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Comparative Analysis of Optimal PMU Placement Methods for State Estimation and Stability Margin Monitoring of Azerbaijans Power System

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Abstract — **To solve the problem of optimal placement of phasor measurement units (PMUs), we compare a method of integer linear programming and a method based on estimating the rate of change in operating parameters under heavy load conditions and disturbances. The former method solves the problem of optimal PMU placement in Azerbaijan's power system with respect to the criterion of full observability. The latter one investigates the rate of change in relative angles of synchronous generators under major disturbances and the rate of change in voltage and its phase in essential cutsets under increased load. The highest rates of change in operating parameters reveal weak nodes where PMUs should be installed.**

Index Terms: **phasor measurement unit, integer linear programming, load conditions, optimal placement, electric power system control.**

Abbreviations

CHPP	–	combined heat and power plant
EMS	–	energy management system
EU	–	European Union
ILP	–	integer linear programming
OHL	–	overhead lines
PDC	–	phasor data concentrator
PMU	–	phasor measurement unit
PP	–	power plant
SCADA	–	supervisory control and data acquisition
TPP	–	thermal power plant
UES	–	unified energy system
WACS	–	wide-area control system
WAMS	–	wide-area monitoring system
WAPS	–	wide-area protection system

I. INTRODUCTION

Combating climate change, reducing greenhouse gas emissions, and meeting commitments under the Paris Agreement pose large-scale challenges for the energy sector being the largest contributor to climate change.

Within the framework of fulfillment of commitments under the Paris Agreement Azerbaijan has undertaken obligations to reduce the share of CO2 by 35% by 2030, compared to 1990 levels, and bring the share of green power to 30% by installing 1 500 MW of renewable energy capacity.

The agreement signed between the governments of the Republic of Azerbaijan, Georgia, Romania, and Hungary on strategic partnership focusing on green energy expansion and transmission envisages the transfer of 4 GW of wind power from the Azerbaijan sector of the Caspian Sea to the European Union countries in the next five years.

The world's longest electric cable will connect Azerbaijan and Europe, laying a green energy bridge between the Caspian region and the EU.

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The goal is to boost the transmission of clean energy from the Caspian Sea to EU countries to 25 GW by 2037. To this end, different transmission schemes are examined: with integration into the power system, without integration into the power system, and asynchronous integration into the power system of Azerbaijan. In all cases, the large volume of transmitted power over long distances places stringent requirements on the reliability, stability, and resilience of Azerbaijan's power system.

The high requirements for reliability and resilience of Azerbaijan's power system, which is the key entity in such interconnections as Azerbaijan–Georgia–Romania–Hungary, Azerbaijan–Turkey–Greece, and Russia–Azerbaijan–Iran, necessitate the intelligentization of the power system [1–3].

II. WAMS AS AN INNOVATIVE INFORMATION AND MEASUREMENT SYSTEM

A most important component of the concept of intelligent power systems is an innovative information and measurement system based on phasor (vector) technology of real-time measurement. One of such systems is wide-area monitoring system (WAMS). PMU is an integral part of its structure, along with WACS, WAPS, and PDC systems [4–6]. WAMS provides information about the power system state every 20 ms with the measurement accuracy of ± 0.1% for voltage, ± 0.2 deg for phase angle, ± 0.2% for current, ± 0.01 Hz for frequency, and ± 0.20 for the angle between branch current and node voltage.

The vector of measurements performed by the PMU is represented as:

$$Y = [U_i\ b_i\ I_{ij}\ \Psi_{ij}], \tag{1}$$

where U_i is voltage magnitude of the i-th node; b_i is voltage phase of the i-th node; I_{ij} is the current flowing from the i-th node to the j-th node; Ψ_{ij} is the phase shift between current and voltage.

The system SCADA/EMS has already been installed and put into operation in Azerbaijan's power system.

