Utilization of Energy Storages in Low Voltage Grids with High Penetration of Photovoltaics – Addressing Voltage Issues

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***Abstract*—This contribution focuses on voltage issues in low voltage distribution grids which are highly penetrated with distributed generation (DG), especially photovoltaic (PV) plants. It describes a model of selected part of distribution network, created in Matlab/Simulink, based on real data, and the impact of PV power plants on voltage amplitude in accordance with DIN EN 50160 during the summer week, depending on the percentage share of PV production in total consumption. Using sensitivity analysis are identified critical nodes and respective share of DG, which causes exceeding of voltage magnitude limit values. Assumptions about negative effect on voltage fluctuations were confirmed at higher penetration levels. In order to prevent this phenomenon, unconventional way of distributed voltage regulation through absorption of active power by energy storages installed in critical nodes is proposed and simulated. The functionality, benefits and drawbacks of this approach are evaluated and compared to similar more commonly used measures.**

Keywords—photovoltaic, renewable, voltage, energy storage, distribution grid, low voltage

I. INTRODUCTION

The electric power system is undergoing constant development, which has been rising in recent years. Today, the trend is to use more and more green energy and renewable energy sources (RES) to the detriment of fossil fuel based sources in order to reduce the production of harmful emissions and greenhouse gas emissions. In the European Union, this trend dictates the targets by 2020 and 2030, which foresee a share of renewable energy production in total gross consumption of 20% [1] and 27% [2] respectively. With ever increasing number of RES, the pressure on their integration into the electricity system in an efficient way arises.

Generators based on RES are installed distributed, predominantly in low and medium voltage networks, which is a change from the original method of electricity production in central power plants. Globally, up to 70% of PV sources are connected to low and medium voltage grids [3]. In addition, these sources have also different and very specific operating characteristics, and therefore it is necessary to face new challenges in the field of control and operation of the power system, especially by distribution system operators [4] [5].

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Nowadays in Slovak republic, there is government support only for installation of PV plants in households with up to 10 kWp. Last year, over 2000 installation were added into low voltage grid with 5 MW overall capacity. This trend getting stronger, what brings concerns about maintaining of present quality of electric power supply in the future, thus there is a need for evaluation of potential problems and assessment of possible solutions.

One of the anticipated problems which can occur in this type of grids is power backflows and voltage deviations, especially voltage rises at long feeders with DG unit connected along or at the end. In case of peak generation and low demand, voltage rise occurs, typically during the noon in summer. At certain level of PV penetration, voltage magnitude along the feeder can exceeds allowed boundaries, which are $Un \pm 10\%$ in low voltage grids defined by EN 50160 [3]. These problems can be transmitted to medium voltage feeder where multiple highly penetrated communities are connected. Main question is not whether or not these are really happening, but at which level of penetration voltage deviation exceeds allowed boundaries and what is the best solution to fix the problem and thereby enable further integration.

In such cases, when mentioned problems occur, there is a set of measures which can be used. Impedance reduction can be used, thus grid needs to be reinforced (laying additional overhead lines or cables, meshing the grid, new transformers). Another option is reactive power control by sources installed in medium and low voltage grid (if they provide such option), or direct voltage regulation using transformers equipped with an on load tap-change, regulated distribution transformer or sting voltage regulator [3]. Last option is active power control, which is further analysed in this paper.

Reduction of active power which is injected to low voltage grid by locally installed sources causes decreasing of voltage rise. This can be achieved in several ways, by generation management (for example PV plants curtailment) at production side, or by demand side management and demand side response at consumption side. Introducing energy storages in problematic parts of distribution is another option [6]. Nowadays, PV plants installed in Slovakia are not regulated in means of active power (also PV power curtailment is ineffective), demand side management and response have low potential at this voltage levels, thus introduction of energy

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storages to prevent voltage rises was chosen as a subject of this study.

