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Usage of grid support inverter on long distribution grid lines

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Abstract. The paper focuses on the evaluation of new possibilities to improve voltage quality in remote branches of 230 V grid. Decrease of power electronic costs may potentially make battery-backed inverters a viable alternative to the costly reconstruction of 230 V distribution grid connections, which are of poor quality or cannot match changing load requirements, extending power transmission lines or adding boost transformers. The object of the current study is a household-type consumer with 20 A single-phase connection to distribution line with a distance of 2 km to a 20 kV transformer station. The calculated resistance of the power line is 2.8 ohms. The load profile was captured during 5 days in summer and 10 days in winter and was used to calculate the capacity of the grid support equipment. Measurements indicated, that in the worst case 2% of time the voltage was below 10% of nominal and 8% of time – below 5% of it. This is outside of the regulatory limits of EU and national regulations. The experimental setup for a voltage quality improvement system was based on an OutBack Power Radian series grid inverter with 7 kW output power. Battery consisting of 12 V 120 Ah VRLA accumulators wired in 48 V system was used. The inverter was configured to work in grid support mode using battery power when the consumer's active load increased above 1.2 kW. Results showed improvement in voltage quality over the full consumer load range. The total efficiency of the grid support system was 89%. The use of DC bus and batteries allows easy incorporation of renewable energy sources, thus giving the opportunity to scale power and battery capacity of the system. An Additional benefit of using a battery-backed inverter in grid support mode is that consumer can temporarily use more power that is allowed by grid due to its capacity constraints.

Key words: distribution grid, load, voltage quality, inverter efficiency.

INTRODUCTION

Installation of accumulator backed inverters at loads along with 1 kV lines and voltage boosters are one of the possible solutions for improving the quality of electrical energy parameters on long distribution lines. Moreover, an inverter-accumulator based system also serves as a starting point for renewable resource integration. Viability of this approach is further governed by the decrease of power electronic costs (Everts et al., 2010). Besides the technical aspect, which implies compensation of losses in distribution lines there is also an economical aspect. When the high load is necessary only temporarily, it is reasonable to limit grid connection capacity to decrease installation and maintenance costs and use accumulated energy or local resources generated from renewables. In addition, the presence of even limited power grid can improve the stability of local renewable energy generators (Allik & Annuk, 2017). Also, the ongoing extensive introduction of electric vehicles can affect the stability of the grid itself during peak load hours (Dharmakeerthi et al., 2014; Lillebo et al., 2018). Local microgeneration could solve this problem too (Meyer&Wang, 2018).

The aim of this study was to evaluate technical outcomes of using a grid supporting inverter on long distribution lines with low-quality voltage on the load side.

MATERIALS AND METHODS

The object of the current study is a household-type consumer with 20 A single-phase connection to distribution line with distance 2 km to 20/0.4 kV 100 kVA transformer station. The transformer feeds additional 4 consumer branches connected before object under study, which is placed at the end of the line, AMKA 3x35+50 cable is used for the connection.

In order to evaluate possibilities of voltage quality improvement using existing cable connection and to avoid its reconstruction, grid interactive OutBack Power Radian series inverter GS7048E with 7 kW output power was used. Choice of this inverter was justified by various grid operation options as well as a built-in optional possibility to connect local renewable energy based sources and back-up generator.

The inverter was configured to operate in grid support mode, which implies grid voltage pass-through until a given load power is reached. When it is reached, the inverter begins to augment grid output using energy from batteries. Thus power taken from the grid is restricted to configured value and voltage drop in distribution line is also limited. When the load power drops, grid capacity is used to recharge batteries. Besides of grid support mode additional modes like grid-tie, microgeneration and UPS are available, but those were not covered in the scope of this study. Battery setup consisted of two series with four 12 V VRLA (ABT TM12-535W) accumulators in series forming a 48 V 240 Ah battery bank. It should also be noted, that when operating GS7048E in grid support mode power is passed-through the inverter, therefore fast transients and flickering in the grid may remain on the load side.Installation of inverter was performed according to connection schematics in Fig. 1.

