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Department of Astronautical, Electrical and Energetic Engineering

University of Rome “Sapienza”
Via Eudossiana 18 – 00184, Rome, Italy
email: luigi.martirano@uniroma1.it, rodolfo.araneo@uniroma1.it

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SCADA system with power quality monitoring in Smart Grid model

Michal Regula, Alena Otcenasova, Marek Roch, Roman Bodnar, Michal Repak
Department of Power Electrical Systems
Faculty of Electrical Engineering, University of Žilina
Žilina, Slovak Republic
michal.regula@kves.uniza.sk

***Abstract* — The paper deals with designing and implementation of Smart Grid model with designing of power quality measurement software in these networks. There was created a simulation model which has the same parameters setting as the real network. Various renewable energy sources represented by small hydropower plant, photovoltaic power plant and wind power plant are integrated in the designed scheme of Smart Grid. A part of the real network model in laboratory environment is controlling and evaluating SCADA system which was designed in LabVIEW programme. This system provides real-time control of power switching relays, obtains information about their status and performs three-phase measurement. The basic system displays information about voltage, current, and total harmonic distortion. SCADA system can perform detailed power quality measurement in individual points. The system supplies three types of customers, namely industrial zone, a city and two villages. The entire system is connected into a mash-grid structure. Several analyses and measurements were carried out for the given structure in order to obtain results for optimal operation of the network focusing on the power quality in Smart Grid.**

Keywords* — *power quality, Smart Grid, electromagnetic compatibility, SCADA, total harmonic distortion, renewable sources

I. INTRODUCTION

The result of this progress and effort to produce "green energy" is the introduction of renewable energy sources (RES) and other devices used for production or consumption of electrical energy. (e.g. static frequency converters (inverters), cycloconverters, inverter cascades, induction motors and others). It is proved that these devices adversely affect the ideal sine in electrical power system, or eventually may have an indirect impact on short-term or long-term interruption of the electricity supply. At electricity buyers, this fact can cause incorrect operation of devices and it can even cause damage to these devices in extreme cases. The issue of power quality is a matter of technical solutions and legislative measures focused on adhering to the prescribed quality as the obligation of the participating entities carrying out the electricity supply [1], [2], [3], [4].

Customer and supplier commit themselves to contractual relation, where the contractor guarantees to customer supplying electricity of a specified quality. However, the contractor is unable to predict power cuts on the side of electricity production and supply with certainty. However, if the consumer suffers financial losses due to poor PQ, he would have the right to claim financial compensation according to current legislation and an agreement between supplier and customer. An alternative solution for the customer and supplier is to ensure PQ at customer´s own expense. Also such solutions help consumers, not only in protecting their own business against power cuts and financial losses, but greatly contributes to increasing PQ in the connecting point and its surroundings [1], [4], [5], [6], [7].

II. SMART GRID

Smart Grid and smart metering in SG in the world are implemented in a very wide spectrum. Their utilization purposes are different. Some of them are used for research, testing technologies, etc. This section addresses power quality monitoring in the distribution network which is involved in the mash-grid structure. Mash-grid structures are considered in SG projects in order to achieve the interconnection of all sources, appliances and energy storage in the network, because of the best value for electricity [4], [5], [7]. The whole model of the SG is designed to monitor the quality parameters of electricity. The model consists of several blocks, individual power line segments from production to consumption [10]. Definitely, the entire model was filled in all ancillary and protective equipment necessary for its proper functioning. There were used various models of transformers, digital and analog protections serving for protection of distribution system outlets [8]. The model also includes Peterson coil as well as the ability to connect FACTS devices such as Static Var Compensator (SVC) and Dynamic Voltage Restorer (DVR) [9]. Essential elements for controlling and measuring are different measuring points where at the beginning of outlets serve for this purpose used protection and at other specified points were created universal units of measurement and control (power switch), which are controlled by PC software where measured data are also processed [8], [9], [10].

The entire smart grid model is constructed so that there was interconnectivity among centralized production of superior system and local RES within the distribution system. As the superior system was used programmable source with software enabling remote control. A group of RES models is based on wind power plant model, photovoltaic power plant model and model of small hydro power plant. PQ was monitored in several voltage levels in the created distribution system. For this purpose there were used

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transformer model (110/22 kV), in the real version in a ratio of 400/220 V, and distribution transformer model (22 / 0.4 kV) in the real diminished version 220/4 V [10]. The 22 kV line model is constructed in 1:100 scale. It consists of different modules, representing the line lengths of 2.5 km, 5 km a 10 km using AlFe 95/15 wire in a planar arrangement of conductors on concrete towers.

