A SIMULATION OF ENERGY STORAGE SYSTEM FOR IMPROVING THE POWER SYSTEM STABILITY WITH GRID-CONNECTED PV USING MCA ANALYSIS AND LABVIEW TOOL

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DOI: 10.15598/aeee.v13i2.1347

Abstract. *The large-scale penetration of distributed, Renewable power plants require transfers of large amounts of energy. This, in turn, puts a high strain on the energy delivery infrastructure. In particular, photovoltaic power plants supply energy with high intermittency, possibly affecting the stability of the grid by changing the voltage at the plant connection point. In this contribution, we summarize the main negative effects of selected and real-operated grid connected photovoltaic plant. Thereafter a review of suitable Energy storage systems to mitigate the negative effects has been carried out, compared and evaluated using Multi-criterion analysis. Based on this analysis, data collected at the plant and the grid, are used to design the energy storage systems to support connection of the plant to the grid. The cooperation of these systems is then analysed and evaluated using simulation tools created in LabVIEW for this purpose. The simulation results demonstrate the capability of energy storage system solutions to significantly reduce the negative feedback effects of Photovoltaic Power Plan to the low voltage grid.*

Keywords

Energy storage, photovoltaic systems, power system stability, simulation, voltage fluctuations.

1. Introduction

Electricity distribution systems (DS) are designed for delivery of energy from transmission systems to the load centers and end customers. DS operators are responsible for the safety of the system operation and for the quality of electricity supply. There have been a number of rules and regulations introduced to ensure compliance with these requirements [1], [2], [3], [4]. The rapid penetration of wind (WPP) and Photovoltaic (PV) plants in many parts of world requires transfers of large amounts of energy, putting energy delivery infrastructure at risk of blackouts [5]. The large number of individual power plants necessitates careful selection of connection points, to ensure that the plants will have minimal disturbing effects on the grid and supply of electricity to other customers [6].

The main problems associated with WPP and PV plants are caused by their stochastic nature. It makes prediction of energy difficult, and complicates the medium- and long-term energy production planning and scheduling [7], [8]. This makes investments into new, green power plants more risky and thus less attractive for investors.

The limited ability to control the production of electricity by these dispersed energy sources makes their integration into electricity grids very challenging [9]. And as the number of Renewable power plants increases, so does the risk of their negative effects on the operation of the Electric Power System (EPS). The most significant negative effects, from the perspective of PV plants, are related to the voltage changes caused by the variability of the plant output. To ensure smooth operation of EPS, it is necessary to control the power flows within the system [9], [10]. There are several possible technologies, how to mitigate the negative effects of distributed generators, such as PV and WPP. Namely that could be energy storage systems, flexible loads, advanced optimization technique, which can mitigate the voltage fluctuation caused by PV operation [11], [12], [13], [14], [15]. To mitigate the flow variations caused by the intermittent nature of energy produced by wind and PV plants conventional power plants must maintain reserves in rotating machines (Auxiliary services). Those auxiliary services are increasing the operation cost of these private power plants not for the owner, but for the DS operator [16].

Based on technology mentioned above the Energy Storage systems seems to be the most appropriate option to mitigate the negative effect or keeping the power quality within the limits. Another advantage can be the forecasted power output from the PV and energy storage device using the control system which is able to release the energy, when required. These advantages are evaluated, simulated and presented in the paper.

2. PV and Negative Effects Analysis

Let us say, there is an actual medium-size PV connected in low voltage network system (LVS). This power plant, with installed power of 70 kWp, is located at the end of a low voltage (LV) AC system radial network with nominal voltage of 400/230 V AC, 50 Hz. This network is connected to a medium voltage (MV) AC system with rated voltage of 22 kV AC through LV/MV transformer. Connection diagram of Grid-connected PV together with grid parameters can be seen on following Fig. 1, where MV is an AC medium voltage network 22 kV AC, Vx are power lines, Zx are loads, PV is grid connected Photovoltaic plant and U5 is connection point of PV. These parameters, along with the measurements and selected energy storage device, are subsequently used to design the energy storage system that facilitates integration of the PV plant into the grid using simulation tools developed in LabVIEW. Finally, the analysis of the plant operation and evaluation of power quality are carried out according to [1], [2], [3], [4].