Voltage relay QS1 is controlling relays QK1 and QK2 used to disable inverter, if there is no grid input to be sure, that only grid-support functionality is tested. The input is protected by a C16 breaker (S1). Three-phase model was already installed at the consumer and was not changed during tests. Fig. 1 also shows the location of the voltage and current sensor probes, signals from which are described in detail in Table 1.

Fig. 2 shows the overall setup after the installation of the inverter. Power distribution and control devices are in separate compartments from the batteries. The compartment with the energy meter is not shown here. A dedicated earthing circuit was installed for all components of the setup.

Measurements of electrical energy quality were performed both before and after installation of the grid support inverter. Prior measurements were performed in two periods: in summer July 5-10, 2017 (120 hours) and in winter February 2-10, 2018 (250 hours). The average hourly temperature for July was +10 to +22 °C and -4 to -6 °C for February. The measurements after adding the grid support inverter were performed from September 24 to October 7, 2018 (370 hours).

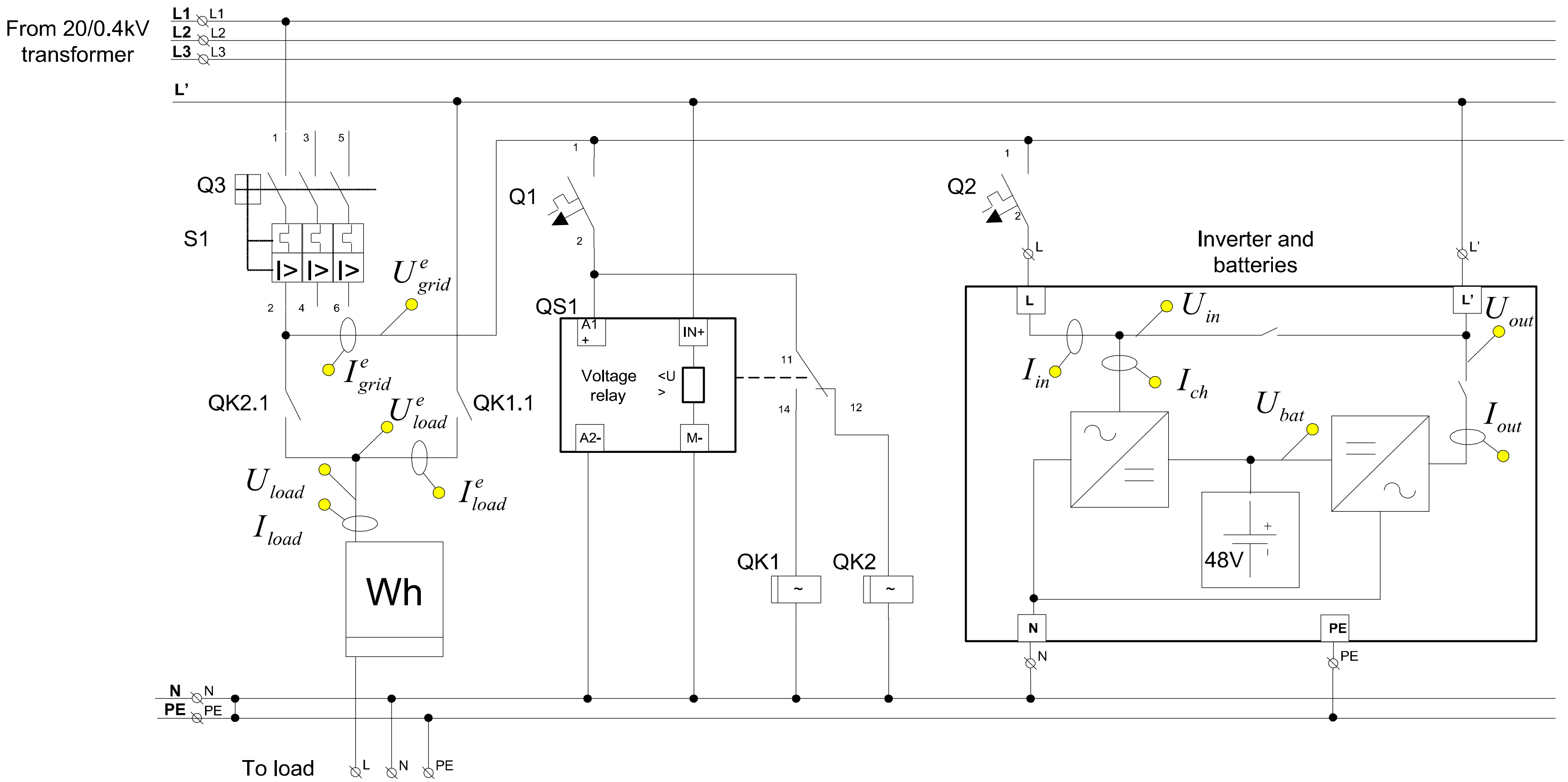

Figure 1. Inverter connection and measurement points.

Advangid GridLink data logger was used at the client's load side right before the energy meter in both measurement periods and it's data was used to compare the voltage characteristics before and after the installation of the inverter. Whereas ELSPEC G-4500 logger measured the voltage quality both before and after inverter only on the last period of the investigation. Additional battery charging related data was acquired by using an OutBack Power Radian system controller Mate3.

The studied object is a typical household, and it was not possible to have a controlled load graph, so there could be some differences in load power graphs between measurement periods, but they were partly mitigated by statistical data.

