Electrical Energy Storage Elements in Fuel-Cell-Based Decentralized Energy Generation

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***Abstract*— A main property of a fuel cell is its comparatively long start-up time, its slow response to load changes and shut-down. If a fuel-cell is used as generator in decentralized energy generation to operate a grid in island or emergency power mode, the required load power - this includes active and reactive power - has to be delivered at all times. In order to meet this demand under island and emergency power modes electrical energy buffers have to be integrated into the decentralized energy generator. These buffers can now also be used for smoothing the power flow and providing active power when connected to the grid.**

Keywords: Decentralized Energy Generation, battery, storage, fuel cell, island grid, UPS

I. Introduction

When a grid is fed solely by decentralized energy generators the configuration can be considered as island grid [1]. Load changes must be provided by the energy generator without delay. In case a fuel cell is the source of the electric energy the decentralized generator will not be able to cover rapid load variations without an electric energy storage element. Therefore a storage element e.g. a battery has to be introduced into the generator system. With this storage it becomes possible to deliver the required power differences between the instantaneously generated power from the fuel cell and the power required in the grid without delay. The main focus in this paper is on various load scenarios, a concrete characteristic of a real fuel cell and deliberately occurring power failures in order to determine the required capacity of the storage element.

II. Modeling of Power Flow

The regarded power system as depicted in *Figure 1* consists of a fuel cell and a battery as power sources. For decentralized energy generation the fuel cell can remain permanently turned on. As long as the fuel cell power is greater or equal the grid power the grid power is delivered by the fuel cell. If the grid power is greater than the fuel cell power the differential power is delivered by the battery. If the fuel cell power is greater than the grid power the battery will be charged or otherwise the fuel cell power must be reduced.

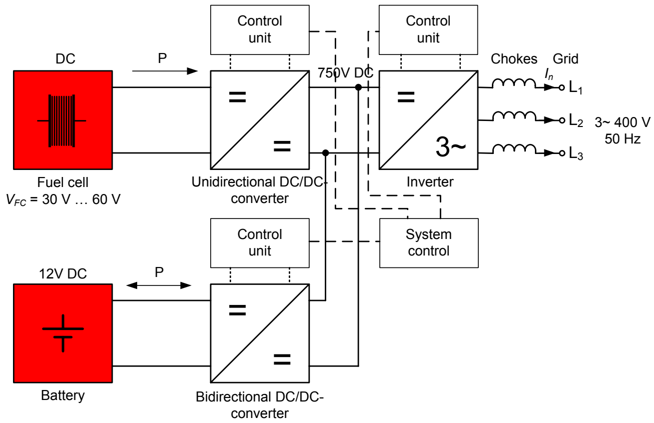

Figure 1. Decentralized Power System (overview)

Another option is the operation as uninterruptable power supply (UPS) that uses a fuel cell and a battery as electric power sources. UPS with fuel cell but without battery as electric energy source are possible [2]. However, in order to ensure very short start-up delays the maximum possible electric power is only used to a fraction. The reason is that an almost instant start-up to about one tenth of the maximum power of a PEM fuel cell is possible without affecting the lifetime. If however the full maximum power of the fuel cell is required start-up takes much more time. As a consequence a battery is required in the system. This operation mode is investigated here.

The start-up of a fuel cell can be divided into different power levels with different durations. The explored fuel cell uses three power levels for reaching a thermally stable operating point [cf. Acknowledgment]. A measured start-up is shown in *Figure 2*. This start-up routine is implemented in a laboratory fuel cell test setup-up based on a low temperature PEM with a maximum electric power of 5.2 kW. This start-up is also the basis for further investigations when using this fuel cell with this start-up in decentralized energy generation. Rather slow start-ups help to extend the life-time of a fuel cell power generating system. Other start-up routines are possible.