During the analyzed 1-day sample of operation, the plant supplied 271 kWh of active electrical energy. The variability of corresponding power flows is shown in Fig. 2.

PV supplied electric power to the network between 6:30 a.m. and 7:00 p.m. The sudden changes in generated power were caused by transitions of clouds over the plant. These abrupt changes of supplied power can affect the power quality in the entire network, as well as the stability of the distribution system.

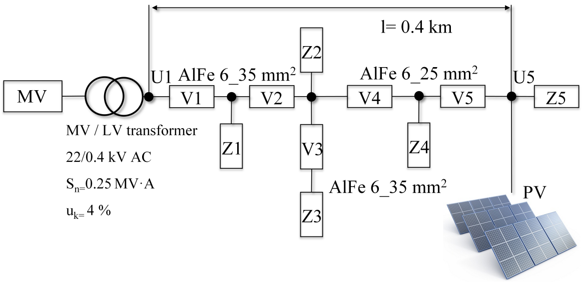

Fig. 1: Connection diagram of a PV and selected part of the grid.

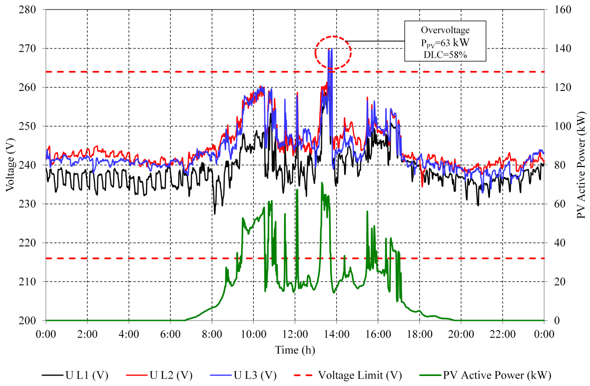

Fig. 2: Rapid voltage changes at connection point of PV.

Energy integration and power quality issues associated with PV plants are of a great interest, since larger and larger PV plants are incorporated into the low and medium-voltage distribution networks. The most significant effects of PV plants operation on distribution grids are [1], [2], [3] and [4]:

- rapid voltage changes,
- voltage changes at the PV connection point.

Rapid voltage changes can be caused by loads switching, by changes of daily load curve (DLC) or by changes of PV power output. According to [1], under normal operating conditions, rapid voltage changes must not exceed ±10 % of the nominal voltage U_n (see detail Fig. 2). These changes can have the form of:

- decreases or increases of voltage over a long period,
- slow or rapid changes in voltage,
- voltage fluctuations (series of changes in the effective value of the voltage).

The effects of such voltage changes are associated with disturbances, such as flicker [1].

Voltage changes in distribution networks occur due to the changes of power of connected sources or loads. A change of voltage at one node is reflected in changes

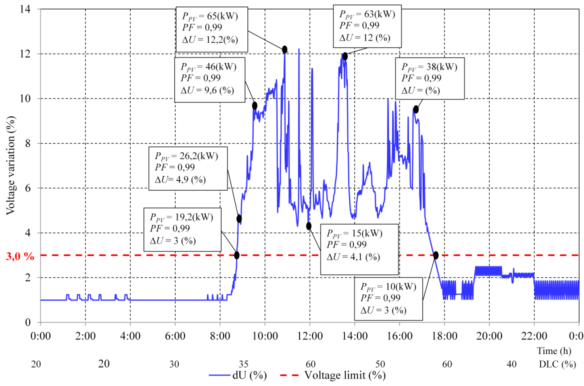

Fig. 3: Voltage fluctuation during the day.

of voltage at other network nodes. With the growing number of distributed energy sources connected to LV and MV systems, the problem of voltage changes becomes increasingly serious.