Figure 2. Inverter and batteries in their compartments.

Table 1. Summary of measured signals and calculated variables

Signal	Unit	Source (instrument or calculation)	Measure step, s	Description
U^e_{grid}	V	ELSPEC G-4500	1	Grid voltage
I^e_{grid}	A		1	Grid current
P^e_{grid}	W		1	Grid power (grid probes)
U^e_{load}	V		1	Load voltage
I^e_{load}	A		1	Load current
P^e_{load}	W		1	Load real power (load probes)
U_{load}	V	Advangid GridLink	5	Load voltage
I_{load}	A		5	Load current
U_{in}	V	Outback Mate3	1	Inverter input voltage
I_{in}	A		1	Inverter input current
I_{ch}	A		1	Charger input current (at 230 V side)
U_{bat}	V		1	Batery voltage
U_{out}	V		1	Inverter output voltage
I_{out}	A		1	Inverter output current
S_{load}	W	$S_{\text{load}}=\text{U}_{\text{load}} \cdot I_{\text{load}}$	-	Load apparent power
E_{grid}	kWh	$E_{\text{grid}} = \frac{\sum P_{\text{grid}}}{7.2 \cdot 10^5}$	-	Energy taken from grid
E_{load}	Wh	$E_{\text{load}} = \frac{\sum P_{\text{load}}}{7.2 \cdot 10^5}$	-	Energy supplied to load
P_{ch}	kW	$P_{\text{ch}}=\text{U}_{\text{in}} \cdot I_{\text{ch}}$	-	Battery charging power (at 230 V side)
P_{disch}	kW	$P_{\text{disch}}=\text{U}_{\text{out}} \cdot I_{\text{out}}$	-	Battery discharging power (at 230 V side)
E_{ch}	kWh	$E_{\text{ch}} = \frac{\sum P_{\text{ch}}}{7.2 \cdot 10^5}$	-	Total charging energy
E_{disch}	kWh	$E_{\text{disch}} = \frac{\sum P_{\text{disch}}}{7.2 \cdot 10^5}$	-	Total discharging energy

The measured signals are summarized in Table 1. For all AC signals, the average RMS values were recorded in each measurement step. The measurement interval of 5 s (limited by Advangid GridLink) was used for all instruments and data was merged in a single table by the timestamp of each instrument. Due to 5 s power to energy conversion coefficient in calculations was $7.2 \cdot 10^{-5}$.

