Application of Battery Storage in Low Voltage Distribution Network for Improving Integration of Distributed Generation

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***Abstract*—In this paper, using of a battery energy storage system in a low voltage distribution network for improving the integration of distributed generation and island operation during the failure in the main grid is presented. Modeling and simulation of the low voltage distribution network are performed using DigSilent Power Factory. The observed network consists of households whose load diagram based on measurement data is modeled. Distributed generation in the observed network is a photovoltaic power plant. Time step simulation is performed to show the impact of battery storage on transformer load. Power flow simulations for two different cases are performed: maximum generation and minimum load and minimum generation and maximum load to show the impact of battery storage on voltages and power flows. Battery storage can cover consumption when the main grid is not available in case of any failure. Time step simulation is done to show how long a fully charged battery can cover consumption during the day when generation is available and during the night when there is no generation from photovoltaic. Power flow simulation is done to show the impact of battery storage on voltages when the main grid is not available.**

***Keywords*—battery storage, distribution network, photovoltaic, own consumption, island operation**

I. INTRODUCTION

The plan for the future is to completely replace the electricity generation from fossil fuels with electricity generation from renewable energy sources (RES) to reduce negative environmental impact. Generation from RES can be centralized generation from large wind farms or hydropower plants connected to the transmission network and distributed generation from biomass, biogas, or photovoltaic (PV) power plants connected to medium voltage (MV) or low voltage (LV) distribution network. PV power plants are most common in LV distribution networks because they are suitable for mounting on roofs of houses and buildings. A high level of PV integration in LV distribution networks can lead to power flows in the opposite direction and voltage increase when load demand is lower than electricity generation. A solution for this problem is using battery storage (BS) which can store energy excess to reduce voltage increase and opposite power flows. Peak load demand for residential consumers is usually in the evening. Energy from the BS can be used to cover peak load demand in the evening when there is no electricity generation from the PV power plants.

There are many published papers dealing with using of BS in the LV distribution grid. An original algorithm for planning and scheduling BS is proposed in [1]. Optimal sizing and placement of BS in LV distribution grid with a high amount of generation from PV power plants are investigated in [2]. Unbalanced installation of single-phase PV power plants in a three-phase grid leads to neutral voltage rise which can be reduced by using BS [3]. Authors of [4] presented using of BS for voltage control in LV distribution grid with a high amount of generation from PV power plants. Authors of [5] compared the impact of centralized and distributed BS on voltage reduction on the critical node. The impact of BS on voltage profiles, loading of cables and transformer, power exchange with MV grid, and power losses in LV rural network is investigated in [6]. Methodology and optimal operating strategy to find optimal location and size of BS using genetic algorithm are presented [7]. LV grid can be supported with static and mobile storage systems [8]. The authors of [9] used power flow simulation to investigate the impact of centralized BS on voltages in a distribution grid with a PV generation. An optimal BS control method to minimize peak power injection considering battery degradation is presented in [10]. A methodology for optimal planning and operation of a BS in a medium-low voltage distribution grid is proposed in [11]. Optimal sizing, placement, and operation of a BS to reduce the impact of the integration of a PV power plant are proposed in [12] through linked simulations in DigSilent and Matlab.

In this paper, time step simulation, in DigSilent Power Factory is a quasi-dynamic simulation, that is done to obtain daily transformer load and to find when the highest and lowest voltages are occurred in a radial LV distribution network with a high amount of generation from PV power plants, without and with a BS. The power flow simulations are done when the maximum and minimum voltages are occurred to obtain voltages on all nodes, without and with a BS. To decide when to charge and discharge BS, optimization is used.

This paper consists of four chapters. Chapter 1 is the introduction of this paper. The low voltage distribution network is presented in chapter 2. Simulation results for different case studies are presented in chapter 3. The last chapter is the conclusion of this paper according to the results.

II. LOW VOLTAGE DISTRIBUTION NETWORK

The impact of a BS on the integration of distributed generation is shown on the radial LV distribution grid with a high amount of generation from the PV power plants. The LV grid is modeled in DigSilent Power Factory. The LV grid used in this study is presented in Fig. 1. The LV grid is powered by the MV grid over a 10/0.4 kV transformer. The installed power of the transformer is 630 kVA.

