.
Fig. 3-33 Simulated Current From/to EU.

Fig. 3-34 Simulated Power Factor of the Grid.
Also, from these Figs 3-33 and 3-34 it can be seen that the power factor is leading in the period of surplus energy and lagging in the period of the deficit energy. Figs. 3-35 and 3-36 show the input current $i_{\alpha}(t)$ and $i_{\beta}(t)$ and their corresponding load voltage $v_{\alpha}(t)$ and $v_{\beta}(t)$. It can be seen from these figures that the input current $i_{\alpha}(t)$ and $i_{\beta}(t)$ and their corresponding load voltage $v_{\alpha}(t)$ and $v_{\beta}(t)$ are in phase. Thus there is a guarantee to operate the inverter with a power factor very close to one as shown in Fig. 3-37. From these figures it can be seen that the proposed model is very excellent.

Fig. 3-35 Simulated Load Current $i_{\alpha}(t)$ and $i_{\beta}(t)$. 

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Fig. 3-36 Simulated Load Voltage $v_\alpha(t)$ and $v_\beta(t)$.

Fig. 3-37 Simulated of the Inverter Power Factor.
3-6 CONCLUSIONS

This chapter concerns with operation control strategy and simulation of PV system interconnected with EU. Applications of an artificial neural network on the operation control of the PV/EU with or without BS to improve system efficiency and reliability have studied.

From the results obtained above, the following are the salient conclusions that can be drawn from this chapter:

- Modeling and simulation of a DC/AC inverter connected to EU have proposed.
- A novel of PV interfaces with the EU for solving modeling and simulation problems by using Matlab/Simulink environment have proposed.
- The total harmonic distortion at the local bus is within acceptable limits and reached to 1.3 % for the inverter current and 0.9 % for the grid current.
- Perform the necessary preliminary studies before investing and connecting PV power system to the grid where purchased and sold power from EU have calculated.
- A novel technique based on NN is proposed to achieve the optimal operation of PV/UG accompanied with or without BS.
- The 3+6+3 is suitable neural network for accurate operation of PV/UG at Zafarâna site, Egypt.
- The 5+9+4 is suitable neural network for accurate operation of PV/UG accompanied with BS at Zafarâna site.