Data processing was performed using R statistics software (R Core Team, 2017). Obtained data from prior measurements without a grid support inverter was used to calculate necessary energy for compensating grid to bring voltage to a client within defined minimum limits according to (LVS EN 50160, 2010). The standard states, that the 10 min mean RMS voltage at a client-side should be within -15% to +10% limits of nominal 230 V at all times and should not exceed ±10% limits no more than 95% of weekly measurements.

The compensated energy for the current object was calculated from the measurement data as losses in the distribution lines knowing it's resistance and assuming only a resistive load (1). The distribution line resistance was obtained from an UI scatter plot using linear regression.

$$E_{\mathrm{comp}(1)} = \frac{T_m \sum P_{\mathrm{comp}}}{7.2 \cdot 10^5} = \frac{T_m \sum I^2_{\mathrm{load<Umin}} R_{\mathrm{line}}}{7.2 \cdot 10^5}, \mathrm{kWh} \tag{1}$$

where T_m – measurement period, s; P_{comp} – compensation power, W; $I_{load<U\mathrm{min}}$ – load current, when the voltage is below limit in the measurement data, A; R_{line} – distribution line resistance, Ω.

This is the precise compensation scenario when the inverter for compensating voltage fluctuations can follow all voltage changes and respond accordingly. Additionally compensation energy was calculated for a scenario, when the inverter starts to augment the grid only when the load current exceeds a given value (2).

$$E_{\mathrm{comp}(2)} = \frac{T_m \sum P_{\mathrm{comp}}}{7.2 \cdot 10^5} = \frac{T_m \sum (I_{\mathrm{load>I'}} - I') U_{\mathrm{load}}}{7.2 \cdot 10^5}, \mathrm{kWh} \tag{2}$$

where I' – current limit to be taken from grid, A.

RESULTS AND DISCUSSION

Measurement results without a grid support inverter are summarized in Figs 3, 4 and Table 2. The current grid connection does not meet LVS EN 50160 as -15% is violated in July measurements, but -10% limit is reached in 2.09 % of measurements in July and 0.32 – in February. Additionally, calculations were performed for more strict 7% and 5% tolerances.

Unconformity to standard is minimal, however, the UI scatter plot shows, that the voltage drop due to distribution line resistance will result in voltages out of limits with load currents between 15 and 20 A almost at all times. Therefore this could lead to more severe unconformities to standard on higher load scenarios. Moreover low distribution line capacity results in voltage fluctuations when there is small or no load due to load changes in other line branches. This can be seen as horizontal lines at currents approximately 3.5, 5 and 10 A. Such voltage changes could be introduced by constant power loads (e.g. switching PSUs).

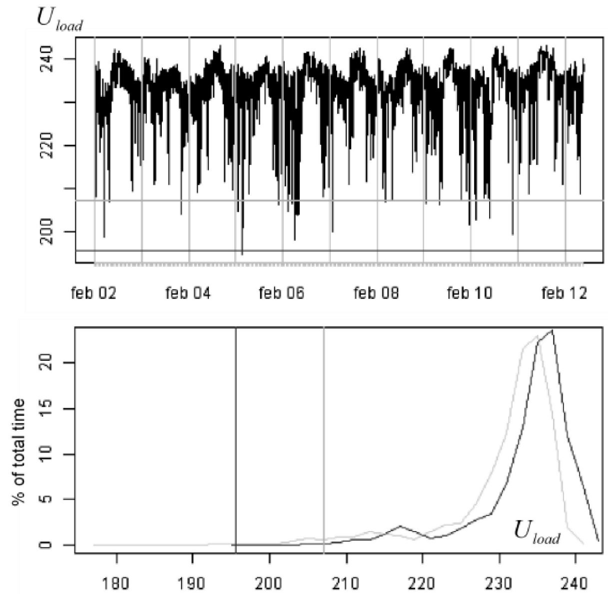

Figure 3. Load voltage time series (February 2018) and histogram (light gray – July 2017, dark gray – February 2018) of measurements without grid support inverter, dark gray vertical line – 15% tolerance, light gray vertical line – 10% tolerance.

