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POWER QUALITY IMPROVEMENT AS AN ANCILLARY SERVICE OF ENERGY STORAGE SYSTEM APPLIED IN LOW VOLTAGE MICROGRIDS

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Abstract: The paper deals with commercially available battery energy storage systems (ESS) and the possibility to apply it for an ancillary services such as the voltage support. Authors present an algorithm that, if used in external ESS controller, can extend the functionality of ESS beyond its primary task for which it was designated. In particular, the voltage control and dip mitigation are considered as the ESS ancillary services.

In the paper the control strategy is described, then the results of simulations are presented to prove the correctness of the control algorithm. Also experiments are described that were executed in the real test microgrid configured in the Laboratory of Distributed Generation at Lodz University of Technology, Poland. The experiments show the implementation of proposed control strategy in the commercially available ESS applied in LV microgrid. Analysis of test results and assessment of the ESS capability in providing voltage support service is included in the paper.

1. INTRODUCTION

Microgrid provides electricity generation, and distribution to supply local loads. There are microgrids owned by the network operator and microgrids that supply industrial or residential customers which belong to their users. The latter one is the subject of this paper.

Microgrids usually operate in connection with the supplying network. The energy exchange with the network fluctuates due to the changes in load demand and changes in energy production by renewable energy sources (RES). Typical RES utilized in LV microgrids are wind and solar systems. Daily power generation of such sources is stochastic and depends on the availability of primary energy. Usually, the production does not match the local demand. The highest generation may be during time periods when load demand is low, e.g. at nights. Thus, the surplus energy is transmitted to the electrical power network during off-peak hours and delivered from the network during on-peak time periods.

From the technical point of view, it is potentially profitable for a microgrid owner to install an energy storage which would take balancing service within the microgrid [1]. This application enables one to store the surplus energy generated during the periods of low power demand and release it when the local demand is high or sell it to the utility during peak hours at higher prizes. When the storage is in operation the energy exchanged with the network is reduced. In this way the storage system takes up the role of a power and energy buffer in the microgrid. From the utility point of view decreasing power exchanged with the microgrid is a relief for the network in peak time periods and keeping it on the constant level may help to increase the network hosting capacity [2].

Another purpose of storage application may be the mitigation of power output fluctuations caused by RES [1]. This effect contributes to the improvement of power quality (PQ) and is particularly useful in networks with high penetration of intermittent renewable power sources.[3]. Additional potential benefit, besides possibility for power dispatching generated by RES, is the increasing use of renewables in electrical power grids. This application is discussed in [4].

Storage technologies differ with power capacity and amount of stored energy [5]. The systems designated for active power and energy management should supply energy for more than a few minutes to several hours. An appropriate technology in this case is a lead-acid battery storage which is commercially mature and economically favorable [6]. Other solutions such as Li-Ion batteries offer a better performance however their costs are higher.

In PQ applications other storage technologies, such as flywheels and ultracapacitors have attracted the great attention recently [7].

Battery storages are connected to the grid through coupling inverters. The inverter ability for reactive power control creates an opportunity for the storage system to obtain additional functionalities. These functionalities can be used for the compensation of power quality disturbances. As a result the storage application becomes more effective.

Some investigations regarding the ancillary services of storage systems have already been undertaken by the authors and published in literature. In [8] simulation results illustrating the application of battery storage for load leveling and voltage stabilization were reported. Paper [9] showed the use of storage for joint energy management and harmonic compensation. In [10] the operation of ESS performing the tasks of energy management and the compensation of load reactive power, harmonics and unbalance was presented.

This paper discusses the results of research on using battery ESS to control energy exchange between the LV microgrid and the supplying network and performing the voltage support as an ancillary service. The voltage support includes the compensation of voltage variations originated from load changes and RES fluctuations and mitigation of voltage dips coming from the supplying network (due to short-circuits).

The paper is organized as follows. In section II the study microgrid is reported and the ESS control strategy is described. It is followed by section III presenting results of simulation for different scenarios of ESS operation. Section IV deals with experiments carried out at test site facility at the Lodz University of Technology (TUL) [11]. The paper is finished with conclusions.

