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CIGRE US National Committee
2019 Grid of the Future Symposium

Optimized Power Flows in Microgrid with and without Distributed Energy Storage Systems

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SUMMARY

This study presents a combined algebraic and power flow model of a microgrid. The aim of this study is to introduce a strong tool which is capable to compare physical parameters of a microgrid which are hardly possible to calculate only by common algebraic optimization methods. Especially interesting is comparison between microgrids without energy storage, with a single bigger battery plant and with distributed batteries. This study focuses mainly on high voltage (HV) part of a transformer, inductive power and power losses in microgrids. Modelled microgrid consists of five robust nodes (which can represent living quarters with renewable energy production and energy storage) connected into a single transformer node, which later leads to the transmission system.

KEYWORDS

Energy storage, OpenDSS, GAMS, Microgrid, Steady state simulation, Battery, Optimization

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1. Introduction

Adopting stochastic power sources such as solar and wind brings strong need of extensive energy storage capacities and new innovative concepts in the future grid architecture. Distributed energy storage systems and microgrids are getting great attention in recent years. These systems have strong potential to play leading role in demand & response management of the future grids. There are numerous different concepts utilizing strong multifunctionality of such systems.

These energy storage capacities can be placed behind-the-meter (on the customer side) or in front of the meter (utility side). If there is no energy storage on the customer side, the customer must rely on grid operator. Grid operator might be able to buy produced surplus energy back into the grid by Net metering programs. These policies are often called “virtual battery” as they do the same functionality for customers as otherwise installed behind-the-meter battery. However; the term virtual battery is usually used for a different concept. Therefore, we define some most common terms for the purpose of this paper. They are usually understood in the same way in numerous other publications as well.

Virtual Energy Storage (virtual battery) [3]–[7]: Distributed behind-the-meter assets which are able to adopt some roles of energy storage. These assets are used for demand & response management by grid operator, even though their owners are electricity customers. The assets are aggregated and controlled as a system. The assets can be real batteries but also other assets with controlled loads e.g. AC units, refrigerators. Virtual energy storage represents also upgraded version of distributed batteries.

Net metering programs [8], [9]: Net metering programs represent opposite philosophy to the Virtual Energy Storage concept. If electricity customer (prosumer) produces more electricity than consumes, the electricity is fed back to the power grid. In the time when the customer needs electricity from the grid, it can be purchased back. From customer (prosumer) point of view the grid represents a battery with unlimited capacity. Net metering programs define conditions of selling and buying electricity. In this case, the energy storage asset is placed on the utility side – in-front-of-the meter. However, the utility does not necessarily require battery plant or different high capacity energy storage system. All these services can be supplied by different ancillary services e.g. flexible generators.

Battery plant: It is usually bigger, compact facility with battery energy storage of high capacity. It is placed in-front-of-the-meter and used for peak shaving and frequency regulation in distribution grids.

Distributed batteries: This term represents smaller energy storage units (batteries) distributed throughout distribution grid on multiple locations. For the purpose of this study, the term is understood that batteries are placed always behind-the-meter. Although in many publications this is not specifically written [1], [2], distributed energy storage is usually meant to be behind-the-meter.

Microgrids with flexible assets and batteries have potential to be part of virtual energy storage. Therefore, it is interesting to compare microgrids without energy storage and fully dependent on Net metering programs, containing a battery plant or distributed batteries.

2. System Description

Presented model describes microgrid of a living quarter. It contains five identical residential buildings with installed different volumes of photovoltaics generating electricity according to the real PV GIS [10] measured data (localized to Los Angeles). The model calculates cases without energy storage, with a battery plant and with distributed batteries which are installed at all buildings.

Microgrid

Modelled microgrid is a low voltage radial network operating on 0.48kV voltage level consisting of 5 loads, 5 photovoltaic generators and inverters, 5 power lines and the main transformer as shown in Fig.1.

