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USE OF ACTIVE ELEMENTS FOR PROVIDING SUITABLE VOLTAGE PROFILES AND PREVENT OVERLOADS IN RADIAL DISTRIBUTION NETWORKS

UPORABA AKTIVNIH ELEMENTOV ZA ZAGOTAVLJANJE USTREZNIH NAPETOSTNIH PROFILOV IN PREPREČEVANJE PREOBREMENITEV V RADIALNIH DISTRIBUCIJSKIH OMREŽJIH

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Keywords: voltage profile, radial distribution network, load flow calculations, active network elements, energy flexibility

Abstract

The article deals with the issue of providing suitable voltage profiles and preventing congestion of network elements in distribution networks. Active network elements and network users' energy flexibility services are used to provide a suitable voltage profile and prevent congestion in distribution networks. The discussed active network elements include a transformer with on-load tap changer, reactive power compensation devices, energy storage systems, distributed energy

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resources, and network users' energy flexibility services, where the active consumers adjust their consumption, production and storage of energy. Based on the Backward Forward Sweep load flow computation method, the case studies are performed for the discussed low voltage distribution network, where the measurement results were available. The case studies for preventing overload of the distribution transformer are performed using a battery energy storage system and network users' energy flexibility services. The case studies for providing suitable voltage profiles are performed using all listed active elements and a combination of different active elements. In addition, to provide suitable voltage profiles, the existing conductors are replaced with conductors of a larger cross-section. Technically acceptable solutions that can provide a suitable voltage profile and prevent the overloading of network elements in the most demanding operating conditions are presented in this article.

Povzetek

V članku je obravnavana problematika zagotavljanja ustreznih napetostnih profilov in preprečevanje preobremenitev elementov omrežja v distribucijskih omrežjih. Za zagotavljanje ustreznega napetostnega profila in preprečevanje preobremenitev v distribucijskih omrežjih so uporabljeni aktivni elementi omrežja in storitev prožnosti energije uporabnikov omrežja. Analize so izvedene z izračunom pretokov energije z uporabo metode *Backward Forward Sweep* za obravnavano nizkonapetostno distribucijsko omrežje, za katero so bili podani rezultati meritev. Izvedeni so bili izračuni preprečevanja preobremenitve transformatorja z baterijskim hranilnikom energije in storitvijo prožnosti uporabnikov omrežja. Izračuni zagotavljanja ustreznega napetostnega profila so bili izvedeni z vsemi naštetimi aktivnimi elementi omrežja in s kombinacijo različnih aktivnih elementov. Zagotavljanje ustreznega napetostnega profila je bilo dodatno izvedeno z zamenjavo obstoječih vodnikov z vodniki večjega preseka. V članku so podane tehnično sprejemljive rešitve z aktivnimi elementi omrežja in s storitvijo prožnosti energije, ki preprečijo preobremenitev elementov omrežja in zagotovijo ustrezen napetostni profil.

1 INTRODUCTION

The increased growth of electricity consumption, especially peak loads, and the integration of DER (distributed energy resources) into the network, can occasionally lead to overloading of individual network elements, such as lines and transformers, and problems in providing suitable voltage profiles. These problems occur mainly in radial distribution networks, due to the network structure and load profile. The properties of radial structured distribution networks are presented in [2].

With active network elements and energy flexibility services, the problems of violation of prescribed voltage profile values and overloading of network elements can be eliminated within certain limitations. In other cases, upgrading and expansion of the network is used, which means the installation of conductors with a larger cross-section and transformers with a higher rated power. The BFS (Backward Forward Sweep) method is used for load flow calculations, which is suitable for radial network calculations. The principle of the BFS method is described in [1].

2 ACTIVE NETWORK ELEMENTS

Active network elements are elements that can be used to change certain parameters in the network, with the aim of providing appropriate and stable operation of the power network. Operational distribution network parameters, such as voltages and energy flows, can be affected with active network elements. Some of the active network elements are: a transformer with OLTC (On-load tap-changer), reactive power compensation devices, ESS (energy storage systems), DER and the network users' energy flexibility services, where the active consumer adjusts the consumption, production and storage of energy.

A transformer with an OLTC can adjust the transformer's ratio, and thus the voltage, whenever the voltage controller detects a secondary voltage that deviates from a predetermined value. Normally there is a voltage control within ±10% of the nominal voltage. This range is divided into nine fixed steps which enable changes of voltage by 2.5% with each step. The operating principle of the transformer with OLTC is described in [3].

Due to a large number of inductive consumers (electric motors, transformers) in the power network, reactive components of the current additionally load the network elements. This phenomenon can lead to undervoltage or overvoltage in distribution networks. The reactive power compensation devices, such as shunt and series compensators, can locally and effectively cover reciprocal energy exchange demand on the consumer side. The principle of reactive power compensation and reactive power compensation devices are described in [4] and [5].