2. STUDY MICROGRID

2.1. Microgrid Structure and Configuration

The microgrid under study, presented in Figure 1, was configured in the Laboratory of Distributed Generation at LUT. It consists of photovoltaic panels (PV) with rated power of 15 kWp, the Capstone C30 gas microturbine (MT) with rated electrical power of 30 kW and linear loads of RL type, with the power adjustable 0–30 kVA. The microgrid is connected to the supplying network at the point of common coupling (PCC).

The impedance of LV feeder L is Z = (0,32 + j0,06) Ω, transformer T has the rated power of 70 kVA and short-circuit voltage u_{sc} = 6%. The transformer has LV/LV voltage ratio but it corresponds to MV/LV ratio. The supplying network is represented by a physical model which includes reactors and resistors representing MV line. Energy storage system ESS with rated power of 44 kVA is connected to the main bus (PCC) of the microgrid. The system includes 50 kWh lead-acid battery pack and the grid inverter.

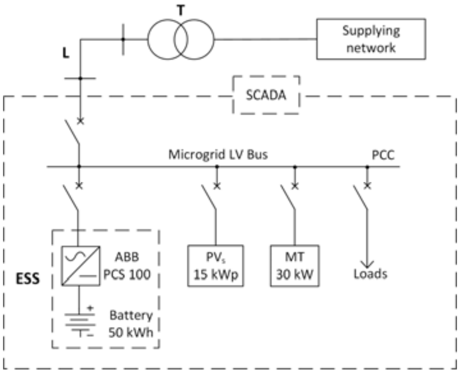

Fig. 1. Diagram of test facility

The PV panels are connected to LV bus through three single-phase SMA Sunny Boy inverters. As uncontrollable sources operate continuously with the maximum power output available under given conditions. The microturbine operates as a current source. Its output can be remotely adjusted with the manufacturer's application Capstone Remote Monitoring System, an hourly or daily/weekly operation schedule can be programmed.

The ESS PCS 100 is a commercial energy storage system manufactured by ABB. The battery voltage U_{DC} is 530 V and the inverter maximum current is 150 A. The manufacturer offers P-Q control scheme. Active and reactive power set-points are input signals to the system. The whole test facility is monitored and controlled with SCADA BTC Prins system.

2.2. Proposed control strategy for ESS Control

The required control strategy for ESS inverter assumes two objectives:

- generation or consumption of active power according to the requirements of external energy management system,
- compensation of voltage disturbances at the PCC.

The two task should be performed simultaneously. This requires two independent control loops, one dedicated to active power control and the other one dedicated to the compensation of voltage variations. To stabilize the voltage the inverter must inject a reactive current of fundamental frequency and positive sequence, which gives an appropriate voltage drop on the reactances of the supply network.

The inverter is operated in current control mode. The reference current is the sum of active component associated with the active power that is to be generated or consumed by the storage and reactive component dependent on the voltage changes, according to the equation (1).

$$\mathbf{i}_{\mathbf{ref}} = \mathbf{i}_{\mathbf{p}} + \mathbf{i}_{\mathbf{q}} \tag{1}$$

where $\mathbf{i}_{\mathbf{ref}} = [i_{L1}, i_{L2}, i_{L3}]^T$ is phase reference currents vector, $\mathbf{i}_{\mathbf{p}} = [i_{L1p}, i_{L2p}, i_{L3p}]^T$ is phase current active components vector responsible for active power generation, $\mathbf{i}_{\mathbf{q}} = [i_{L1q}, i_{L2q}, i_{L3q}]^T$ is the phase currents reactive components vector responsible for reactive power generation.

The block diagram of proposed storage inverter control is shown in Fig. 2. The active and reactive currents are determined according to the formula (2) and (3) respectively:

$$i_p = \frac{P_{control}}{U^2} u \tag{2}$$

$$i_q = \frac{Q_{control}}{\omega U^2} \frac{du}{dt} \tag{3}$$

where $P_{control}$ and $Q_{control}$ are the output signals of PI controllers and U is the RMS voltage value at the LV bus where the ESS is connected.

Active component of phase currents is responsible for generating the active power in order to keep power exchange with the supplying network on the required level; in the paper power exchange is assumed 0. Reactive components are responsible for generating reactive power that should compensate voltage variations at the point of common coupling.

