VALIDATION OF ADVANCED INTEROPERABILITY FUNCTIONS FOR BATTERY ENERGY STORAGE SYSTEM

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ABSTRACT

Decentralized battery energy storage systems will play a key role for voltage and frequency grid control, especially in future cell-based power systems. It is crucial to validate new individual functions for the purpose of secure and reliable operation. Furthermore, the functions must be tested against reproducibility in laboratory environment encompassing multiple domains and various interfaces. This work validates test procedures and definitions of advanced interoperability functions for BESS by means of laboratory tests including a battery storage setup as the equipment under test (EuT).

INTRODUCTION

Due to a high penetration of renewable energy in the electricity grid, decentralized battery energy storage systems (BESS) will play a key role for voltage and frequency grid control [1]. The provision of ancillary grid support services by grid-connected BESS is already mandatory in several European countries. Qualitative and quantitative aspects of requirements have been increased for regulatory frameworks. Applicable regulatory frameworks for grid connected BESS are mostly referenced to documents for generation units or inverting units with unidirectional power flow.

As BESS are providing ancillary grid services for grid feed-in and grid-import condition, revisions of grid codes are ongoing. For instance, the Italian CEI 0-21 [2], the Californian UL1741 SA [3], the new VDE-AR-N 4105 draft [4] and Australian AS4777.2 [5] explicitly include BESS. The validation of these functions requires new testing procedures and criteria of acceptance. An early harmonization of definitions, functions, parametrization, and the provision of generic testing procedures is beneficial for efficient validation of advanced interoperability functions of BESS. A first approach is done with the "SIRFN Draft Test Protocol for Advanced Battery Energy Storage System Interoperability Functions" [6]. It is based on the IEC/TR-62850-90-[7] function definitions for power converters in distributed energy resources (DER).

The SIRFN draft test protocol provides generic testing procedures for a subset of functions and adopted definitions to meet the requirements of BESS. It may be useful as basis for future technical documents. This work validates testing methods of the "SIRFN Draft Test Protocol for advanced BESS interoperability functions" by means of laboratory tests including a physical BESS. Insights are given on characteristics of new testing procedures and definitions.

ADVANCED FUNCTIONS OF BESS

Advanced interoperability functions are defined as ancillary grid services to stabilize the grid at critical voltage or frequency deviations. The functions are categorized into two types: firstly, autonomous running functions that continuously monitor the grid status and react with provision of active (P) or reactive power (Q), if necessary; secondly, the remote control possibility for external use such as distributed system- or transmission system operators (DSO, TSO). Definitions of functions can be obtained from technical documents such as IEC[7], SunSpec [8], EPRI [9] and national grid codes.

Advanced interoperability functions are described in the function domain and the time domain. The function domain is specified as the relation between independent and dependent variable such as $P(f)$ or $Q(V)$. Power gradients settings or arrays of set points may define this relation. In time domain, delays or power ramps have to be respected according to given timing parametrization. A variety of parametrization and definitions can be found in technical documents, as summed up in Table 1.

Table 1: Overview over different timing parameter

Symbol	Description
t_W	Time window; a specific mode or command is executed randomly.
t_D	Constant time delay; the mode or command is executed.
t_O	Timeout period after which the device reverts to its default operation [7].
t_R	Ramp time for moving from a current to a new operational state. The invocation ramp time only applies during the initial enabling of the mode [10].
t_{REC}	Recovery delay expressing the minimum waiting time during the recovery phase until the device returns to its default operation
$t_{R,PT1}$	Time in seconds to accomplish a change of 95% of a step change in the input value [7].
r_R	Requested ramp rate the device must move from the current set point to the new set point
r_{RI}	Maximum rate at which the output is increased in response to changes of the input variable
r_{RD}	Maximum rate at which the output is reduced in response to changes of the input variable
r_{REC}	Recovery rate which the device maintains after the reentry to default operation again.