III. SCADA SOFTWARE DRAFT FOR MEASURING IN SMART GRID NETWORK WITH USING LABVIEW

Created SCADA system has several advantages, mainly in terms of using for teaching purpose. As it is shown in Fig. 1, the system operates with nine measured remotely managed nodes. Each node contains ON/OFF button, which can be used to control power switching element of universal measuring block. This block of network each time sends a file with analog measured parameters and their average values are displayed in the main window of SCADA system. Specifically, it is the average values of voltage and current, total active and reactive power and out of the quality parameters it is a parameter of total harmonic distortion of voltage and current. The operator thus has the possibility to monitor clearly what is happening in the given network and operatively manages individual production and supply points in the network. Of course, any parameter can be added to be displayed in the main scheme. But in this case, there were used only the most important parameters for the determination of power flow. All more detailed measurements in the individual nodes are displayed to an operator after clicking on blue button „Measurement“. Here are the options to display all measured and calculated values for the individual phases, and also preview of the oscilloscope records of voltages and currents waveforms according to his choice. There is also possibility to select a vector diagram, FFT analysis for individual measured signals, unbalance measurement and other parameters which are more detailed described in the chapter IV.

There is also a yellow window „Control“ for each source of electrical power. After clicking this window operator has an option of managing individual energy sources. Operating was carried out by means of Compact RIO Hardware with module NI9205 (32 analog I/O) from National Instrumental Company. For RES there were used the following outputs:

- photovoltaic power plant - software for control of panel temperature and light intensity using two analog outputs in a range of ± 10 V,
- wind power plant - software for control of wind speed using an analog output in a range of ± 10 V,
- small hydro power plant – software for control of opening the jet with using the analog output in a range of ± 10 V,
- PCC (superior system) – infinitely software for voltage control at programmable source from Applied Precision Company.