According to [1], the increase of voltage caused by the operation of connected plants must not exceed $\Delta uMVS \leq 2$ % and $\Delta uLVS \leq 3$ % (compared to the voltage without any connected plants). The limit values relate to the effective value of the operating voltage at the point of plant connection. When these conditions are satisfied, significant changes of voltage in the network are averted. This facilitates proper control and stabilization of voltage across the network [1], [2], [3] and [4].

Figure 3 contains measured data, which are showing the voltage changes at the PV plant connection point during a day with variable cloudiness. Exceeding of the 3 % threshold started at 8:45 a.m. at 27 % of PV production and 33 % of the network load, and lasted until 5:40 p.m. The maximum overvoltage occurred around 11:00 at 93 % of the PV production and 60 % of the network load.

2.1. PV Energy Storage Systems Possibilities

There are several possible ways to suppress the voltage changes at the point of PV plant connection point. From a technical perspective, a good approach would be to increase the short circuit power of the network, in our case the transformer. However, this approach would be very costly. A PV plant is typically connected to the network using a 22/0.4 kV AC transformer that should operate as a source for a particular network feeder. However, in systems with medium to large size PV plants, the function of the transformer is taken over by the plant itself and this can lead to the overflow of power to the higher voltage level. In such situations, the output power at the connection point is not determined by the transformer, but by the PV plant.

Another option is the reduction of power supplied by the PV plant. For example, if the maximum power supplied by the analysed plant was 35 kW instead of 70 kW, the change in voltage at the connection point would drop to 4.8 % from 12.5 % (both at the network load of 60 % of DLC), based on analysis performed using in LabVIEW software tools. While this solution might be acceptable for network operators, it is not effective from the perspective of PV plant owners/operators.

As an opposed option to Energy storage system can be used the financial policy of the distributor of electricity in the region, which would be established a financial advantage to undelivered electricity in extreme cases, when the electricity jeopardize the grid stability by PV power output. This idea, however, is inconsistent with the original idea of this paper, when the aim of the authors is to find a suitable energy storage system for suppressing the negative effects caused by the operation of the PV.

After discounting the solutions based on increasing short circuit power, decreasing the plant output or the financial policy there is a third group of possible solutions based on storage of produced energy. Energy storage can be used to capture the short-term power peaks during periods of unloading network, and also to cover power drops during normal operation, for example when clouds pass over the plant. There are many possibilities of energy storage suitable for this purpose [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27]:

- battery energy storage (BES) [22],
- regenerative energy storage (RES) [18],
- flywheel energy storage (FES) [19],
- supercapacitor energy storage (SCES) [17]
- superconducting magnetic energy storage (SMES) [17].

Methods described below are a selection of basic and currently realizable systems with the aim of effective integration of decentralized electricity generation from Renewable sources, while the importance of energy storage increases with the spread of renewable sources in the electricity grid.

1) Flywheel Energy Storage (FES)

FES system stores electrical energy in kinetic form using a special flywheel coupled with an engine and generator. These solutions are rather expensive due to the need for high speed of the flywheel and thus great demands on materials and manufacturing of its rotor. In addition, the rotor must be placed in vacuum to minimize air friction, the bearing shields must withstand high speeds and have minimal friction too. The main advantage of FES is high performance, long life and high efficiency, especially for short-term energy storage [21]. The reaction time of flywheel systems is in tenths of milliseconds. If used for the PV plants, such systems would eliminate voltage fluctuations caused by short-term occlusions by passing clouds. Flywheel systems can last for decades with low or no maintenance, providing efficiency as high as 90 % [20]. The cost of FES is between 400 and 800 $\$\cdot\mathrm{kWh}^{-1}$ [21].

