Power Quality in Islanded Microgrids supplied by Vehicle-to-Grid: Norwegian Pilot Study

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***Abstract*—This paper presents vehicle-to-grid (V2G) tests performed in the microgrid at university Campus Evenstad, Norway. The purpose of the tests was to investigate the power quality in the connection point to the grid during transitions to/from island mode. These transitions are generated by disconnecting and reconnecting the microgrid from the surrounding distribution grid. During the short islanding period, the energy in the microgrid is supplied by an electric vehicle (EV) battery, in interaction with battery energy storage systems (BESS). The frequency, voltage variations, and voltage harmonics are measured and found to be within the Norwegian regulatory limits. However, high current spikes (500-800 A) and irregular current and voltage waveforms are observed during the transitions. The test results show that an EV battery, in interaction with BESS, can supply a microgrid within the regulatory limits of power quality. Hence, V2G can contribute to supplying loads in microgrids during supply interruptions.**

***Keywords*—batteries, islanding, microgrids, power quality, vehicle-to-grid**

I. INTRODUCTION

The power system has traditionally been a unidirectional system consisting of centralised power generation, a power grid, and distributed electricity consumption. With the recent technology and price developments within distributed energy resources (DERs), the amount of intermittent distributed generation, energy storage, and controllable loads connected to the power system has been increasing rapidly. Examples of popular DERs are photovoltaic (PV) systems, battery energy storage systems (BESS) and electric vehicles (EVs). Electrification of the transport sector and the recent development of vehicle-to-grid (V2G) technology are important factors that are increasing the distributed flexibility of the power system. The structure of the power system is rapidly changing. The increased flexibility introduced by DER technology has been an important driving force for the development of local microgrids. In this paper, results from V2G tests in the microgrid at Campus Evenstad are presented. Campus Evenstad is situated at the Inland Norway University of Applied Sciences (INN University) and is owned by Statsbygg, the Norwegian government's building commissioner, property manager and developer.

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A. Microgrids

In research literature, a *microgrid* is defined as a geographically limited distribution grid with DERs that can be observed as a single controllable entity from the external grid, which may be operated in both grid-connected mode and island mode [1], [2]. Microgrids are being developed all over the world to enable electrification of remote areas, increased penetration of renewable and distributed generation, a more reliable power supply, and a better optimised power flow in local distribution grids. In Norway, microgrid pilots are being developed in rural areas as an alternative to traditional grid investments, e.g. postponing reinvestment in subsea cables to islands, to ensure reliability of supply [3].

In the future, microgrids could be an important flexibility resource that provides services to both the microgrid owner and the distribution system operator (DSO). The future roles of a microgrid in the power system, including interaction between the microgrid and the distribution grid, are discussed in [4]. Microgrids introduce some technical challenges, as they are usually complex installations. Advanced control strategies and protection systems are required to ensure a successful operation both in grid-connected and island mode. An overview of methods for planning, operation and protection of microgrids is presented in [5].

One of the main challenges related to microgrid operation is ensuring that the power quality is within the regulatory limits both in grid-connected and island mode, as well as during disconnection and reconnection to the surrounding distribution grid [6], [7]. In [8] and [9], measurements and results from field testing of the Simris microgrid were presented. The first study investigated the operation of the microgrid in island mode and the transitions to/from island mode, while the second study analysed the performance of the management system, which was based on a model-predictive-control approach. An investigation of the power quality in the microgrid at Campus Evenstad was presented in [10]. The study showed that there were power quality issues related to the transitions to/from island mode. The current paper studies these transitions at Campus Evenstad even further, by analysing the measurement data from power quality analysers installed at different locations in the microgrid. In addition, this paper presents the results from the first-ever V2G test performed in Norway, including V2G operation in the microgrid in island mode.

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B. *Vehicle-to-grid*

V2G can be described as using an EV battery for other purposes than the operation of the electric vehicle. Several different terms are used in addition to the well-known V2G, such as vehicle-to-home (V2H), vehicle-to-building (V2B), and the more generic vehicle-to-X (V2X) [11]. The focus of this paper is how the EV can be used in a microgrid. An EV battery can be used for several purposes, such as voltage control or frequency regulation, but the focus of this paper is to establish how the EV can serve as backup-power in a microgrid during islanding, and how this affects power quality in the microgrid.