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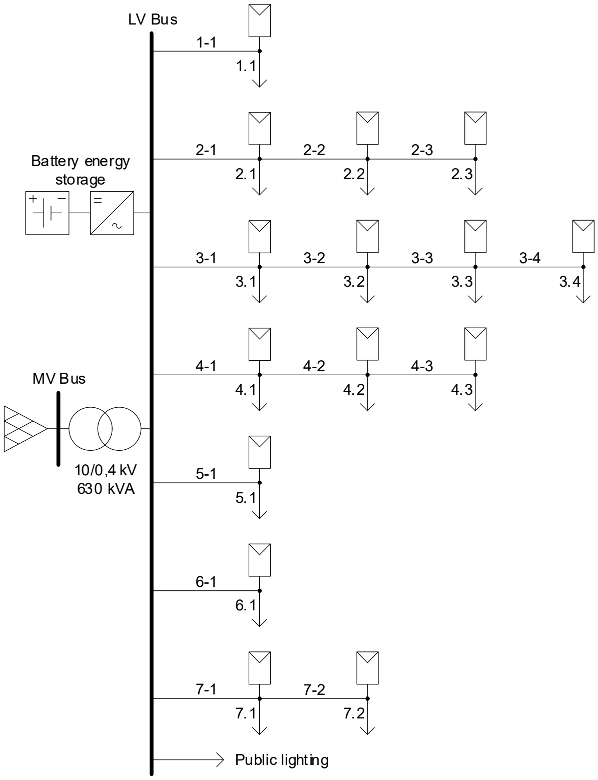

Fig. 1. Low voltage distribution network

There are seven feeders in the radial LV distribution grid. Loads and PV power plants are connected to 15 nodes and there is one additional load connected to the LV bus which represents public lighting with a rated power of 20 kVA. Public lighting is turned on from 20:00 to 6:00. Battery storage is connected to the LV bus. In Table 1, the type and length of cables, as well as connected loads and installed generation from PV power plants are presented. The power factor of load and PV generation is set to 0.95.

TABLE I. CABLING, LOAD, AND PV GENERATION DATA

Cabling data			Load and PV generation data		
Line	***Type***	***Length* [m]**	***Node***	***Load* [kVA]**	***PV* [kVA]**
1-1	NAYY 4x120	67	1.1	50	50
2-1	NAYBY 4x120	64	2.1	50	50
2-2	NAYBY 4x120	41	2.2	20	20
2-3	NAYBY 4x50	36	2.3	20	20
3-1	NAYBY 4x120	70	3.1	50	50
3-2	NAYBY 4x120	15	3.2	20	20
3-3	NAYBY 4x120	70	3.3	10	20
3-4	NAYBY 4x120	56	3.4	10	20
4-1	NA2XY 4x240	160	4.1	10	20
4-2	NA2XY 4x120	125	4.2	5	10
4-3	NA2XY 4x120	139	4.3	5	10
5-1	NA2XY 4x150	100	5.1	70	50
6-1	NAYY 4x150	60	6.1	70	50
7-1	NAYY 4x150	117	7.1	50	50
7-2	NA2XY 4x150	52	7.2	20	20

A. PV generation

Generation from PV power plants is modeled for an ideal sunny day according to the measured output power of a real PV power plant. PV generation is then scaled to different sizes of PV power plants. PV generation obtained as a sum of the rated power of all PV power plants connected in the radial LV distribution network is presented in Fig. 2.

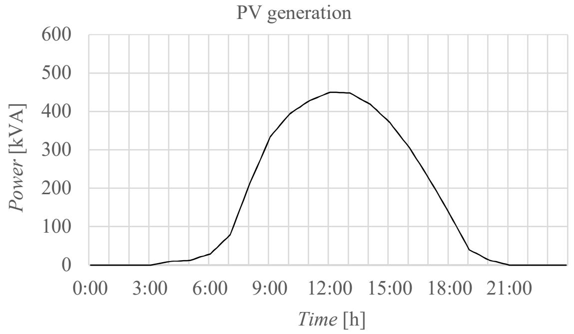

Fig. 2. PV generation in LV radial distribution network

B. Load

Consumers in the observed radial LV distribution network are households. Load data is measured in households and then scaled to different load sizes. Load demand in LV distribution network obtained from transformer load as the result of quasi-dynamic simulation with only PV load connected is presented in Fig. 3. The minimum load demand is in the morning at 6:00 and the maximum load demand is at 21:10.