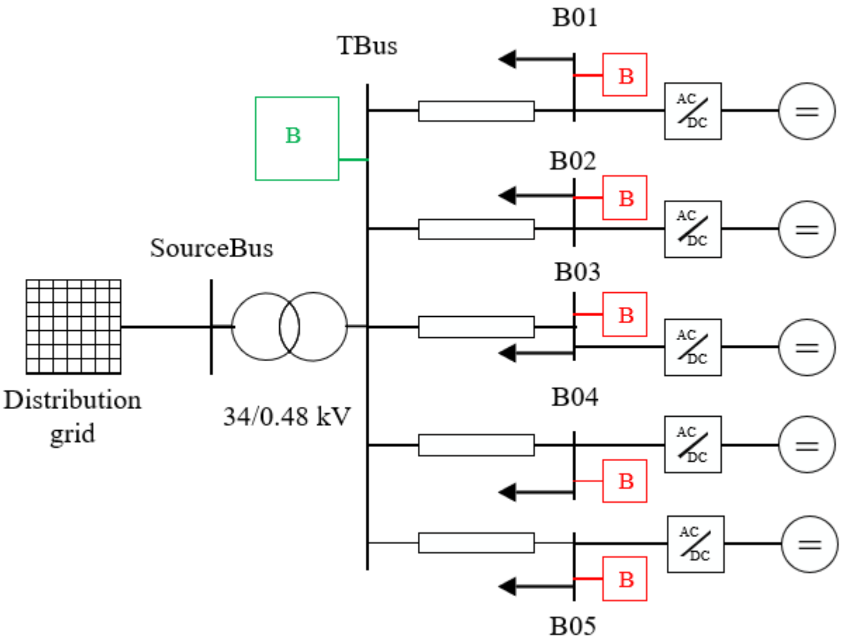


Fig. 1: Sketch of modelled small distribution grid. Case 1 - Red B represents distributed batteries, Case 2 - Green B represents Battery plant.

The grid is connected to the distribution network through this main two winding transformer; TS1 (1000kW, 34/0.48kV, delta/wye connection). Transformer percent losses at rated voltage are 0.81%, percent no load losses at nominal voltage are 0.15%, magnetizing current is 0.5%. TS1 is connected from low voltage side to the TBus, which has five separate feeders. Loads connected to buses B01- B05 are connected to TBus through AYKY cable conductors (parameters in Table 1). All lines have the same length of 0.3km.

Tab. 1: Power line parameters

Power line Type	Marking	*Resistance* R_1 [Ω/km]	*Reactance* X_1 [Ω/km]	*Length* L [km]
AYKY 240	L1-L5	0.125	0.0785	0.3

Every building has the same load curve with maximum fixed at 90 kW. Power factor was set to 0.98. The daily consumption loads, which were generated for this case study correspond to the daily load patterns for residential buildings in California according to [11]. The model input loads were generated with 1h resolution representing 7 typical days (Fig. 2). The microgrid is managed by an entity which is obliged to define reserved peak load on the transformer. By the transformer low voltage site (Tbus), there is a meter measuring all power flows entering and leaving the microgrid.

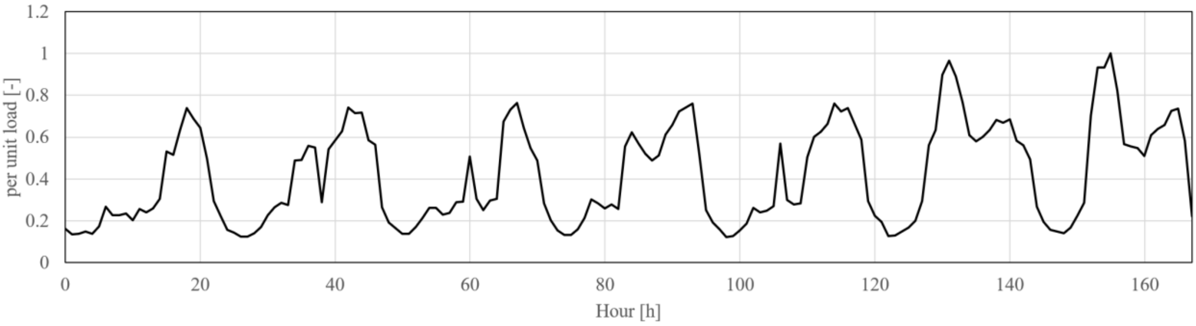


Fig. 2: Per unit load in 1h resolution representing 7 typical days.

PV systems

Photovoltaic system consisting of PV panels and the inverters is connected to the buses B01-B05. The installed power capacity of each PV system is different and listed in Tab 2.