The input signals for PI controllers are errors between measured and reference values of active power and bus voltage, respectively. The reference values of active power can be set accordingly to management priorities based on the contract with network operator or on the technical constraints. In particular, the reference power can be determined as an average power of microgrid or can be set to 0.

The current components i_p and i_q are used to form the reference currents for the inverter. Hysteresis control is applied, in which switching input signal to the inverter is generated when measured inverter currents exceed the bandwidth of reference currents.

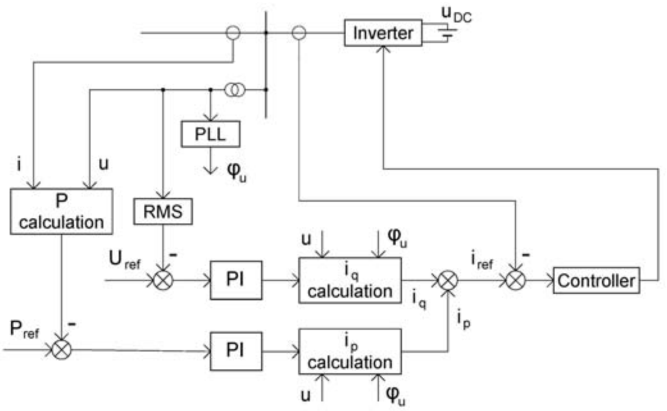

Fig. 2. Block diagram of the storage inverter control

Effectiveness of the ESS operation in the regime of active power management and ancillary services was examined, by means of simulation in PSCAD/EMTDC environment and the experiments.

3. SIMULATION

The simulator was built taking into account all devices and elements present in the microgrid with its nominal parameters. The load were reproduced by means of passive R, L elements. Their values were being adjusted according to the established schedule of active and reactive power changes defined for test scenarios. The power sources (i.e.: microturbine and PV) were modeled in a simplified manner as a current sources. The microturbine model carried out the preconfigured generation program, while the active power generated in PV modules varied stochastically in accordance with a normal distribution. Conversely to the previous devices, the ESS was modeled in details with the representation of battery, grid inverter and the control systems shown in Figure 2.

Simulations were performed for three test scenarios:

- the microgrid without the ESS,
- the microgrid with the ESS connected and enabled option of active power management,
- the microgrid with the ESS connected and enabled options of active power management and voltage variations compensation.

3.1. Microgrid without ESS

Loads and controllable energy sources are operated according to the assumed profiles. The active power generated by PV system is stochastic thus the power which is exchanged with the supplying network is also stochastic. The profiles of loads (P_l), microturbine (P_{mt}) and PV panels (P_{PV}) are presented in Figure 3a.

The changes of loads active and reactive powers are correlated, the power factor is 0.93. The reactive power generated in the sources (PVs and microturbine) is equal zero. The load changes cause the variation of voltage RMS values at the PCC, mainly due to reactive power. The measured voltage is lower than the nominal value and if more heavy loads are applied exceeds the lower limit.

3.2. Microgrid with ESS connected and enabled option of active power management

It was assumed that the ESS performs the balancing service in the microgrid, thus the power exchange with the supplying network Pg is minimized. The results of simulation are presented in Figure 3b. The ESS generates or consumes active power dependently on load and RES changes (mainly stochastic fluctuations of active power generated by the PVs).

a) b)