The tests presented in this paper were performed at Campus Evenstad, a microgrid pilot with a V2G charger in Norway. According to [12], there are several other demonstration projects in Europe that include V2G, such as ACES [13], WiseGRID [14] and INSULAE [15]. None of these pilots investigate the power quality when using an EV as back-up power in a microgrid. Instead, they cover topics such as optimal control of an EV fleet, profitability when using EVs for frequency regulation, and degradation of vehicles. Hence, the focus in this paper seems to be unique for pilot testing.

Power quality of actual grids with V2G has been studied in [16], where a simulation study was performed, considering frequency, total harmonic distortion (THD), and voltage stability. Their main finding was that the charging and discharging state of the EV did not affect voltage stability, and that using V2G at high charging rate did not affect the stability and power quality of the power system. The article did not, however, study this in a microgrid.

Refs. [17] and [18] have performed simulation studies on V2G in a microgrid. In [17], the aim was to assess the contribution of the EVs to improve reliability of supply in a microgrid. It was found that in an islanded grid with low spinning reserve, the electric vehicles can improve the stability of the grid. Hence, the focus was on how the EV could provide a stability service, while this paper investigates how the EV affects the power quality in the microgrid. In [18], a model was developed to study the increase of self-consumption of PV power by smart charging of EVs and V2G, and the model was applied to a microgrid in the Netherlands. This study only considered energy and power flow, not power quality. Both [17] and [18] are simulation studies, while in the current paper actual field measurements are presented.

Ref. [19] studied the use of EVs for frequency regulation in connection with wind power at the Danish island of Bornholm. The simulation results showed that V2G systems are able to integrate more fluctuating wind power while replacing most of the conventional generator reserves in the islanded power system. The study did not consider transitions to and from island mode.

C. *Contributions and research questions*

This article presents field measurements of frequency, voltage, current, and voltage harmonics in a microgrid with V2G, as well as analyses of the measurement results. Based on this, the article aims to answer the following research questions:

- Do the transitions to and from island mode comply with the Norwegian regulation on quality of electricity supply (FoL) when an EV battery is supplying the microgrid?
- Can an EV battery, in interaction with BESS, supply a microgrid without compromising power quality?

In this way, the article contributes to more knowledge about microgrids, which in turn can increase the public acceptance. Furthermore, the field measurements can be used for validation of simulation results.

II. System Description

A. *Campus Evenstad Microgrid*

The microgrid consists of several loads, distributed generation, three BESS and a vehicle-to-grid charger, as shown in Fig. 1. The combined heat and power (CHP) production was not in operation on the test day referred to in the current paper. The microgrid can be operated in island mode, for example during supply interruptions. The islanding protection introduces a delay of around 1 minute before the BESS can reconnect after islanded operation. The surrounding 230 V IT grid is operated by the distribution system operator Elvia. Campus Evenstad is a pilot in the research project IntegER.

B. *Vehicle-to-grid*

The V2G charger can be manually connected to Nissan Leaf EVs. When the charger is connected, a touchscreen by the charging box can be used to set the EV battery to charge or discharge. The charging or discharging power is not controllable, but the maximum value is 10 kW. Whether the microgrid is connected to the grid or islanded does not affect the V2G control. The battery of the EV used during the tests has an energy capacity of 62 kWh.

III. Measurements

A. *Test specification*

The test was specified using a test template from the ERIgrid project [20]. The system under test includes the whole Campus Evenstad microgrid. The circuit breaker (CB) XQ001 (see Fig. 1) was manually disconnected and reconnected to generate transitions to and from island mode.

The test was performed on 9 March 2020. At the beginning of the test, the EV was charging and the microgrid was in grid-connected mode. The charging power was 9.1 kW