The huge functionality of the system SCADA/EMS notwithstanding, it is outperformed by WAMS in several indices, including synchronization of measurements, volume, speed, and accuracy of information transfer. Tasks such as oscillatory stability monitoring, disturbance detection, event logging, post-fault analysis, and other tasks that require millisecond-order synchronous phase measurements are difficult to accomplish by means of SCADA/EMS. Under these conditions, the best performance is achieved by combining the capabilities of both SCADA/EMS and WAMS.

As mentioned above, the system SCADA/EMS has already been put into operation in Azerbaijan's power system, hence the focus should be on the PMU placement [7, 8].

One of the main criteria for optimal placement of PMUs in the power system is the criterion of full observability of the power system, which means that the number and composition of measurements suffice to control the power system operation under all conditions (before/during/after the accident). Naturally, this criterion (the observability criterion) can be met if PMUs are installed at all nodes.

However, the high cost of PMUs themselves with their current and voltage channels, the need to link these channels to the data concentrators (PDCs) at the locations of the latter, etc. requires a preliminary study.

Full observability can be ensured by using the measurements of voltage at the nodes with PMU and currents coming from these nodes to calculate the voltage and current at adjacent nodes. In this case, accuracy is preserved.

In the context of power system state estimation, where the identification of the power system layout plays a crucial part, of great importance is the topological aspect of observability, which is based on a linear system of equations.

The problem of optimal PMU placement in Azerbaijan's power system is solved by integer linear programming (ILP), where the extreme value of a linear function of many variables is found subject to linear constraints that relate these variables. In this case, the integer constraint is imposed on the variables. The original function to be minimized is represented as:

$$\min \sum_{k=1}^{N} x_k, \quad \mathrm{Ax} \geq \mathrm{b}, \tag{2}$$

where: N – the number of nodes in the system; x – a binary solution vector; A – an integer matrix, the structure of which depends on the network layout; b – an integer vector. In (2), the elements of matrix A take the following values:

$$a_{ij} = \begin{cases} 1, & \text{if } i = j, \\ 1, & \text{if } i \text{ and } j \text{ are connected,} \\ 0, & \text{if } i \text{ and } j \text{ are not connected,} \end{cases}$$

$\mathrm{x} = |x_1, x_2, \ldots, x_N|^{\mathrm{T}}$, where

$$x_i = \begin{cases} 1, & \text{if a PMU is installed an node } i, \\ 0, & \text{if there is no PMU,} \end{cases}$$