2) Supercapacitor Energy Storage (SCES)

Storage of energy in supercapacitors (SCES) has been commercially developed only during the last decade. Energy is stored in an electric field of a charged capacitor. Supercapacitor electrodes are separated by a liquid electrolyte. Using modern electrolytes, the single cell voltage can reach about 3 V. The cells can be connected in series to store energy under higher voltage [22]. The main disadvantage of using SCES to store energy from PV plants is their very small internal resistance, at the order of mΩ. Therefore, to charge a supercapacitor, it is necessary to use a voltage converter that reduces the large charging current from the PV plant. Another drawback is the dependence of the voltage on the stored charge. This problem can be also minimized using voltage converters [21]. The price of supercapacitors is still relatively high, at the order of 4,000 kWh^{-1}. However, the prices are expected to drop down after these components become more commonly used by industry and subsequently produced in large series. High self-discharge rates of SCES (about 20 % of the rated capacity in 12 hours) are acceptable for typical PV applications. Their small series resistance makes supercapacitors suitable for a fast storage and use of energy. Peak power during the discharge in proportion to supercapacitor weight (power density) is relatively high, reaching 1–100 $\mathrm{kW}\cdot\mathrm{kg}^{-1}$. They are also characterized by high storage efficiency, of up to 95 % [20], [23].

3) Battery Energy Storage (BES)

BES is the most widely used energy storage technology. Batteries are also the most suitable storage technology for the analyzed PV plant. In BES, energy is stored in electrochemical form. There are many types of batteries on the market [22] lead-acid, nickel-metal hydride and lithium-ion, to name a few. The lithium cells, made up of lithium compounds ($\mathrm{LiCoO_2}$, $\mathrm{LiFePO_4}$, and many others) with carbon anodes (made of a special form of graphite) are most suitable for applications considered in this paper [23]. In addition, lithium does not pose a significant threat to the environment. Because of its high reactivity, lithium cells have a relatively high voltage of 3.7 V, high energy density (in some cases above 500 $\mathrm{Wh}\cdot\mathrm{kg}^{-1}$), and storage efficiency of up to 99 %. This method allows charging lithium-based batteries to full capacity in a very short time and keeps their lifespan. This characteristic is ideal for charging from a PV plant [17].

The lifespan of lithium batteries is longer (up to 5,000 cycles) compared to other types of batteries, but shorter than that of supercapacitors. Their main disadvantage is relatively high price of about 630–900 $\$\cdot\mathrm{kWh}^{-1}$ [18] and loss of capacity over the time. If used in a large numbers, these batteries also pose a significant risk of fire and explosion due to the flammable electrolyte. Their daily self-discharge ranges between 1–5 % of their capacity [19], [20], which is acceptable for storage of energy produced by PV plants, because the PV plant works in daily cycle mode, what means one charge and one discharge cycle per day.

A sodium–sulfur battery is a type of molten-salt battery constructed from liquid sodium (Na) and sulfur (S). This type of battery has a high energy density energy output of more than 400 $\mathrm{Wh}\cdot\mathrm{kg}^{-1}$, high efficiency of charge/discharge (89–92 %) and long cycle life, and is fabricated from inexpensive materials. The high operating temperature of 300 to 350 °C along with the highly corrosive nature of the sodium polysulfide allows this technology to only be used in stationary (non-mobile) applications such as grid energy storage [24], [25].

4) Regenerative Energy Storage (RES)

Flow batteries differ from classic by using liquid electrolyte stored in external tanks. Electrolyte is circulating across electrodes by pumps. Each electrode has separate circulating system, so battery needs two tanks and two pumps. There are several types of flow batteries according to used principle [20], [21] and [26].

The type mentioned in this study is electrochemical oxidation and reduction of vanadium. Advantages of this type are unlimited count of charge and discharge cycles and low self-discharge. During charging there is ion exchange between both electrolytes, so electrolytes must be separated by ion-permeable polymer membrane. Storage capacity depends on electrolyte quantity in tanks. Available volume energy density of electrolyte in full charge-discharge cycle is from 15 $\mathrm{kWh}\cdot\mathrm{m}^{-3}$ up to 25 $\mathrm{kWh}\cdot\mathrm{m}^{-3}$. Specific weight of cells is from 6.5 $\mathrm{Wh}\cdot\mathrm{kg}^{-1}$ to 10 $\mathrm{Wh}\cdot\mathrm{kg}^{-1}$. Electrolyte mass presents about 90 % of all device mass. From 85 % to 90 % of built-up area occupies electrolyte tanks, from

15 % to 10 % remains for cells and control unit. Full charged cell voltage is 1.35 V at 25 °C, voltage differs during discharging due to electrolytes composition changes down to 1 V in case of full discharged cell [27].