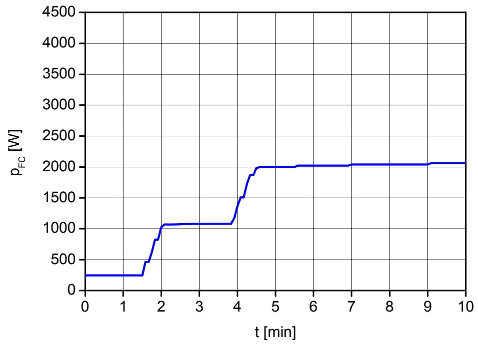

Figure 2. Start-up of a 5.2 kW LT PEM fuel cell to a thermal stable operating point at 2.06 kW

An overview over the considered decentralized power generation is shown in *Figure 3*. The three power sources/sinks are

- grid
- decentralized power generator and
- load which represents the subnetwork that can be fed either by the grid or by the decentralized power generator.

The switch "Grid connection/Island grid" allows operation either in parallel with mains or isolated operation (island mode).

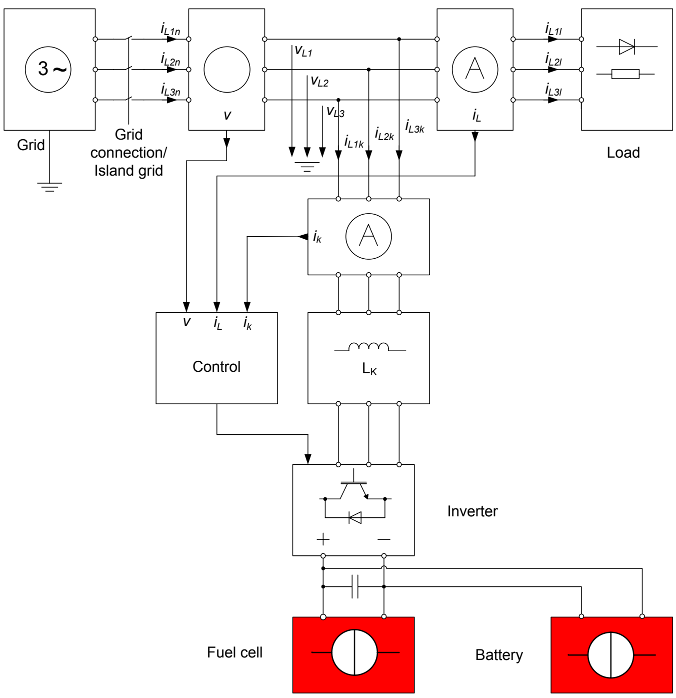

Figure 3. Decentralized power system (model)

A system model was established in Matlab. It is shown in *Figure 4*. This model is primarily based on instantaneous power *p(t)*, i.e. the power flow between fuel cell p_{FC}, battery p_B, and load *pL* (grid and/or the subnetwork) is modeled.

$$p_B(t) = p_L(t) - p_{FC}(t) \qquad (1)$$

The AC power which is the sum of grid power p_G and subnetwork p_{SN} power is labeled as p_L.

$$p_L(t) = p_G(t) + p_{SN}(t) \qquad (2)$$

In order to evaluate the system behavior static and start-up properties of fuel cells were inserted into the Matlab system model. The default system condition in UPS mode is fuel cell off and battery in the state of charged or fully charged.

In order to evaluate the system behavior grid failures at various points in time over different periods of time were simulated. The moment a power failure occurs the system switches into power delivery mode. The battery instantly delivers the required power while the fuel cell starts up according to its start-up waveforms, cf. *Figure 2*. The waveforms used in this simulation were used to demonstrate the general nature of this behavior. While the fuel cell power $p_{FC}(t)$ rises, the required battery power $p_B(t)$ declines if the load power $p_L(t)$ remains constant. Otherwise the power difference changes accordingly.