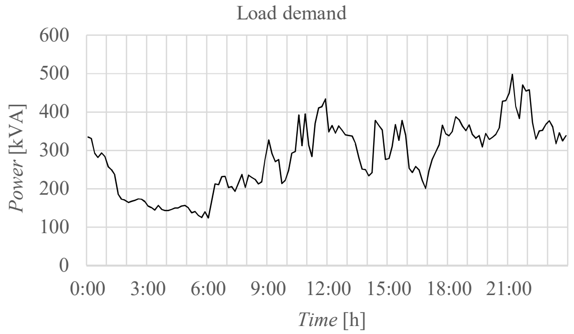

Fig. 3. Load demand in LV radial distribution network

C. Battery storage

The main purpose of using battery storage in the observed LV distribution network is to reduce the negative impact of the integration of a large number of PV power plants. To ensure enough power and capacity in islanded operation mode, BS with 500 kW rated power and 1104 kWh of energy capacity is selected. BS consists of 8 battery racks with a capacity of 138 kWh. The efficiency of the battery converter is 99.5% at the full load [13].

Optimization is required to decide when to charge and discharge the battery storage system. An optimization problem is modeled with linear programming (LP) and solved with a Gurobi optimizer in a Python environment.

The objective function for this optimization problem is a minimization of electricity cost for the observed day which is equal to the sum of products of electricity received from the grid and electricity price for every time interval *i* (1).

$$\text{Min} \sum(E_{\text{received,i}} \cdot Price_{\text{i}}) \qquad (1)$$

Where:

- $E_{\text{received,i}}$ [kWh] – electricity received from the grid;
- $Price_{\text{i}}$ [€/kWh] – electricity price.

The electricity pricing model considered in this paper is two tariff pricing in Croatia. Electricity price is 0.16 €/kWh from 8:00 to 22:00 and 0.08 €/kWh from to 22:00 to 8:00 [14]. Lower electricity cost means that a lower amount of electricity is received from the grid which results in lower transformer loading. Electricity received from the grid for every 10 minutes time interval is calculated according to (2).

$$E_{\text{received},i} = S_{\text{fromgrid},i} \cdot cos\varphi \,/\, 6 \quad (2)$$

Where:

- $S_{\text{fromgrid},i}$ [kVA] – power received from the grid;
- $cos\varphi$ – power factor.

Power received from the grid is obtained from (3). If there is an excess of generation and BS is charged, it is delivered to the grid (4). To disable delivering and receiving power from the grid at the same time, binary variables X_i and Y_i are required. The sum of X_i and Y_i is never higher than 1.

$$S_{\text{fromgrid},i} = X_i \cdot (S_{\text{demand},i} - S_{\text{pv},i} + S_{\text{c},i} - S_{\text{d},i}) \quad (3)$$

Where:

- $S_{\text{demand},i}$ [kVA] – load demand power;
- $S_{\text{pv},i}$ [kVA] – generation from PV power plants;
- $S_{\text{c},i}$ [kVA] – battery charging power;
- $S_{\text{d},i}$ [kVA] – battery discharging power.

$$S_{\text{togrid},i} = Y_i \cdot (S_{\text{pv},i} - S_{\text{demand},i} - S_{\text{c},i} + S_{\text{d},i}) \quad (4)$$

Where $S_{\text{togrid},i}$ [kVA] is the power delivered to the grid.

Battery charging power is obtained from (5) while battery discharging power is obtained from (6). Binary variables, C_i and D_i are required to disable charging and discharging at the same time. The sum of C_i and D_i is lower or equal to 1 (6).

$$S_{\text{c},i} = C_i \cdot (S_{\text{pv},i} - S_{\text{demand},i} + S_{\text{fromgrid},i}) \quad (5)$$

$$S_{\text{d},i} = D_i \cdot (S_{\text{demand},i} - S_{\text{pv},i} - S_{\text{fromgrid},i}) \quad (6)$$

Battery capacity for every time interval i is calculated according to (7). Battery state of charge (SOC) is obtained from battery capacity according to (8).

$$C_{\text{bat},i} = C_{\text{bat},i\text{-}1} + ((S_{\text{c},i} \cdot \eta_{\text{bat}} - S_{\text{d},i} \cdot (1/\eta_{\text{bat}})) \cdot cos\varphi)/6 \quad (7)$$

Where:

- $C_{\text{bat},i}$ [kWh] – battery capacity in time interval i;
- $C_{\text{bat},i\text{-}1}$ [kWh] – battery capacity in time interval $i - 1$;
- η_{bat} – battery converter efficiency.

$$SOC_i = C_{\text{bat},i} \,/\, C_{\text{bat,rated}} \cdot 100 \quad (8)$$

Where:

- SOC_i [%] – battery SOC in time interval i
- $C_{\text{bat,rated}}$ [kWh] – rated battery capacity.