II. Studied Locality

To verify assumptions mentioned in introduction, and partially to find the answers for questions raised, a part of distribution grid in Eastern Slovakia have been chosen for this purpose. Subsequently, grid model of this residential locality have been established using Matlab/Simulink based on real data provided by distribution system operator. Chosen part of distribution grid and its topology is shown in Fig. 3; presented study was performed in highlighted part. It consists of distribution transformer and radial feeder, which provides electric power supply to all of the residential customers connected through the overhead lines. Types of overhead lines together with corresponding length are marked in Fig. 3. There are overall 43 customers connected in the community, which can be divided into 3 groups due to their typical daily load curves.

III. Assembled Model and Input Data

Distribution grid model was created using Simpowersystems toolbox. Grid topology was completely modeled using standard blocks from library of the toolbox. Besides the grid model itself, it was needed to establish model of the PV plant and energy storage model in order to observe their impact on voltage fluctuations. All of these parts are further described below. Overview of the created model is shown in Fig. 4.

A. Grid model

Model of the grid consists of external grid equivalent, medium voltage feeder, transformers and low voltage feeder. Medium voltage feeder was created by series of overhead lines and loads, which were modeled using pi sections and RLC load blocks. The low-voltage feeder is divided into several sections

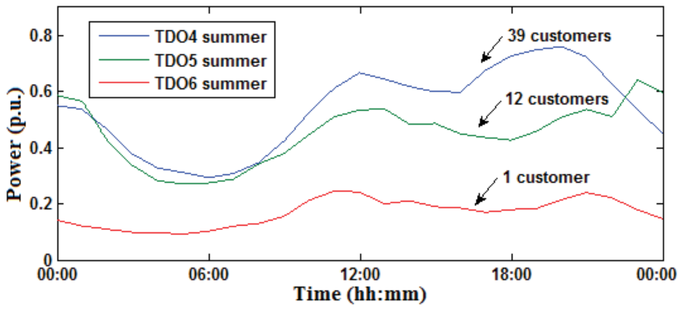

Fig. 1 Typical daily load curves in summer

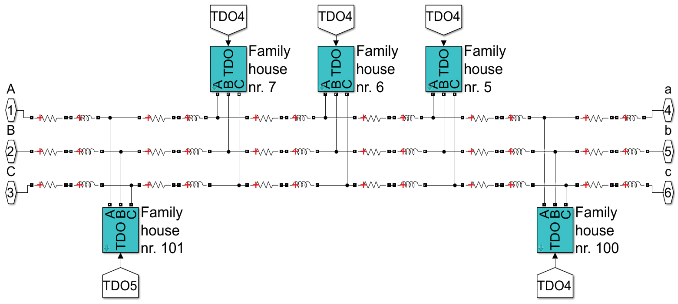

Fig. 2 Connections of individual customer in Matlab/simulink

(marked by letters A-G in Fig. 3), where each customer is connected with respecting of their true distances. The electrical lines between individual customers were modeled by R and L elements based on the type of the line and respective length. Implementation of one of the smaller sections (section B-C) can be seen in Fig. 2. Customers themselves have been modeled using blocks called dynamic PQ load that model load as constant impedance. A load factors were set and type of typical load curves in per unit for each customer were assigned based on information provided by distribution system operator. There are overall 3 types of customers. Typical daily load curve during the summer day, together with the appropriate number of customers is shown in Fig. 1.