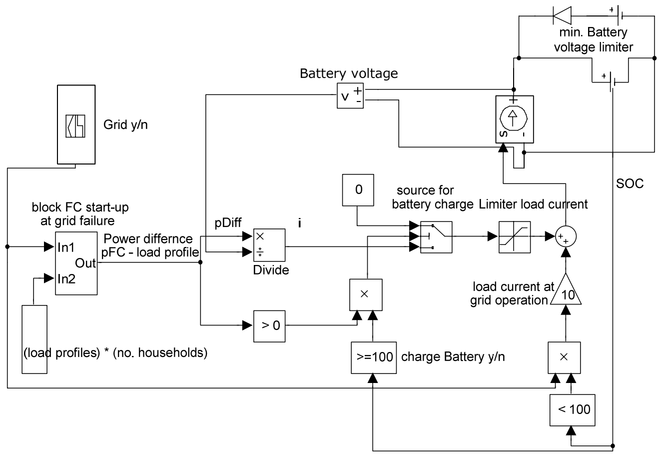

Figure 4. Dynamic Matlab model of the decentralized power system comprising fuel cell and battery

When the power difference *Δp* is positive the battery is charged with the power difference *Δp*.

$$\Delta p(t) = p_{FC}(t) - p_L(t) \qquad (3)$$

$$p_B(t) = \Delta p(t) \qquad (4)$$

After grid power is restored the fuel cell is turned off again. A following power failure leads to the same start-up procedure for the fuel cell.

Simulations have been used to determine the required battery capacity for specific load scenarios. During normal grid operation the battery is charged up to its full capacity. During emergency power mode the battery can be charged if the required grid power greater than the fuel cell power, cf. (2).

Once the battery is fully charged and the grid power is less than the fuel cell power the full cell power can be reduced or if there are only small amounts of energy surpluses then they can be dissipated.

A start-up commences with the query whether or not the electric grid is available or not. This operation is signaled through the block “Grid y/n?”. Based on that answer UPS-mode is either set active or not active. Further, if the grid is available the state of charge (SOC) of the battery is considered. Unless the SOC is 100% the battery will be charged with power from the grid. Otherwise the battery charge changes to trickle charging or off-state.

If the grid is not present the fuel cell is started up while the power difference is taken from the battery.

The considered load scenarios are UPS-mode with fuel cell start-up, UPS-mode under permanent fuel cell operation for selected standardized load profiles (VDI 4655). Two averaged load scenarios for one household (consumer) are shown over a week in summer and in winter as depicted in *Figures 5* and *6*. Especially with only a few consumers connected to the subnetwork this curve does not reflect the true behavior of individual customers. Greater load fluctuations must be considered in such cases.

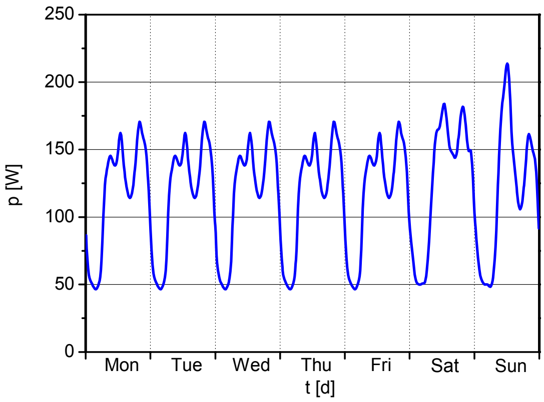

Figure 5. Load profile $p_L(t)$ for one household in summer

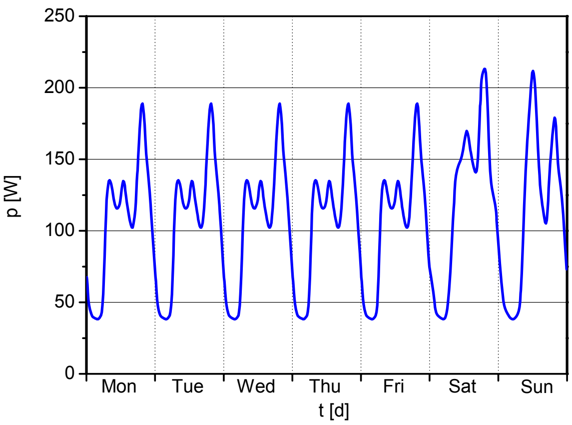

Figure 6. Load profile $p_L(t)$ for one household in winter

III. GRID FAILURES

Power disturbances are classified as interruptions, sags, swells, long duration variations, impulsive and oscillatory transients harmonic distortion, voltage fluctuations and noise [3]. It depends on the load and the amount of stored energy how long normal grid operation can be maintained. In any case longer times of operation require larger electrical storages.

