UDC 621.316.1 **doi: 10.20998/2224-0349.2022.02.07**

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INTRODUCTION OF STATE-OF-THE-ART LOW-VOLTAGE DISTRIBUTION NETWORK DEVICES

Trends towards the development of distributed generation involve a number of problems related to maintaining the quality of electric energy in medium and, especially, low-voltage networks. The article examines the impact of monitoring the quality of electricity of low voltage classes on the reliability of the electrical network. MSZ EN 50160 and Hungarian Energy and Utilities Regulatory Office (MEKH) standards are considered. In accordance with MSZ EN 50160, the main indicators of the quality of electric energy are considered, such as: frequency, voltage fluctuations, rapid voltage changes, dose of flicker, voltage dips, short-term voltage interruptions, long voltage interruptions, temporary overvoltages of industrial frequency, transient overvoltages between current-carrying conductors and voltage ground , harmonic voltage fluctuations, interharmonic voltage fluctuations. SAIFI and SAIDI are calculated according to the Hungarian Energy and Utilities Regulatory Office. The devices for monitoring the quality of electricity of low-voltage networks are analyzed. The factors affecting the choice of the place of installation of monitoring devices are considered. It is presented how power quality monitoring systems can reduce the number of malfunctions in the 0.4 kV network, and the influence of monitoring systems on the quality of electric power in 6-35 kV networks is considered.

Keywords: power quality, network monitoring, measurement, distributed generation, smart meter, distribution network.

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ВПРОВАДЖЕННЯ НОВІТНІХ ПРИСТРОЇВ ДЛЯ НИЗЬКОВОЛЬТНИХ РОЗПОДІЛЬНИХ МЕРЕЖ

Тенденції до розвитку розповсюдженої генерації несуть в собі ряд проблем, пов’язаних з дотриманням якості електричної енергії в мережах середньої і, особливо, в мережах низької напруги. У статті розглянуто питання впливу моніторингу якості електроенергії низьких класів напруги на надійність роботи електричної мережі. Розглянуто стандарти MSZ EN 50160 та Hungarian Energy and Utilities Regulatory Office (MEKH). Відповідно до MSZ EN 50160 розглянуто основні показники якості електричної енергії такі як частота, коливання напруги, швидкі зміни напруги, доза флікера, провали напруги, короткочасні перебої напруги, тривалі перебої напруги, тимчасові перенапруги промислової частоти, перехідні перенапруги між струмопровідними провідниками та землею напруги, гармонічні коливання напруги, інтергармонічні коливання напруги. Відповідно до Hungarian Energy and Utilities Regulatory Office розраховані SAIFI та SAIDI. Проаналізовано пристрої моніторингу якості електроенергії низьковольтних мереж. Розглянуто фактори, що впливають на вибір місця встановлення пристроїв моніторингу. Представлено, як системи моніторингу якості електроенергії можуть зменшити кількість несправностей у мережі 0,4 кВ та розглянуто вплив систем моніторингу на якість електричної енергії у мережах 6–35 кВ.

Ключові слова: якість електроенергії, моніторинг мережі, вимірювання, розподілена генерація, розумний лічильник, розподільна мережа.

Introduction. The current stage of the development of electrical networks indicates the need to transition from centralized to distributed generation of electrical energy. This concept has both advantages and a number of questions that require research. Usually, renewable energy sources in electrical networks are connected at low voltage, so one of the main issues is the issue of the quality of electrical energy in low-voltage networks. The issue of quality is regulated by both international and state regulatory documents, namely MSZ EN 50160 standard and the Hungarian Energy and Utilities Regulatory Office (MEKH). Since MEKH can determine indicative quality indicators such as SAIFI, SAIDI and the Expected Energy Consumption Index every year, and revoke the licenses of distributors that do not meet the requirements, all energy suppliers are interested in the continuous improvement of the quality of their services. So let's look at how you can improve the quality of electricity in terms of the transition to distributed electricity generation.

Purpose of the article. Examine quality indicators according to MSZ EN 50160 standard and the Hungarian Energy and Utilities Regulatory Office (MEKH).