Limitations for this optimization problem are referred to the power received from the grid (9), charging power (10), discharging power (11), and battery SOC (12).

$$0 \le S_{\text{fromgrid},i} \le S_{\text{grid,max}} \quad (9)$$

$$0 \le S_{\text{c},i} \le S_{\text{battery,max}} \quad (10)$$

$$0 \le S_{\text{d},i} \le S_{\text{battery,max}} \quad (11)$$

$$SOC_{\text{min}} \le SOC_i \le SOC_{\text{max}} \quad (12)$$

Where:

- $S_{\text{grid,max}}$ [kVA] – maximum power from the grid;
- $S_{\text{battery,max}}$ [kVA] – maximum battery power;
- SOC_{min} [%] – minimum battery SOC;
- SOC_{max} [%] – maximum battery SOC.

III. SIMULATION RESULTS

Results of simulations for different cases will be presented in this chapter as follows:

- Case study 1: PV without BS;
- Case study 2: PV and BS;
- Case study 3: PV, BS, and grid outage during the day;
- Case study 4: PV, BS, and grid outage in the evening.

A. *Simulation results for case study 1*

In case study 1, the LV network with a high amount of PV power plants is simulated. The result of the quasi-dynamic simulation is the load on the transformer presented in Fig. 4. The maximum load on the transformer is 497.80 kVA at 21:10. The maximum power flow to the grid is 176.58 kVA at 14:00. The electricity cost in the case study 1 is 389.26 €.

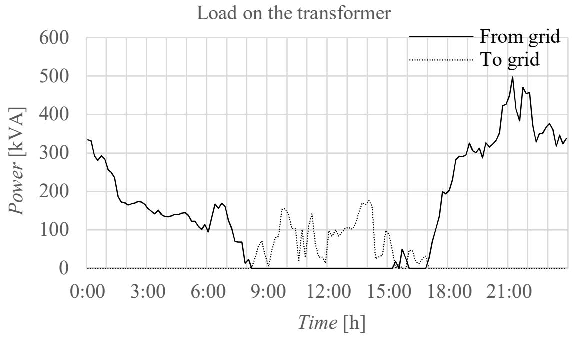

Fig. 4. Load on the transformer without battery storage

B. *Simulation results for case study 2*

In case study 2, the LV network with a PV generation and BS are simulated. The charging and discharging power of BS obtained with optimization and battery SOC are presented in Fig. 5. The electricity cost is 294.88 €. BS is charging from the grid in the morning when the electricity price is low and during the day when there is a surplus of PV generation. BS is discharging in the evening to cover peak load demand. Battery SOC is limited between 20% and 80% to increase battery life. Battery SOC is 20% at the start and the end of the day.

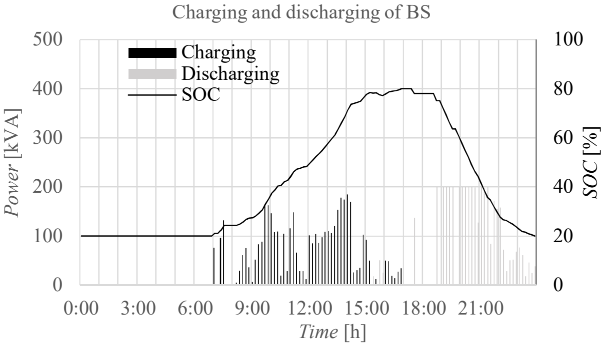

Fig. 5. Charging and discharging of battery storage

The impact of BS on transformer loading is visible from quasi-dynamic simulation results. The load on the transformer is presented in Fig. 6. The maximum load on the transformer in case study 2 is 334.84 kVA at 00:00. Power flows to the grid are reduced due to charging BS with generation surplus. Load demand in the evening is lower due to discharging BS.