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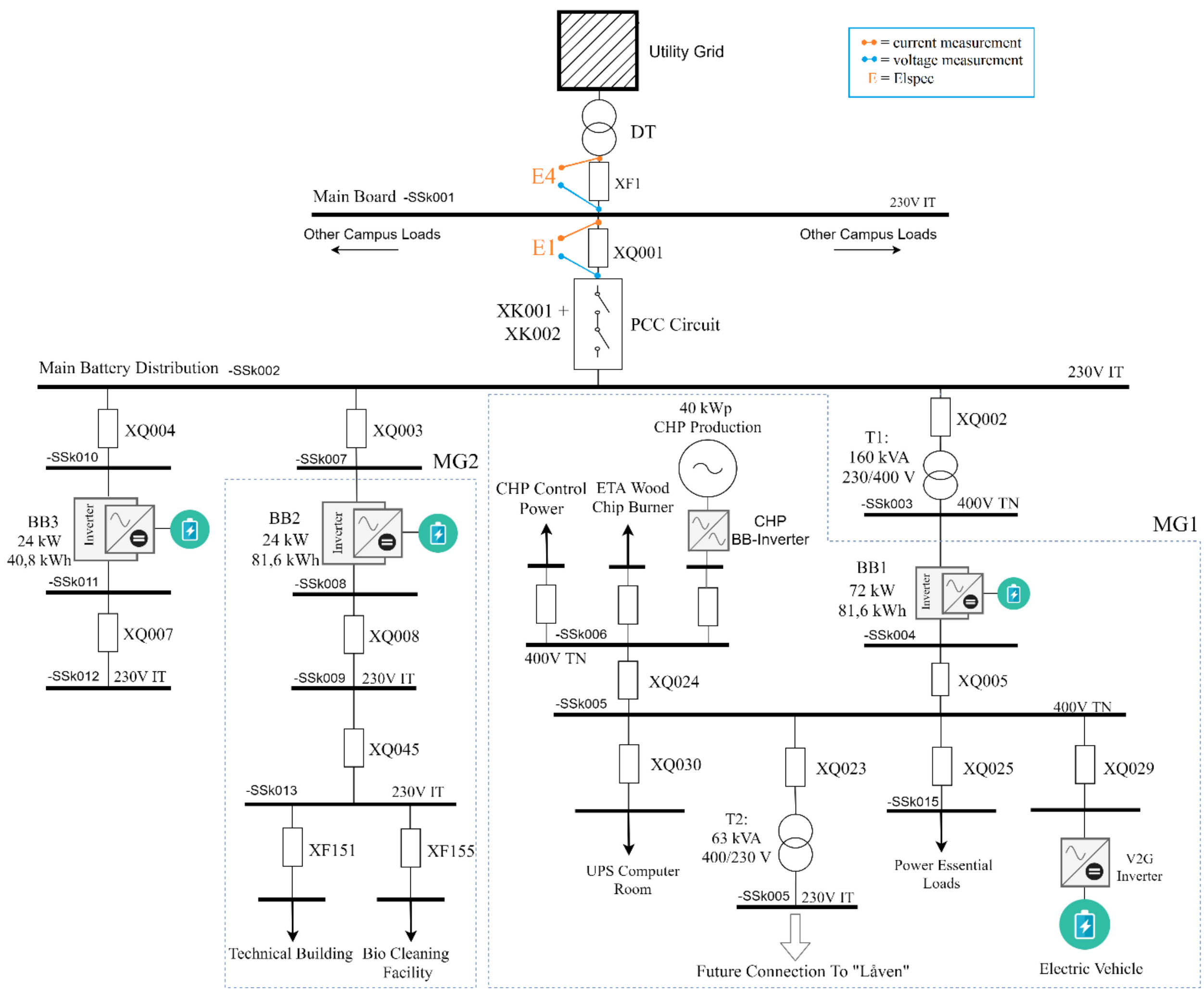

Fig. 1. Single-line diagram of the Campus Evenstad microgrid [21]. Current measurements are marked in orange and voltage measurements in blue.

and the state of charge (SoC) of the EV battery was 57 %. At 15:02 hrs. the CB was disconnected and the microgrid transitioned to island mode. The EV was then set to discharge and the discharging power was 9.4 kW. At 15:08 hrs the CB was reconnected and the microgrid transitioned from island mode. The EV was then set to charge. The SoC was now 55 % and the charging power was 9.05 kW. The test sequence is described in Table 1.

Two power quality analysers from Elspec were used for measuring voltage, current and frequency (based on voltage).

TABLE 1. TEST SEQUENCE

Time (Hrs.)	V2G	CB	SoC EV battery
15.02	Charging 9.1 kW	Disconnected XQ001	56 %
15.04	Discharging -9.4 kW		57 %
15.07		Connected XQ001	
15.09	Charging 9.05 kW		55 %
15.15	Stop charging		

The uncertainty of the voltage and current measurements is 0.1 %, and the frequency accuracy is ±10 mHz.

