Methods for optimal placement of PMU devices to assess the stability of the Azerbaijan power system

Nurali Yusifbayli¹, Valeh Nasibov²* and Kamran Suleymanov²

¹Azerbaijan Technical University, AZ1073 Baku, Azerbaijan
²Azerbaijan Scientific-Research and Design-Prospecting Power Engineering Institute, AZ1012, Baku, Azerbaijan

Abstract. This article discusses the method of integer linear programming, a method based on estimating the rate of change in operating conditions when conditions become more complex or disturbances occur. In the first method, the criterion for placing PMUs in the energy system of Azerbaijan is to ensure full observability; the second method examines the rate of change in the relative angles of synchronous generators under large disturbances. Based on the obtained parameters, weak nodes are identified where it is necessary to install PMU devices.

1 Introduction

Fulfilling the obligations of the Paris Agreement related to the problems of reducing greenhouse gas emissions and climate change poses large-scale challenges for the energy sector, as the most responsible industry for climate change.

For the purposes of the fulfillment of obligations under the Paris Agreement, Azerbaijan has committed itself to reducing the share of CO2 by 2030 compared to 1990 by 35% and increasing the share of green electricity to 30% by installing 1,500 MW of renewable energy sources.

According to the agreement signed between the governments of the Republic of Azerbaijan, Georgia, Romania and Hungary on a strategic partnership in the field of development and transfer of green energy, it is planned to transfer 4 GW of wind power from the Azerbaijani sector of the Caspian Sea to the countries of the European Union in the next five years.

The longest electric cable in the world will connect Azerbaijan and Europe, laying a green energy bridge between the Caspian Sea to the countries of the EU.

It is planned to bring up the transmitted green power from the Caspian Sea to the EU countries to 25 gigawatts by 2037. At that, various schemes of transmission are analyzed: with integration into the power system, without integration with the power system and asynchronous integration into the power system of Azerbaijan. In all cases, the large volume of transmitted power over long distances puts forward stringent requirements for the reliability, stability and survivability of the Azerbaijan power system.

The high level of requirements for ensuring the reliability and survivability of the Azerbaijan power system, as a central subject in the Azerbaijan-Georgia-Romania-Hungary, Azerbaijan-Turkey-Greece and the Russian Federation-Azerbaijan-Iran schemes, stipulates the need for the process of its intellectualization [1, 2].

2 Innovative information-measuring system WAMS

One of the most important components of the intellectualization concept is an innovative information-measuring system based on synchrophasor (vector) real-time measurement technology. Such a system is the WAMS system, in the structure of which, along with the WACS, WAPS and PDC systems, the PMU device operates [4-6]. In general, the WAMS system provides information about the state of the power system with an accuracy of voltage measurement ± 0.1%, phase angle ± 0.2 degrees, current ± 0.2%, frequency ± 0.01 Hz, angle between branch current and node voltage ± 0.20c with a frequency of 20 ms.

The vector of measurements carried out by the PMU device is represented as:

\[ Y = [U_i \ b_i \ \Psi_{ij}] \] (1)

where

- \( U_i \) – voltage modulus of the \( i^{th} \) node;
- \( b_i \) – voltage phase of the \( i^{th} \) node;
- \( I_{ij} \)– current flowing out of the \( i^{th} \) node and flowing into the \( j^{th} \) node;
- \( \Psi_{ij} \) – phase shift between current and voltage.

The SCADA/EMS system has already been installed and is operating in the Azerbaijan power system. Despite its enormous functionality, the SCADA/EMS system is inferior to the WAMS system in a number of indicators, such as measurement synchronicity, volume, speed and accuracy of information transfer. Tasks such as monitoring of oscillatory stability, disturbance detection, event recording, post-accident analysis and...
other tasks that require millisecond synchronous phase measurements are difficult to solve within the framework of SCADA/EMS. In these conditions, the greatest efficiency is achieved by combining the capabilities of both SCADA/EMS and WAMS systems.

As mentioned above, the SCADA/EMS system is already operating in the Azerbaijan power system, so the main attention needs to be paid to the problem of PMU placement [3-5].

As a rule, one of the main criteria for the optimal placement of PMUs in the power system is to ensure full observability of the power system, which means that the number and composition of measurements are sufficient to control the power system modes in all conditions (before an accident, during and after an accident). Naturally, this criterion (observability criterion) can be implemented if PMU is installed in all nodes.

However, the high cost of the PMU devices themselves with their current and voltage channels, the need to connect these channels with data centers (PDC) at the locations of the latter, etc. require preliminary research.

Full observability can be ensured by using voltage measurements at the nodes of the PMU installation and currents from these nodes and by calculating the voltages and currents in adjacent nodes. At that, the accuracy is maintained.

In relation to the problem of assessing the state of the power system, where the main issue is the identification of the power system diagram, the topological aspect of observability, which is based on a linear system of equations, is important.