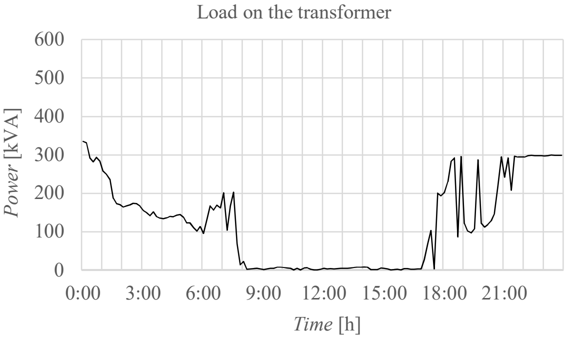

Fig. 6. Load on the transformer with battery storage

Power flow simulations are done when maximum and minimum voltages are occurred to obtain voltages on all nodes and to see the impact of BS. The maximum voltage is at 14:00 due to the largest surplus of PV generation. The minimum voltage is at 21:10 due to the peak load demand. Voltages in case study 1 (U_1) and case study 2 (U_2) are presented in Table 2. With BS, the maximum voltage on node 4.3 at 14:00 is reduced from 414.0 V to 410.4 V and the minimum voltage on node 4.3 at 21:10 is increased from 382.0 V to 386.0 V.

TABLE II. VOLTAGES WITHOUT AND WITH BS

Bus/ Node	**Voltages at 14:00**				**Voltages at 21:10**			
	U_1 [V]	U_2 [V]	ΔU [V]	ΔU [%]	U_1 [V]	U_2 [V]	ΔU [V]	ΔU [%]
LV	403.2	400.0	3.2	0.8	390.8	394.8	4	1
1.1	404.0	400.8	3.2	0.8	388.4	392.4	4	1
2.1	404.8	401.2	3.6	0.9	386.8	390.8	4	1
2.2	405.2	401.6	3.6	0.9	385.6	389.6	4	1
2.3	405.6	402.0	3.6	0.9	384.4	388.4	4	1
3.1	405.6	402.4	3.2	0.8	386.4	390.4	4	1
3.2	406.0	402.8	3.2	0.8	386.0	390.0	4	1
3.3	407.2	403.6	3.6	0.9	384.8	388.8	4	1
3.4	407.6	404.4	3.2	0.8	384.8	388.4	3.6	0.9
4.1	412.4	408.8	3.6	0.9	383.2	387.2	4	1
4.2	413.2	410.0	3.2	0.8	382.4	386.4	4	1
4.3	414.0	410.4	3.6	0.9	382.0	386.0	4	1
5.1	403.6	400.4	3.2	0.8	386.8	390.8	4	1
6.1	403.6	400.4	3.2	0.8	388.4	392.4	4	1
7.1	405.2	402.0	3.2	0.8	384.8	388.8	4	1
7.2	405.6	402.0	3.6	0.9	384.4	388.4	4	1

C. Simulation results for case study 3

In case study 3, the possibility of the islanded mode of the LV network when the main grid is not available during the day is simulated. The charging and discharging power of BS, shown in Fig. 7 are obtained with optimization when grid outage from 16:00 to 19:40 is considered. The electricity cost is 288.36 €. Fig. 8 presents the load on the transformer. The maximum load on the transformer is 401.90 kVA at 20:20.