B. *Test criteria*

The test was considered successful if the requirements in the Norwegian regulation on quality of electricity supply (FoL) were met [7]. FoL is based on the European standard EN 50160 [6] developed by CENELEC. Thus, most of the technical requirements coincide with the requirements in EN 50160. The regulation includes the following requirements relevant to our pilot study, which are applicable for the voltage levels 230 V-35 kV:

- The voltage frequency should be kept within 50 Hz ± 2 %, that is between 49 Hz and 51 Hz.
- The supply voltage variations shall be kept within a range of ± 10 % of nominal voltage, measured as a 1-minute average. For a 230 V IT network that is between 207 V and 253 V. This requirement is different from the requirement in EN 50160, where supply voltage variations are measured as a 10-minute average [22].

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- Voltage swells, voltage dips and rapid voltage changes (RVCs) shall not occur more than 24 times over a rolling 24-hour period.
- The degree of voltage asymmetry shall not exceed 2 %, measured as a 10-minute average.
- The total harmonic distortion (THD) shall not exceed 8 %, measured as a 10-minute average. Limits for the individual harmonic voltages are also specified in [7]. As opposed to EN 50160, the requirements in FoL also include limits for individual harmonic voltages above the 25th order [22].

In the test, the islanding period only lasts for around 5.5 minutes. To assess whether the voltage asymmetry and the THD are within the FoL requirements, it is assumed that the steady-state values would be similar for 10 minutes.

The FoL regulation applies for the connection point to the grid, not inside the microgrid. Nevertheless, the test criteria were based on the requirements above since there are currently no such regulation that apply inside islanded microgrids.

IV. Results

A. Voltage

1) RMS: Fig. 2 presents the average RMS line voltages for the power quality analysers on each side of the circuit breaker that is disconnected and reconnected (E4 and E1). At the utility grid side (E4), the line voltages are between 230-232 V both before, during and after the islanding period. A voltage drop of 10 V can be observed approximately 1 minute after the reconnection of the circuit breaker (at 15:09 hrs.). This is assumed to be when the converters of the BESS are reconnecting to the grid.

At the microgrid side (E1), the voltage is 0 during the islanding period, as expected. Here too, the line voltages are between 230-232 V both before and after the islanding period. Rapid voltage changes between approximately 220 V and 240 V occur in the transition from island mode to grid-connected mode (at 15:08 hrs.). The voltage waveforms during this period are examined in the next section. Furthermore, an RVC of 22 V can be observed when the converters are reconnecting. Nevertheless, the voltage is well within the limits of FoL (207-253 V), both in E4 and E1.

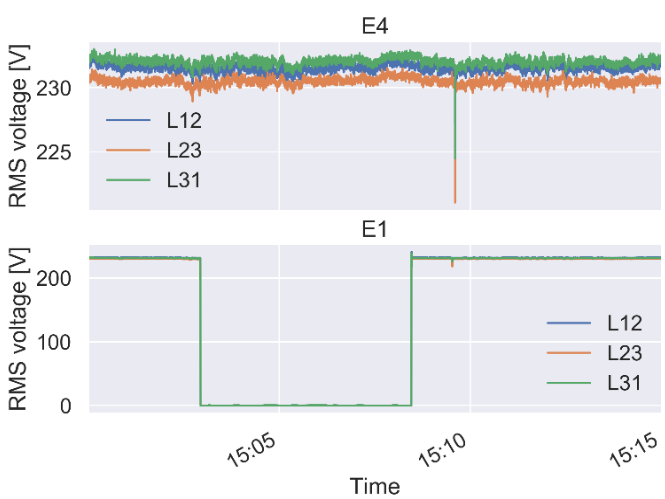

Fig. 2. RMS line voltages in E4 (top) and E1 (bottom).

The charging and discharging of the EV battery have no significant effect on the voltage in E4 and E1.

2) Waveforms: Fig. 3 presents the phase voltage waveforms at the microgrid side (E1) during the transition from island mode to grid-connected mode. It can be observed that the waveforms are distorted for several frequency cycles and have an offset from 0 of approximately 90 V.