With the established model longer interruptions up to permanent island mode can be investigated. The main focus is on the guarded start-up of the fuel cell and therefore the bridging of the power difference between the power required from the grid and the currently produced power by the fuel cell.

The actually required power from the grid is given by standardized load profiles [4]. This is the reason why power requirements can differ significantly depending on point in time the failure occurs. The load profiles are influenced by the amount of domestic, industrial or off-peak consumers that are involved. Within the simulation power interruptions can be chosen directly by entering start and end.

General guidelines for voltage tolerances were first standardized with the CBEMA (Computer Business Equipment Manufacturers) curve [5,6]. It was later modified to the ITIC (Information Technology Industry Council) curve. One version has now become the ANSI (American National Standards Institute) curve within the IEEE 46, *Figure 7* [7, 8].

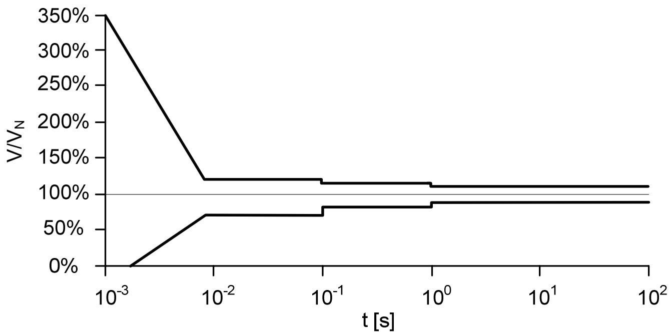

Figure 7. ANSI curve

IV. SUITABILITY OF CONFIGURATIONS, LIMITING QUANTITIES

The fundamental question whether or not a configuration is suitable depends on the available amount of energy for bridging the necessary energy difference. This value is solely dependent on the storage capacity of the battery. However, other physical quantities also require attention.

A. *Battery current I_{bat}*

Battery current can be charging and discharging current. The battery discharge current must be kept below maximum value. This value is set by the power electronic that processes the battery current. The maximum permissible current of the battery is usually much greater.

Accordingly, the charge current is quantified. However, here the condition of the battery can set the lower limit as well as limitations of the power electronics.

B. State of Charge (SOC)

The SOC must not drop below its minimum permissible SOC. Once this value is reached discharge operation must be halted. Otherwise the battery could be harmed.

C. Battery voltage V_{bat}

The battery voltage has a minimum value that is set in consideration with the converter that processes the battery power. Further, there must be taken care of the fact that with a lower SOC the battery voltage drops more at higher power levels than at 100 % SOC. That is the reason why there is a connection between battery power, battery voltage and SOC.

If any of the limiting quantities is exceeded the power flow from the storage is interrupted or reduced. That in turn means the grid can no longer be maintained and fails. Therefore those operating points must be avoided by keeping a reasonable margin to all of the three mentioned quantities.

V. SIMULATION RESULTS

An important question is the initial SOC of the battery at start-up. Usually, it can be considered as fully charged which is also the standard for a regular UPS operation.