Tab. 2: Parameters of installed PV systems

Installed PV capacity [kWp]	Inverter rating [kVA]	Bus connection
20	25	B01
40	45	B02
60	65	B03
80	80	B04
100	105	B05

Comprehensive and highly precise method using OpenDSS software was applied for PV power outputs calculation. OpenDSS is a publicly available power flow software. OpenDSS is primarily designed to simulate utility distribution systems in arbitrary detail for most types of analysis related to distribution planning [12]. Photovoltaic modules in the model are considered as building mounted. Installed capacity varies in every generation node representing living quarter; however, as the nodes are relatively close, all of them receive exactly same radiation levels and spot temperature at all the nodes is also identical. For the exact estimation of generated power from the photovoltaic panels, a PV-GIS online tool was used. [10]. As PV output is apart from solar irradiation strongly dependent on temperature of the panels, temperature of the panels is included in the calculations. Dependency of power output on the panel temperature and inverter efficiency is shown in Figure 3.

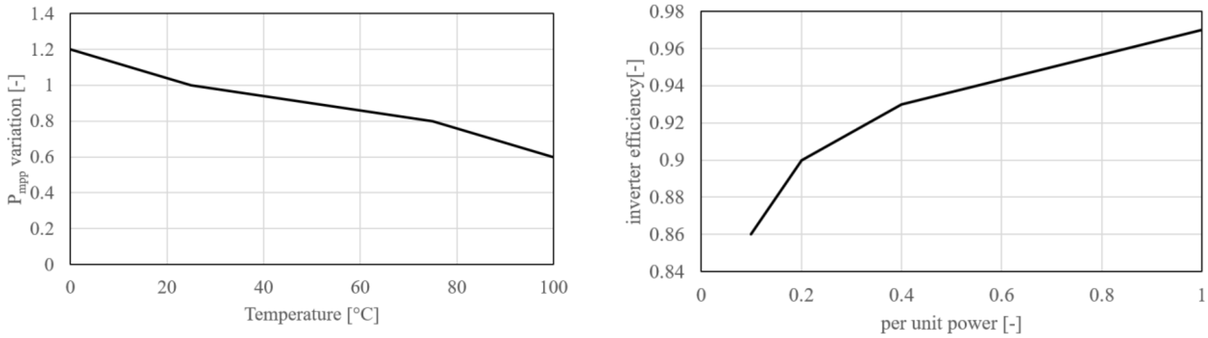


Fig. 3: Per unit variation of P_{mpp} (max power point) vs. temperature of the panel at 1 kW/m^2 irradiance (left). Efficiency curve for the inverter, per unit efficiency vs per unit power (right).

The required panel temperature was calculated from the ambient temperature and wind speed using simple empirical approximation [13], [14]:

$$T_{module}\left(^{o}C\right)=0.943\times T_{ambient}+0.0195\times Irradiance-1.528\times WindSpeed+0.3529$$

The calculated module temperature for considered time interval together with gathered meterological (typical week in LA, in Februari) data is shown in Fig. 4.

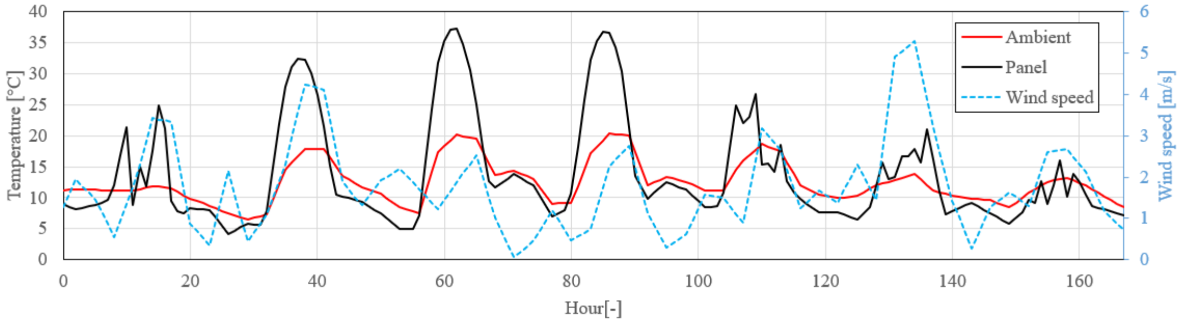


Fig. 4: Metrological data and panel temperature.