3) Asymmetry: The voltage asymmetry is computed for the islanding period. The transitions to and from island mode are not included, in order to compute the steady-state value. At the utility grid side (E4), the voltage asymmetry is 0.43 %, which is well within the regulatory limit (2 %). The voltage asymmetry is not computed for the microgrid side, since the voltage here is 0 during the islanding period.

B. Current

1) RMS: Fig. 4 presents the maximum RMS line currents for the power quality analysers on each side of the circuit breaker that is disconnected and reconnected (E4 and E1). At the utility grid side (E4), the currents increase gradually from 190-230 A to 285-310 A before the islanding period. Then the currents vary between 250 A and 325 A. When the BESS converters reconnect (just before 15:10 hrs.), a current spike above 800 A can be observed. This is as expected, and most likely the inrush current of the transformer T1 (see Fig. 1).

At the microgrid side (E1), the currents are 20-30 A in the beginning of the test period, before they increase to 30-40 A around 1 minute before the islanding period. From the disconnection of the circuit breaker to the reconnection of the converters, the current is 0, as expected. Just before 15:10 hrs, a current spike above 500 A can be observed. This is also most likely the transformer inrush current. Then the currents are reduced to 12-18 A, before they increase gradually to 30-45 A. Two current spikes of 56 A and 59 A can be observed during the last charging period of the EV. At the end of the test period, the currents reduce to 22-38 A. The current waveforms during the transition from island mode to grid-connected mode are examined in the next section.

The charging and discharging of the EV battery have no significant impact on the current in E4 and E1.

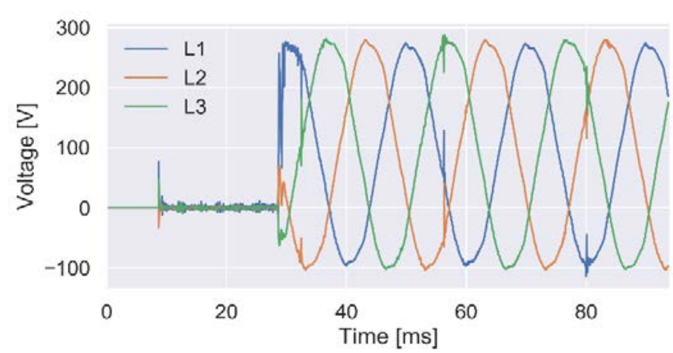

Fig. 3. Phase voltage waveforms in E1 during the transition from island mode to grid-connected mode.

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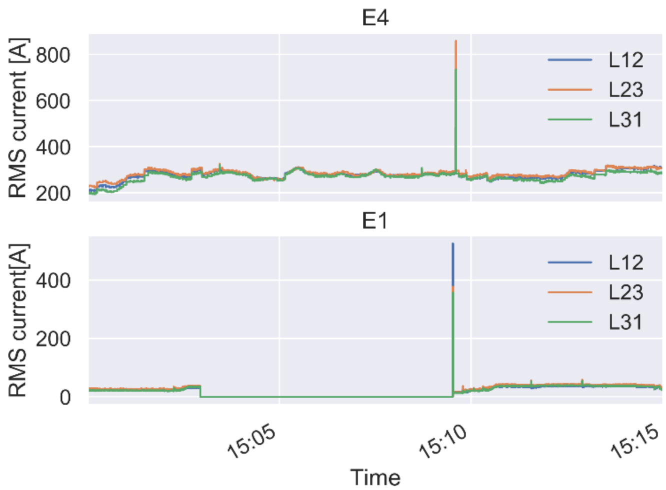

Fig. 4. RMS line currents in E4 (top) and E1 (bottom).

2) *Waveforms:* Fig. 5 presents the phase current waveforms at the microgrid side (E1) during the transition from island mode to grid-connected mode. The current waveforms are highly distorted, with values of 2-2.55 kA for a short time before they gradually reduce (ref. current spikes in Fig. 4). These values correspond with the documented peak inrush current of the 160 kVA transformer T1 (see Fig. 1), which is 2.8 kA [23].

C. *Voltage harmonics*

Voltage harmonics are computed for the islanding period. The transitions to and from island mode are not included, in order to compute the steady-state value. At the utility grid side (E4), the average THD values during the off-grid period are between 2.65 % and 2.82 % for the different line voltages (Table 2). This is well within the FoL limit (8 %). All the individual voltage harmonics are also within the FoL requirements. Table 2 shows the harmonics with the highest average values during the off-grid period. At the microgrid side (E1), the voltage is 0 during the islanding period, hence the THD and the individual voltage harmonics are not computed.