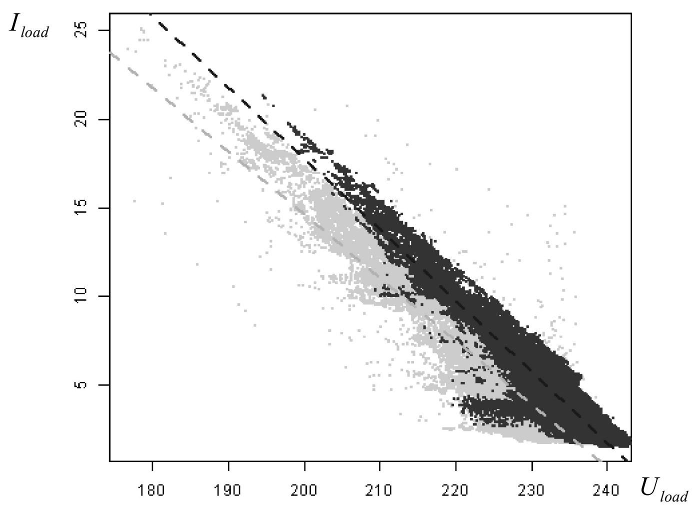

Figure 4. Voltage drop depending on current: light gray – July 2017, dark gray – February 2018.

Line resistance was calculated by adding linear regression lines to the UI scatter plot. For July it was 2.8 Ω, for February – 2.5 Ω. The average temperature difference between the measurement periods was 20 ºC, which was the main source of resistance difference as the temperature coefficient of copper is 0.393% per °C. The theoretical calculations using this temperature coefficient taking winter's 2.5 Ω as 100% will give 2.7 Ω in summer, which is 0.1 Ω less than the data obtained from measurement statistics shows. As it can be seen from Table 2, the resistance increase results in a increase of compensation energy $E_{comp(1)}$ necessary to keep the load side voltage within limits. Interesting to note, that seasonal effect has significant impact on necessary compensation energy. In winter $E_{comp(1)}$ is decreased by 42% for -5% limit and more than 90% for -15% limit.

In the case of the current limiting scenario (Table 3, 5 A row is highlighted as actual inverter setting in grid support test) the tendency is the same: when increasing the current limit from the grid, thus decrease the necessary hourly average compensation energy and in winter the conditions for energy requirements are smaller.

However at smaller current limits from the grid (increased need to compensate energy) the situation is the opposite. This could be explained by current measurement errors at smaller loads and by differences in load scenarios between winter and summer.

Table 2. Allowable load voltage *Uload* variation, percent of time, when the limit is exceeded and calculated energy necessary to compensate voltage variations during all period *Ecomp*(1) and hourly average *Ecomp*(1)avg

K_{Utol}, %	U_{min}, V	U_{max}, V	K_{U-}, %	K_{U+}, %	$E_{comp(1)}$, kWh	$E_{comp(1)}^{avg}$, kWh
July 5–10, 2017 (120 hours)						
5	218.5	241.5	7.92	0.00	3.942	0.033
7	213.9	246.1	5.43	0.00	3.152	0.026
10	207.0	253.0	2.09	0.00	1.666	0.014
15	195.5	264.5	0.29	0.00	0.357	0.003
February 2–10, 2018 (250 hours)						
5	218.5	241.5	5.19	1.34	5.123	0.020
7	213.9	246.1	1.65	0.00	2.192	0.009
10	207.0	253.0	0.32	0.00	0.594	0.002
15	195.5	264.5	0.00	0.00	0.008	0.000

Nevertheless, this can serve as an additional argument for the successful use of photovoltaic microgeneration for voltage loss compensation in distribution grids. As in Northern Europe, the conditions available to produce energy between seasons vary around yearly average from -95% in winter to 110% in summer (Šúri et al., 2007).