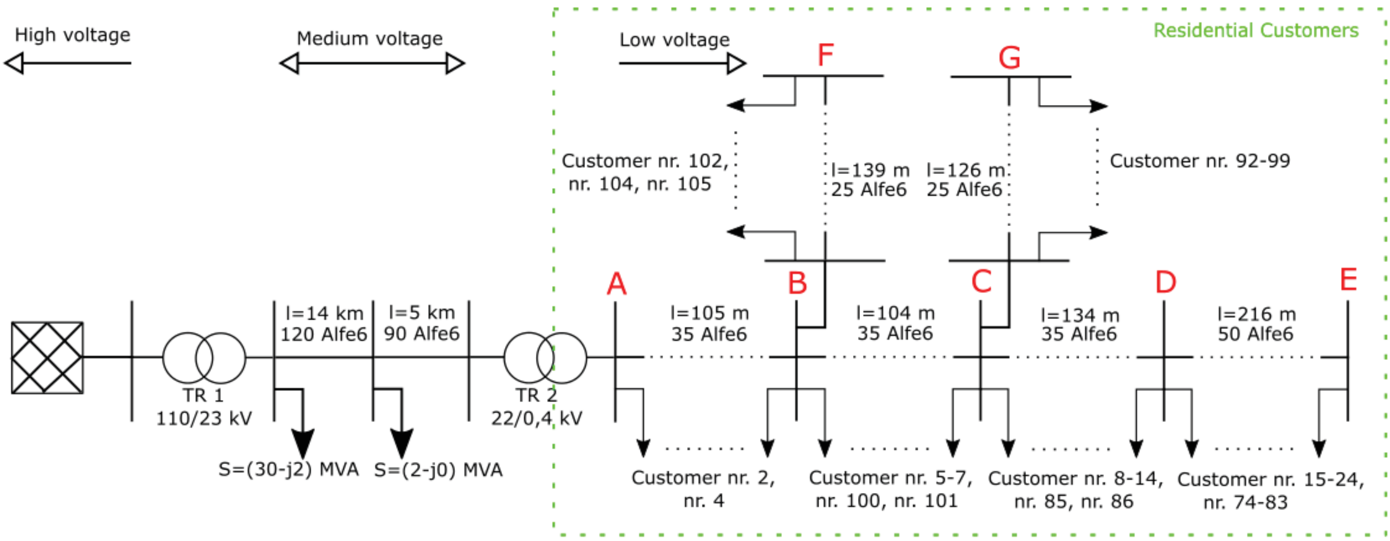

Fig. 3 Topology of studied distribution grid

energy storage needs to calculate state of charge level (SOC) in every simulation step and also has to have some charging strategy.

1) SOC Calculation

For SOC calculation, a simple relationship was established[7]:

$$SOC(t) = SOC_{INIT} + \frac{100 * E_{CH}(t)}{E_{FULL}} - \frac{100 * E_{DISCH}(t)}{E_{FULL}} \quad (2)$$

, where:

- SOC_{INIT} – initial state of charge (%)
- E_{CH} – energy stored during charging (Wh)
- E_{DISCH} – energy stored during discharging (Wh)
- E_{FULL} – total capacity of ESS (Wh)

2) Charging strategy

Charge/discharge strategy was designed according to this purpose, thus for preventing voltage rise in low voltage feeder with high penetration of PV plants. Following algorithm shown in Fig. 5 describes the principle of the operation.

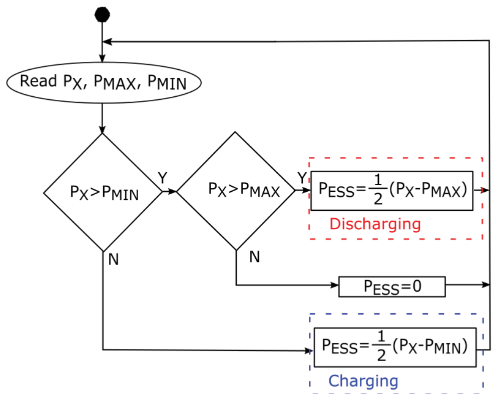

Fig. 5 Algorithm for charge/discharge of BESS

It uses power shifting. By taking active power at time when in distribution grid excess electricity is produced and suppling it at time when PV plants does not produced any power it helps to stabilize the voltage. It is designed for two ESSs that work same way and are connected at the beginning and end of problematic grid part. Both storages sensing the power flow P_X at the point of branching from the main line (X). If the power drops below the minimum preset value P_{MIN}, the storage is charged at a power that will keeps the power flow at the “X” location at mentioned value P_{MIN}. If power flow is higher but lower than P_{MAX} storage remains idle. In case when power flow through “X” location is higher than P_{MAX}, storage is discharged at a power that maintains the power flow at required P_{MAX} value.