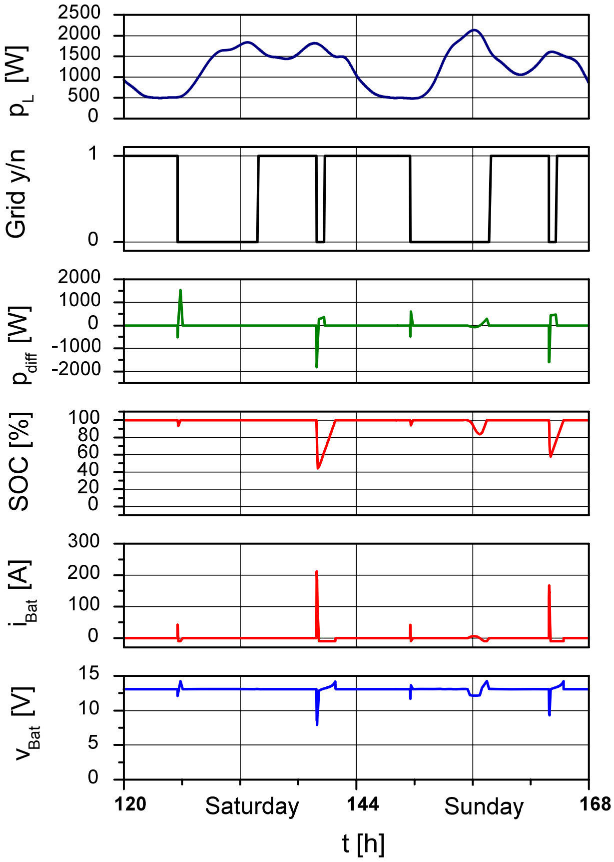

Figure 8. Grid failures with standardized load profile for 10 households (summer) – uninterrupted subnetwork operation is maintained

Three simulation results are presented here. All three simulations are based on a maximum fuel power of 2060 W and a storage capacity of 30 Ah at 12 V nominal voltage.

Figure 8 shows four power failures occurring at the same time of day on Saturday and Sunday. A total of 10 households is connected to the subnetwork. The first and longer power failure requires only a little amount of stored electrical energy from the battery. More energy is required for the second power failure that occurs at a high power demand. Still, it is fully provided by the battery. The SOC reduces to a minimum of about 42% on Saturday and to about 59% on Sunday. This is because the power required during the same time of day on Sunday is lower than on Saturday.

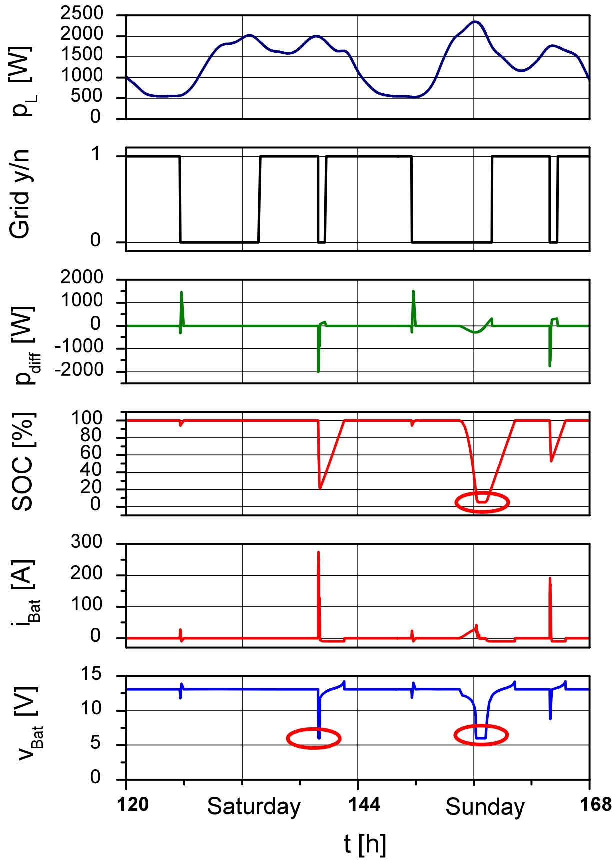

Figure 9. Grid failures with standardized load profile for 11 households (summer) – subnetwork operation is interrupted

The situation changes for 11 households as shown in *Figure 9*. The second power failure on Saturday exceeds the minimum battery voltage value which is set to 6 V. Therefore the delivered power must be reduced at this point which means grid failure because the required power is greater than the delivered one. The simulation continues because of the inserted voltage limiter, cf. *Figure 4*. A current through the diode in the voltage limiter indicates its tripping. The third grid failure occurring on Sunday exceeds two limiting quantities at the same time. The minimum battery voltage is reached and the state of charge approaches a critical value. The battery voltage limiter protects the battery here from a complete discharge. In short, those power interruptions cannot be handled within this design. Either the battery capacity must be increased and/or the fuel cell power must be raised. However, shortening the start-up time does not change the general situation as the next figure illustrates.

