Test Scenarios and Test Results for the Qualification of PV-Diesel Power Systems and Hybrid Controllers

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Abstract—**PV-Diesel hybrid systems are consisting of different generators and storage systems whose operating behavior must be coordinated in order to reach a stable and secure power supply. In particular the diesel gensets and battery inverters as flexible power generators are the key components of such a system and play an essential role for the system behavior and control. In addition to test procedures for qualifying these components, this paper presents various exemplary results of laboratory tests. Furthermore, first results of system tests and significant influences on the control of such a system are shown.**

Keywords: diesel genset; battery inverter; hybrid system control; test procedures; voltage and frequency response

I. MOTIVATION

Many villages, towns, islands and industrial sites (such as mines) in sun-blessed regions without a (reliable) grid connection are supplied with electrical power from diesel generators. Nowadays, these systems will be complemented by PV systems, in order to reduce fuel consumption and thus to achieve savings in operational costs and a more sustainable and reliable electrical energy supply. Within the framework of the German research project PV-Diesel [1], the interaction of PV systems and diesel generators is investigated with the aim to optimize their joint operation. A major disadvantage of such a PV diesel hybrid system is that, due to the volatile generation of solar power, the diesel generator is all the time necessary to form the local grid and hence it has to run non-stop. Furthermore, the operation of diesel generators usually requires a minimum load to achieve an efficient operation and a long life time. These constraints provide a strong incentive to apply battery storage systems in order to maximize the PV contribution to the local power mix while ensuring a smooth operation of the diesel generator.

To achieve this, a hybrid controller is useful to calculate suitable operating strategies for the full hybrid power system and its components. To parametrize this controller it is essential to know important technical characteristics of (at least) its major components. Particularly important issues are for example:

- Characteristics of island and parallel operation
- Ensuring of power quality characteristics with regard to voltage and frequency stability
- Compliance to EMC requirements and protection limitations
- Compliance of the complete hybrid power system to local grid-codes (in case of a present grid)

For these reasons, the technical design of PV diesel hybrid system setups based on individual components requires a high degree of engineering effort and experience. However, if technical characteristics and essential parameters of the applied components are known by means of well-defined tests, both the technical design and the parameterization of the hybrid controller can be implemented via standardized design methods and thus the engineering effort can be significantly reduced.

In this paper, the test scenarios and results of different laboratory measurements performed at Fraunhofer IEE SysTec with different PV diesel hybrid system configurations in the 100 kW class are presented and the consequences for the hybrid system control are examined.

II. TEST PROCEDURES

A. Objectives and test environment

Main objectives of the described laboratory tests are the qualification of PV diesel hybrid system components and the identification of system and component characteristics which are needed to parametrize the hybrid controller. Here, a major focus is set on frequency- and voltage control of battery inverters and diesel gensets. The investigations include island operation with symmetrical and non-symmetrical RLC loads as well as on transitions between grid-parallel and island operation. For example the behavior of different generators (diesel genset vs. battery inverter) is analyzed in the event of sudden load changes or when operated with external set-point specifications. The tests can be divided into the following divisions:

- grid-parallel operation with external power set-points
- system voltage- and frequency response to dynamic load changes in island operation
- dynamic transitions between grid-parallel and island operation

Figure 1 schematically shows the test setup of the described investigations.

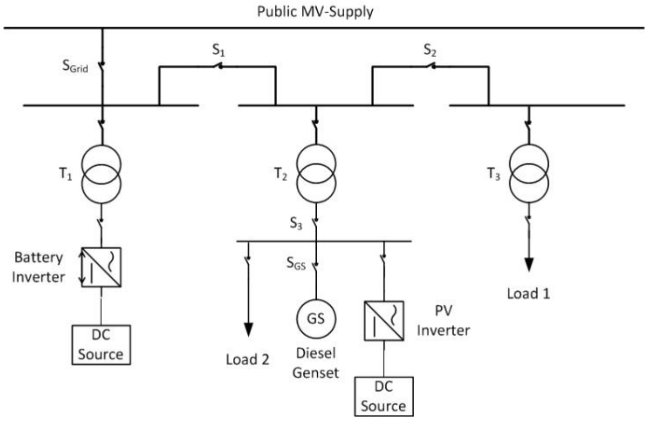

FIGURE 1: SCHEMATIC OF SETUP FOR TESTING OF PV DIESEL HYBRID SYSTEM COMPONENTS

Important components of this test setup are [2]:

- LV/MV Power Transformers T_1, T_2 and T_3
- Controllable circuit breakers S_{Grid}, S_1, S_2 and S_3
- LV RLC-Loads Load 1 and Load 2 (Each 200 kW (ohmic) and 100 kvar (inductive/capacitive))
- Battery inverter (2200kW) powered by a uni-directional DC-Source
- Diesel Genset (200 kVA)
- PV inverter (100kVA)

B. *Test of grid-parallel operation with external setpoints*

The tests of grid-parallel operation with external set-points are used in particular to identify the operational ranges with regard to active and reactive power output (PQ-Diagram) and the accuracy and response time when operated with external power set-points from a central control unit. The required test procedures are already sufficiently defined and can be transferred from the German technical guideline for grid code compliance testing in MV/HV/EHV networks [3].

To analyze the active and reactive-power ranges the interface to the system control of the Device Under Test (DUT) is used to specify set-points. The positive sequence of active and reactive power is calculated from three-phase measurements of current and voltage at the mains of the device. The results are plotted in the PQ-diagram and compared to the corresponding set-points. In order to assess how fast and how exactly the DUT can follow changes in the set-points the accuracy and response time is tested with two different procedures which differ in the deviation of the set-point specifications (Partial Test 1: $\Delta P_{Setpoint} = 0.1 P_{rated}$; Partial Test 2: $\Delta P_{Setpoint} = 0.5 P_{rated}$). Here, the accuracy and response time is calculated from 200ms averages of the active and reactive power output with respect to a +/-5% tolerance band around the specified set-points.

C. *Test of island operation with local control*

The tests in this chapter serve in particular to study the static and dynamic frequency and voltage stability in island operation. For this purpose, the DUT behavior during dynamic load changes and the resulting system voltage and frequency time series are analyzed. For the investigations presented in this work, a test procedure with different load steps in island operation was designed. This procedure is subdivided into a part with symmetrical and a part with unbalanced changes of the load. The evaluation of the system frequency and voltage is based on the standard ISO 8528-5 [4] with the objective to examine how fast and how exactly set-point deviations are compensated by the DUT.

To determine the load steps for the test procedure the following definitions are used:

P_R – Rated active power output of the DUT

P_M – Mean value between the maximum and minimum possible continuous active power output of the DUT

Q_M – Reactive power output of the DUT that leads to a $\cos(\varphi)$ of 0.95 (inductive) for $P_{DUT} = P_M$

Q_H – Reactive power output of the DUT that leads to a $\cos(\varphi)$ of 0.9 (inductive) for $P_{DUT} = P_M + 0.2 * P_R$

In the initial situation of the test, the DUT works in voltage controlled mode (VSI), with a medium load:

$$P_{DUT} = P_M$$

$$\cos(\varphi)_{DUT} = \cos(\varphi)_M = 0.95$$

This required initial situation is achieved by suitably setting the RLC loads. Based on this initial situation the system response is tested for different variations of the complex island load (see Table I and Table II). For each step the operating point is changed by switching on/off load steps after steady state conditions are reached for system frequency and system voltage.