Finally, the PV generation was calculated using a simple OpenDSS model. Fig. 5 shows calculated PV solar production per unit from all the solar systems.

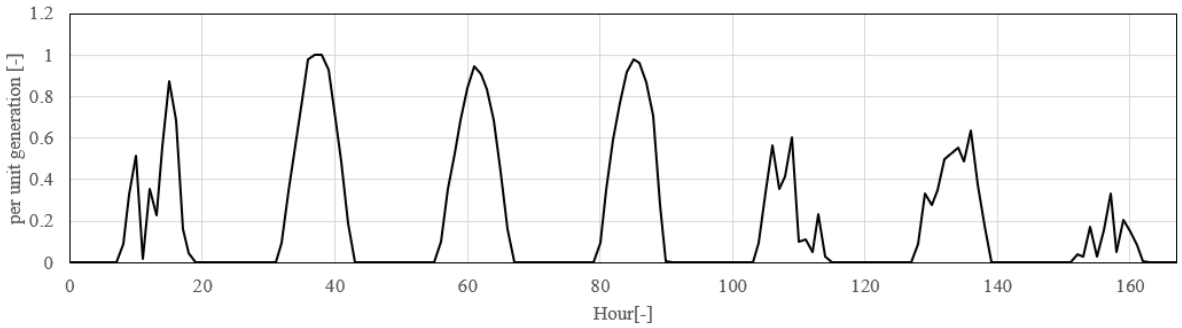


Fig. 5: PV generation per unit.

3. The model and calculations

The Model presented in this study combines algebraic optimization (GAMS) and power flow simulation (OpenDSS). The flow chart of the model is shown in Fig. 6. The main benefit of this model is very comprehensive output which gives optimal dispatching sequence for the batteries but also complete information about the system such as spot voltages, power flows and power losses in each part of the microgrid. This hybrid model is capable to calculate real time power flows, voltages and losses in the microgrid with optimal dispatching strategy of energy storage. Presented microgrid was modelled in scenarios without PV and energy storage, With PV and without energy storage, with a battery plant placed at TBus (250 kWh and a 3phase inverter of 125 kW) and with 5 identical distributed batteries of capacity 50 kWh and 3 phase inverter of 25 kW placed on each BUS according to Fig.1.

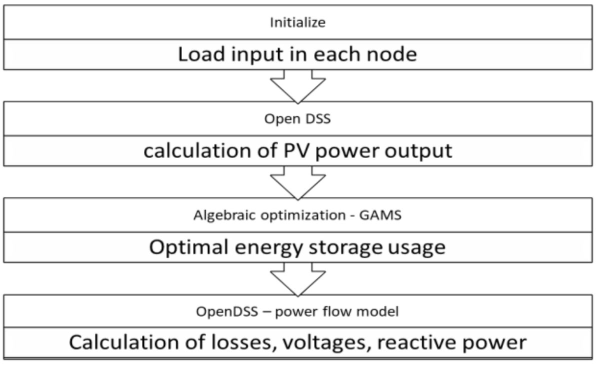


Fig. 6: Model flow chart.

Algebraic optimization tool GAMS was used for calculation of the optimal dispatch strategy for the batteries. Optimal dispatching strategy of installed energy storage is determined by minimizing costs of electricity which consists of peak load cost and energy cost. Optimization algorithm was designed similar as described in [13] with objective function.

Minimize

$$PL + \sum_{t} EC_t + \sum_{n} SC_n$$

Where, PL – peak load cost, EC_t – cost of supplied energy from main grid per time unit, SC_n – storage cost of battery n , n – bus index , t – time index

For calculation parameters in objective equation, following input data were used.