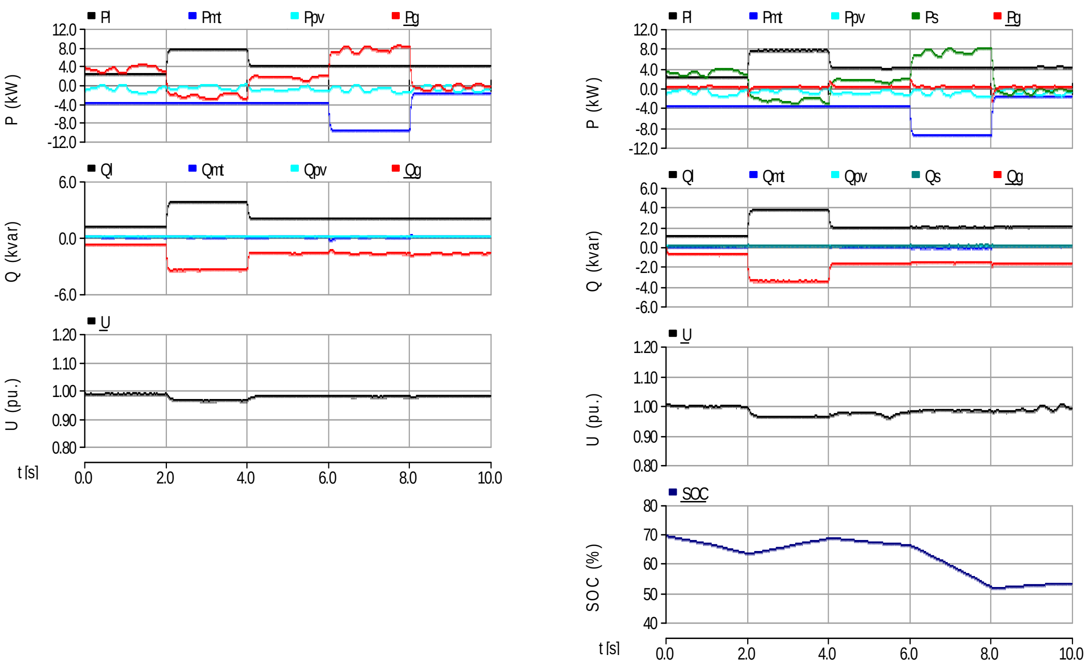

Fig. 3. Active (P), reactive (Q) powers and RMS voltage (U) in the microgrid operating a) without ESS, b) with ESS: P_s, Q_s – storage active and reactive power, respectively, P_g, Q_g - grid active and reactive power, respectively.

The ESS does not generate any reactive power and therefore the impact on the voltage level is negligible.

3.3. Microgrid with ESS connected and enabled options of active power management and voltage stabilization

In this scenario it was assumed that the ESS performs the balancing service in the microgrid and at the same time stabilizes the voltage at the PCC. As previously, the active power exchange with the network is equal 0. The RMS voltage value is maintained by delivering reactive power from the ESS to the microgrid. Figure 4 illustrates the microgrid operation.

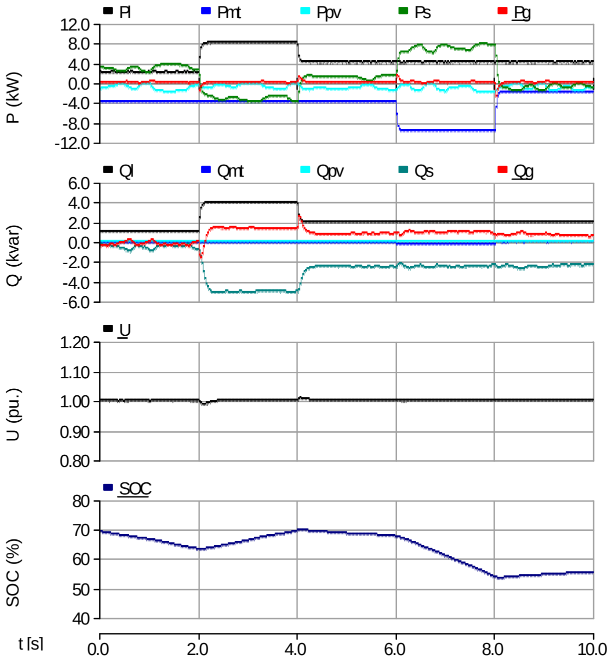

Fig. 4. Active (*P*) and reactive (*Q*) powers and RMS voltage (*U*) in the microgrid with ESS minimizing active power exchange with the supplying network and stabilizing voltage at the PCC

It should be noted that the impact of active power changes on the voltage level is negligible. In particular, this can be observed during significant changes of microturbine power generation.

4. EXPERIMENTS

Experiments were performed in the test microgrid described in Section II. To adopt the ESS for performing the required services it was necessary to utilize the external PLC programmable controller. The PLC controller was connected to two power analyzers located in the feeder and the PCC. On the basis of online measurements the controller with the implemented control algorithm processes new set-points of active and reactive powers and executes them in the inverter.