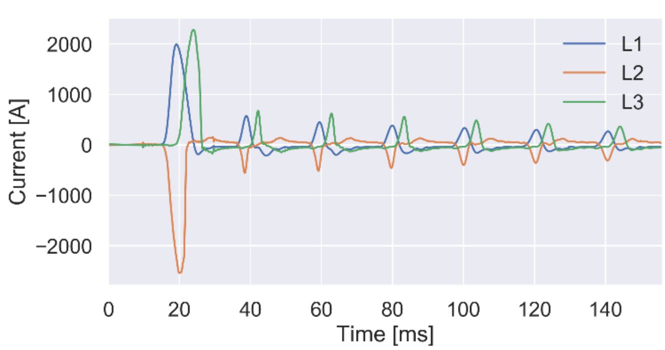

Fig. 5. Phase current waveforms in E1 during the transition from island mode to grid-connected mode.

TABLE 2. AVG. VALUES FOR THD AND INDIVIDUAL HARMONICS OF LINE VOLTAGES

Harmonic	THD	5th	7th	11th	13th
L12 avg. value (%)	2.82	2.62	0.56	0.47	0.72
L23 avg. value (%)	2.74	2.59	0.49	0.44	0.55
L31 avg. value (%)	2.65	2.45	0.55	0.42	0.66

D. *Frequency*

The average system frequency was found to be well within the FoL requirements (49-51 Hz) throughout the test period. The transitions to and from island mode and from charging to discharging the EV battery had no significant effect on the frequency, hence the frequency measurements are not shown here.

E. *Other test results*

Power quality analysers located downstream from the BESS (not used in the analysis in this paper) show frequency and voltage values exceeding the regulatory limits during the test. However, as mentioned, the FoL regulation applies for the connection point to the grid, not inside the microgrid.

Other tests that are not within the scope of this paper were also performed in the Campus Evenstad microgrid. In some of the tests, the circuit breaker XQ002 (see Fig. 1) was disconnected and reconnected to generate the transitions to and from island mode. These test results showed that the FoL requirements for voltage frequency and individual harmonic voltages were not met on the microgrid side of the circuit breaker during the transitions. Furthermore, rapid voltage changes exceeding the limit of ± 10 % of nominal voltage occurred on the microgrid side of the circuit breaker during the transitions. This does not comply with FoL if it occurs more than 24 times per 24-hour period.

V. DISCUSSION AND CONCLUSIONS

This paper presents results from V2G tests performed in the microgrid at Campus Evenstad. Transitions to and from island mode are generated by disconnecting and reconnecting the microgrid from the surrounding distribution grid. The purpose of the tests was to investigate the impact on power quality of using V2G to supply the islanded microgrid.

The test results show that all requirements in the Norwegian regulation on quality of electricity supply (FoL) are met, both upstream and downstream from the circuit breaker which is disconnected and reconnected. However, power quality analysers located downstream from the BESS (where the FoL regulation does not apply) show frequency and voltage values exceeding the regulatory limits.

Even though the FoL requirements are met in the test described in this paper, distorted voltage and current waveforms can be observed in the transitions to and from island mode. High current spikes can also be observed when the BESS converters reconnect after islanding. This is most likely due to the transformer inrush current. The microgrid at Evenstad is designed to withstand such high current values for

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short periods. This should be the case for all microgrids since current spikes can damage electrical equipment.

While some issues are observed during the transitions to and from island mode, the charging and discharging of the EV battery does not seem to affect power quality. Hence, the findings in this paper suggest that the anticipated increase in use of V2G in microgrids will be unproblematic.

However, there is a need for more knowledge about the control algorithms of battery systems in microgrids, in order to further investigate the interaction between BESS, EV batteries and the rest of the microgrid. Furthermore, requirements for power quality inside islanded microgrids should be defined.

Based on analysis of the test results, the main conclusions of this paper are:

- The microgrid's transitions to and from island mode comply with the Norwegian regulation on quality of electricity supply (FoL) when an EV battery is supplying the microgrid.
- An EV battery, in interaction with BESS, can supply a microgrid without compromising power quality.

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