In distribution networks, the use of ESS can improve the stability and reliability of the network. Electrical energy from the network or a DER is converted and stored in an ESS and used later when needed. During times of higher production and lower consumption, excess electrical energy can be stored for a certain period and used when there is lower production and higher consumption in the network. Different methods of energy storage are described in [6]. For use in distribution networks, a BESS (battery energy storage system) is currently the most suitable. Important parameters for choosing a BESS are nominal capacity, power, the battery management system and the type of batteries used to store energy. Different types of BESS are described in [7].

DER is nowadays integrated in almost all distribution networks. Most of them are in the form of renewable energy sources, such as PV (photovoltaic) power plants, wind power plants, biomass energy, geothermal energy, etc. With DER, energy flow in network can be impacted by adjusting the production of active and reactive power. Some of the DER and their impact in distribution networks are described in [8], [9] and [10].

The network users' energy flexibility service represents a new concept where passive consumers of electricity become active consumers – prosumers who can adjust the consumption, production and storage of electricity. With flexibility, it is possible to solve problems of balance of production and consumption of electricity and thus prevent network overloads or provide a suitable voltage profile. The prosumer would, on demand, adjust their consumption, production and storage of electricity to ensure the stable operation of the network. The concept of flexibility and the inclusion of a prosumer in the electricity market is described in [11].

3 DISCUSSED DISTRIBUTION NETWORK

The LV (low voltage) distribution network, for which the measurement results were given, is discussed. A transformer substation (TS) feeds the discussed radial network. It contains three feeders with nineteen connected consumers. Figure 1 shows the diagram of the discussed network. In Figure 1 it can be seen that this network has thirty-nine nodes and thirty-eight branches. Nodes with a consumer are in blue, sections of conductors which are intended to be replaced are in green.

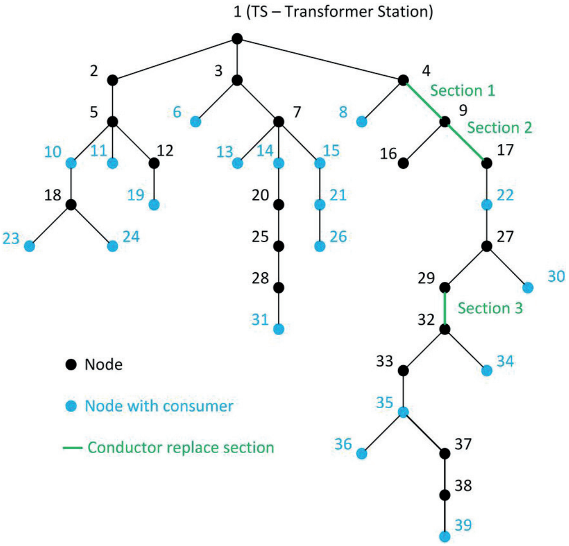

***Figure 1:** Diagram of discussed network*

The corresponding installed power of the consumers and the rated power of the transformer in the TS are stated in Table 1.

***Table 1:** Installed power of consumers and associated nodes.*

Node	1 (TS)	6	8	10	11	13	14	15	19	21
Installed power [kW]	100 kVA	43	14	14	17	6	17	17	17	17
Node	22	23	24	26	30	31	34	35	36	39
Installed power [kW]	17	17	6	14	17	17	17	17	17	5

4 ANALYSIS

The article deals with two problems, namely transformer overload and violation of the prescribed voltage profile values in the discussed radial distribution network. For each problem a different solution method was used. All calculations were performed in MATLAB.

To prevent transformer overload, the rated data of the transformer was checked. Rated power of the discussed transformer is 100 kVA, as shown in Table 1. Based on the measurement results, it was determined as to whether the transformer was overloaded in any of the observed 15-minute time intervals. For the day with the highest consumption, transformer overload is prevented by employment of active elements and energy flexibility services. In the 15-minute time interval, when the transformer would be overloaded, the necessary active power was generated by the BESS in order to prevent overloads. Another way to prevent overloads in the transformer was the utilisation of network users' energy flexibility services in the form of peak shaving.

To provide a violation of the prescribed voltage profile limits, a network model suitable for load flow calculations was prepared. The model input data were the results of measurements on the transformer, the data of the customers' installed power and load profiles, as well as the parameters of all lines in the discussed network. The topology of the discussed network used in the BFS based load flow calculations is shown in Figure 1. The BFS load flow method [1] is used to determine the voltages in all nodes of the discussed network. Based on the results of load flow calculations, the nodes, in which the voltage profile limits are violated, were identified. In the identified nodes, active network elements, energy flexibility services provided by the network users, and the replacement of unsuitable network elements were all used to prevent violation of the voltage profile.