2.2. Evaluating and Comparison of Energy Storage Systems using MCA

As has been mentioned above, renewable sources in last decades are gaining attention, because their widespread impacts affect backbone of EPS. Renewable sources, especially PV plants, cause negative effects, which can jeopardize system grid stability. In the context of energy storage can be defined and summarized the basic aspects and conditions of use of storage devices:

- Accumulation of electricity, hence the electricity storage device can be used for Renewable sources for balancing the supply of electricity to the EPS.
- It is necessary to create terms and conditions for energy storage used in the EPS in the context of decentralized control, then could be achieved better controllability of EPS using battery-based energy storage.
- Energy storage can be used to improve power quality parameters and to back up the energy for the first category of consumption.
- Energy storage devices are necessary for operation of Smart-Grids as well as for the local networks Micro-Grids.

Multi-criteria decision-making and analysis (hereinafter MCA) is a modelling of complicated situations and solving complicated decision-making tasks in which set of variants and criteria is defined. The MCA deals with the evaluation of particular variants according to several criteria. The aim of the MCA can be to locate a set of the best variants, determination of the best variant, or arrangement of all variants. The term "variants" designates each of the solutions of the selection report. The "criteria" is a property that is being evaluated with the given variant. To each criterion is assigned weight that expresses the importance of particular criteria with regard to the others. The value of each weight is from interval $\langle 0, -1 \rangle$.

The initial step of each MCA is to form an evaluating matrix, which elements reflect the evaluation of particular criteria for each alternative:

$$\mathbf{Y} = \begin{array}{c} \\ a_1 \\ a_2 \\ \vdots \\ a_p \end{array} \begin{array}{c} \begin{array}{cccc} f_1 & f_2 & \cdots & f_k \end{array} \\ \begin{pmatrix} y_{11} & y_{12} & \cdots & y_{1k} \\ y_{21} & y_{22} & \cdots & y_{2k} \\ \vdots & \vdots & \ddots & \vdots \\ y_{p1} & y_{p2} & \cdots & y_{pk} \end{pmatrix} \end{array}. \tag{1}$$

The matrix $\mathbf{Y}$ according to an Eq. (1) consists then of elements y_{ij} where $i = 1 \cdots I$ variants (rows of the matrix) and $j = 1 \cdots J$ criteria (column matrix). Rating variant according to various criteria forms the elements of the matrix. The evaluation matrix $\mathbf{Y}$ is defined by Eq. (1).

MCA require information concerning relative importance (weights) of criteria, which can be expressed by mean vector of criteria weights according to a Eq. (2). The higher the weight for criterion has, the more is important:

$$\vec{v} = (v_1, v_2, \cdots, v_k), \sum_{j=1}^{k} v_j = 1, v_j \geq 0. \tag{2}$$

The following methods are suitable for MCA:

- weighted sum approach (WSA),
- ideal points analysis (IPA),
- technique for order preference by similarity to ideal solution (TOPSIS),
- concordance-discordance analysis (CDA).

1) Weighted Sum Approach (WSA)

The WSA method is based on linear utility function by using alternatives as the weighted sum of normalized criterion values. The original data are usually in different units of measure, so it is necessary to unify these units or to get rid of them. First we create a standard criterion matrix $\mathbf{R} = (r_{ij})$, which elements are obtained from the matrix $\mathbf{Y} = (y_{ij})$ using the transformation Eq. (3):

$$r_{ij} = \frac{y_{ij} - d_j}{h_j - d_j}, \tag{3}$$

where r_{ij} are the normalized values for i alternative and j criterion, d_j are the values of the basal alternative and h_j are values of the ideal alternative. Basal alternative is worse alternative that could exist, it has the worse values selected from each criterion. Ideal alternative is the opposite, the best values in each criterion. Via this recalculation, the comparability of the values is assured. Values r_{ij} are from the interval $\langle 0, -1 \rangle$. The way of the normalization has one disadvantage –

Tab. 1: Available and suitable energy storage systems.