Three test scenarios were investigated corresponding to the simulation scenarios described in Section 3. The same profiles of load and microturbine power generation were repeated in each case. Conversely, the PV active power generation resulted from real current weather conditions. During tests the real active and reactive powers were measured and evaluated. The measurements were performed utilizing power quality analyzer - Fluke 1760. Results were averaged in 1-minute increments.

The results of tests are presented in the following Figures: Figure 5a shows the microgrid operation with ESS off, Figure 5b illustrates the microgrid operation with ESS executing both control options, i.e. active power management and voltage stabilization.

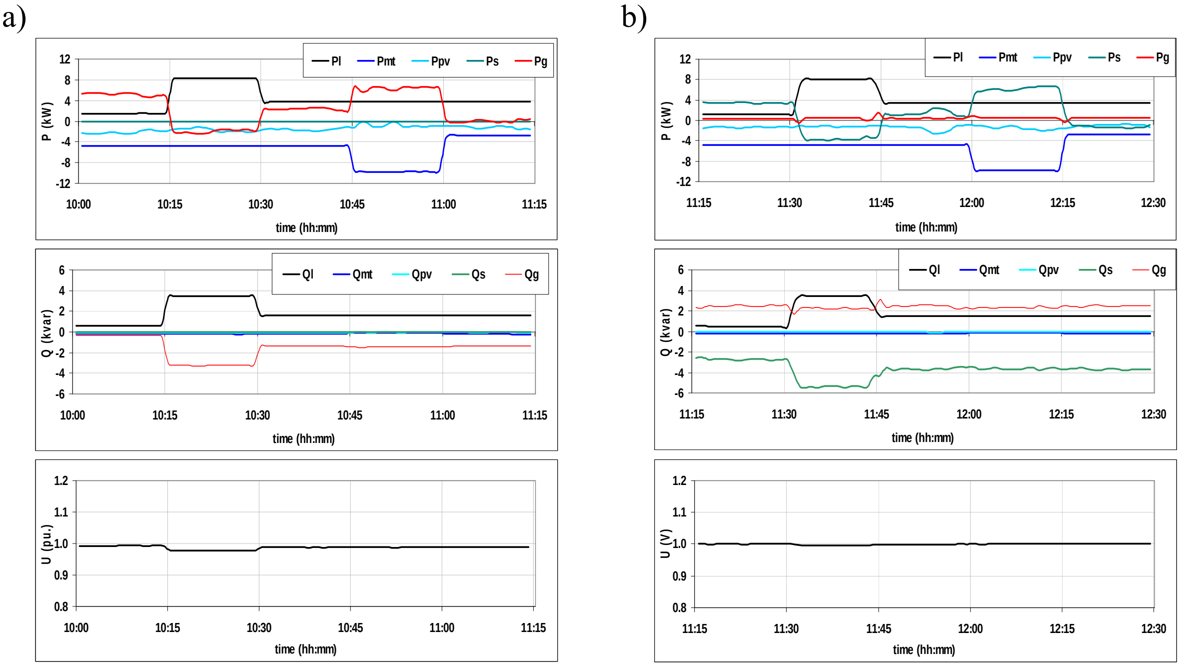

Fig. 5. Changes of active power (*P*), reactive power (*Q*) and PCC voltage (*U*) in the microgrid operating a) without ESS, b) with ESS

The test results confirm the correct operation of the ESS with the implemented control functions. One should note that transients are not visible due to averaged measurement values. Also, due to the technical limitations tests were performed at lower, than in simulation, power values of load (40%) and generation (60%). This resulted in smaller voltage changes (from 1.0 to 0.97 U_n during experiment against from 0.97 to 0.89 U_n during simulation).

5. DIPS COMPENSATION

The capability of the ESS to mitigate the effects of dips in the study microgrid had been evaluated. For that purpose a series of symmetrical short-circuits were applied in the real model of MV supplying network. These resulted in the voltage dips at the LV bus (at the PCC) in the microgrid. Voltage measurements were performed at the LV bus using Fluke 1760 analyzer. Voltage values were averaged in the time periods of 200 ms.

In Figure 6a the phase voltage waveform with corresponding RMS values are presented. The test was performed with the ESS off. The RMS voltage during dip was 95 V.