The measurement results with a grid support inverter installed are presented in Figs 5 and 6. The inverter was configured to operate in a grid support mode with a current limit from grid 5 A. The value was chosen graphically from the UI scatter plot (Fig. 4) for a nominal voltage of 230 V.

Table 3. Compensation energy calculation results for grid current limiting scenario during all period $E_{comp(2)}$ and hourly average $E_{comp(2)}^{avg}$

Grid limiting current *I'*, A	July 5-10, 2017 (120 hours)		February 2-10, 2018 (250 hours)	
	$E_{comp(2)}$, kWh	$E_{comp(2)}^{avg}$, kWh	$E_{comp(2)}$, kWh	$E_{comp(2)}^{avg}$, kWh
3	27.589	0.230	82.046	0.328
5	**15.995**	**0.133**	**38.659**	**0.155**
7	9.964	0.083	20.739	0.083
10	3.911	0.033	7.058	0.028

It can be clearly seen from the time series and voltage histogram, that -15% and -10% limits are met in this case (Fig. 5). The UI scatter plot (Fig. 6) in its turn shows a non-linear behavior as the voltage drop on the distribution line is mitigated by the inverter.

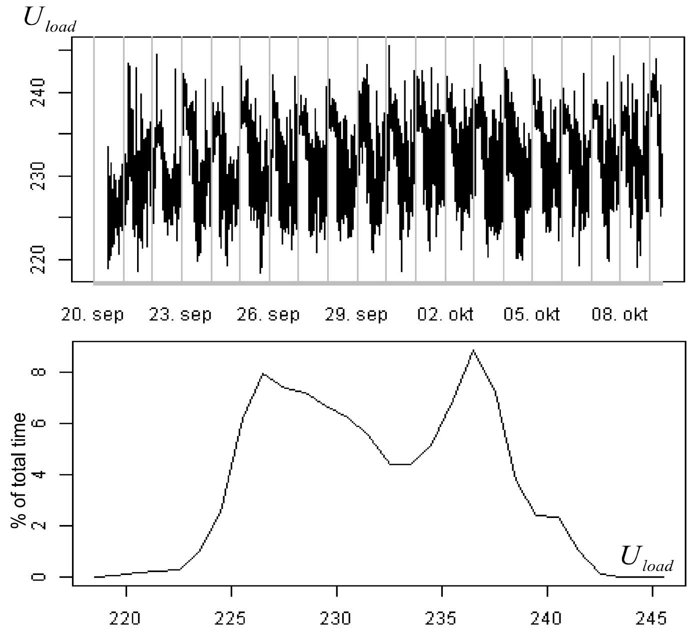

Figure 5. Load voltage time series and histogram of measurements after installation of grid support inverter.