IV. Simulation and Results

Overall, performed simulations can be divided into two categories. To the first category includes the simulations of distribution grid with different levels of PV plants penetration. The aim of these simulations was to verify the assumed

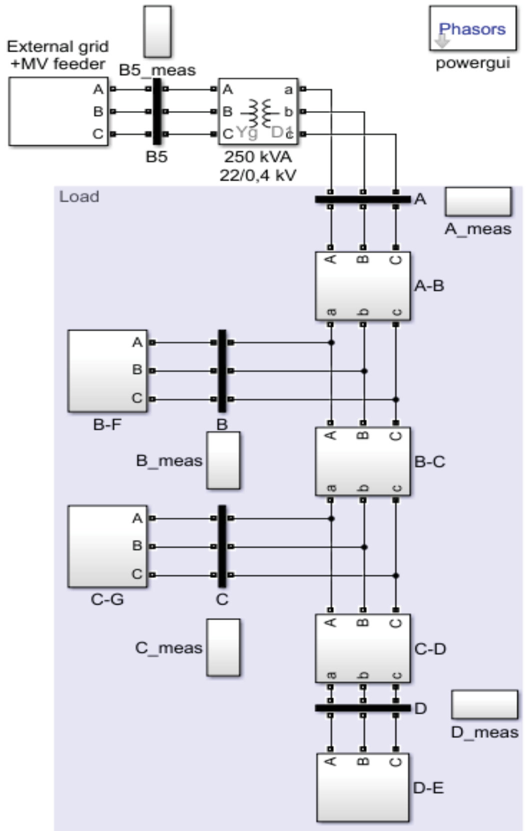

Fig. 4 Overall view on the model implementation in Matlab/Simulink

B. PV plant model

In order to model PV power plants, current sources for injection of currents into the selected locations were used in dependence on the voltage. Created model calculates the actual values of currents, given by actual voltage at the point of common coupling and the amount of power to be supplied to the grid at given time. Current amount of power is calculated based on the actual irradiance and the simple relationship (1) that was established for this purpose:

$$P = G * S * \eta \quad (1)$$

, where:

- P – power generated by PV plant (W)
- G – irradiation (W.m^{-2})
- S – panel area (m^2)
- η – efficiency (-)

PV plant irradiation was retrieved from an external data set. Efficiency of the PV modules was set to 15%. The area of all panels was calculated based on the required installed power assuming 1.6m^2 for the 250W PV module.

C. Eenergy storage system (ESS) model

Exchange of power between ESS and distribution grid as its connection to the grid was modeled by the same way like in the previous case (using currents injection). Besides that, model of influence of the photovoltaic power plants on the voltage at the monitored nodes (voltage rise). The target was also to find out, what share of renewable energy sources and in which nodes causes, that voltage exceeds allowed limits according to EN 50160. For this purpose, sensitivity analysis was carried out, in which voltage changes were observed in dependence on percentage share of renewable generation on total energy consumption ranging between 0-100 %.

Another category of simulations were performed in a similar manner, in addition with presence of installed ESS and proposed control, in order to verify their ability to maintain the voltage by taking active power from the distribution network.

The simulations were performed using a phasor simulation method and ode45 solver with a variable simulation step during one week interval.

A. *Input data*

Input data are the same for both categories of simulations. The input data represents solar radiation and load consumption data based on typical daily load curve for each day (Fig. 6). Solar radiation data (Fig. 7) were measured in studied locality during first week of September (1.9-7.9.), 2016, in five minute intervals.