TABLE I. OPERATING POINTS FOR STABILITY TESTS OF THE DIESEL GENSET

Operating Point	Setting of RLC Load		
	P *Active Power*	***Q*** *Reactive Power*	***cos(φ)*** *Power Factor*
1	P_M	Q_M	0.95 (inductive)
2	P_M+0.2*P_R	Q_H	0.9 (inductive)
3	P_M	Q_H	
4	P_M-0.2*P_R	Q_M	
5	P_M	Q_M	0.95 (inductive)
6	P_M	Q_M/2	
7	P_M	Q_M	0.95 (inductive)

Table I contains the operating points for the stability tests with symmetrical loads. These are chosen in a way that the following aspects are covered by the test procedure:

- Switching of a complex load (Point 2 and Point 4)
- Switching of a resistive load (Point 3 and Point 5)
- Switching of an inductive load (resp. capacitive load) (Point 6 and Point 7)

The test points in Table II are intended to investigate the DUTs operational range at unbalanced load. Starting from stationary island operation with P_M and Q_M resistive load steps are implemented on one phase while the inductive load remains unchanged. During the test the load is increased and reduced on a single phase and then again returned to the starting conditions. Similar to the test described before the operating points are changed after steady state conditions for system frequency and system voltage are reached.

TABLE II. OPERATING POINTS FOR STABILITY TESTS WITH UNBALANCED LOAD

Operating Point	Setting of RLC Load		
	P – L1* *Active Power* *Phase 1	***P – L2, L3* *Active Power* *Phase 2 and 3***	***Q – L1, L2, L3* *Reactive Power* *Phase 1, 2 and 3***
1	$P_M/3$	$P_M/3$	Q_M
2	$0.8*P_M$	$P_M/3$	Q_M
3	P_M	$P_M/3$	Q_M
4	$1.2*P_M$	$P_M/3$	Q_M
5	P_M	$P_M/3$	Q_M

Figure 2 shows the PQ diagram of the diesel genset MAB SEA200DE including the operational limitations. In this figure, the red lines indicate the limitations due to minimum and maximum power of the diesel engine. These form the basis for calculating the mean effective power P_M. The individual operating points to be measured according to Table I are shown in purple.

The operating points selected in Table I and Table II were chosen in a way, that they can be flexible applied to different diesel gensets and other types of DER (Distributed Energy Ressources) used in PV diesel hybrid systems. In many designs of battery inverters, the definition of P_M should lead to an initial operating point at the boundary between charging and discharging mode, so that the choice of operating points in Table I and II leads to changes in the operation mode in the course of testing. In the context of the investigations presented here, the procedure could not be completely applied to the battery inverter. The reasons for this are in particular due to the very high nominal power of the inverter compared to the available test loads and in the operation of the inverter with means of a unidirectional dc-source which does not allow any investigations on the charging operation.

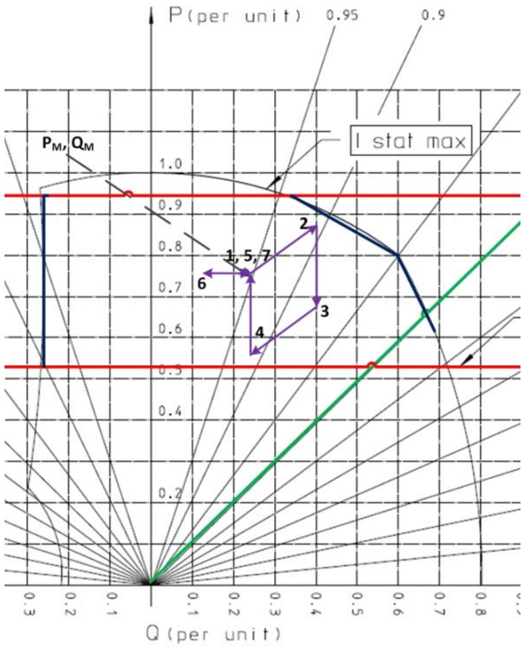

FIGURE 2: THE OPERATION POINTS OF TABLE I IN AN EXEMPLARY PQ DIAGRAM OF A DIESEL GENSET

D. *Dynamic Island Operation*

These tests investigate the dynamic transitions between island and grid-parallel operation as well as the DUTs black-start capability. A particular focus is set on the voltage and frequency control of the generator. Three test scenarios are defined:

- Scenario 1: Load transfer and switching to island operation
- Scenario 2: Black start and subsequent supply of island loads
- Scenario 3: Transition to grid-parallel operation after grid-recovery

The choice of these scenarios covers all transitions happening in PV diesel hybrid systems which are operated in a microgrid structure that is able to be operated grid-parallel as well as in island mode.