PD_u - load of each building as shown in Fig. 2
u – building index
PL_y – peak load cost per unit per year (defined as 55 000 USD/MW/year)
EC_kwh - Energy cost is set to 0.04245 USD/kWh (6am-12am) and 0.036 USD/kWh (12am-6am)
BAT_lif – lifetime of lithium batteries (set to 15 years)
Bat_E_C – purchasing cost of battery storage per kWh (set to 300 USD/kWh)
Bat_P_C – purchasing cost of battery per kW (set to 200 USD/kW)

Optimal battery according to defined parameters was calculated to 178.41 kWh with 96.12 kW inverter. Algebraic model does not consider power flows and losses in the microgrid. The microgrid is designed in the way that every battery can be charged or discharged to every node which is solution with the best resiliency. If batteries distributed in each of 5 nodes, the sum of all distributed battery capacities and sum of inverter powers corresponds to the values presented for a single battery (178.41 kWh, 96.12 kW). As real-life applications must consider some reserve for battery capacity and also inverter power, reasonable real-life energy storage system would have higher parameters. Aging of the battery and also the fact that lithium batteries are recommended to operate between 10%-90% are the main factors to be counted. Therefore, for purpose of this study battery of size 250 kWh, 125 kW (case 2 model) was chosen as reasonable real-life option considering the result of algebraic calculations. If considering distributed batteries, five units of 50 kWh, 25 kW (case1 model) batteries were distributed on each node together with buildings.

Calculated optimal dispatch strategy for battery pool is shown in Fig.7. similar results were calculated for distributed batteries. According this dispatch strategy, calculations for high voltage (HV) part of the transformer bring following results (Fig.8).

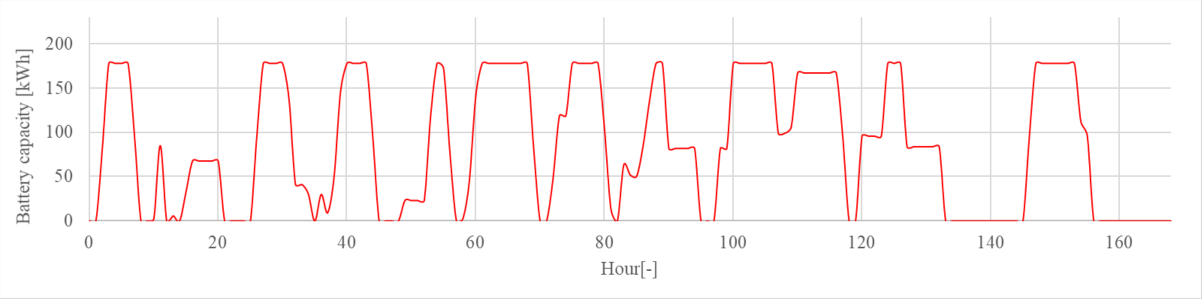
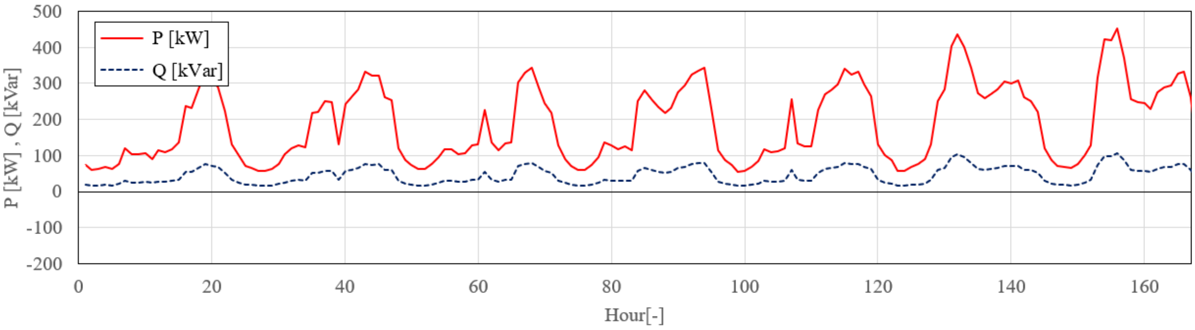
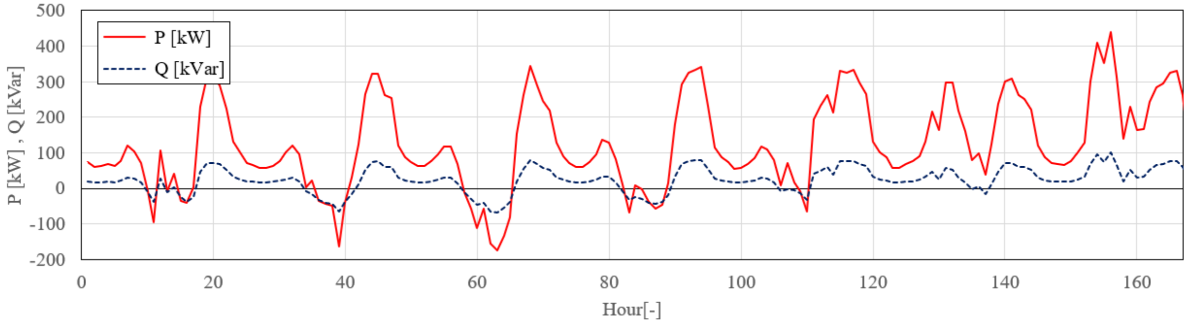