$$\mathrm{b} = |1,1,1,\ldots,1|^{T}_{1\times N}.$$

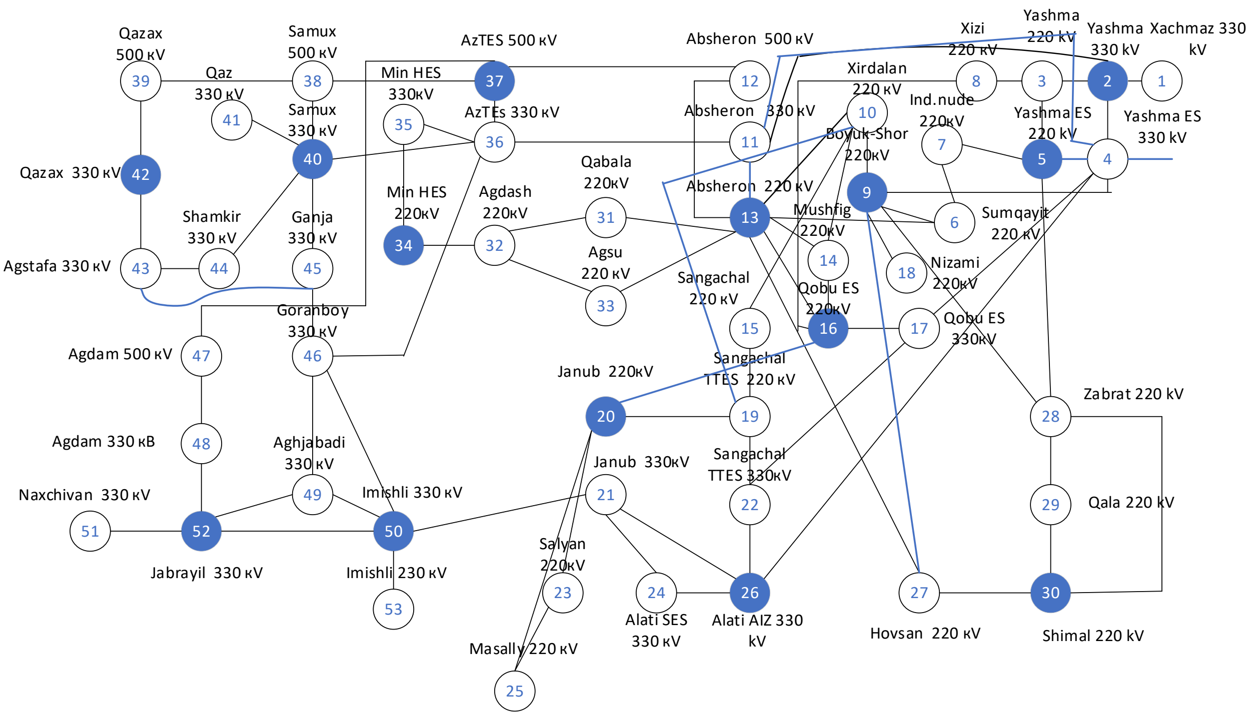

Fig. 1. Layout of the 500–330–220 kV network of Azerbaijan's power system (with PMUs indicated).

The ILP method is applied to a future possible layout of the 500–330–220 kV grid of Azerbaijan's power system, which has 53 nodes, including 24 nodes in the 500–330 kV grid and 29 nodes in the 220 kV grid (Fig. 1). Decomposition was made along the tie lines with the power system of Russia (330 kV OHL Khachmaz–Derbent), power system of Georgia (550 kV OHL Samukh–Gardabani, 330 kV OHL Agstafa–Gardabani), and power system of Iran (230 kV OHL Imishli–Parsabad, 330 kV OHL Imishli–Taqi–Dizaj).

The calculations implemented in the Matlab environment yielded the following PMU placement by node:

$$x = (0\ 1\ 0\ 0\ 1\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 1\ 0\ 0\ 1\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 1).$$

These results indicate that full observability can be ensured by placing PMUs at 14 nodes (26% of the total number of nodes) of the power system, namely:

2 – 330 kV Yashma Substation (S),
5 – 220 kV Yashma Power Plant (PP),
9 – 220 kV Boyukshor S,
13 – 220 kV Absheron S,
16 – 220 kV Qobu 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 Azerbaijan TPP,
40 – 330 kV Samukh S,
42 – 330 kV Gazakh,
50 – 330 kV Imishli S,
52 – 330 kV Jabrayil S.

At the nodes adjacent to these nodes, observability is provided computationally by voltage and power flow measurements from the nodes where PMUs are installed. The analysis of the computational results shows the following. Each PMU has one voltage channel. The PMU at the 220 kV Absheron substation (node 13) has the highest number of current channels (9 channels). The node is essentially a boundary node for two decomposition subsystems: 500–330 kV (transmitting part) and 220 kV (receiving part) of Azerbaijan's power system.

A PMU with 5 current channels is installed at the 330 kV Imishli substation (node 50), which is the boundary node for the interconnection with the power system of Iran from the side of Azerbaijan's power system.

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

If the cost per channel is 1 notional unit, then the PMU cost would be 60 notional units.

Observability at the nodes of intersystem tie lines with the power system of Georgia (nodes 39, 42 and 43) and the power system of Russia (node 1) is provided by calculation (either for branches on the PMU side at the adjacent nodes of Azerbaijan's power system or the corresponding neighboring power systems).

Measurements of voltage phases at the ends of lines of the key cutsets of the transmission part (e.g., 37-12, 36-11, 34-13, 50-21) enables real-time monitoring of transfer capability and steady-state stability margins.