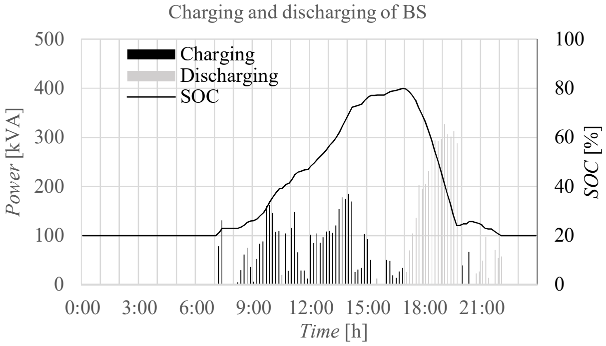

Fig. 7. Charging and discharging of BS when grid outage is during the day

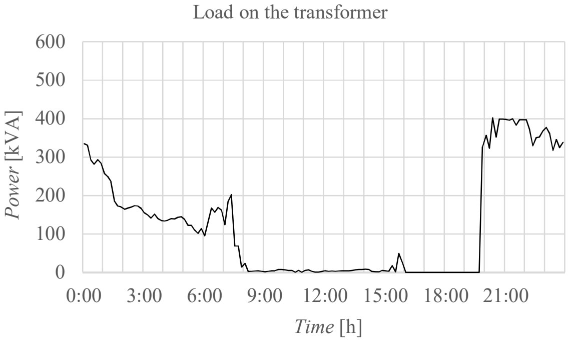

Fig. 8. Load on the transformer with grid outage from 16:00 to 19:40

A comparison of voltages in case study 3 (U_3) with voltages in case study 2 (U_2) is presented in Table 3. The maximum voltage in islanded mode is 406 V on node 4.3 at 16:00 which is equal to the voltage on the same node in normal mode at the same time. The minimum voltage in islanded mode is 394.8 V on node 4.3 at 19:00 which is 2 V higher than the voltage on the same node in normal mode at the same time.

TABLE III. VOLTAGES IN ISLANDED AND NORMAL OPERATION MODE

Bus/ Node	**Voltages at 16:00**				**Voltages at 19:00**			
	U_3 [V]	U_2 [V]	ΔU [V]	ΔU [%]	U_3 [V]	U_2 [V]	ΔU [V]	ΔU [%]
LV	400.0	400.0	0	0	400.0	397.6	2.4	0.6
1.1	400.4	400.0	0.4	0.1	398.4	396.4	2	0.5
2.1	400.4	400.4	0	0	397.2	395.2	2	0.5
2.2	400.4	400.4	0	0	396.4	394.4	2	0.5
2.3	400.8	400.4	0.4	0.1	395.6	393.6	2	0.5
3.1	401.2	400.8	0.4	0.1	397.2	394.8	2.4	0.6
3.2	401.2	401.2	0	0	396.8	394.8	2	0.5
3.3	402.0	401.6	0.4	0.1	396.4	394.0	2.4	0.6
3.4	402.0	402.0	0	0	396.0	394.0	2	0.5
4.1	405.2	405.2	0	0	395.6	393.6	2	0.5
4.2	405.6	405.6	0	0	395.2	392.8	2.4	0.6
4.3	406.0	406.0	0	0	394.8	392.8	2	0.5
5.1	399.6	399.6	0	0	397.2	395.2	2	0.5
6.1	400.0	399.6	0.4	0.1	398.4	396.0	2.4	0.6
7.1	400.4	400.4	0	0	396.0	394.0	2	0.5
7.2	400.8	400.4	0.4	0.1	396.0	393.6	2.4	0.6

D. Simulation results of case study 4

In case study 4, the possibility of the islanded mode of the LV grid when the main grid is not available in the evening is simulated. Charging and discharging power of BS, shown in Fig. 9 are obtained with optimization when grid outage from 20:40 to 22:00 is considered. The electricity cost is 295.37 €. Fig. 10 presents the load on the transformer. The maximum load on the transformer is 376.75 kVA at 23:00.

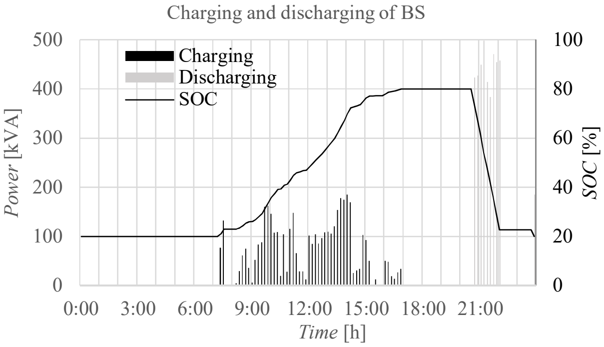

Fig. 9. Charging and discharging of BS when grid outage is in the evening

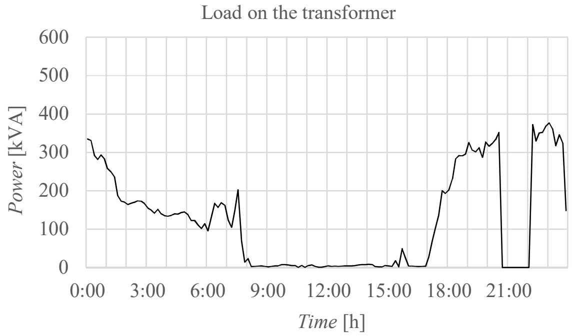

Fig. 10. Load on the transformer with grid outage from 20:40 to 22:00

A comparison of voltages in case study 4 (U_4) with voltages in case study 2 (U_2) is presented in Table 4. The maximum voltage at 21:30 on node 4.3 in islanded mode is 393.6 V which is 5.6 V higher than the voltage in normal mode at the same time. The minimum voltage at 21:10 on node 4.3 in islanded mode is 391.6 V which is 5.6 V higher than the voltage in normal mode at the same time.