Power quality indicators according to MSZ EN 50160. In order to ensure the long-term economic sustainability of the quality of service, the electricity suppliers aim to continuously improve the power quality indicators of the networks.

The power quality indicators for voltage, based on MSZ EN 50160, are provided in Tables 1 and 2 [1].

Measuring and testing of the power quality according to MSZ EN 50160 requires special devices and methods of measurement. The measuring instrument and measurement arrangement defined by the standard are suitable for continuous monitoring of the following characteristics for 7 days: voltage, frequency, voltage harmonic distortion factor (THD_U), voltage unbalance factor. These are multiple positive and negative order voltage components, fast and slow voltage changes, which are short-term (P_{st}) and long-term (P_{lt}) and can be determined by the flicker rate:

$$P_{lt} = \sqrt[3]{\sum_{i=1}^{12} \frac{P_{sti}^3}{12}}. \qquad (1)$$

The standard-compliant equipment is also capable of measuring voltage dips and interruptions, their frequency and duration. The measured characteristics are to be processed and recorded with 10-minutes time intervals, called segments (1008 intervals in 7 days). For each time interval, the measured typical average value is to be calculated [2].

Table 1 – Quality indicators based on MSZ EN 50160

No.	Characteristic	Voltage characteristics according to MSZ EN 50160
1	Frequency	LV[a], MV[b]: average value of the base harmonic frequency measured over 10 seconds time intervals; ±1% (49.5–50.5 Hz) for 99.5 % of the week; -6%/+4% (47–52 Hz) for 100 % of the week
2	Supply voltage variations	LV, MV: ±10% during 95 % of the 10-minute root-mean square (RMS) values over each one week period (Fig. 1)
3	Rapid voltage changes	LV: usually 5 %, rarely 10 %, only indicative values are given MV: usually 4 %, rarely 6 %, only indicative values are given
4	Flicker	The aggregation interval is 10 minutes LV, MV: long term severity $P_{lt} \leq 1$ for 95 % over an observation period of one week
5	Supply voltage dips	In general: duration < 1 second, depth < 60 %. Locally occurring breaks due to loads, switching: LV: 10–50 %, MV: 10–15 % (Fig. 1)
6	Short voltage interruptions	LV, MV: duration ≤ 3 minutes, occurrence from a few tens to a few hundred times per year. Duration of 70 % of them is < 1 second
7	Long voltage interruptions	LV, MV: duration > 3 minutes, < 10–50 times/year
8	Long voltage interruptions	LV, MV: duration > 3 minutes, occur < 10–50 times per year
9	Temporary power frequency overvoltages	LV: magnitude < 1.5 kV, RMS MV: magnitude from 1.7 U_c (for solid or impedance earth networks) up to 2.0 U_c (for unearthed or resonance grounded networks), where U_c is the declared voltage
10	Transient overvoltages between live conductors and earth	LV: usually < 6 kV, but occasionally it can get higher; upswing time: ms–μs; MV: not specified
11	Voltage unbalance	LV, MV: ≤ 2 % for 95 % of the week, 10 minutes RMS values; in some locations ≤ 3 %
12	Harmonic voltages	LV, MV: see Table II
13	Interharmonic voltages	LV, MV: under consideration
Note: [a] low-voltage 0.4 kV distribution networks [b] medium-voltage 10, 20 and 35 kV distribution networks		

After the 7-day observation period, the so-called "orderly diagram" is formed, which shows the sum of the given disturbance levels during the observation period. For frequency measurements, the duration of each segment is 10 seconds. An example of an ordered chart is shown in Fig. 1, which helps to clearly see whether the measured voltage characteristics are within the permissible range during 95 % of the test time (see Table 1 for a reference).