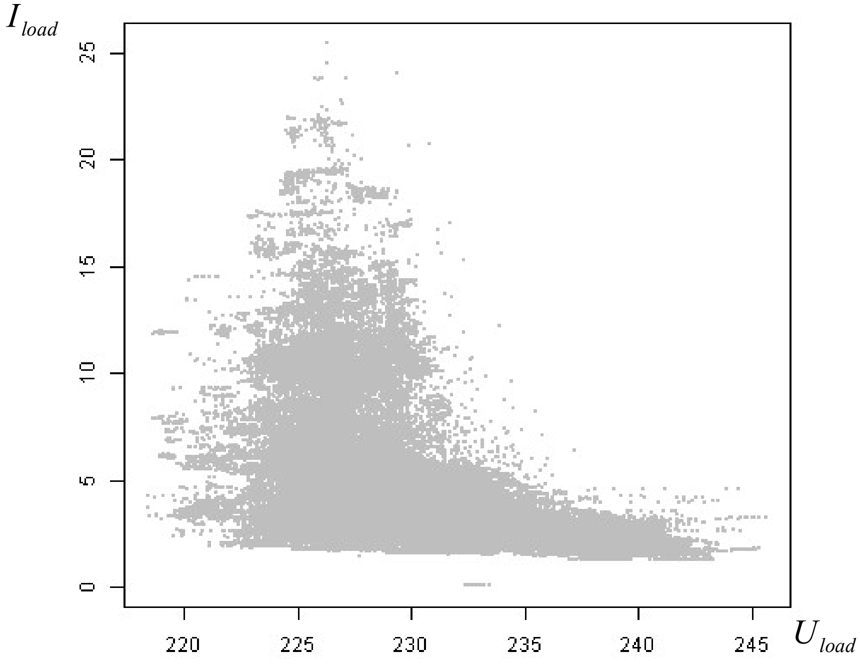

Figure 6. Voltage drop depending on current after installation of the grid support inverter.

The dynamics of energy drawn from grid and fed to the load as well as energy used to charge the battery and the energy taken from the battery during the measurement period are given in Fig. 7. The overall efficiency of the system was calculated from total energies (E_{load}/E_{grid}) and was 89%. It is affected by the inverter efficiency, the battery and it's charger's efficiency. The battery efficiency (E_{dich}/E_{ch}) was 63%. As the battery is the main source of power loss (affected by discharge rate and depth, age and temperature), the total system efficiency will increase if the battery usage is minimized.

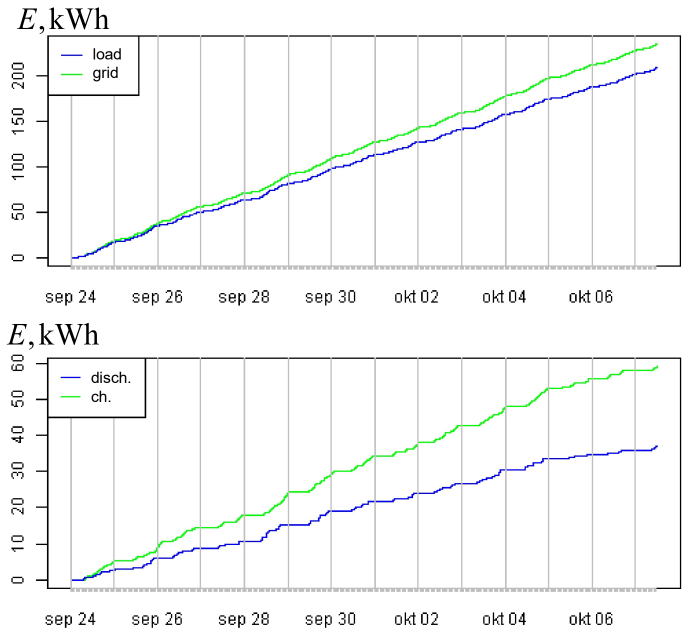

Figure 7. Cumulative charts of energy taken from the grid and supplied to the load (top) and battery charge and discharge energy (bottom).

The total energy taken from the batteries during the 370 hour test period was 36.81 kWh. It resulted in an hourly average of 0.099 kWh of grid compensation energy. It was smaller than the theoretically calculated hourly average of 0.133 kWh in summer conditions (see Table 3).

CONCLUSIONS

Adding a grid support inverter resulted in voltage levels above the -5% limit of nominal voltage in all measurements in an 370 hour period, which fully meets the standard requirements.

The overall efficiency of the GS7048E grid support inverter was 89 %, but the efficiency of the batteries was 63 %.

A grid support inverter can be used from a technical point of view on long distribution lines to increase the available power and from an economical point of view to decrease the necessary grid connection current, when high power consumers are used only occasionally.

The decrease of losses in the winter season due to changes of ambient temperature can serve as an additional factor for the successful use of photovoltaic microgeneration for voltage loss compensation in distribution grids. In Northern Europe, the conditions for PV output between seasons can vary significantly, but the necessary grid support energy to keep the voltage within limits for typical a household consumer in winter's negative temperatures can be significantly smaller.

Further research at this point can be conducted in two main directions: reliability of the system in winter conditions and use of short-term storage technologies (e.g. supercapacitor banks) to extend the lifespan of chemical batteries.

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