TABLE IV. VOLTAGES IN ISLANDED AND NORMAL OPERATION MODE

Bus/ Node	**Voltages at 21:30**				**Voltages at 21:10**			
	U_4 [V]	**U_2 [V]**	**ΔU [V]**	**ΔU [%]**	**U_4 [V]**	**U_2 [V]**	**ΔU [V]**	**ΔU [%]**
LV	400	394.4	5.6	1.4	400	394.8	5.2	1.3
1.1	398.4	392.8	5.6	1.4	397.6	392.4	5.2	1.3
2.1	397.2	391.6	5.6	1.4	396.0	390.8	5.2	1.3
2.2	396.0	390.8	5.2	1.3	395.2	389.6	5.6	1.4
2.3	395.2	389.6	5.6	1.4	394.0	388.4	5.6	1.4
3.1	396.8	391.2	5.6	1.4	395.6	390.4	5.2	1.3
3.2	396.4	390.8	5.6	1.4	395.2	390.0	5.2	1.3
3.3	395.6	390.4	5.2	1.3	394.4	388.8	5.6	1.4
3.4	395.6	390.0	5.6	1.4	394.0	388.4	5.6	1.4
4.1	394.4	388.8	5.6	1.4	392.8	387.2	5.6	1.4
4.2	394.0	388.4	5.6	1.4	392.0	386.4	5.6	1.4
4.3	393.6	388.0	5.6	1.4	391.6	386.0	5.6	1.4
5.1	397.2	391.6	5.6	1.4	396.0	390.8	5.2	1.3
6.1	398.4	392.8	5.6	1.4	397.6	392.4	5.2	1.3
7.1	395.6	390.4	5.2	1.3	394.4	388.8	5.6	1.4
7.2	395.2	389.6	5.6	1.4	394.0	388.4	5.6	1.4

IV. CONCLUSION

The impact of the integration of PV power plants in the LV grid can be positive and negative. If PV generation is lower or equal to load demand, the loading of cables and transformers is reduced and voltages are slightly increased, the impact of the integration of PV power plants is positive. If PV generation is higher than load demand, there are power flows from LV to MV grid, the loading of cables and transformers is increased, voltages are increased over the rated values, and the impact of the integration of PV power plants is negative.

A solution to overcome the negative impact of PV power plants integration in LV distribution grids is using BS. The main idea is that BS is charging when the PV generation is higher than load demand to reduce power flows to the grid, loading of elements, and voltages. BS is then discharging when there is no generation and load demand is high to reduce loading of elements and to increase voltages which are low during peak load demand. In this paper, centralized BS connected to the LV bus is used to overcome the negative impact of the integration of PV power plants. Charging and discharging power of BS are obtained from optimization whose goal is to minimize electricity costs. With optimal use of BS, electricity cost is reduced from 389.26 € to 294.88 €. The impact of BS on transformer loading is significant. The peak load on the transformer is reduced from 497.80 kVA to 334.84 kVA. The impact of centralized BS on voltages is not significant. The maximum voltage is reduced by 0.9% and the minimum voltage is increased by 1%.

BS can cover load demand when the main grid is not available. In the afternoon, when there is still a significant generation from PV power plants, BS can cover load demand for a long time because load demand is covered from PV generation and then from BS. In the evening, when there is no generation from PV power plants and load demand is high, BS can cover load demand for a short time. Voltages in islanded mode are higher than in normal mode, which is not expected. It is because the amount of active and reactive power of BS are controlled according to a defined battery profile which is obtained from optimization.

In future work, distributed BS can be implemented and compared with centralized BS. Different daily load profiles, with lower and higher load demand, can be simulated. Results for days with a high and low PV generation can be compared.

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