5 RESULTS

Based on the measurement results, which were available for the transformer in the TS, load flow calculations were performed to solve the problem of overloading and provide a suitable voltage profile with active elements. Measurement results data on the transformer were for the voltage of all three phases, active and reactive power, and were given as 15-minute readings.

5.1 Transformer overload

When reviewing the measurement results for years 2018 and 2019, the transformer in the TS was not overloaded at any time. Therefore, for the purposes of the analysis, a linear 2% annual growth in consumption based on the measurement results was assumed. A calculation was made about what the consumption would be after 30 years, that is, in 2049. The consumption increased by 81.14% compared to the baseline data. With these calculated data, an attempt was made to prevent transformer overload with the BESS and network users' energy flexibility service for the day with highest consumption, which was 22.4.2019. Figure 2 shows the apparent power of the measurement results for the day with the highest consumption (year 2019) and calculated data after linear 2% annual growth in consumption for 2049.

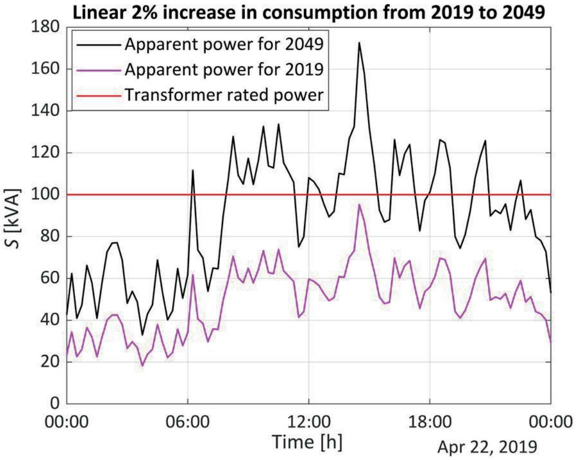

***Figure 2:** Apparent power over time for 2019 (pink curve) and for 2049 (black curve)*

5.1.1 Usage of BESS

Under assumptions that the BESS operates between 20% and 80% of nominal capacity, and it was discharged the previous day, it was calculated that a BESS with a minimum nominal capacity of 248 kWh at nominal power of 72.61 kW is needed to prevent overload of the transformer. Figure 3 shows the SOC (state of charge), charging and discharging power of the BESS. It was considered that the BESS is a consumer of electricity while it is being charged and that it generates active power while it is being discharged. In Figure 3b, the blue curve shows charging when the BESS receives active power from the network, and the red curve shows discharging when the BESS outputs active power to the network.

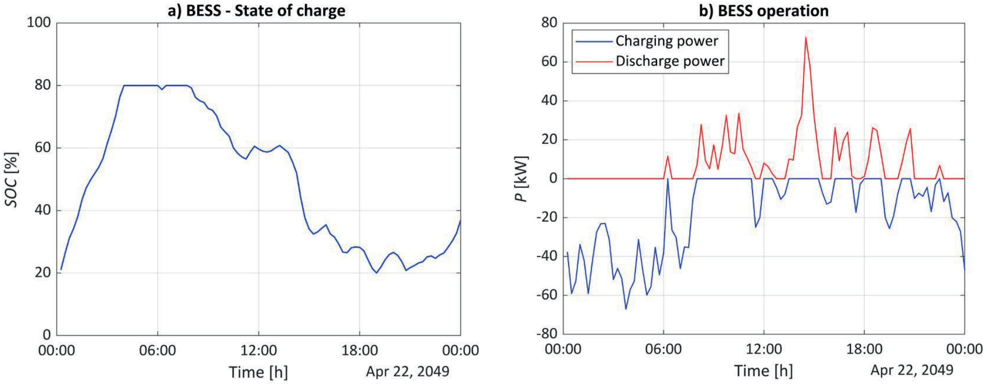

***Figure 3:** SOC (a) and operation of BESS (b) over time*

5.1.2 Usage of network users' energy flexibility service

To be able to use the network users' energy flexibility service, the amount of energy that flows through the transformer in an overloaded state and how much energy and power is available to perform flexibility services was calculated. The energy of the overloaded state, in the form of active power with the corresponding share of reactive power was moved to moments when the transformer was not overloaded. The participation of all consumers in the considered network was taken into account. The selected time interval for the flexibility service lasted from 07:00 to 22:00, so that consumption was not shifted to the early morning or night hours. Figure 4 shows the apparent power of the transformer over time and the use of the flexibility service over a 15-hour interval. Transformer overload was not prevented, because after using the flexibility service, the transformer was still overloaded at certain times, as shown by the blue curve in Figure 4.