Table 2 – Harmonic voltages at the supply terminals, based on MSZ EN 50160

Odd harmonics				Even harmonics	
Not multiples of 3		Multiples of 3			
Order-number h	Relative amplitude (%)	Order-number h	Relative amplitude (%)	Order-number h	Relative amplitude (%)
5	6	3	5	2	2
7	5	9	1.5	4	1
11	3.5	15	0.5	6 ... 24	0.5
13	3	21	0.5		
17	2				
19	1.5				
23	1.5				
25	1.5				

During normal operation, it is not a complicated task for electricity suppliers to meet the requirements of MSZ EN 50160. The characteristics of the power supply should be kept within the prescribed range only for 95 % of the period under consideration (see Table I), and the permissible deviations may be significantly greater during the remaining 5 % of the period [3]. For example, the mean value must be between 90 % and 110 % of the nominal voltage only for 95 % of the time.

However, it is necessary to take into account international trends that predict a large-scale spread of decentralized energy production. The proportion of water and other renewable energy sources in the total energy generation mix has never been as high as nowadays [4].

The trend in Fig. 2 [4] predicts an increase in decentralized energy production. As a result, the power networks must be prepared for two-way energy flows and problems caused by decentralized energy production.

Voltage problems caused by decentralized energy production. Renewable-based electricity generation equipment is capable to deliver electricity depending on the current intensity of the primary energy carrier (wind, sun, etc.). However, the presence of primary energy carriers depends on a number of environmental parameters. Due to rapid cloud transits and sudden gusts of wind the electrical output can change significantly even in a short period of time and, therefore, the stochastic nature of the weather leads to a variable output performance (Fig. 3) [5]. When a distributed energy resource (DER) is connected to the electricity system, the network's voltage changes at the connection point as a result of the action of transmission impedance between them. In the event of an incorrect placement of the DER from a network-topological point of view, this voltage change can be significant [6]. The extent of the effective performance is also gradually determined by the input. So, in case of an improperly deployed (i.e., placed) high-performance system the voltage at the point of power consumption changes.

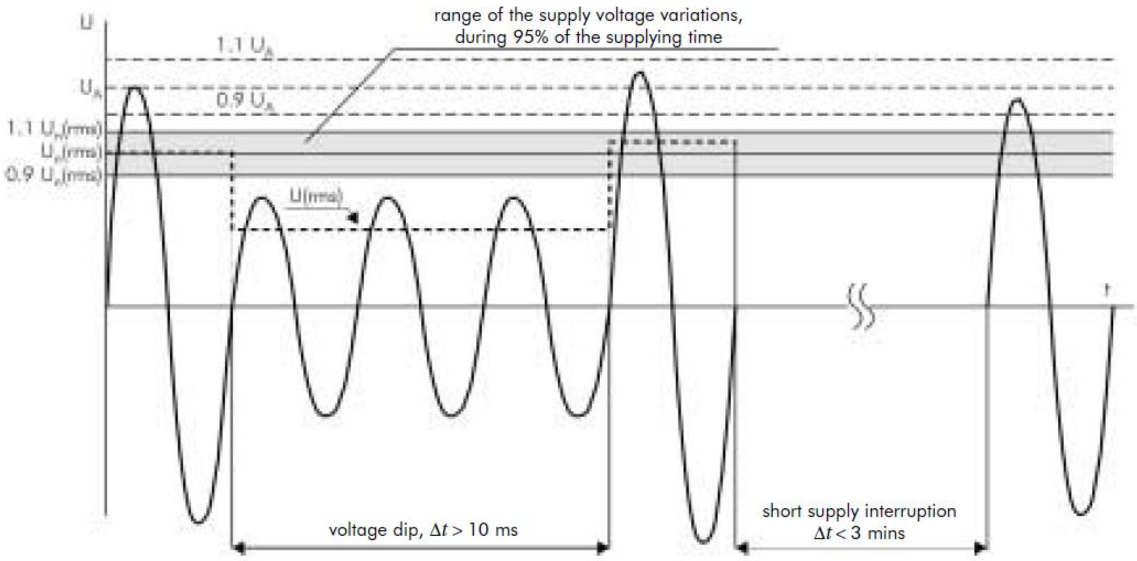

Figure 1 – Illustration of voltage break-off according to MSZ EN 50160 and short-circuit power supply:
U_n – nominal voltage of the power grid (effective value), U_A – amplitude of the power supply, U(effective) – actual effective value of the power supply