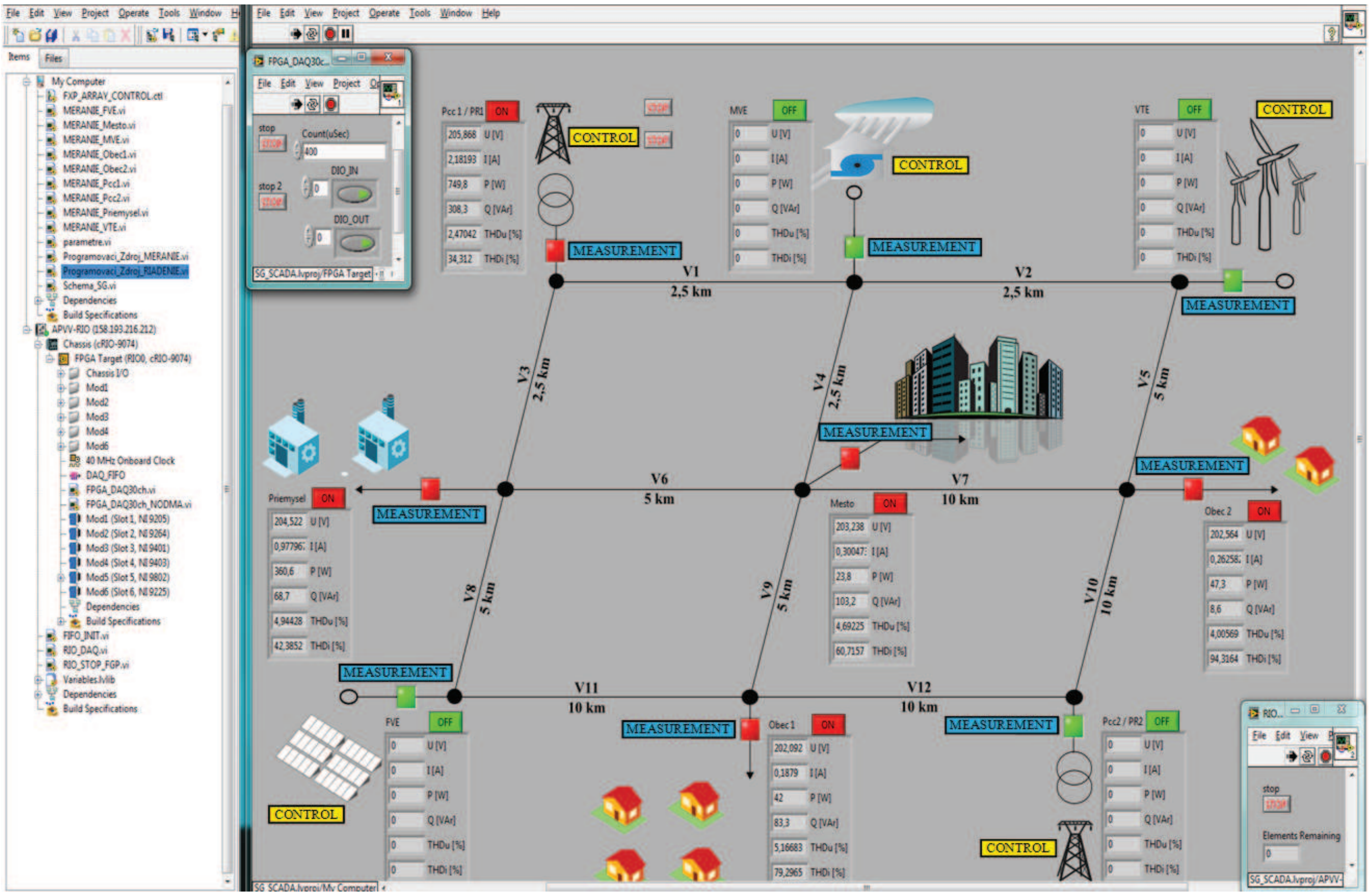

Fig. 1. Developed SCADA system

IV. SOFTWARE FOR POWER QUALITY MEASUREMENT

Measurement was carried out in several parts which were formed as individual SubVI. All these SubVI, as well as other additional subprograms, are linked in the main program of measurement for the single node. As shown in the designed scheme, there are 9 nodes, where each has a separate program for power quality measurement. The difference among single nodes measurements are only channels of measurement which are processed for a particular point. Front panel of the main VI (Fig. 2) can be divided into two parts, where the left side shows all parameters for each phase and total power and the right side displays the window with cards where is the possibility of switching display with the vector diagram (Fig. 3), oscilloscope, harmonics analysis (Fig. 4), voltage ratio between individual phases in a given node and frequency measurement. All data are distinguished by color, as well as at commercial devices, where the values of the phase A (L1) are in red color, the values of the phase B (L2) are blue, and the values of the phase C (L3) are green.