Methods of Energy Storage	**Parameters**				
	η (%)	Energy Density (Wh·kg^{-1})	Lifetime (Cycles)	Temp. Range (°C)	Cost (\$·kWh^{-1})
Lead-Acid Bat.	0.75	30–50	2,000	−5 to 40	50–150
Vanadium Redox	0.85	20–50	10,000	0 to 40	360–1000
Sodium Sulfur Bat.	0.89	100-175	2,500	300–350	400–600
Flywheels	0.92	5–130	100,000	−40 to 55	400–800
Lithium Ion Bat.	0.95	80–200	3,000	−30 to 60	700–1000

big difference between maximum and minimum value of one criterion can influence the results.

2) Ideal Points Analysis (IPA)

This method is based on the principle of utility maximization. As with methods WSA, there must first perform normalization criteria matrix. The Ideal Point Analysis rests upon the deviation between the set of ideal solutions and the set of effective solutions. The best compromise solution is the nearest to the ideal solutions. The increasing distance from the ideal solution for factors located upper on the scale of importance induces greater consequences than the increasing distance from the ideal solution for factors located lower on the scale of importance.

3) Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

In case of TOPSIS method this is again the question of principle of maximization of distance from ideal variant. The ideal variant means that all criteria have the best assessments. Ideal variant is mostly suppositional; the best of variants is that one which is the nearest to ideal variant.

4) Concordance-Discordance Analysis (CDA)

The Concordance-Discordance Analysis is composed of comparison of alternatives of pair selection. This method measures the degree by which the alternatives of selection and the weights of factors prove or disprove the ratio between the alternatives. The index of concordance between the alternative A and the alternative B is defined as a proportion of the sum of weights of those criteria, for which the evaluation A is greater than or equal to the evaluation B, and the sum of weights of all criteria. The differences in the weights of factors and in the evaluations of criteria are analyzed by means of the procedures of concordance and discordance separately. Detailed description of above mentioned methods can be found in [28].

Table 1 below shows suitable possibilities of energy storage systems. Individual variant represents a group of energy storage systems with following necessary requirements, which will be compared using MCA:

- energy efficiency (%),
- energy density (Wh·kg^{-1}),
- lifetime (cycles),
- temperature range (°C),
- price (\$·kWh^{-1}).

To design individual criteria served mainly the technical and economic point of view. The systems effectiveness using today, in almost all cases are close to 90 %, except Lead-Acid battery type. Lead–Acid battery are also represented in the variants, because of their mass utilization, even at present time.

Another very important parameter/criteria is the Energy density, due to the limited possibilities of construction area of potential large energy units, which could interfere with the landscape, even in environments where are situated the PV power plant. Lifetime cycles basically determine the lifetime of the entire system, because this lifetime is necessary to exchange the most expensive part of the system, thus energy storage media itself. In the case of the standard battery is it up to 5,000 cycles, i.e., if we count as a 1 cycle per day (1 charging/discharging cycle per day) and with decreasing the battery capacity then the estimated lifetime is ca. 10 years. The Temperature Range is the next important required parameter, because in cases of different climatic conditions would have to be to build up object, where it would be possible to use this technology to preserve and protect the energy storage system in adverse climatic conditions. As a typical conditions can be very cold or very hot environment, which

Tab. 2: Selected criteria and their weights.

Criteria	**Criteria Weight**
η (%)	0.07
Energy Density (Wh·kg^{-1})	0.23
Lifetime (Cycles)	0.22
Temp. Range (°C)	0.15
Cost (\$·kWh^{-1})	0.33

Tab. 3: MCA analyses results.