III. COMPONENT TESTING

In this chapter selected results of the test procedure application are presented. The following devices were used as DUT:

- MAB SEA 200 DE (Diesel Genset, 200 kVA)
  - Motor: Deutz BF 6M 1013 FC
  - Generator: Marelli MJB 250 LA/4
  - Genset Control: DEIF AGC 233
- SMA Sunny Central Storage 2200 (Battery Inverter, 2200 kVA)
  - Voltage controlled inverter (VSI)

A. *Diesel Genset*

Figure 3 and Figure 4 show active power, reactive power, frequency and voltage during the test of island operation with local control. It can be seen how changes in the island load affect the system frequency and voltage and how they are brought back to their set-point by the speed and voltage controllers of the diesel genset. For a more detailed analysis of these processes selected transitions are shown in more detail below in Figures 5-8.

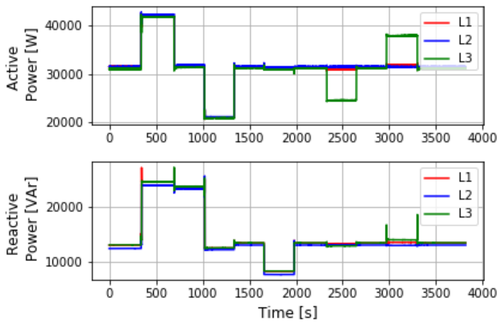

FIGURE 3: ACTIVE AND REACTIVE POWER DURING THE DIESEL GENSET TESTS ACCORDING TO TABLE I AND TABLE II

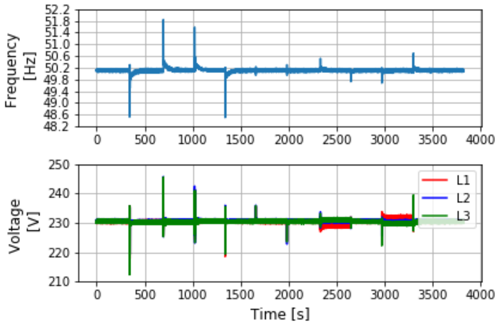

Figure 4: Voltage and Frequency during the DIESEL GENSET tests according to Table I and Table II

Figure 5 shows active and reactive power during the transition from operating point 2 to operating point 3 where the active power of the island loads is decreased on all three phases. In Figure 6 it can be clearly seen how these active power variation directly affects the system frequency and voltage. After an almost instantaneous reaction of the diesel genset to the frequency change the generator speed is slowly adjusted, so that the frequency reaches its set-point again after 30-40 seconds.

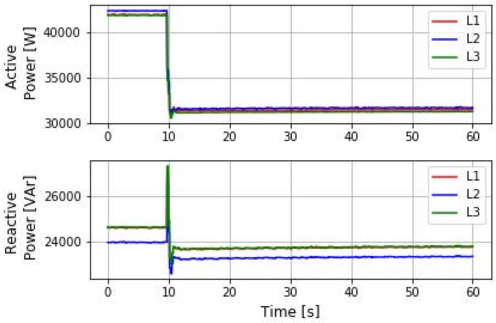

Figure 5: Active and reactive power of the Diesel Genset during transition from Operating Point 2 to operating point 3 from Table I

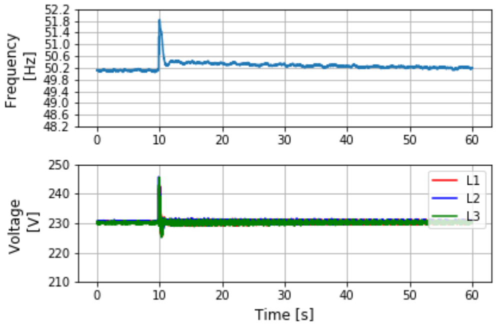

Figure 6: Frequency and voltage of the Diesel Genset during transition from Operating Point 2 to operating point 3 ofTable I

Figure 7 and Figure 8 show the measurements during transition from operating point 5 to operating point 6 where the reactive power of the island loads is decreased. It becomes obvious, that compared to Figure 6, the effects on system voltage are compensated within a few seconds by the voltage regulator of the diesel genset.