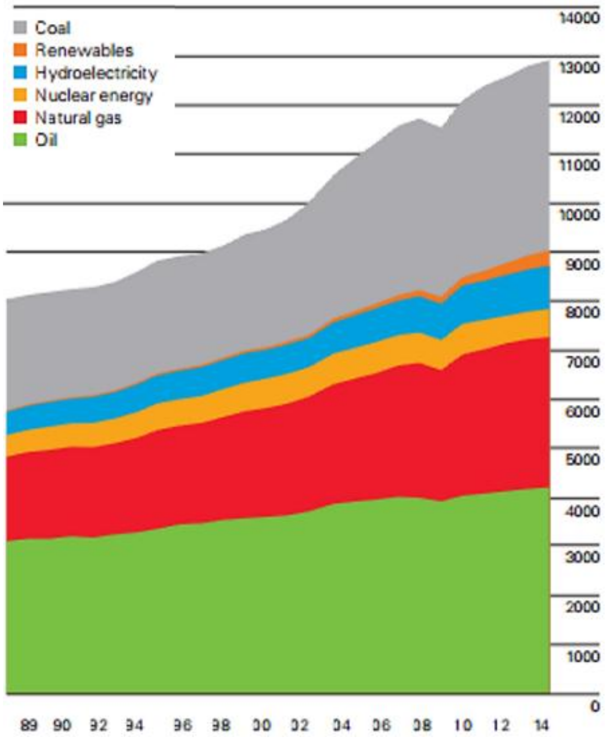

Figure 2 – Dynamics of the world energy consumption by type of primary energy carriers

In case of larger systems, the phenomenon of flickering cannot be neglected. This phenomenon is mainly caused by rapid cloud transits and sudden breezes, which results in short-term voltage changes.

However, there are weather conditions that last longer, resulting in long-term voltage changes. This can include persistently stormy, cloudy weather or long-term wind chills.

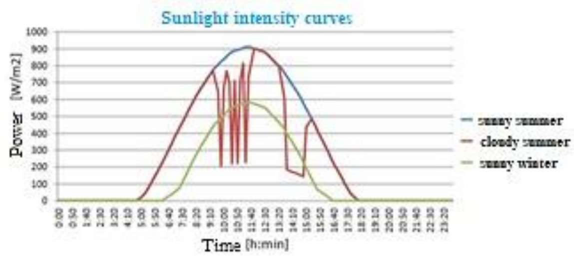

Figure 3 – Sunlight intensity curves

If larger distributed generation (DG) systems are installed, in addition to local consumption, the delivery of power to the network may cause overloading of the transmission lines. This should be taken into account when scaling the wires to transmit the excess of energy.

The connection of the DG to a radial distribution network can alter the one-way power flow: a phenomenon of reverse power flow may occur if the production of a DER is greater than the performance requirements of the consumers at the same connection point. In this case, the direction of the current flows is reversed: the currents flows towards the network parts with higher voltage, which can have a serious impact on the operation of the network [7]. As a result, various protection equipment can be erroneously activated, which can even cause a malfunction [8]. Above a certain input power, the reverse power flow may cause the excessive energy produced by the DERs to flow into adjacent areas (Fig. 5) [9].

In the event of a short circuit, the lockdown current is fed not only by conventional power plants, but also by DG units connected to the grid. Thus, the DG connected to the distribution network increases the value of the operating current [7].

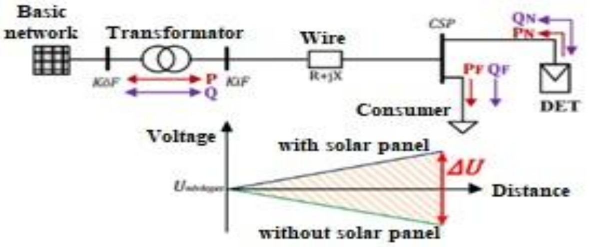

Figure 4 – Illustration of the phenomenon of voltage increase in the node with a DER