Fig 7. Calculated optimal dispatch strategy for single battery

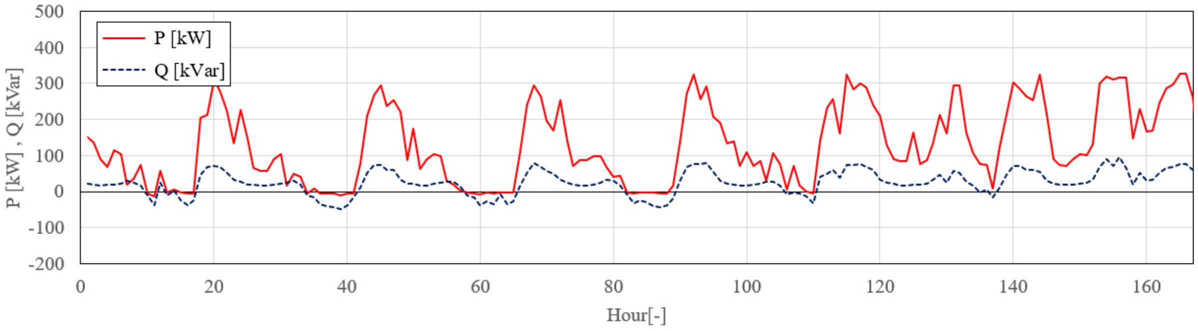
a) – no PV and no storage



b) – PV and no storage



c) – case 1 : battery plant



d) – case 2 : disributed batteries

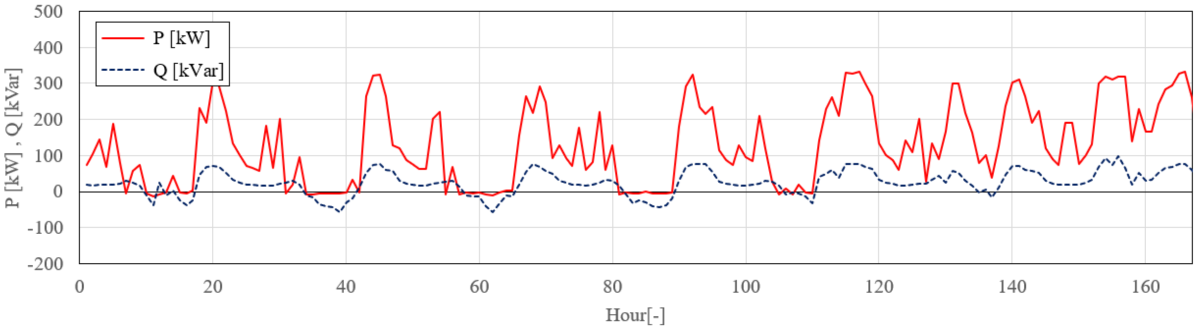
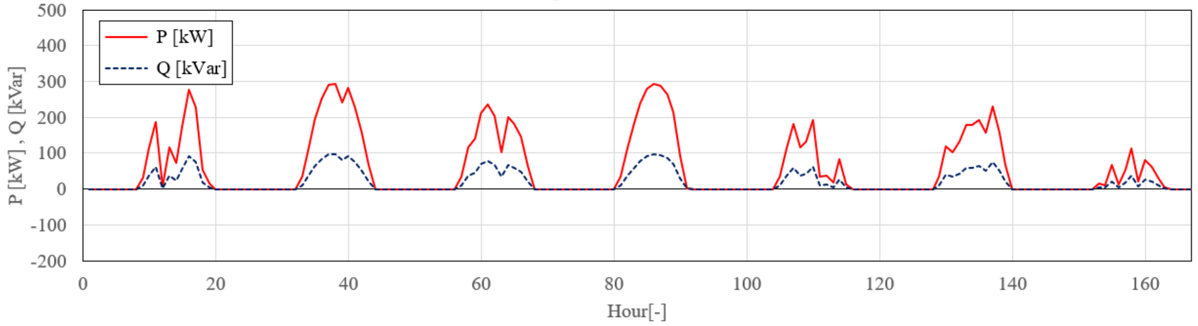