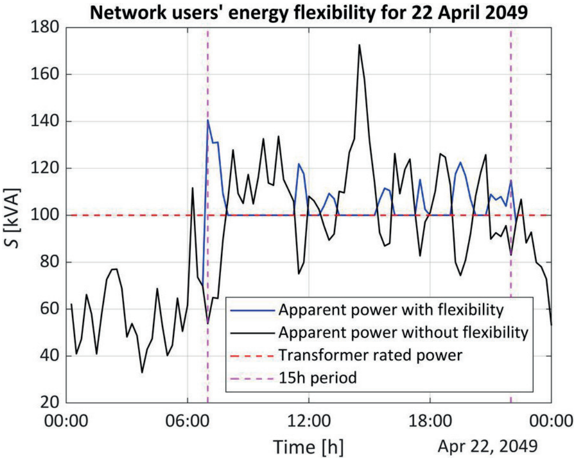

Figure 4: Apparent power over time and use of flexibility service

5.2 Providing a suitable voltage profile

When reviewing the measurement results, the voltages of all three phases at the transformer terminals were within the permissible limits. Based on the network data, a network model was prepared, and load flow was calculated using the BFS method [1]. Voltage profiles for all nodes for the day and the moment of highest consumption were calculated. Figure 5 shows the voltage profile over time and nodes for the day with the highest consumption. The point of highest consumption is at 14:30 on 22.4.2019. Figure 6 shows the voltage profile over nodes for the moment of highest consumption. It was discovered that undervoltage occurs at the end of the third feeder. With this data, an attempt was made to provide a suitable voltage profile with all listed active elements of the network.

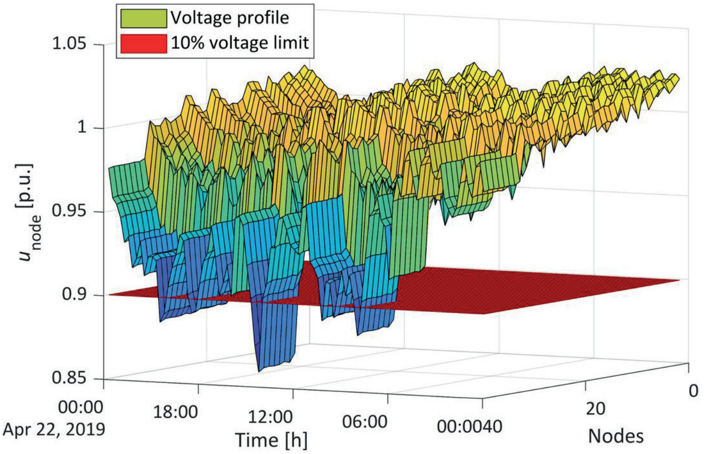

Figure 5: *Voltage profile over time and nodes for the day with highest consumption*

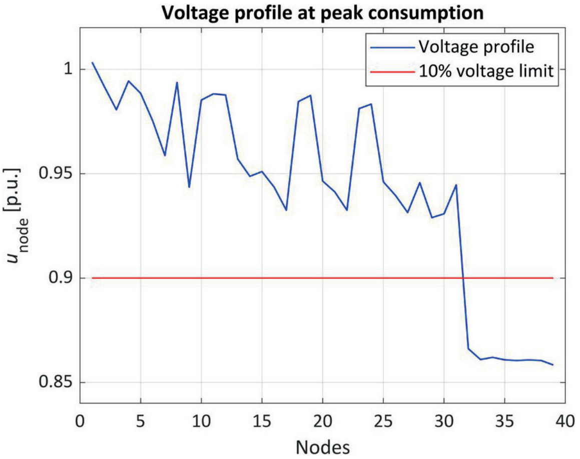

Figure 6: *Voltage profile over nodes for the moment of highest consumption*

5.2.1 Usage of transformer with OLTC

Using a transformer with OLTC, voltage on the secondary side of the transformer was raised by 2.5% and 5%. Standard distribution transformers have five steps, which enable voltage adjustment in the range of ±2 × 2.5% U_n. It was assumed that the transformer is currently set on the mid tap. Figure 7 shows the node-wise voltage profile using a transformer with OLTC with balance node voltage increased. When raising the voltage of the balance node (node 1) by 5%, a suitable voltage profile is provided, which is shown by the pink curve in Figure 7.