The data from the PMUs installed at busbars of the 500 kV Azerbaijan TPP (node 37), 220 kV Janub plant (node 20), and 220 kV Shimal plant (node 30), as well as the data obtained by calculation at busbars of the 330 KV Azerbaijan TPP (node 36) and the 220 kV Sumgait plant (node 6) are merged with information from SCADA/EMS at the same nodes, which allows monitoring the dynamic processes under major disturbances.

III. PMU PLACEMENT AT “WEAK” COMPONENTS OF THE POWER SYSTEM

In the previous section, the sites for PMU placement in the 500–330–220 kV grid of Azerbaijan's power system were determined based on topological rules ensuring full observability of the power system. To that end, the integer linear programming method was used. It was recommended to install PMU at 14 nodes (≤ 27%) for the 53-node scheme of the 500–330–220 kV network (76 branches). The dynamics of operating parameters at other nodes and adjacent branches is calculated based on the measurements performed by installed PMUs.

Another approach to addressing the placement problems can be based on the physical content of the processes occurring in the system during disturbances. It is based on such concepts as heterogeneity, sensitivity, sensing capability, and weakness of the components of the topological structure of the power system.

In what follows we focus on the last two concepts being the sensing capability and “weakness” of components, which may suffice to solve the above problem.

Sensors are power system components whose operating parameters change to a large extent with random changes in such power system components as generation units, the grid, loads.

Weak components of the power system are those whose parameter changes have the greatest impact on the power system response to disturbances [9–11].

The uncertainty of the power system structure, operating conditions, disturbances, and the nature of dynamic processes under disturbances has led to differences in approaches applied to identify weak spots in the power system.

One such approach is a technique based on comparing the rate of change in operating parameters U, P, and δ under heavy-load conditions or disturbances, where U is node voltage, P is active power (stations, power transmission lines), and δ is relative angle between generators. Below we present examples of the approach in use.

The scheme and operating conditions taken as a basis are characterized by the following parameters:

$$P_G = 4\ 459 \text{ MW},\ P_L = 4\ 330 \text{ MW},$$

where P_G is generation power, P_L is load power,

power transfer to Iran's power system	– 500 MW,
including from the UES of Russia	– 300 MW,
from Azerbaijan's power system	– 200 MW.

IV. RATE OF CHANGE IN RELATIVE ANGLES OF SYNCHRONOUS GENERATORS UNDER MAJOR DISTURBANCES

The outage of the 2nd 500 kV Absheron overhead line during the power flow of 464 MW without auto-reclosing was taken as a disturbance.

To compare the intensity of the dynamics of change in the angles, Table 1 shows the rates of change in relative angles between the main synchronous generators of the power system in the first swing cycle after disturbances (here δ_0 is initial relative angle, t_0 is initial relative time). They were calculated using the equation

$$V_\delta = \frac{\delta_{\max} - \delta_{\min}}{360\left(t_{\max} - t_{\min}\right)},$$

where V_δ is rate of angle change in the first swing cycle, $\delta_{\max}$ is maximum relative angle, $\delta_{\min}$ is minimum relative angle, $t_{\max}$ is time corresponding to the maximum relative angle, $t_{\min}$ is time corresponding to the minimum relative angle.

According to the Table, the highest rate of change in relative angles occurred between the following synchronous generators:

Azerbaijan TPP, 500 kV – Baku CHPP
Azerbaijan TPP, 500 kV – Shimal TPP
Azerbaijan TPP, 500 kV – Sumgait TPP
Azerbaijan TPP, 330 kV – Baku CHPP
Azerbaijan TPP, 330 kV – Shimal TPP

Therefore, for the purposes of monitoring of mutual angles on voltage busbars of synchronous generators it is advisable to install PMUs at the 500 kV Azerbaijan TPP and 330 kV Azerbaijan TPP in the surplus capacity part,