The solution to the problem of optimal placement of PMUs in the Azerbaijan power system is implemented using the integer linear programming (ILP) method, where the extreme value of a linear function of many variables is found in the presence of linear constraints connecting these variables. At that, the integer requirement is imposed on the variables. The initial function to be minimized is represented as:

\[ \min \sum_{k=1}^{N} x_k \]

where:
- \( N \) – number of nodes in the system;
- \( X \) – binary solution vector;
- \( A \) – integer matrix, the structure of which depends on the network scheme;
- \( b \) – integer vector.

In (2), the elements of matrix A take the values

\[ A_{ij} = \begin{cases} 
1 & \text{if } i = j \\
1 & \text{if } i \text{ and } j \text{ are connected} \\
0 & \text{if not connected}
\end{cases} \]

\[ |X| \text{ - binary vector} \]

\[ |X| = |X_1 X_2 X_3 ... X_N| \]

\[ X \in \{0,1\} \]

\[ x_i = \begin{cases} 
1 & \text{if PMU is installed in node } i \\
0 & \text{is absent}
\end{cases} \]

\[ |b| = |1,1,1 ... 1| \]

The ILP method is applied to the prospective scheme of the 500–330–220 kV electrical network of the Azerbaijan power system, which has 53 nodes, including 24 nodes in the 500–330 kV network and 29 nodes in the 220 kV network (Figure 1). The decomposition was carried out according to intersystem connections with the Russian power system (330 kV Khachmaz-Derbend OHL), the Georgian power system (500 kV Samukh-Gardabani OHL, 330 kV Akstafa-Gardabani OHL), the Iranian power system (230 kV Imishli-Parsabad OHL – 330 kV Imishli-Tagi-Dize OHL).

The calculation using the Matlab program presented the following placement of PMUs by nodes:

\[ |X|=(0 1 0 0 1 0 0 0 1 0 0 01 0 0 0 0 0 0 1 0 0 0 0 0100 0 0 0 0 0 0 1 0 0 1 0 0 1 0 1 0 0 0 0 0 0 1 0 1) \]

That is, to ensure full observability, PMUs must be installed in 14 nodes (26% of the total number of nodes) of the PS, namely:

- 2– 330 kV Yashma SS
- 5– 220 kV Yashma PP
- 9– 220 kV Boyuk-Shor
- 13– 220 kV Absheron
- 16– 220 kV Gobu PP
- 20– 220 kV Janub PP
- 26– 330 kV Alat Free Economic Zone
- 30– 220 kV Shimal PP
- 34– 220 kV Mingechevir HPP
- 37– 500 kV Az TPP
- 40– 330 kV Samukh
- 42– 330 kV Gazakh
- 50– 330 kV Imishli
- 52– 330 kV Jabrayil

In adjacent nodes, observability is ensured by calculations based on measurements of voltages and flows from nodes where PMUs are installed.

In the obtained calculated results shows the following:

Each PMU has one voltage channel. The PMU at the 220 kV Absheron substation (node 13) has the largest number of current channels (9 channels). The node is practically the boundary for two decomposition subsystems: 500–330 kV (transmitting part) and 220 kV (receiving part) of the Azerbaijan power system.
At the 330 kV Imishli substation (node 50), which borders the interconnection with the Iranian power system from the Azerbaijan power system, a PMU with 5 current channels is installed.

Another 3 PMUs are installed with 5, 6 PMUs with 4, 1 PMU with 3 and 2 PMUs with 2 current channels.

If the cost of one channel is 1 USD, then the cost of a PMU with 5 current channels is installed.

Another 3 PMUs are installed with 5, 6 PMUs with 4, 1 PMU with 3 and 2 PMUs with 2 current channels.

At the 330 kV Imishli substation (node 50), which borders the interconnection with the Iranian power system from the Azerbaijan power system, a PMU with 5 current channels is installed.

Another 3 PMUs are installed with 5, 6 PMUs with 4, 1 PMU with 3 and 2 PMUs with 2 current channels.

If the cost of one channel is 1 USD, then the cost of a PMU with 5 current channels is installed.

Another 3 PMUs are installed with 5, 6 PMUs with 4, 1 PMU with 3 and 2 PMUs with 2 current channels.

Another approach to solving problems of determining installation locations can be based on the physical content of the processes occurring in the system during disturbances. It is based on concepts such as heterogeneity, sensitivity, sensority and weakness of elements of the topological structure of the power system.

We focus on the last two concepts: sensority and “weakness” of elements, which may be sufficient to solve the problem.

Sensors are elements of the power system whose mode parameters change to a large extent due to random changes in the elements of the power system: generation, network, load.

Weak elements of the power system are those elements of the power system, changes in the parameters of which have the greatest impact on the magnitude of the power system’s response to disturbances [6, 7].

The ambiguity of the structure of the power system, its modes, disturbances, and the nature of dynamic processes during disturbances has led to different approaches to identifying weak points in the power system.