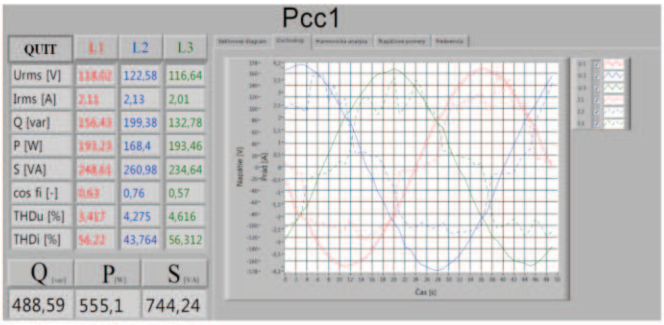

Fig. 2. View of the Front panel for measurements in the point Pcc1

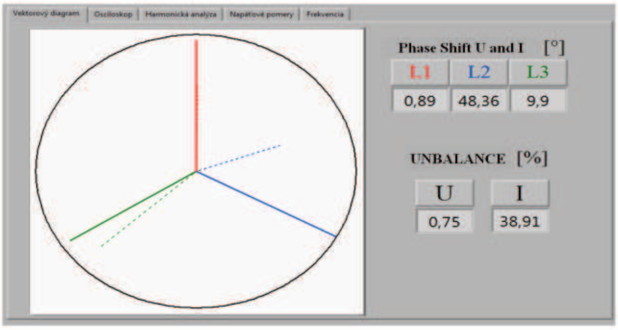

Fig. 3. Displaying of vector diagram

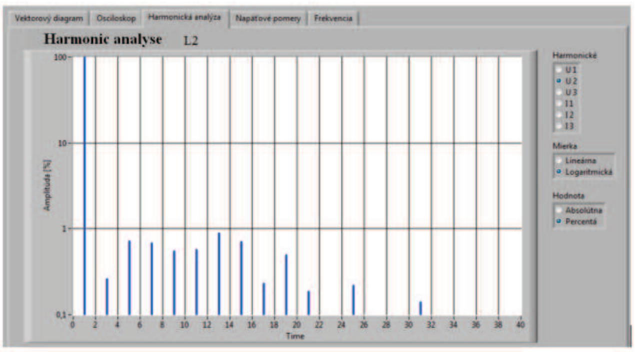

Fig. 4. Harmonic analysis

V. DRAFT OF THE NETWORK SIMULATION MODEL

After designing software for power quality measurement and verifying its proper operation, measurement results are appropriate to be implemented in the simulation model. Correctly designed simulation model on the one hand confirms the accuracy of the obtained results and on the other hand it is possible to design and implement various devices for power quality improvement in individual points of power supply. After individual compensation devices designing and debugging in the simulation model, compensation devices can be created for the real model. To create a simulation model there was used software MATLAB/Simulink. By using this simulation tool there was made the same scheme as used for real measurements in completed SG network. Firstly, it was necessary to parameterize individual blocks of the network lines. As a network block there were used three-phase π-cells, because the real line model consists just of π-cells. All the blocks of line are in the simulation model (Fig. 7) highlighted in gray color. Secondly, it was necessary to construct a simulation tool for the superior network. In the real model, there was used programmable source and subsequently transformer 400/220 V. In the simulation model there was created three-phase transformer in a 1: 1 scale with real transformer and instead of programmable source there was constructed own model of programmable source (Fig. 5). In the programmable source an operator can set the content of higher order harmonics up to the 15th harmonic, for each phase separately. This way operator can set any superior system, both in terms of harmonic distortion and short circuit power.

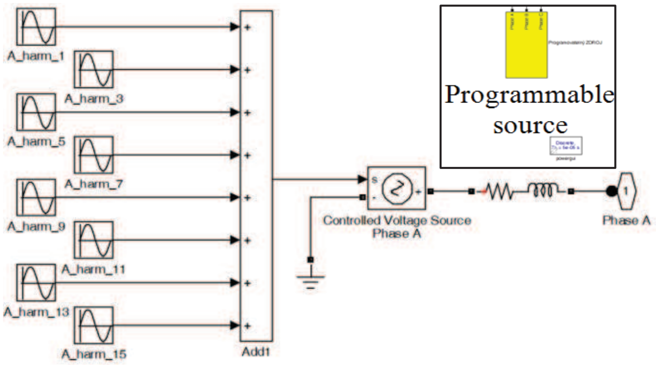

Fig. 5. The model of programmable source for one phase (similar for tree phases)

Next step of the simulation model creation was to create a block of universal load. All the blocks of universal load are in the simulation model (Fig. 7) highlighted in green color. In the block of universal load, an operator is allowed to set various character, shape and size of current consumption in the different points of delivery. Created blocks which were used in the block of universal load are:

- dynamic load - using this load it is possible to set the size of active and reactive power, as well as whether this power is consumed by the network or delivered to the network,

- three-phase RLC load – in this load can be set consumption of active and reactive power of inductive and also capacitive character,
- three-phase rectifier bridge – this bridge by its consumption type replaces all devices containing rectifiers, where it is possible to set size and shape of consumed current according to RLC element size on directed side,
- created model of programmable current source – this model is used for settings of higher order current harmonics up to the 15th harmonic for each phase separately. Thus an operator is able to replace any appliance in the network and spectrum of current harmonics measurements can be carried out on it. The maximum harmonic order is selected based on experience from harmonics measurements in the network, because higher order harmonics not often occur above the permissible values. However, whenever the operator is able to fill in above or even odd components.

Beside the main power supply network, there were added also models of individual RES to the model. As it was defined in the basic scheme it was a source of small hydro power plant, wind power plant and photovoltaic power plant. The model of small hydro power plant was created according to the real model of hydro power plant with Pelton turbine constructed in our department. For wind power plant model there was used model with asynchronous generator. We have used also the photovoltaic power plant model which consists of three basic parts, namely the field of PV cells, DC-DC converter and AC-DC converter.