Methods of Energy Storage	**MCA methods**			
	WSA	IPA	TOPSIS	CDA
Lead–Acid	0.578	0.422	0.474	4.137
Vanadium Redox	0.544	0.466	0.367	3.173
Sodium Sulphur	0.417	0.583	0.410	3.468
Flywheels	0.365	0.635	0.514	4.156
Lithium Ion	0.197	0.803	0.256	4.708

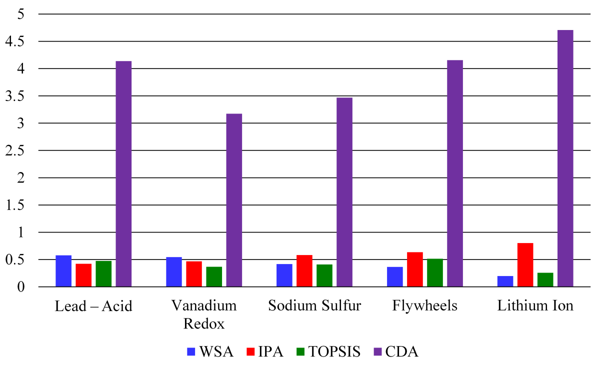

Fig. 4: MCA analyses results.

may occur at the place of installation. The last parameter is the system initial cost, which determines, if is the system a cost-effective or no. In the case of acceptable financing costs and costs related to maintenance, it is possible to build up this kind of energy storage system.

After we define the criteria for MCA, determine their weights, selection and testing methods for multi-objective analysis, it was possible to proceed to the implementation of the MCA methods. Table 2 represents the Criteria and Criteria Weights selected by authors, such an experts.

Table 3 and Fig. 4 show the analysis results using MCA. As a reference calculation method was chosen the CDA method. These results are used as input for the designing of the appropriate parameters of the battery bank as energy storage system to mitigate the negative effects caused by PV operation.

For the PV plant analyzed in this paper has been chosen Lithium Ion batteries. This solution offers several options to configure the operation of storage system connected to the PV plant. Energy storage is used to evenly distribute produced PV power during a day and to limit changes of supplied power parameters. A special tool in LabVIEW has been developed for this purpose. This software tool enables to calculate the necessary parameters to design the energy storage system.

Tab. 4: MCA analyses results.

Parameters	**Value**
Maximal Power of a PV (kW)	70
Battery Max. Charging Power (kW)	35
Battery Max. Discharging Power (kW)	35
Battery Type	Lithium Ion
Battery Depth of Discharge (%)	90
Expected Lifespan (1 cycle/day)	3,000
Minimal Battery Size (kWh)	235
Battery Capacity (Ah)	2,800
Battery Voltage Level in V_{DC}	84

The battery size is equal to the maximum amount of energy that can be produced by the plant in one day. Parameters of battery for the analyzed PV are summarized in Tab. 4.

However, in this case, the threshold of maximum power supplied into a network was set to the 50 % of the PV plant capacity. Energy produced above this threshold is stored in batteries which can later cover drops in power supplied by the plant. Any excess of stored energy is used to extend the supply of power to the network and to cover drops in power generation during the following day.

Figure 5 and Fig. 6 illustrate 2 operation states of energy storage system corresponding to one day of operation. In the first operation state 1, the PV plant supplies power up to 50 % of its installed power capacity, and no energy is stored.

Any rapid drops in the PV supplied power are covered by the existing, previously charged storage. When the PV production exceeds the threshold of 50 % nominal capacity, the system operates in the second state 2. The excess energy is stored in the batteries, and the stored energy then covers eventual drops in PV supply, if occurred.

This operation mode continues for the remainder of the day and can extend power supply to the network until the batteries discharge to their pre-set Depth of Discharge (DoD) limit. This balanced operation also allows more efficient prediction of energy production by the entire system (PV plant and energy storage).