The situation when the fuel cell fully delivers the electric power for a subnetwork with 11 households is shown in *Figure 10*. From the moment the requested power exceeds the maximum fuel cell power of 2060 W power from the battery is withdrawn. The peak that surpasses the maximum fuel cell power is long enough to fully discharge the battery. Moreover, it exceeds two limiting quantities minimum battery voltage and SOC. This configuration is not suitable for the considered load scenario. An increase of battery capacity and/or higher maximum fuel cell power would be necessary in this situation.

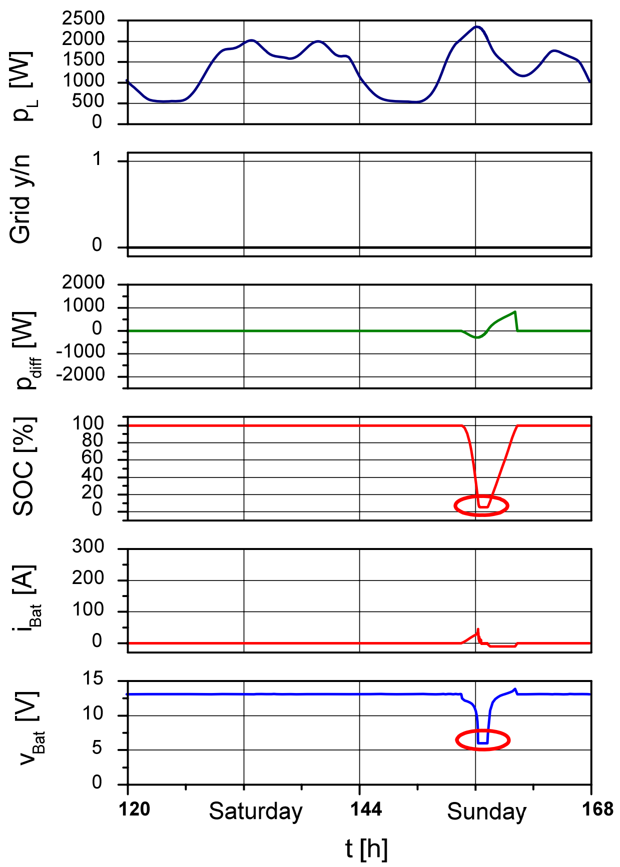

Figure 10. Island operation with standardized load profile for 11 households (summer) – operation is interrupted

VI. Power Factor Correction

For grid operation specific properties of the fuel cell and grid requirements have to be determined. A compensation of reactive power of the fundamental and harmonics can be realized as additional system service [9]. This operation mode is possible as soon as the grid inverter can deliver a greater apparent current than the signed sum of the active currents from the fuel cell and the storage element. Software for this purpose that operates in real time on a DSP-based system has been developed [9].

Figure 11 and 12 show a laboratory decentralized power generator in a simulation and a practical environment as Active Power Filter (APF) in grid operation. The load of the subnetwork comprises a B6U rectifier with resistive load. A full compensation is realized by determining the active power of the load and calculating the mains current consisting only of the active component for it [10]. Now the set value for the inverter current can be determined, which contains exclusively reactive current components and therefore does not cause DC power flow from or to the DC link of the inverter.