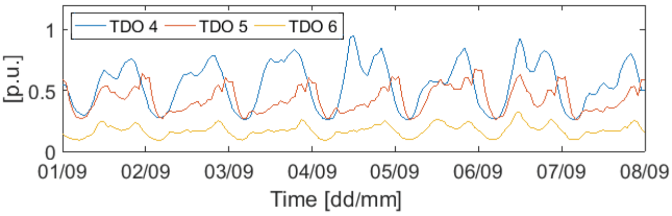

Fig. 6 Typical daily load curves for different customers

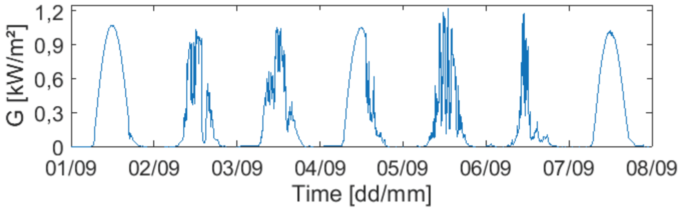

Fig.7 Solar radiation in PV module plane during simulated week

B. *Distribution grid +PV plants*

PV plant model was added to every third customer, evenly over entire distribution grid, at total of 17 locations. Power output ranged from 0 to 100 %, calculated based on total consumption of the residential locality, and PVGis software, which calculates average annual amount of energy produced by PV plant equals to 0,970 MWh/kW in subjected locality. The annual consumption of residential locality was 162,341 MWh. For example, installed power of one source at 20% penetration was determined as a ratio between 20% of annual consumption and average annual energy production per kW installed, divided by number of sources, i.e. 17 (Tab. II). Based on required installed power, the modules area for one source was determined according to assumptions given in the description of PV model, and subsequently fitted into (1).

Results of simulations are summarized in Tab. I. Exceeded allowable voltage values were detected at 60% penetration at nodes D and E. At higher penetration, the voltage is exceeded at nodes C and G. Nodes closer to the transformer showed more stable values. In Fig.8, the voltage course in the measured nodes is shown. It is possible to see which voltages and during which days of the week exceed the allowed limits.

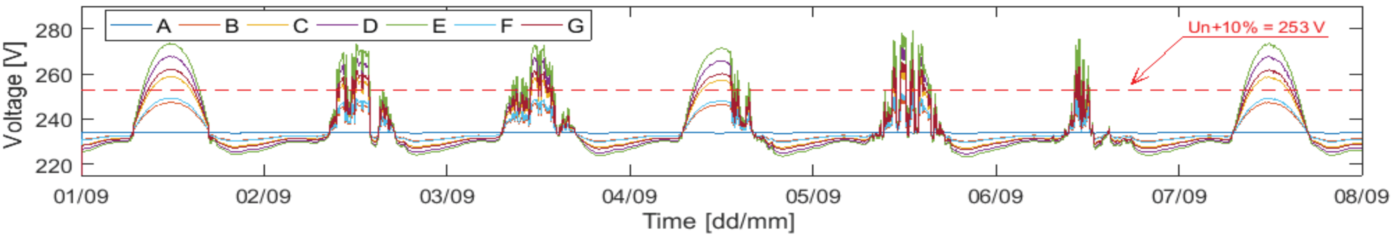

Fig. 8 Course of voltage in monitored nodes (A-G) with 100% share of PV plants during the simulated week

TABLE I SENSITIVITY ANALYSIS OF VOLTAGE FLUCTUATIONS IN DEPENDENCE ON PERCENTAGE SHARE OF PV GENERATION IN TOTAL ENERGY CONSUMPTION

Share of PV generation in total energy consumption [%]	**Voltage [V]**													
	A		***B***		***C***		***D***		***E***		***F***		***G***	
	U_{MIN}	U_{MAX}	U_{MIN}	U_{MAX}	U_{MIN}	U_{MAX}	U_{MIN}	U_{MAX}	U_{MIN}	U_{MAX}	U_{MIN}	U_{MAX}	U_{MIN}	U_{MAX}
0	233,64	234,02	229,57	232,71	226,34	231,65	223,57	230,69	222,08	230,17	229,09	232,58	225,66	231,46
20	233,68	234,02	229,91	235,39	226,91	236,74	224,32	237,64	222,93	238,35	229,47	235,65	226,28	237,23
40	233,68	234,05	229,91	239,34	226,92	243,99	224,34	247,53	222,95	249,87	229,48	240,12	226,29	245,34
60	233,68	234,07	229,91	242,98	226,92	250,71	224,34	256,69	222,95	260,53	229,48	244,27	226,29	252,87
80	233,68	234,08	229,91	246,36	226,92	256,99	224,34	265,27	222,95	270,51	229,48	248,14	226,29	259,93
100	233,62	234,09	229,91	249,49	226,92	262,87	224,34	273,29	222,94	279,84	229,48	251,77	226,29	266,55