Energy storage can cover sudden load peaks by changing the discharge algorithm and by increasing the maximum allowable discharge power of the batteries. These solutions, sometimes used in power distribution systems enable a lot of positive properties e.g. shift the power generated by PV plants into the morning to evening peak hours of DLC. Such systems can, for ex-

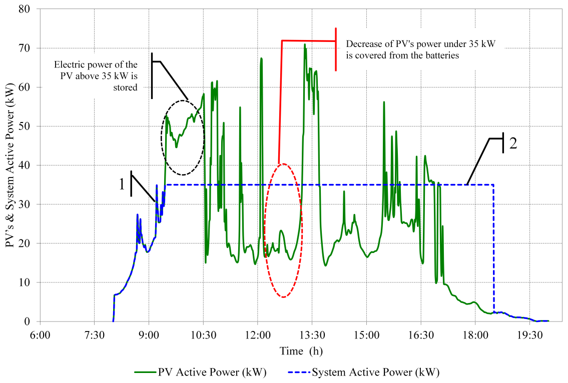

Fig. 5: A simulation of applying the Energy Storage System for variable cloudiness day.

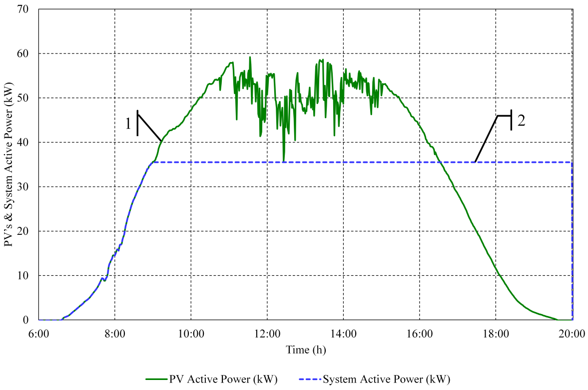

Fig. 6: A Simulation of applying the Energy Storage System for sunshine day, the worst case.

ample, supply power of up to 70 kW into the network during the periods of from 6–9 a.m. and 6–9 p.m. (i.e. during the morning and evening load peaks). If, during a day, the battery charge were sufficient to cover the following evening and morning supplies, the generated PV power can be supplied to the network.

3. Conclusion

In this paper has been summarized the main negative effects caused by operation of dispersed Renewable energy sources, such as PV in energy systems. Deployment of such sources with intermittent generation can cause serious problems related to voltage regulation in distribution and transmission systems. Low voltage distribution systems are the most affected by changes of voltage at the PV plant connection point. To mitigate the PV plant connection issues in such systems, solution based on energy storage appear to be the most suitable. A review of a number of modern energy storage technologies has been carried out. Selected energy storage systems has been compared to each other using Multi Criterial Analysis, which is suitable in cases of complicated situations modelling and solving complicated decision-making tasks in which set of variants and criteria is defined. As a best solution from the energy storage systems has been selected Lithium Ion battery type. The properties of battery-based solution are illustrated on a real, operational PV plant with installed power of 70 kWp. Based on the energy system requirements and Lithium Ion battery properties were carried out simulations in developed LabVIEW tool to show, how useful can be energy storage system with Grid-connected PV. The system with energy storage can not only suppress the rapid voltage changes caused by the intermittency of PV production, but also reduce the network voltage changes caused by connecting PV plant. Another advantage is the increased consistency of energy production and thus the improved accuracy of its prediction.

In addition to mitigating the negative effects of grid connected PV plants on the networks, storage solutions can also improve the security and reliability of a power supply. This aspect of a power system operation has been recently of great interest, especially in relation to the development of Renewable energy sources as an integral part of the overall concept of energy supply.

Acknowledgment

This paper was conducted within the framework of the IT4Innovations Centre of Excellence project, reg.

no. ED1.1.00/02.0070, project LO1404: Sustainable development of ENET Centre, Students Grant Competition project reg. no. SP2015/170, SP2015/178, project LE13011 Creation of a PROGRES 3 Consortium Office to Support Cross-Border Cooperation (CZ.1.07/2.3.00/20.0075) and project TACR: TH01020426.

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