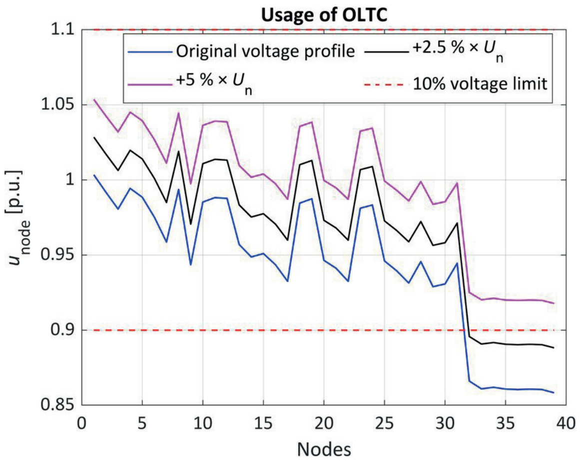

Figure 7: *Voltage profile when the voltage of the balance node is increased*

5.2.2 Use of a reactive power compensation device

Reactive power of a capacitive character was generated with a reactive power compensation device. The location of the compensation device was determined in the third feeder from the TS in which the undervoltage occurred. A undervoltage location at node 27 was determined. The calculations were performed for different power levels of the compensation device. Figure 8 shows the node-wise voltage profile with reactive power compensation at node 27. A suitable voltage profile was not provided.

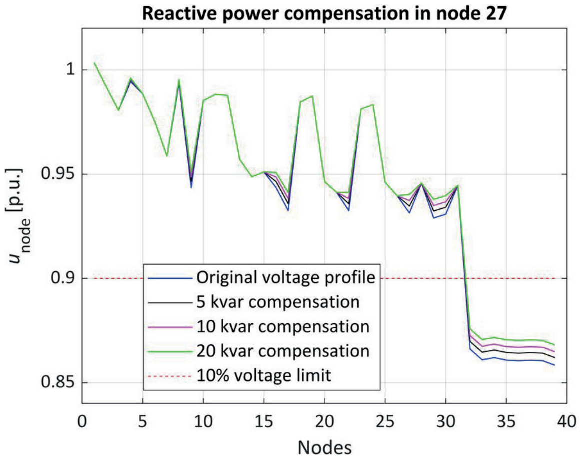

Figure 8: *Voltage profile with reactive power compensation device*

5.2.3 Usage of BESS

With the BESS, active power was generated while the BESS was discharging. While charging, the BESS responded as a consumer of electricity. BESS charging was implemented from 00:00 to 06:00. Discharge of the BESS was done as necessary to provide a suitable voltage profile. The BESS location was chosen in the same node as for the reactive power compensation device. It was calculated that a BESS with a minimum nominal capacity of 29 kWh at a nominal power of 8 kW is needed to provide a suitable voltage profile. To charge the BESS, a charging power of 3.5 kW is required. Figure 9 shows the SOC, charging and discharging power of the BESS at node 27. Figure 10 shows the voltage profile over time and nodes with a BESS installed at node 27. The results clearly show that a suitable voltage profile is provided.