TABLE II INSTALLED PV POWER IN LOCALITY

Share of PV on total electricity consumption [%]	Energy need to be produced by PV [kW]	Total installed power in residential locality [kW]	One source power [kW]
20%	32468	33,47	1,97
40%	64936	66,94	3,94
60%	97404	100,42	5,91
80%	129873	133,89	7,88
100%	162341	167,36	9,84

C. Distribution grid +PV plants+ESS

In this case, the simulations were performed in the same way, with the same settings. The difference lies in connecting of ESS with control system based on charge/discharge strategy described in previous chapter. Problem with voltage was recorded at 4 measuring points (C, D, E, and G). ESS with 30 kW nominal power output was connected in node D and E, while ESS with 15 kW nominal power output was connected at C and G. ESS capacity was not limited (thus it was set to very high value in (2)), because sizing optimization of ESS was not a subject of this study.

TABLE III PARAMETERS SET FOR ENERGY STORAGE CONTROL

Parameter	Power [W]			
	C	D	E	G
P_{MIN}	-2000	-8000	-8000	-2000
P_{MAX}	-1500	-5000	-5000	-1500
$P_{NOMINAL}$	15000	30000	30000	15000

ESSs were charged and discharged according to proposed algorithm and set of values and parameters. By this setting, in addition to shifting the power from time of large PV production and low load consumption to the time when PV produced small or zero power that did not cover the demand, the voltage magnitudes was also maintained within allowed limits. The limit values of power flow for storage management have been set based on the evaluation of previous simulations and they are shown in Tab. III.

The results of simulations in the form of maximum and minimum effective values of voltage are presented in Tab. IV.

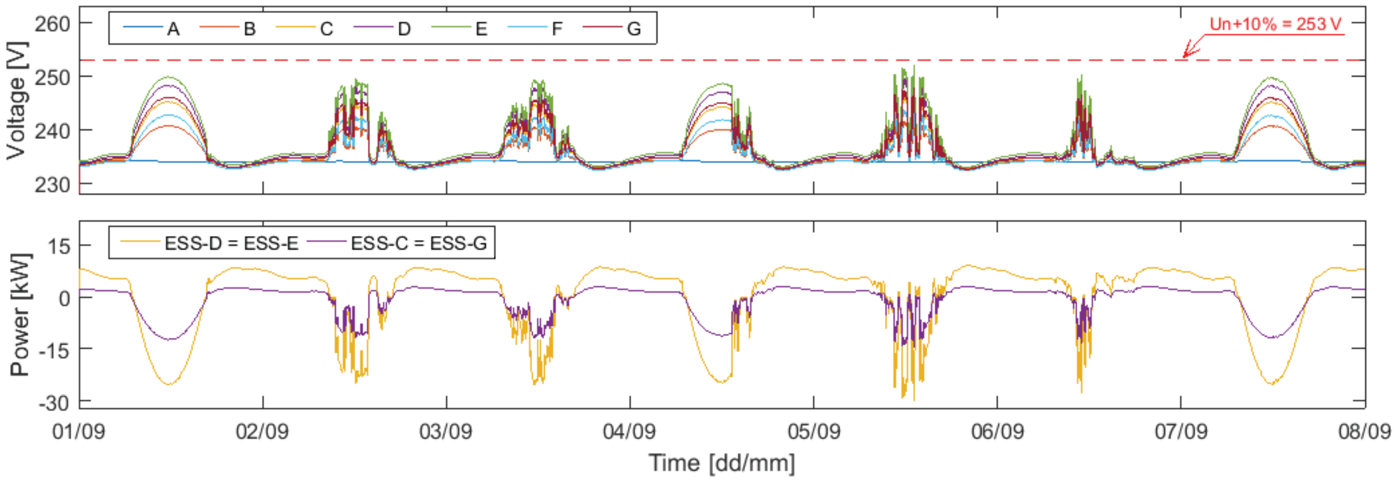

Fig. 9 Course of voltage and power delivered by ESSs in monitored nodes (A-G) with 100% share of PV plants during the simulated week

TABLE IV SENSITIVITY ANALYSIS OF VOLTAGE FLUCTUATIONS IN DEPENDENCE ON PERCENTAGE SHARE OF PV GENERATION IN TOTAL ENERGY CONSUMPTION