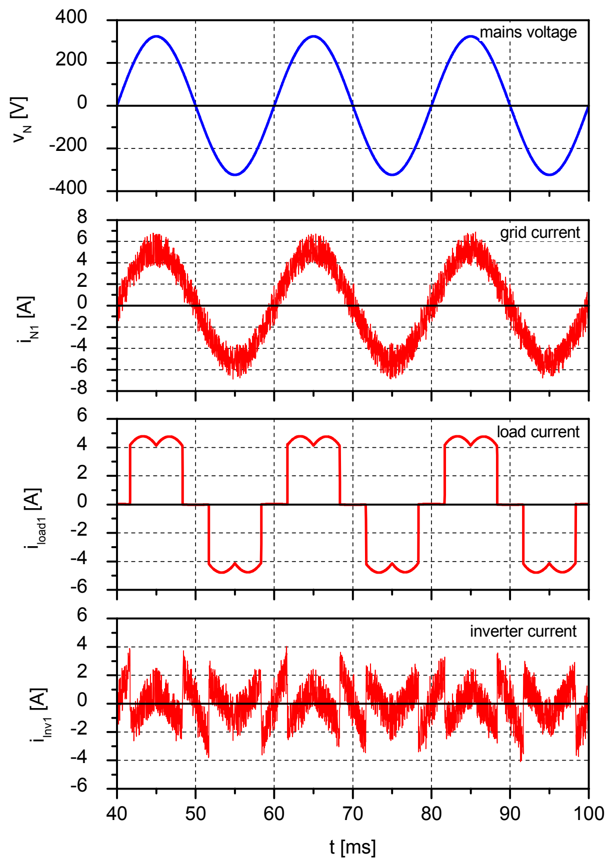

Figure 11. Simulation of power factor correction for a B6U rectification with resistive load, only one phase is shown

A combination of this full compensation with a power feed from the DC link is possible. In that case the total current for the inverter must stay below its maximum value.

Practically the control of the inverter current with its steep slopes sets limits to the harmonic content that can be compensated due to a natural limit that is set by the voltage over the inductors and their inductances.

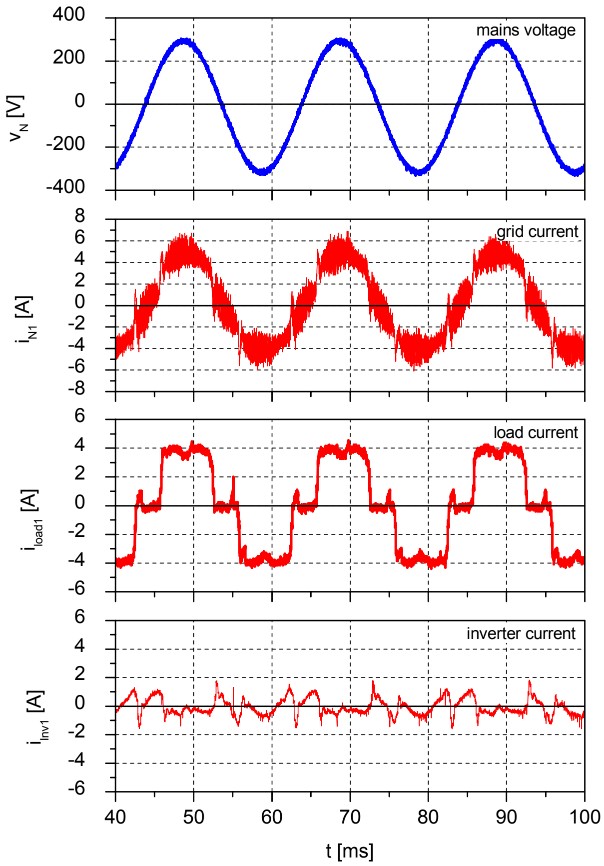

Figure 12. Measurement of power factor correction for a B6U rectification with resistive load, only one phase is shown

VII. Conclusions

Decentralized energy generation can provide active power to maintain grid stability and reactive power for compensation purposes. It can also be used as power supply for island grids and as uninterruptable power supply. Especially the two latter applications require the determination of the control power for maintaining the stability of a subnetwork. The energy difference between the instantaneously delivered power of the fuel cell as the primary energy source and the power necessary for maintaining the subnetwork must be stored in a storage element. The determination and verification of its storage capacity has been addressed in this paper. It was realized by using an authentic start-up routine of a laboratory fuel cell and known standard load profiles. Concrete storage elements considerations are required for further investigations. Apart from capacity considerations further limiting parameters in the decentralized energy generation system must be taken into account, such as maximum battery current, minimum battery voltage, minimum state of charge.

The introduced simulation model provides an evaluation basis for the estimation of the suitability of a given parameter configuration.

The ability to deliver active and reactive power within a short response time can be advantageously used by providing optional system services of decentralized energy generation systems.

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