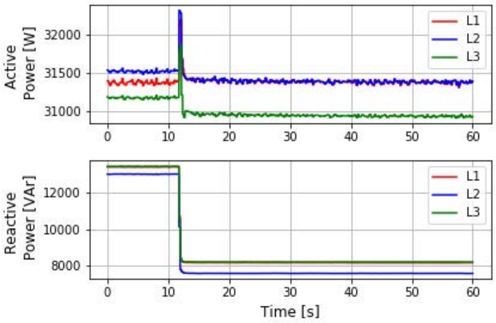

Figure 7: Active and reactive power of the Diesel Genset during transition from Operating Point 5 to operating point 6 of Table I

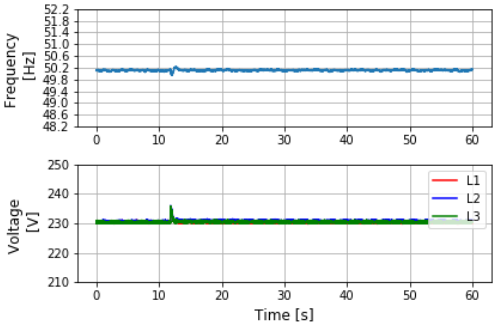

Figure 8: Frequency and voltage of the Diesel Genset during transition from Operating Point 5 to operating point 6 of Table I

The measurements of exemplary transitions from grid-parallel to island mode of the diesel genset are depicted in Figure 9. Shown there are active power, frequency and voltage at a transition to island operation and later resynchronization to the public MV grid. It can be clearly seen that the voltage and frequency fluctuations in island operation are higher than in grid-parallel mode, but a stable supply of the island loads is always provided by the diesel genset.

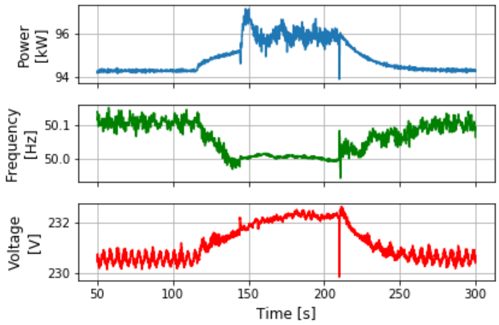

Figure 9: Active Power, Frequency and voltage of the DIESEL genset during transition from Island Mode to Grid-Parallel Mode and back to Island Mode

B. Battery Inverter

In this section the behavior of the battery inverter in island operation with different droops of the frequency control is shown. Figure 10 and Figure 11 show the behavior with a droop setting of 1 Hz per rated power while for the tests in Figure 12 and Figure 13 a droop setting of 2 Hz per rated power has been applied. As can be seen in Figure 1, the island loads are to a certain degree both electrically and geographically distant from the inverter and are each connected to the LV side of a power transformer which is supplied by a medium-voltage network formed by the battery inverter.

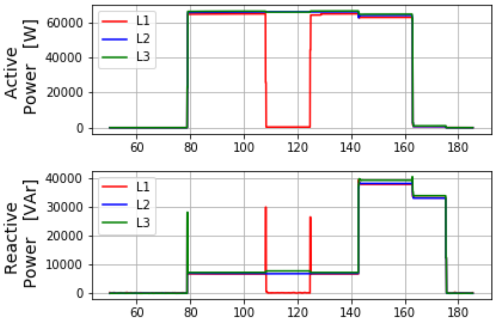

FIGURE 10: ACTIVE AND REACTIVE POWER DURING THE BATTERY INVERTER TESTS ACCORDING TO TABLE I WITH A DROOP SETTING OF 1 HZ

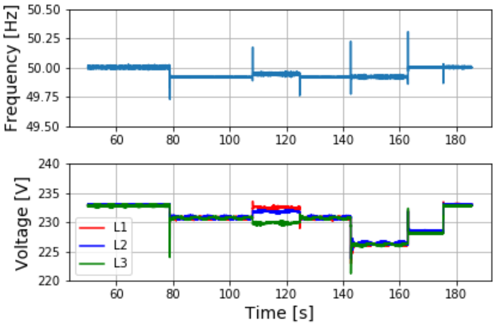

FIGURE 11: SYSTEM FREQUENCY AND VOLTAGE DURING THE BATTERY INVERTER TESTS ACCORDING TO TABLE I WITH A DROOP SETTING OF 1 HZ