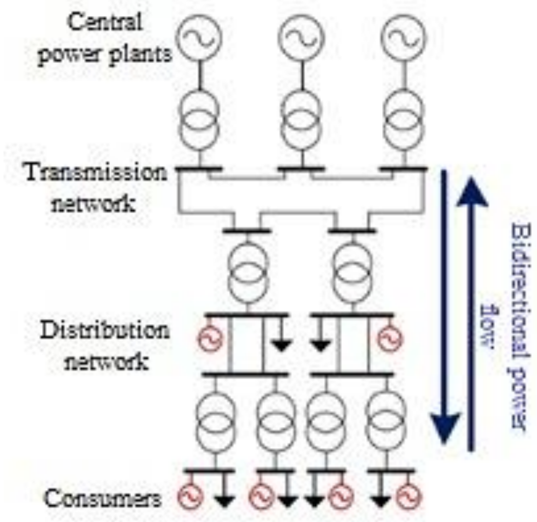

Figure 5 – Appearance of the DERs in a power system

Reliability indicators used in Hungarian Energy and Utilities Regulatory Office (MEKH). The network quality and malfunction indicators employed by the Hungarian Energy and Utilities Regulatory Office (MEKH), which are also used internationally, determine power outages which last for longer than 3 minutes. They are as follows:

1. Relation of the number of consumers affected by malfunctions to the/total number of consumers (MEKH 1 indicator; SAIFI in the international terminology):

$$SAIFI = \frac{\sum \lambda_i N_i}{N_T}, \tag{2}$$

here λ_i is the average failure rate at load point i;

N_i is the number of consumers at load point i;

N_T is the total number of consumers.

2. Relation of the amount of interruption times per consumer to the total number of consumers (MEKH 2 indicator; SAIDI in the international terminology).

$$SAIDI = \frac{\sum U_i N_i}{N_T}, \tag{3}$$

where U_i is the annual outage duration at load point i.

3. Expected Energy Not Supplied Index.

The expected level of these indicators (due to the different technical characteristics) should be determined separately each year by the MEKH for each distributor licensee. MEKH is entitled to impose a penalty if the network operator does not keep the indicators prescribed to it. Therefore, it is the fundamental interest of all service providers to continuously improve the network's reliability and, thus, the quality of service.

Summary and possible management of the named problems. Improving the reliability indicators of the network, according to this aspect, consists of two distinct tasks. The first task is to comply with the requirements, which, given the problems, requires local voltage control intervention. The second task is the improvement of the MEKH indicators, which envisages a reduction of the number, extent, time-lapse and response time of both the LV and the MV distribution networks.

Voltage problems caused by DERs. Although research on the DERs' management is being carried out, the requirements of the standards of regulation can only be met under certain technical conditions. Another problem with the decentralized power management is that some elements of the network start to behave as stochastic and are "unseen" for regulation. This means that it is difficult to control the voltage in the power network. When controlling devices sense higher than allowed voltage levels, they try to decrease the voltage. When the DERs do not generate electricity, the voltage level can drop down, which would require controlling devices to send an order to increase the voltage. Consequently, this solution is a kind of voltage ripple, which, taking into account the effects caused by the DERs, can lead to regulatory anomalies. However, complementing decentralized control tools, centralized management and decentralized measuring and signaling equipment make the problem easy to deal with [10, 11]. The question arises as to which DERs' density it is worth installing such devices at all, where and with what means it is worth implementing measurements, signals and regulations.

Management of MEKH indicators. A number of tools is available for operators to improve the MEKH indicators. The most effective solution, which is also the most expensive, is the complete replacement and reconstruction of a given part of the network. The network's extensiveness is large, and some lockdown-induced protection operations do not yet justify the replacement of network elements.

There are diagnostic procedures that can be used to assess the status of network's elements. From the entire survey, a so-called disease history can be made, from which a reconstruction strategy can be determined on the basis of technical and economic aspects.

In addition to the aforementioned – radical - procedure, there is a number of tools and methods for improving of indicators, from the preparation of those involved in the prevention of malfunctions to the well-developed maintenance strategy and application of excellent network monitoring systems. Their summary is given in Table 3 [12].

Table 3 clearly shows that while classic interventions lead to lower investment costs/quality improvements, the installation of ETMs provides several times better solution. Effectiveness of the ETM can be assessed with Fig. 6 [10].