One of these approaches is a method based on comparing the rate of change of mode parameters U, P, δ when the mode becomes heavy or when disturbances occur. Below are examples of the implementation of this approach.

One of the existing schemes and modes, characterized by the following data, is taken as the basis:
3.1 Rate of change of relative angles of synchronous generators at large disturbances

As a disturbance, the shutdown of the 500 kV 2nd Absheron overhead line in the power flow mode was taken - 464 MW without automatic reclosure.

Table 1. Rates of their change in the first cycle of oscillations after disturbances

<table>
<thead>
<tr>
<th>No.</th>
<th>δ₀</th>
<th>δmax</th>
<th>t₀</th>
<th>tmax</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>330 kV Az.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TPP - Shimal PP</td>
<td>152-170</td>
<td>19</td>
<td>36.1</td>
<td>1.1</td>
<td>1.68</td>
</tr>
<tr>
<td>500 kV Az.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TPP - Shimal PP</td>
<td>157-170</td>
<td>18.5</td>
<td>40.6</td>
<td>1.1</td>
<td>1.64</td>
</tr>
<tr>
<td>Janub PP -</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shimal PP</td>
<td>170-211</td>
<td>10</td>
<td>-0.2</td>
<td>1.1</td>
<td>1.8</td>
</tr>
<tr>
<td>330 kV Az.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TPP - 110 kV Janub PP</td>
<td>152-211</td>
<td>29</td>
<td>36.5</td>
<td>1.1</td>
<td>1.56</td>
</tr>
<tr>
<td>330 kV Az.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TPP - 220 kV Sumgait PP</td>
<td>152-181</td>
<td>28.2</td>
<td>41.4</td>
<td>1.1</td>
<td>1.58</td>
</tr>
<tr>
<td>500 kV Az.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TPP - 220 kV Sumgait PP</td>
<td>157-181</td>
<td>27.6</td>
<td>46.3</td>
<td>1.1</td>
<td>1.56</td>
</tr>
<tr>
<td>330 kV Az.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TPP - Baku CCPP</td>
<td>157-43</td>
<td>21.9</td>
<td>41.3</td>
<td>1.1</td>
<td>1.62</td>
</tr>
<tr>
<td>500 kV Az.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TPP - Baku CCPP</td>
<td>157-43</td>
<td>21.4</td>
<td>46.0</td>
<td>1.1</td>
<td>1.6</td>
</tr>
<tr>
<td>110 kV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Janub PP - 220 kV Sumgait PP</td>
<td>211-181</td>
<td>-0.8</td>
<td>4.93</td>
<td>1.1</td>
<td>1.6</td>
</tr>
<tr>
<td>110 kV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Janub PP - Baku CCPP</td>
<td>211-43</td>
<td>-</td>
<td>7.02</td>
<td>5.17</td>
<td>1.1</td>
</tr>
<tr>
<td>Shimal PP -</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baku CCPP</td>
<td>170-43</td>
<td>2.98</td>
<td>6.44</td>
<td>1.1</td>
<td>1.46</td>
</tr>
<tr>
<td>Shimal PP -</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>220 kV Sumgait PP</td>
<td>170-181</td>
<td>9.2</td>
<td>3.7</td>
<td>1.1</td>
<td>1.78</td>
</tr>
</tbody>
</table>

In Table 1, to compare the intensity of the dynamics of changes in angles, the rates of change in relative angles between the main synchronous generators of the power system in the first cycle of oscillations after disturbances, calculated by the formula, are given:

\[ \frac{\delta_{\text{max}} - \delta_{\text{min}}}{360(t_{\text{max}} - t_{\text{min}})} \]

The analysis shows that the highest rate of change in relative angles occurs between synchronous generators:
- Azerbaijan TPP – 500 kV – Baku CCPP
- Azerbaijan TPP – 500 kV – Shimal TPP
- Azerbaijan TPP – 500 kV – Sumgait TPP
- Azerbaijan TPP – 330 kV - Baku CCPP
- Azerbaijan TPP – 330 kV - Shimal TPP

Therefore, to monitor the mutual angles on the voltage buses of synchronous generators, it is recommended to install PMU at the 500 kV Azerbaijan TPP and 330 kV Azerbaijan TPP in the redundant and main stations of the deficit part (Shimal TPP, Sumgait PP, Baku CCPP).

Conclusions

The high cost of PMU requires their placement based on the operating characteristics of the power plant. The presence of intersystem connections of a transit function in the Azerbaijan ES, the presence of critical sections, predetermines the need to place PMU in “weak” places, where monitoring of stability levels and stresses, etc. based on measurements is necessary.

For the promising scheme of the Azerbaijan ES, to take into account the regime features, it is necessary to install PMU on the buses of power plants in the deficient part of the power system.

References

6. DF 800 SCADA/EMS for Power Dispatch Center