Compared to the behavior of the diesel genset it has to be noticed, that frequency and voltage do not return to their nominal values by the battery inverter. These stationary deviations show a dependency on the droop settings of the battery inverter according to its design and increase as the droop is changed e.g. from 1 Hz to 2 Hz per rated power. System frequency and voltage would be readjusted to its nominal values by means of an hybrid system controller (if available).

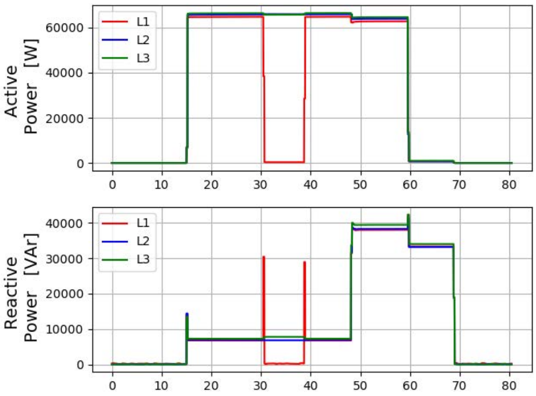

FIGURE 12: ACTIVE AND REACTIVE POWER DURING THE BATTERY INVERTER TESTS ACCORDING TO TABLE I WITH A DROOP SETTING OF 2 HZ

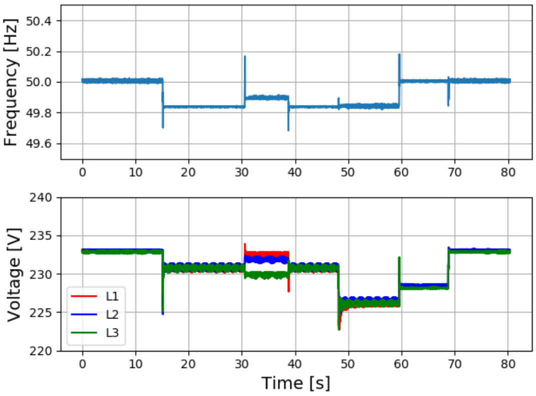

FIGURE 13: FREQUENCY AND VOLTAGE DURING THE BATTERY INVERTER TESTS ACCORDING TO TABLE I WITH A DROOP SETTING OF 2 HZ

To compare the temporal behavior of the diesel genset and the battery inverter Figure 14 and Figure 15 show the measurements with a simultaneous change in the resistive and inductive load in the island. Again, it can be seen that a stationary deviation of frequency and voltage remains during the supply with the battery inverter. Anyhow, the frequency response of the inverter is completed after few milliseconds and thus the inverter shows a much faster control behavior. This result should be taken in account for the parametrization of the hybrid controller.

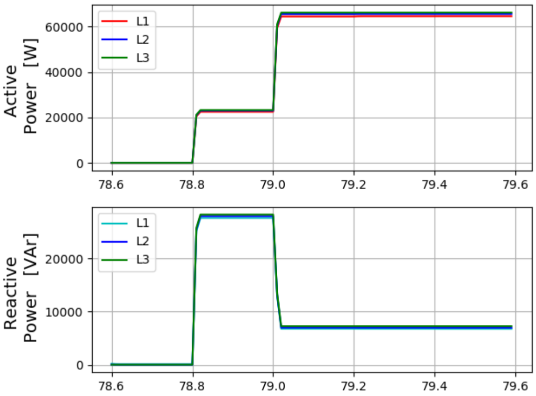

FIGURE 14: ACTIVE AND REACTIVE POWER OF THE BATTERY INVERTER DURING A SIMULTANEOUS INCREASE OF ACTIVE AND REACTIVE ISLAND LOAD WITH A DROOP SETTING OF 1 HZ