For the analysis of total network state, there was created universal measuring block (Fig. 6), which measures parameters in analogy to the SCADA system. These parameters are average value of voltage and current as well as the total active and reactive power. The last two displayed parameters are THD, voltage and current. The operator also has an option after clicking on one of the oscilloscope to display waveforms of voltages and currents. All the measurement blocks are in the simulation model (Fig. 7) highlighted in pale-blue color.

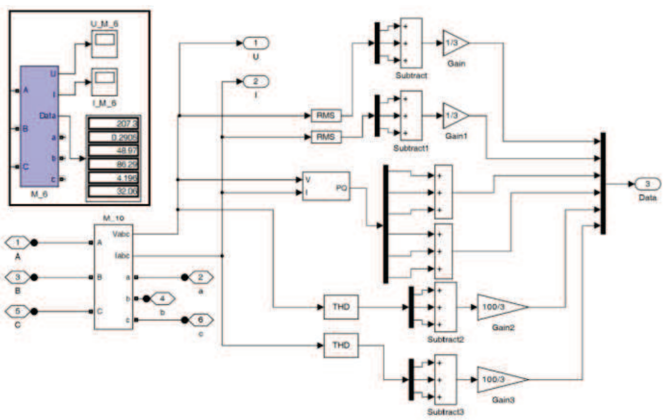

Fig. 6. Measurement unit in the simulation model

Constructed models create the overall concept of SG network, which was used for verification of the measured results. Thus formed simulation can serve as a powerful tool for analyzing results measured in real models. It enables experimental designing and debugging of filtering and compensating devices.

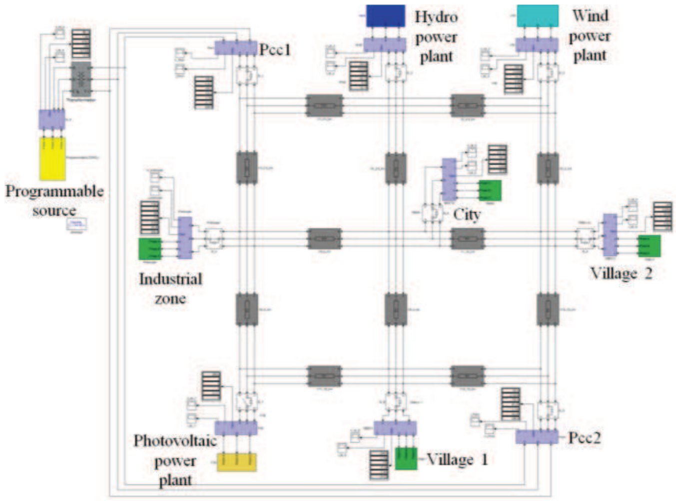

Fig. 7. Complete simulation model

VI. Comparison of the Real and Simulation Model

The values measured in the SCADA system compared to the values measured with PNA device at different variants are shown in the following table.

TABLE I. MEASURED VALUES

	PNA (ENA 330)					*SCADA system in LabView*				
	U [V]	*P* *[W]*	*Q* *[var]*	*THDu* *[%]*	*THDi* *[%]*	*U* [V]	*P* *[W]*	*Q* *[var]*	*THDu* *[%]*	*THDi* *[%]*
Pcc1	206	745	204	2,1	21,1	206	758	207	2,12	21
Industrial	203	374	114	3,87	27,2	204	372	114	3,91	27,4
City	203	159	51,3	4,14	29,1	204	159	51,9	4,18	29,2
Village1	202	125	37,9	4,84	27	203	124	37,8	4,85	27,1
Village2	202	46,9	78,3	4,3	32,9	203	47	78,4	4,28	33,1
Pcc1										
Pcc2	206	712	206	1,7	19	207	714	207	1,7	19,1
Industrial	196	334	109	8,99	25,8	197	334	109	9,12	25,6
City	197	151	50	7,6	28,5	197	151	19,8	7,82	28
Village1	199	119	38,5	6,5	27,1	199	120	37,8	6,48	27,1
Village2	199	46,4	75,8	6,2	31,7	200	47	78,4	6,21	31,8
Pcc2										
Pcc1+2	206	747	204	2,1	21,3	206	750	205	2,15	21,3
Industrial	204	375	113	3,7	27,1	205	376	114	3,81	27
City	204	160	53	3,6	30,2	204	160	53	3,58	30,1
Village1	203	127	38,3	3,88	27,2	203	127	38,3	3,85	27,3
Village2	204	48,2	79	3,33	30,9	203	48	80,1	3,3	31
Pcc1 + Pcc2										
Pcc1+2	208	703	331	1,99	25,2	208	703	331	2,02	25,2
Industrial	206	387	120	3,23	28	207	388	120	3,21	28
City	207	164	46,9	3,06	25	207	164	47,2	3,1	24,9
Village1	206	130	40,8	3,24	28,2	206	130	42	3,19	28,2
Village2	208	48,3	78,9	2,84	31,2	208	48,1	59,1	2,81	31,1
Pcc1 + Pcc2 + RES (Hydro power plant + Wind power plant)										