Table 3 – Impact of certain inquiries on the MEKH 1 indicator

Measure	Efficiency[a]
Replace aging column switches	21
Replacement of aging insulators on a 20 kV free wire network	42
Complete reconstruction 20 kV free-line network	36
Complete reconstruction of 0.4 kV free-line network	28
Complete reconstruction on a 10 kV cable network	5
Replacing old, faulty assemblies on a cable network based on diagnostics	35
Installing 10 kV and 20 kV ETM[b]	63–500
Note: [a] Specific MEKH 1 indicator improvement (10^{-6} pcs/MFt) [b] Distribution Network Telemechanics	

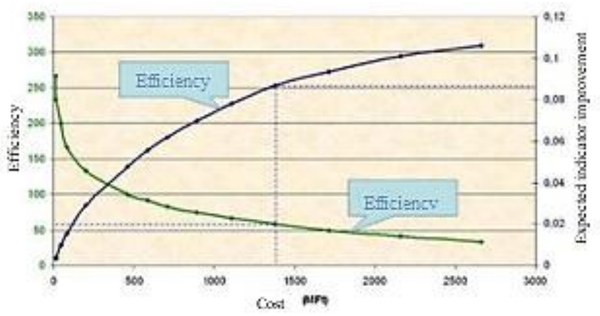

Figure 6 – Effectiveness of ETM

Since a similar device on the MV network does not yet exist today, it is worth considering what telemechanized devices should be installed to address the issue discussed earlier.

Smart meters and smart switch boards. The low-voltage network runs from the MV side outlet of the MV/LV transformer station (elements of the MV/LV transformer are built so, that the MV tap is still the responsibility of MV plant management) to the first connection and binding point of the consumer. Within this part of the network there are low-voltage distribution cabinets with fuses, that selectively protect the network.

Fig. 7 clearly shows that measurements and interventions are possible on the following network elements:

- on the LV busbar,
- in the distribution boxes,
- on the LV feeder fuses,
- at the LV meters,
- and at adjustable inverters.

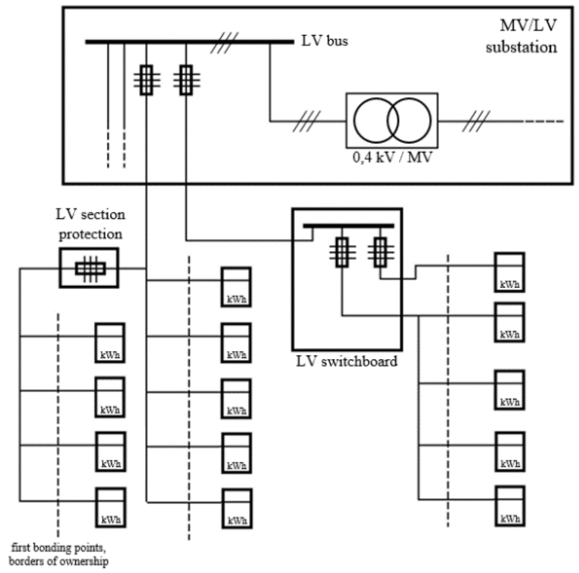

Figure 7 – MV distribution network illustration

Use of controllable inverters.

Smart switch boards (SSB). At many points on the LV side, it is possible to use the remotely operated distribution cabinets with motor-driven circuit breakers, which are now widely used in the industrial environment. With proper communication and intelligence, such as the introduction of reclosing cycles as in the MV networks, enabling voltage and current measurement, intelligent gradient monitoring, these devices can function as SSB for network operators. Example of a sophisticated communication system is shown in Fig. 8.