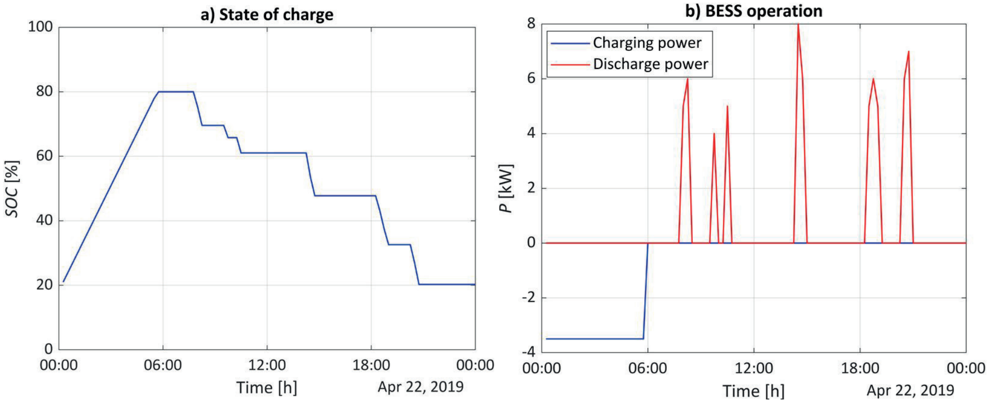

Figure 9: *SOC (a) and operation of BESS (b) at node 27 over time*

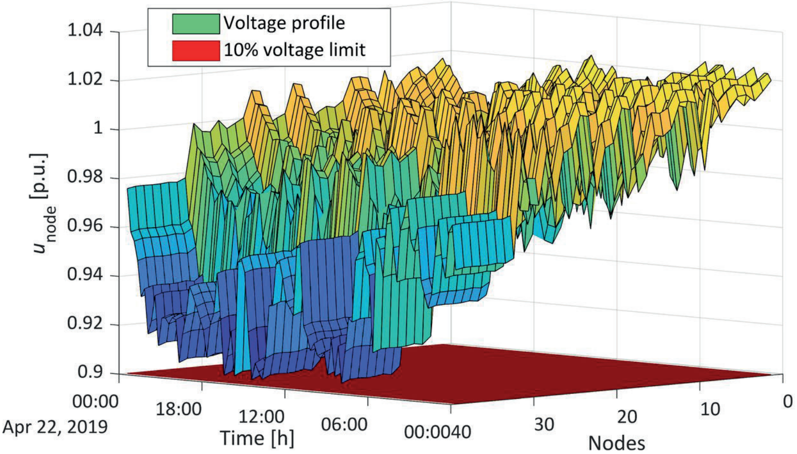

Figure 10: *Voltage profile over time and nodes with BESS at node 27*

5.2.4 Usage of PV power plant

A PV power plant enables the production of active or reactive power. Since it was found in subsection 5.2.2 that it is not possible to provide a suitable voltage profile with reactive power compensation, the PV power plant will generate only active power. It was considered that the power plant is installed at node 35. Based on [12], the maximum power of a PV power plant in the Slovenian distribution network can be up to 80% of the customer's installed power. The installed power of the customer at node 35 is 17 kW, which means that the maximum power of the PV power plant can be up to 13.6 kW. Based on solar irradiation data for 22.4.2019, the output power of the PV power plant was calculated. All the output power was fed into the network to provide a suitable voltage profile. Figure 11 shows the power output profile of the PV plant for the whole day. Figure 12 shows the voltage profile over time and nodes, using the PV power plant installed at node 35. The results show that a suitable voltage profile cannot be provided.

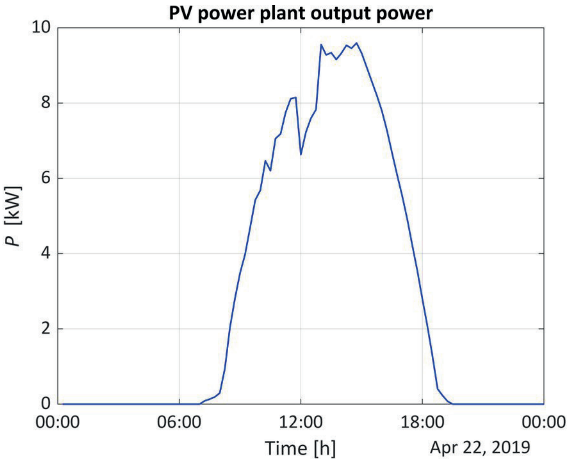

Figure 11: *Output power profile of PV power plant over time*

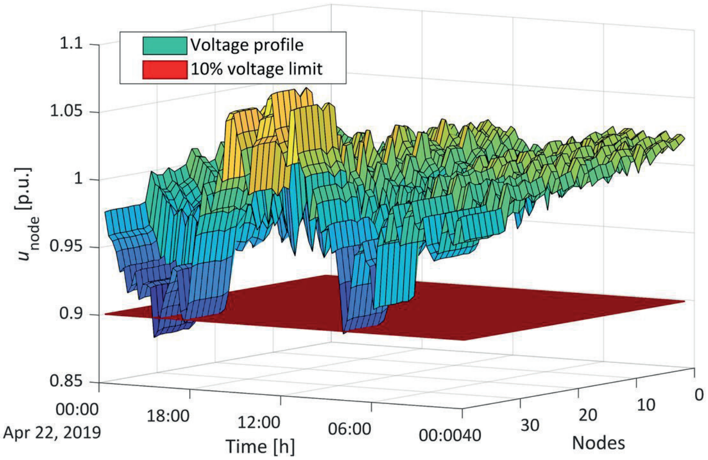

Figure 12: *Voltage profile over time and nodes with PV power plant installed at node 35*

5.2.5 Use of a combination of BESS and PV power plant

In section 5.2.4, it was found that a suitable voltage profile is not provided by using a PV power plant only. Therefore, a combination of the BESS and PV power plant was used. The operating principle is such that when the voltage is too low, all the output power of the PV power plant is fed to the network. When the voltage is within the prescribed limits, all the output power of the PV power plant is used for charging the BESS. It is assumed that the BESS is half charged from the previous day. If the PV power plant alone cannot provide a suitable voltage profile, then the BESS is discharged as necessary to provide a suitable voltage profile. It was calculated that a BESS with a minimum nominal capacity of 30 kWh at a nominal power of 11 kW is needed to provide a suitable voltage profile in combination with the PV power plant. The output power profile of the PV power plant is shown in Figure 11. Figure 13 shows the SOC, charging and discharging power of the BESS at node 35. Figure 14 shows the voltage profile over time and nodes with a PV power plant and the BESS at node 35. In the discussed case, a suitable voltage profile is provided.