Table 1. Rates of the Change in the First Swing Cycle After Disturbances

	No.	δ_0	$\delta_{\max}$	t_0	$t_{\max}$	V_δ
Azerbaijan TPP, 330 kV – Shimal PP	152-170	19	36.1	1.1	1.68	0.081
Azerbaijan TPP, 500 kV – Shimal PP	157-170	18.48	40.63	1.1	1.64	0.114
Janub PP – Shimal PP	170-211	10	–0.20	1.1	1.8	0.042
Azerbaijan TPP, 330 kV – Janub PP, 110 kV	152-211	29	36.49	1.1	1.56	0.045
Azerbaijan TPP, 330 kV – Sumgait PP, 220 kV	152-181	28.2	41.39	1.1	1.58	0.076
Azerbaijan TPP, 500 kV – Sumgait PP, 220 kV	157-181	27.69	46.33	1.1	1.56	0.113
Azerbaijan TPP, 330 kV – Baku CHPP	152-43	21.98	41.31	1.1	1.62	0.103
Azerbaijan TPP, 500 kV – Baku CHPP	157-43	21.46	46.08	1.1	1.60	0.138
Janub PP, 110 kV – Sumgait PP, 220 kV	211-181	–0.8	4.93	1.1	1.60	0.116
Janub PP, 110 kV – Baku CHPP	211-43	–7.02	5.17	1.1	1.66	0.060
Shimal PP – Baku CHPP	170-43	2.98	6.44	1.1	1.46	0.027
Shimal PP – Sumgait PP, 220 kV	170-181	9.2	3.7	1.1	1.78	0.023

Table 2. Values of Power for the Cutset Lines, Voltage at The Ends of Lines, and Their Phases

	Original conditions				Feasible conditions				Limiting conditions			
	P, MW	*U*, kV		δ^0	*P*, MW	*U*, kV		δ^0	P, MW	*U*, kV		δ^0
		U_L	U_k			U_L	U_k			U_L	U_k	
500 kV OHL Azerbaijan TPP – Absheron	433	504	463.3	7.8	468.4	504	460.3	8.5	581	493.4	431.8	11.4
330 kV OHL Azerbaijan TPP – Absheron	193	335.45	305.9	7.6	219	335	304	8.7	300	326.7	284.3	13.3
330 kV OHL Goranboy–Imishli	206.9	330.38	314.5	5.9	229.5	329.3	313	–6.6	305.3	318.3	294.6	9.7
330 kV OHL Goranboy–Agjabedi	317.1	330.38	316.2	4.4	351.3	329.3	314.4	5	458.8	318.3	296.1	7.1
220 kV OHL Mingechevir HPP–Aghdash (1)	113.9	231.41	228.2	2.2	123.3	231	227	2.3	151.6	221.4	216.1	3.1
220 kV OHL Mingechevir HPP–Aghdash (2)	113.9	231.41	228.2	2.2	123.3	231	227	2.3	151.6	221.4	216.1	3.1

and at the main stations in the part with the capacity shortage (Shimal TPP, Sumgait PP, Baku CHPP).

V. Rate of Change in Voltage and Its Phase in Cutset 2 Under Heavy-Load Conditions

Under the same initial operating conditions, the process of increasing the load forcing power system to operate under heavy-load conditions is initiated and the dynamics of change in the operating conditions of (500–330 kV) line of cutset 2 is considered successively: initial (1 378 MW), feasible (1 515 MW = 0.8 $P_{\lim}$ – 43, $P_{\lim}$ is limit power) and limiting (1 948 MW) conditions. Table 2 (where U_L is line start voltage, U_k is line end voltage, δ_0 is initial voltage phase) shows the values of power along cutset lines, voltage at the ends of lines, and their phases under the considered operating conditions.

Tables 3 and 4 presents the values of the rates of change in voltage at the ends of the cutset lines and the phase difference at the ends of these lines during the stepwise transition from the initial to the limiting conditions during the process of load increase.