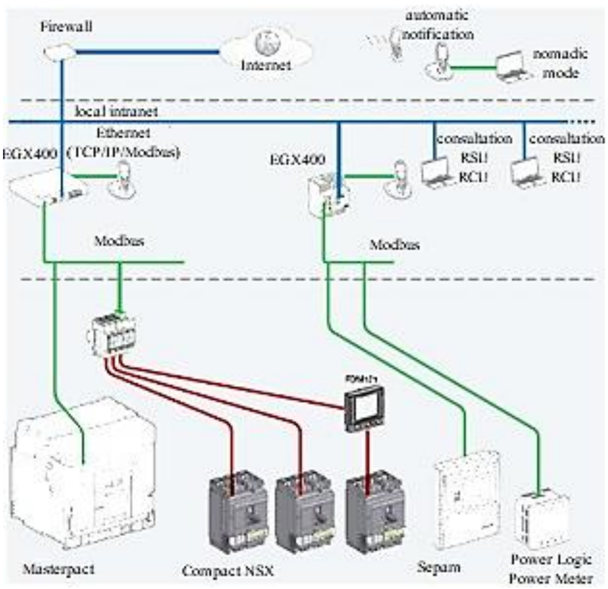

Figure 8 – Communication system for Schneider Electric's protection equipment

This solution, in addition to the fact that it can lead to a significant improvement in the MEKH indicators, also significantly reduces the number of repairing due to fuses' replacement, improving the use of the working hours of network installers.

To counteract the voltage problems caused by the spread of DERs, SSBs can play a kind of central role in decentralized voltage control (performance control). Based on the measurement data received from the SSBs at the control centers in real time a real-time model can be created for the known network's topology. On the basis of this model, voltage problems can not only be detected, but the optimal level of regulation can also be calculated in real time, using electrical and graph theory methods. The local optimal operating state can be achieved by using remotely controlled intervention points.

Smart Meters (SM). Research into the possibilities of electric metering equipment has been on the agenda during the recent decade; international experience [13], [14] and the first results of pilot projects in Hungary are now available. However, smart metering (SM) research does not go beyond remotely reading of energy consumption and active engagement of the consumers (in the latter case, the aim is to divert consumption into the valleys of consumption with the help of economic means, thereby reducing the extremes of the daily national consumption curve). In addition to these benefits, there are other arguments for extending SMs:

- Thanks to the advantage of two-way online communication, a SM can provide customers with fast and reliable data: starting troubleshooting, notifying before maintenance, "sending a reassuring message" in case of snowfall, etc.
- In case of the installed DG, more transparent monitoring of the produced and consumed energy.
- Detecting unspecified receptions.
- Helps to identify locations of errors and causes of malfunctions.

Identifying the fault sites is a priority task, as at present only consumer reports of MV failures are received, no remote signals are available. With help of a mathematical algorithm from the signals of a SM, the faulty network element and the fault location can be identified. Such a mathematical algorithm is still being developed. With the mathematical algorithm and the sporadically placed SM, the process of identifying the fault site can be fully automated in the future, first in part, and then after technical development.

SMs & SSBs. With parallel use of SMs and SSBs, the error site identified by a SM can only confirm the remote signal sent by a SSB. However, for economic reasons, the widespread deployment of SSBs is not expected in the short term, so the introduction of SMs is highly recommended for network operators, taking into account the advantages listed earlier.

Remote controllable inverters. Electricity suppliers, protecting their own networks, only allow inverters approved by them to be connected to the distribution network, on the basis of technical criteria. The connection point voltage of these devices cannot be controlled remotely today.

Remotely load-controlled transformers. A MV/LV transformer (Fig. 9) is referred as a possible point of intervention, which can be used under load by means of a remotely adjustable transmission, to deal with voltage problems of a longer duration and to influence the infertile energy flow. Research of its effectiveness and integration into the system is currently underway.

Figure 9 – Communication system for Schneider Electric's protection equipment

Conclusions. At present, compliance with the quality indicators prescribed by the actual edition of MSZ EN 50160 standard does not cause problems for network operators. However, due to the expected widespread use of decentralized energy generation, it is already necessary to prepare to deal with the expected problems today.

Compliance with the expected MEKH reliability indicators is a constant challenge for operators. Therefore, it is important to take stock of all possible means, to examine them from a tec hnical and economic points of view, which will lead to the improvement of these indicators.

The solutions described in this article aims to prepare the network for the problems arising from the mass spread of DERs, which has been predicted by the current trends. Some of the solutions can help to improve the network's reliability indicators and efficiency of the network's operation.