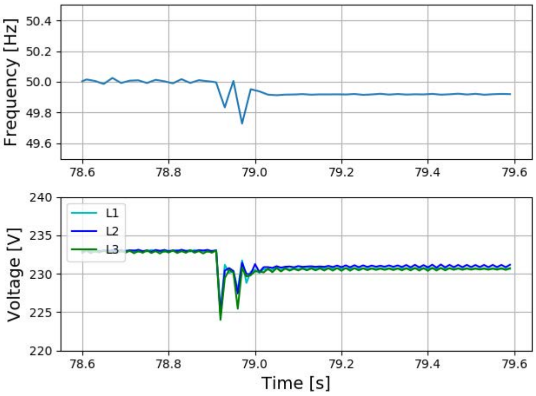

FIGURE 15: FREQUENCY AND VOLTAGE OF THE BATTERY INVERTER DURING A SIMULTANEOUS INCREASE OF ACTIVE AND REACTIVE ISLAND LOAD WITH A DROOP SETTING OF 1 HZ

IV. System Tests

As a final investigation the joint operation of the battery inverter and the diesel genset in island mode was tested. For this the battery inverter was parametrized with a droop setting of 1 Hz per rated power while the diesel is kept at constant active power output of 160 kW and constant power factor of 0.95.

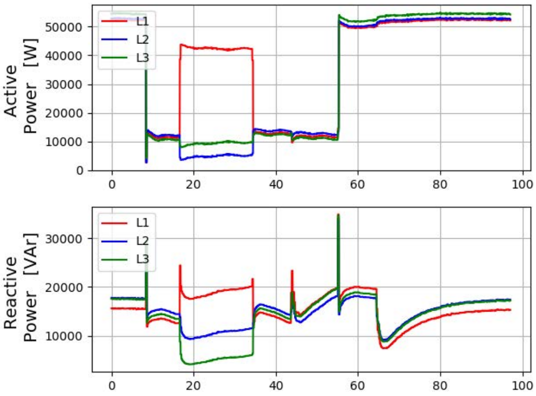

Figure 16: Active and reactive power during a hybrid system test with diesel genset, battery inverter and island loads

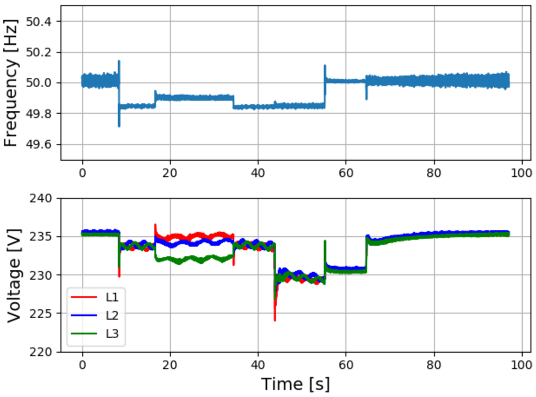

Figure 17: Frequency and Voltage during a hybrid system test with diesel genset, battery inverter and island loads

Figure 16 and Figure 17 exemplary show active and reactive power, frequency and voltage during one of these tests. Here, different load steps have been carried out (see Figure 16) to analyze the system behavior. Since this tests were carried out without using a separate hybrid system controller again stationary deviations of the frequency and voltage remain in the system. However, it becomes clear, that even without this controller a stable system operation is achieved. This is, for example, of high relevance if a failure of the controller can happen during operation.

V. Outlook

After the component tests and system tests without a separate hybrid system controller shown in this document, comparable system tests involving such a controller are planned in future. Furthermore, various tests with modified settings on the diesel genset are important to investigate mutual influences between the active components. Another relevant test scenario is involving solar irradiation curves representing the fluctuating solar generation in order to analyze how the system behaves under variable PV infeeds.

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