Then, the test was repeated with the ESS operating. The phase voltage waveform and its RMS value are shown in Figure 6b. The voltage increased by 33 V. The effect of dip compensation was achieved by the generation of reactive power, which was accompanied by the rise of inverter current, presented in Figure 7.

One can note that the capability of the tested ESS to compensate voltage dips is limited and dependent on the network impedance and the ability of the ESS to generate reactive power. Maximum reactive power generation is determined mainly by the inverter permissible current and the battery voltage. The battery increased voltage value can improve the ESS capability for dip compensation. This statement was confirmed in simulation where the battery voltage was increased to U_b = 1500 VDC. The dip was reduced with no much overcurrent. The minimum voltage value was 0.9 U_n, so it was within the required range.

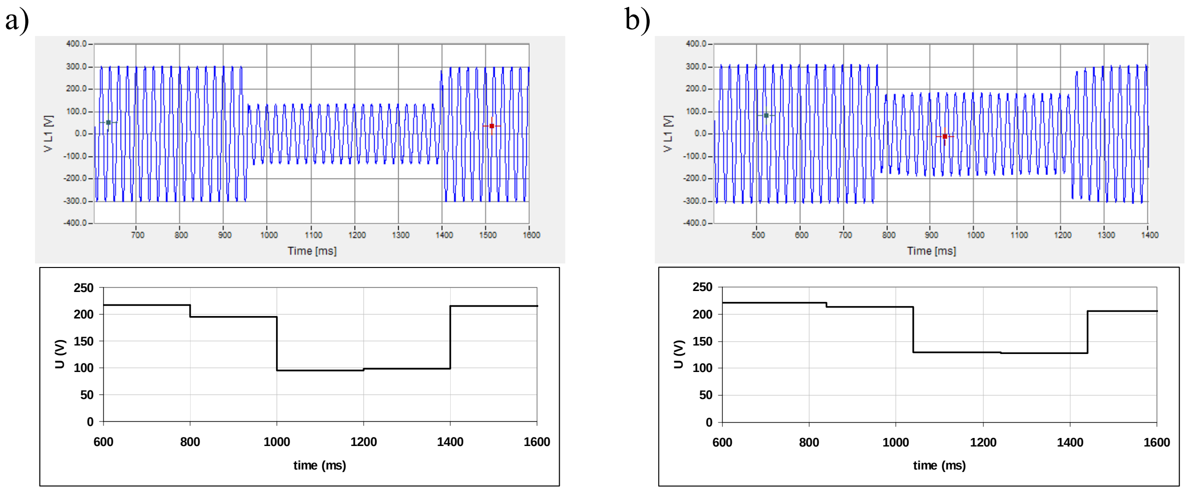

Fig. 6. Phase voltage waveform and corresponding RMS voltage values during the dip: a) ESS turned off, b) ESS on

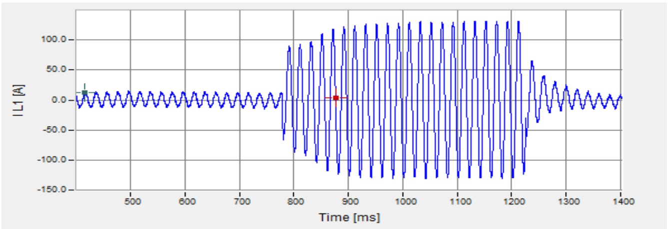

Fig. 7. Waveform of current injected to the grid during the dip

6. CONCLUSIONS

In this paper authors discuss the capability of the commercially available battery storage system to provide ancillary services such as PQ regulations. The control algorithm that extends the storage functionality to mitigate voltage variations is presented. The algorithm was evaluated by means of simulation in the PSCAD environment then implemented in commercially available ESS installed in the test facility at Lodz University of Technology. Results prove that the ESS inverter, by an appropriate reactive power generation, can control the voltage level at the PCC without compromising its primary function. The system effectiveness depends on the nature of voltage changes. In microgrids, where voltage variations result from load changes it is possible to maintain the voltage at nominal level. The ESS system can compensate voltage variations due to the load changes or voltage fluctuations caused by RES. However, in case of voltage dips the compensation capability is limited. Besides, in certain cases, even small dip mitigation might be beneficiary (e.g. from the point of view of anti-islanding protection of some RES devices).

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