Fig 8. HV site of the transformer bus : a)No PV and no energy storage, b)PV , no energy storage c) single battery 250 kWh, 125 kW inverter d) distributed batteries 50kWh with 25kW inverters

Fig.9. shows comparison of active and reactive power generation in the microgrid with energy storage. In the case of energy storage is present in the microgrid, microgrid cannot feed electricity back to the TS. Therefore, PV generation must be limited in the case no load or storage capacity is available.

a) – case 1 generation



b) – case 2 generation

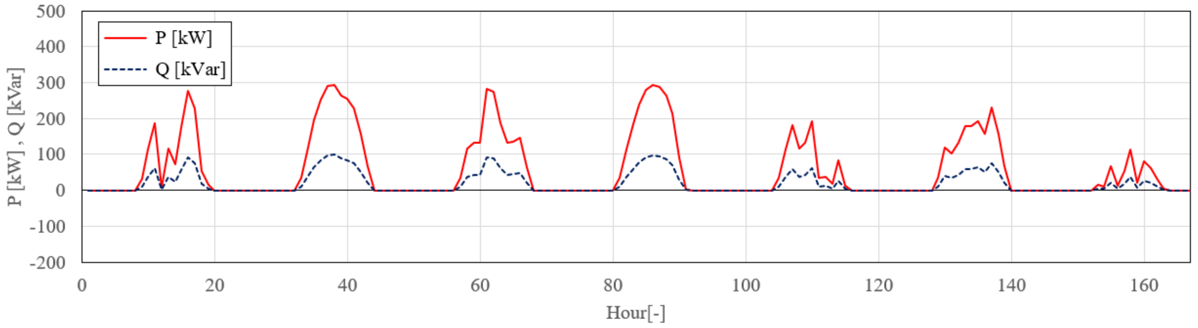


Fig.9. Active and reactive power generation in the microgrid a) battery plant case b) distributed batteries case.

Fig.10 compares HV part of the transformer with PV and without PV and cases with the battery plant and distributed batteries. Just real P was taken for this comparison.