Share of PV generation in total energy consumption [%]	Voltage [V]													
	A		*B*		*C*		*D*		*E*		*F*		*G*	
	U_{MIN}	U_{MAX}	U_{MIN}	U_{MAX}	U_{MIN}	U_{MAX}	U_{MIN}	U_{MAX}	U_{MIN}	U_{MAX}	U_{MIN}	U_{MAX}	U_{MIN}	U_{MAX}
0	233,74	234,02	229,57	232,71	226,34	231,65	223,57	230,69	222,08	230,17	229,09	232,58	225,66	231,46
20	233,75	234,06	232,68	235,07	232,39	236,12	232,41	236,95	232,81	237,61	232,24	235,31	232,39	236,41
40	233,76	234,06	232,69	237,01	232,39	239,34	232,42	241,13	232,81	242,28	232,25	237,39	232,40	239,81
60	233,76	234,07	232,69	238,59	232,39	241,86	232,43	244,19	232,82	245,54	232,26	239,91	232,40	242,50
80	233,76	234,07	232,69	240,14	232,40	244,31	232,43	247,18	232,83	248,72	232,26	241,97	232,41	245,13
100	233,76	234,08	232,69	241,62	232,41	246,69	232,44	250,07	232,83	251,79	232,26	243,97	232,41	247,67

It can be observed that, even with higher penetration of PV plant, the voltage did not exceed allowed limit value of 253 V throughout the whole simulated period. It can also be seen that in nodes where voltage problems have been identified in the previous simulations, during this simulations the maximum voltage value is 251,79 V, because active power was consumed from distribution grid.

The complete voltage trend along with the power delivered or consumed from the distribution grid in the case of 100 % share of PV generation in total consumption is shown in Fig. 9. It is possible to observe the reactions of individual storages and voltage changes in monitored nodes of distribution grid, where they are simultaneously connected. If voltage rises, there is usually a low load and a high PV generation in the grid. In this case, after reaching the preset value of power flow, storage starts to be charged according to proposed algorithm, resulting in energy shifting and maintaining the voltage in prescribed limits, and this also affected the voltage across whole low voltage feeder. Storage stopped charging if power flow rose above preset value P_{MIN}. With the end of charging, storage stops its operation, and is waiting for next run. If the value for the start of the discharge state is reached, there is usually a low voltage and higher power flow in the problematic part of distribution grid than in the previous case and therefore a high load and little or no generation, the storage is discharged to maintain a preset value P_{MAX}. By discharging, a shifting of energy generated from photovoltaics during the low demand period (around the noon) to the period of high demand (usually to the evening hours) is achieved. If none of the above mentioned values are reached after the charging or discharging cycle ends, the storage is idle, continue sensing the power flow, and waiting for some of the preset values. Same behavior can be observed for all of the storages connected.

V. Conclusion

In this paper, an unconventional approach to voltage regulation in the distribution network with high penetration of PV using active power consumption by energy storage has been verified and described. The model was inspired by a real distribution grid in Slovakia, which can be considered as standard grid in Central European conditions.

The simulations performed have shown an unfavorable effect on the voltage in case of a significant penetration by PV power plants, namely from 60% of the PV production share in total consumption. The nodes of the distribution grid in which the problem was encountered were identified, i.e. the nodes C, D, E and G. Allowed voltage limits have first been exceeded at the farthest distance from the distribution transformer. At 100 % penetration level, the effective value of phase voltage was exceeded by approximately 20 % at some nodes. This does not comply with EN 50160 and may cause damage to devices of connected customers and that is why this paper was dealing with possible solutions. For the purposes of verifying the use of energy storage for power shifting and maintaining voltage in prescribed limits, a charging/discharging strategy has been developed that has proved to be functional, especially at higher levels of penetration. In simulations with ESS connected at problematic nodes, the voltage in the worst case (100 % penetration level, node farthest from the transformer) reached a maximum of 251,79 V, which is comply with the above-mentioned standard. The same situation occured in all other cases.

Further research will be conducted to obtain a capacity needed for such type of control and improve charging and discharging strategy.

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