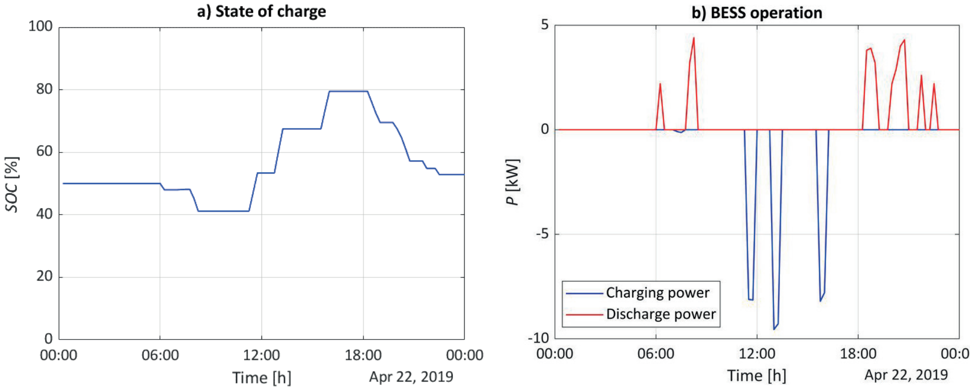

Figure 13: *SOC (a) and operation of BESS (b) at node 35 over time in combination with PV power plant*

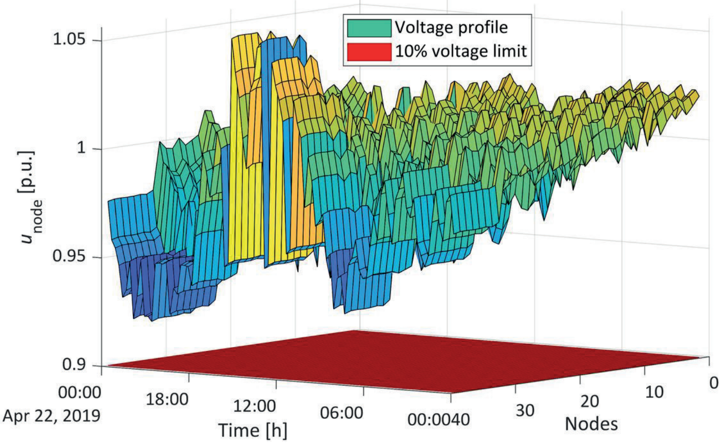

Figure 14: *Voltage profile over time and nodes with PV power plant and BESS at node 35*

5.2.6 Use of network users' energy flexibility service

At critical moments of the day, when the voltage was out of tolerance, we reduced and shifted consumption using the network users' energy flexibility service. The consumption was adjusted in a certain time interval, which lasted from 12:00 to 20:00, since in this interval there is the highest consumption. Consumers in the third feeder of the TS, where voltage profile violation occurred, were included in the flexibility service. There are five consumers with an installed power of 17 kW and one consumer with an installed power of 5 kW. Figure 15 shows the consumption profile using the flexibility service provided by the consumers with an installed power of 17 kW and 5 kW. Figure 16 shows the voltage profile using the flexibility service over an eight-hour time interval. Figure 16 shows that a suitable voltage profile is provided in this time interval.

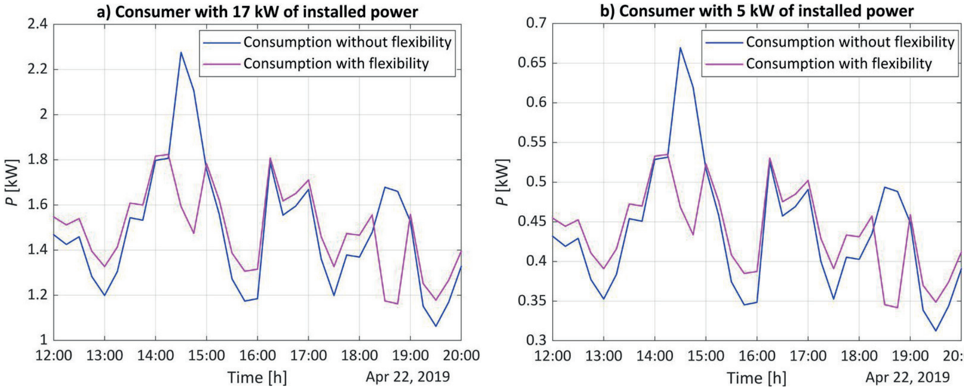

Figure 15: *Consumption profile over time using the flexibility service for consumer with an installed power of a) 17 kW, and b) 5 kW*