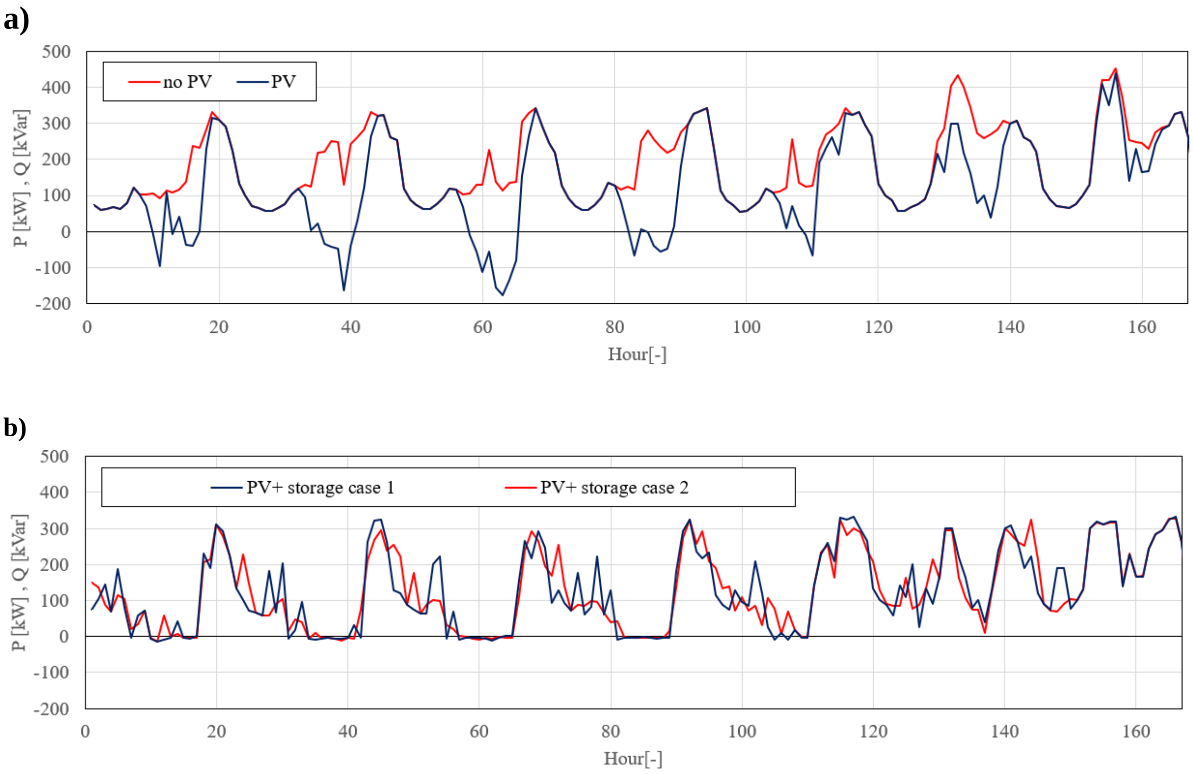


Fig.10 : HV transforrmer part. a) comparison microgrid with PV and without PV – no energy storage, b) Comparison scenario with one 250 kWh 125kW battery and five distributed batteries of 50kWh and 25 kW.

Other important parameters of the microgrid calculated by presented OpenDSS model are presented in following tables. As it can be seen from Tab 3. The active power flow into grid was reduces by implementing PV but also battery storages. In addition, the model does not optimize reactive power flows. It is important to note that storage systems reduced the power flow into the grid by circa 3.4 % for both cases. This only shows the main benefit of energy battery storage.

Tab. 3 : Transformer power flows

	Into the grid		Out of the grid	
	P [kWh]	Q [kVArh]	P [kWh]	Q [kVArh]
no PV	31477.33	7558.02	0.00	0.00
PV	22360.10	5009.73	1583.41	1082.91
PV+ storage case 1	21645.09	4999.34	192.85	904.33
PV+ storage case 2	21617.30	4991.30	128.60	906.73

Calculated losses in the microgrid are shown in Tab. 4. In general power losses on transformer were lower for both storage cases. In case of distributed storage (case 2), lower power line loses were calculated compared to the system with battery plant (case1). This is result of reducing the necessary power flows between storages as in the case of central battery plant generated unused energy must be always stored away from the source.

Tab 4 : Calculated losses in the microgrid.

	Lines	Transformer
		ΔP [kWh]
no PV	260.00	321.00
PV	194.00	194.00
PV+ storage case 1	188.00	296.00
PV+ storage case 2	180.00	180.00

Tab.5 shows calculated maximum transmission loading of the transformer. This was reduced significantly by implementing energy storage. It is interesting to note that optimally regulated distributed batteries performed better than central battery plant and created additional 6.57 kW load reduction.

Tab 5 : Maximum transmission loading of transformer.

	P [kW]	Q [kVar]	S [kVA]
no PV	451.14	106.34	463.51
PV	439.08	101.89	439.08
PV+ storage case 1	333.68	98.66	347.95
PV+ storage case 2	327.11	96.67	341.09

4. CONCLUSION

Comprehensive model of a microgrid using algebraic optimization and OpenDSS was presented in this paper. The model was demonstrated by a study of a microgrid without energy storage, with a single energy storage unit – battery plant and with distributed batteries. It is widely known that distributed batteries are more resilient but also more expensive solution. However; there are other crucial parameters in the microgrid operation which need to be evaluated in order to decide which option is more favorable. Presented model is tailored for this purpose as only scenarios with optimal operation od energy storage assets are evaluated because the model uses advanced algebraic optimization methods. In the following, parameters such as maximal loading of the transformer and power losses in the microgrid can be than calculated by OpenDSS functions. Presented case study shows important comparison between these parameters which can be easily financially valuated and help decision makers to choose the most reasonable structure of the microgrid.

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