Undesirable status in the network occurred while supplying from PCC2 where THDU values were exceeded above the limit value laid down in STN EN 50160. This limit is defined at level of 8%. Also, there was decreased voltage value below 90% of the U_N. As the most suitable option of the network power supply was supplying from several points of the network, what in this case is represented by a supply from PCC1 and PCC2 points. The measurement confirmed that when supplying from these points at full network load, there was no exceeding of limit values of qualitative parameters. Electrical rotary machines in generator mode cause increasing of short circuit and suitable location reduces electric distance between the source and appliance. This statement was confirmed by last measurement, where small RES (small hydro power plant and wind power plant) were joined to the system according to the proposed scheme. There was even greater improvement in voltage conditions as well as the total harmonic distortion at individual delivery points.

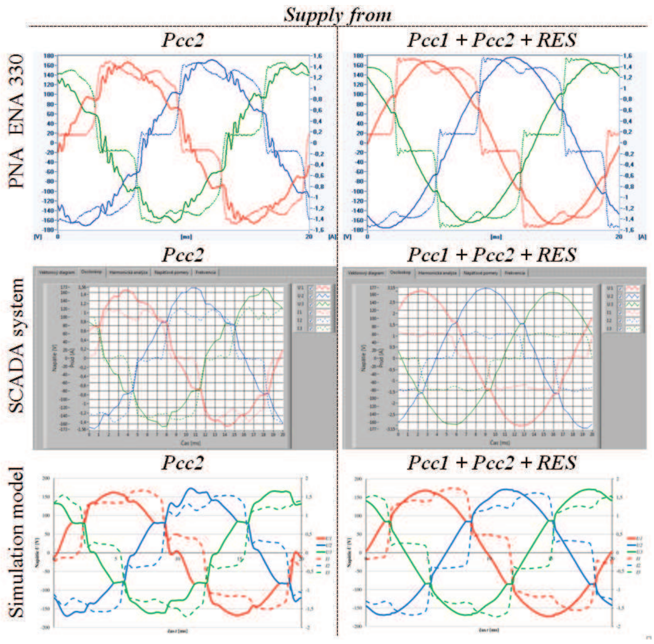

Fig. 8. Waveforms comparison among different systems

VII. Results

In this work we dealt with SG networks and pilot projects of these networks, so that we could subsequently create a laboratory model of SG. In this network, we have tried to achieve an interconnection of centralized production and production of RES for power supplying all customers' types in the network. There was created original controlling and measuring SCADA system, as well as all hardware components for the network analysis. It was also necessary to construct all models of RES and assemble individual supply points by combining different appliances and all other installations.

One of the biggest benefits of this work we consider designed operating and measuring SCADA system for the designed network of SG. An operator of the system can easily control switching elements of the network and monitor electrical parameters changes in the real time. He can monitor changes in power flow, voltage variations and total harmonic distortion at different points of the system, all from a single control unit. Based on the results of this paper, it can be concluded that SG is a feasible system in compliance with several indicators. Connecting RES to the network seems to be the right step, but only at the correct location in the network and at clearly specified conditions for power electronics used in the converters of these RES. It means using of control algorithms in order not to have a negative impact on power quality. The energy sources using synchronous or asynchronous generators cause increased short-circuit power in the network and at close location to the source of consumption results in an improved power quality. As the best operating system in terms of PQ in individual delivery points, was shown the SG system operating with common power supply from several points of superior system and contemporary production from RES. As regards the island operation of the SG system, we cannot confidently talk about ensuring compliance with the quality parameters for individual customers in the system. But this is only an assumption and we propose to build more network elements, such as sources, converters, energy storage devices and programmable loads and incorporate them into the network model. Subsequently, it is appropriate to use created system to manage the entire network in order to comply with the best parameters characterizing power quality.

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