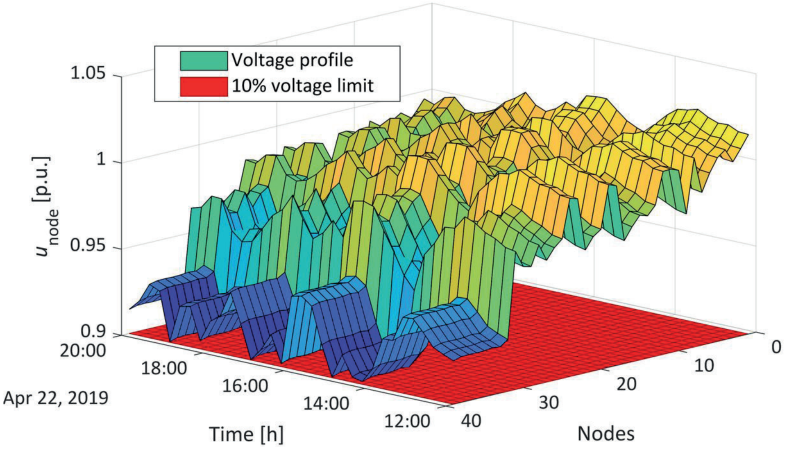

Figure 16: *Voltage profile using the flexibility service of consumers in third output of the TS*

5.2.7 Replacing network elements

The last solution to provide a suitable voltage profile is the replacement of network elements. It was assumed that the existing conductors would be replaced with conductors of a larger cross section in certain sections of the network in the third feeder of the TS. A larger conductor cross-section has a positive effect on the voltage profile and at the same time reduces losses in the network. In Figure 1, the feeder sections selected for the replacement of conductors are marked in green. These three sections were selected for replacement, because these are the longer lines in the third feeder with a smaller cross section of only 35 mm^2. All other lines in this feeder have a cross section of 70 mm^2. The existing conductors of type PP00-A 4x35+2.5 (cross section of 35 mm^2) were replaced with conductors of type PP00-A 4x70+2.5, which have a cross section of 70 mm^2. Conductors were replaced gradually in the three selected sectors. Figure 17 shows the voltage profile using a PP00-A 4x70+2.5 type conductor. A suitable voltage profile is provided when conductors in all three sectors are replaced.

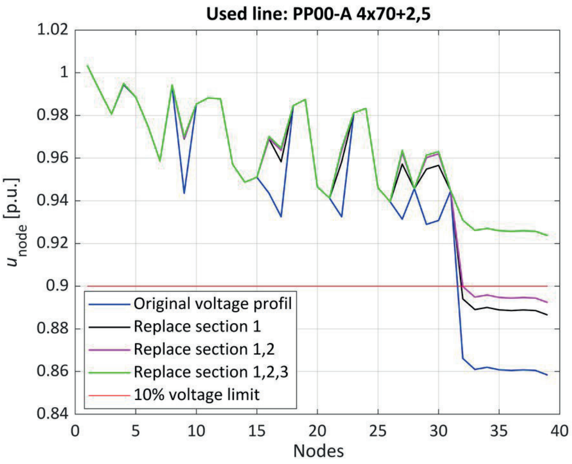

Figure 17: *Voltage profile with conductor type PP00-A 4x70+2.5 in selected sectors*

6 CONCLUSION

This article presents the results of the transformer overload analysis and the provision of suitable voltage profiles. The results were determined using load flow calculations. Calculations to provide a suitable voltage profile were performed for a symmetrical three-phase load using the BFS load flow method.

Transformer overload can be prevented by using a BESS of appropriate nominal capacity and power. With the network users' energy flexibility service, it is not possible to prevent overloading during the selected time interval. A longer time interval could be used, but this would shift the consumption to night-time hours, which does not make sense from the consumers' point of view.

A suitable voltage profile can be provided with a transformer with OLTC, where the voltage on the secondary side of the TR is increased. With a BESS of appropriate nominal capacity and power, a suitable voltage profile is provided. A combination of a BESS and a PV power plant can provide a suitable voltage profile. With the use of the network users' energy flexibility service, a suitable voltage profile is provided in the selected time interval. These results were obtained considering that all consumers in the third feeder of the TS participate, where the voltage profile violation occurred. By replacing the existing conductors with conductors of a larger cross-section in problematic sections, a suitable voltage profile is provided. A suitable voltage profile cannot be provided when reactive power compensation and a PV power plant are used as active network elements.

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Nomenclature

BESS	Battery energy storage system
BFS	Backward-forward sweep
DER	Distributed energy resources
ESS	Energy storage system
LV	Low voltage
OLTC	On-load tap-changer
P	Active power
PV	Photovoltaic
Q	Reactive power
S	Apparent power
SOC	State of charge
t	Time
TS	Transformer station
u_{node}	Node voltage
U_{n}	Nominal voltage