The rate of change in voltage V_U was calculated using the following equation:

$$V_U = \frac{\Delta U_i}{\Delta P_i} \frac{P_{mi}}{U_{Ni}},$$

Table 3. Rate of Change in Voltage at The Ends of the Lines of Cutset 2 Under Heavy-Load Conditions

Cutset line	$P_{\text{in}}\rightarrow P_{\text{feas}}$	$P_{\text{feas}}\rightarrow P_{\text{lim}}$
500 kV OHL Absheron 2	0.1	0.294
330 kV OHL Absheron 1	0.0654	0.221
330 kV OHL Goranboy–Imishli	0.053	0.229
330 kV OHL Goranboy–Aghdash	0.071	0.266
220 kV OHL Mingechevir HPP–Aghdash	0.089	0.226

Note: P_{in} is initial power, P_{feas} is permissible power.

Table 4. Rate of CHANGE in Voltage Phase Difference at the Ends of the Lines of Cutset 2 Under Heavy-Load Conditions

Cutset line	$P_{\text{in}}\rightarrow P_{\text{feas}}$	$P_{\text{feas}}\rightarrow P_{\text{lim}}$
500 kV OHL Absheron 2	0.198	0.26
330 kV OHL Absheron 1	0.221	0.296
330 kV OHL Goranboy-Imishli	0.167	0.217
330 kV OHL Goranboy-Aghdash	0.140	0.156
220 kV OHL Mingechevir HPP-Aghdash	0.0284	0.0738

Note: $P_{\text{feas}} = 0.8\ P_{\text{lim}}$.

where ΔU_i, ΔP_i is voltage and power change at the end of the i-th power flow line; U_{Ni} is nominal voltage value; P_{mi} is value of power on the i-th line under the limiting conditions.

The rate of change in voltage phase difference at the ends of the lines V_δ is calculated using the following equation:

$$V_\delta = \frac{2\pi}{360}\frac{\Delta\delta_{ij}}{\Delta P_i}P_{mi},$$

where $\Delta\delta_{ij}$ is voltage phase difference at the ends of the considered line; ΔP_i is change in power on the i-th line under the limiting conditions, P_{mi} is power value on the i-th line under the limiting conditions.

Analysis of the data presented in the table attests to the following:

1. The rate of voltage drop increases as the limiting conditions are approached, it occurs to the greatest extent at the end of the 500 kV OHL Absheron 2, i.e., at the 500 kV Absheron substation.
2. The rate of increase in the voltage phase difference at the ends of the cutset lines rises as well, and it occurs most intensively along the 330 kV OHL Absheron 1.

These findings indicate that control of voltage and its phase under the minor disturbances along cutset 2 should be carried out at the 500 kV Absheron and 330 kV Absheron substations.

The results support the conclusions on the installation of PMUs in the power system, which were reached by applying the integer linear programming technique.

According to Fig. 1, phasor measurements at 500 kV Azerbaijan TPP are carried out by a PMU, and at 330 kV Azerbaijan TPP, 500 kV Absheron substation, and 330 kV Absheron substation, they are calculated based on measurements at opposite ends of adjacent branches.

This study provided the rationale for additional installation of PMUs at the plants of the network part that experiences the capacity shortage, i.e., the Sumgayit power plant and Baku CHPP.

VI. CONCLUSION

The sites for placement of PMUs in Azerbaijan's power system and their number obtained by integer linear programming were in strict compliance with the criterion of topological observability. However, their high cost, which is due to both their number and the number of current channels, requires adjustment of the obtained results to match operating conditions specific to the power system. The available tie lines used for transit flows and the presence of critical cutsets in Azerbaijan's power system drive the need for PMU placement at "weak" points, where measurement-based monitoring of the stability and voltage levels, damping properties, low-frequency oscillations, and others are necessary.

In addition to complying with the observability criterion, which factors in the specific features of operating conditions, the future layout of Azerbaijan's power system necessitates PMUs to be installed at the busbars of power plants in the deficient part of the power system.

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