References

1. *A közcélú elosztóhálózatokon szolgáltatott villamos energia feszültségjellemzői*, MSZ EN 50160, 2001. (in Hungarian)
2. H. Markiewicz and A. Klajn, *Voltage Disturbances: Standard EN 50160 – Voltage Characteristics in Public Distribution Systems*. Wroclaw University of Technology, 2004.
3. I. Diahovchenko, N. Sushchenko, A. Shulumei, and O. Strokin, "Influence of supply voltage and frequency variations on the electrical equipment and power consumption in LV and MV distribution networks," *Energetika*, vol. 65, no. 4, pp. 172–187, Jun. 2020, doi: https://doi.org/10.6001/energetika.v65i4.4246.
4. "Energy intensity of GDP | Global Energy Intensity Data | Enerdata." World Energy Statistics | Enerdata. https://yearbook.enerdata.net/total-energy/world-energy-intensity-gdp-data.html (accessed Nov. 1, 2022).
5. S. Papp and B. Hartmann, "Solar panels in the electrical distribution network," in *Researchers' Night 2013: Young Researchers' Night – Talented Students in Energy*, Budapest, Hungary, Sep. 27, 2013.
6. I. Diahovchenko and V. Zalotov, "Optimal composition of alternative energy sources to minimize power losses and maximize profits in distribution power network," in *2020 IEEE 7th International Conference on Energy Smart Systems (ESS)*, Kyiv, Ukraine, May 12–14, 2020. pp. 247–252, doi: https://doi.org/10.1109/ess50319.2020.9160259.
7. S. Yu. Shevchenko, V. V. Volokhin, and I. M. Diahovchenko, "Power quality issues in smart grids with photovoltaic power stations," *Energetika*, vol. 63, no. 4, pp. 146–153, Feb. 2018, doi: https://doi.org/10.6001/energetika.v63i4.3623.
8. V. V. Volokhin, I. M. Diahovchenko, and B. V. Derevyanko, "Electric energy accounting and power quality in electric networks

with photovoltaic power stations," in *2017 IEEE International Young Scientists' Forum on Applied Physics and Engineering (YSF)*, Lviv, Oct. 17–20, 2017. pp. 36–39, doi: https://doi.org/10.1109/ysf.2017.8126588.

9. K. T. Kovács, "Local voltage control feasible by inverters of solar panels connected to low voltage networks," in *Scientific Student Group Thesis*, Budapest, Hungary, 2014. p. 9.
10. V. Volokhin and I. Diahovchenko, "Peculiarities of current sensors used in contemporary electric energy metering devices," *Energetika*, vol. 63, no. 1, pp. 8–15, Aug. 2017, doi: https://doi.org/10.6001/energetika.v63i1.3504.
11. V. V. Volokhin, I. M. Diahovchenko, and B. V. Derevyanko, "Prospects of nanomaterials use in current and voltage hall sensors to improve the measurements accuracy and reduce the external impacts," in *2017 IEEE 7th International Conference "Nanomaterials: Application & Properties" (NAP)*, Odesa, Ukraine, Sep. 10–15, 2017. pp. 03NE08-1–03NE08-5. doi: https://doi.org/10.1109/nap.2017.8190239
12. A. Csank, "Implementation of remote operation on the distribution network of ELMŰ-ÉMÁSZ, in order to improve the MEH indicators, MEE 55," in *Travelling Assembly*, Eger, Hungary, Sep. 9–12, 2008.
13. I. Diahovchenko, B. Dolník, M. Kanálik, and J. Kurimský, "Contemporary electric energy meters testing under simulated nonsinusoidal field conditions," Electrical Engineering, vol. 104, no. 2, pp. 1077–1092, Apr. 2022, doi: https://doi.org/10.1007/s00202-021-01365-8.
14. I. Diahovchenko, R. Mykhailyshyn, D. Danylchenko, and S. Shevchenko, "Rogowsky coil applications for power measurement under non-sinusoidal field conditions," *Energetika*, vol. 65, no. 1, pp. 14–20, May 2019, doi: https://doi.org/10.6001/energetika.v65i1.3972.

Received 17.11.2022

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