Table 2: Timing parameter and related technical documents The '~' Symbol marks that definitions vary to others.

	t_w	t_D	t_O	t_R	t_{REC}	$t_{R,PT1}$	r_R	r_{RI}	r_{RD}	r_{REC}
IEC [7]	✓	✗	✓	✓	✗	✓	✓	✓	✓	✓
SSp [8]	✓	✗	✓	✓	✗	✓	✓	✓	✓	✓
DNP3 [11]	✓	✗	✓	✓	✗	✓	✓	✓	✓	✓
2030.5 [11]	✓	✗	✓	✓	✗	✓	✓	✓	✓	✓
SIRFN [6]	✓	~	✓	~	~	✓	✓	✗	✗	✓
CA [3]	✗	✗	✗	✗	✓	~	~	✓	✗	✓
IT [2]	✗	✓	✗	✗	✓	✓	✗	✗	✗	✓
DE [4]	✗	✗	✗	✗	✗	✓	✗	✗	✗	✓
EU [12,13]	✗	✓	✗	✗	✗	✓	✗	✗	✗	✓

The unit for the time settings 't' is second (s). The ramp rates 'r' are defined as change of power related to the maximum power per second or minute (% $P_{max}\cdot s^{-1}$ or % $I_{max}\cdot s^{-1}$). Some documents refer to current instead of power [10]. The parametrizations linked to the corresponding documents is referenced in Table 2.

TEST SETUP

The test setup is shown in Figure 1. It consists of a 500 kVA grid simulator, a measurement system Yokogawa WT3000 and WT1800, a data acquisition DL850E, and a SCADA system for data visualisation and control purpose. The EuT is a 3-phase 50 kVA inverter from SanREX with a 16.5 kWh battery system.

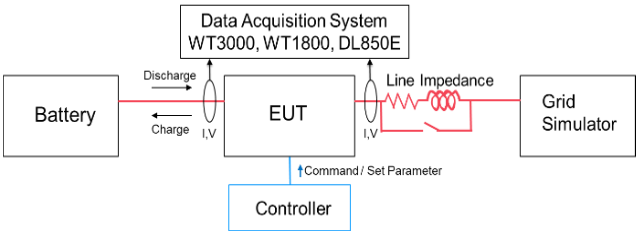

Figure 1: Test setup of the AIST – FREA Smart DER Research Facility

Table 3 contains the advanced interoperability functions, which are tested at the EuT. The name definitions are based on the the SIRFN draft test protocol and the IEC/TR-62850-90-7 technical report.

TEST RESULTS AND INSIGHTS

The advanced interoperability functions are tested both in function and time domain according to the SIRFN Draft Test protocol. The tests shall reveal deficiencies in test procedures and function definitions, or whether proper functionality and accuracy is maintained by the EuT. Automated testing is beneficial due to the high amount of possible combination of different parameter settings [14].
As an initial step, the power capability of the inverter is determined and shown in Figure 2. Because of battery current limitations, the maximum power output is limited to 80% of the inverter capability. The maximum reactive power is limited to 50% of the rated apparent power.

Table 3: Advanced interoperability functions of the EuT

Name	Description	Parameter
INV3	Request power factor	r_R, t_D, t_O
INV4	Request active power	r_R, t_D, t_O
VV13	Request reactive power	r_R, t_D, t_O
VV11	Voltage-var Q(V)	r_R, t_D, t_O
VV12	Voltage-var Q(V)	r_R, t_D, t_O
VV14	Voltage-var Q(V)	t_D, t_O
VW51	Voltage-watt P(V)	t_D, t_O, r_R, r_{REC}
VW52	Voltage-watt P(V)	r_R, t_D, t_O
WP41	Watt-power Factor PF(P)	r_R, t_D, t_O
WP42	Watt-power Factor PF(P)	r_R, t_D, t_O
FW21	Frequency-watt P(f)	t_O,r_R, r_{REC},
FW22	Frequency-watt P(f)	t_D, t_O, t_{REC}, r_R, r_{REC}

The function domain is used to describe the behavior of the BESS as the relation between an independent input and the dependent output variable. Tests in the function domain determine the accuracy of the device which tries to follow the reference curve perfectly matched. The SIRFN draft test protocol does not include procedures for the watt-power factor (WP41, WP42) and voltage-watt functions (VW51, VW52). Thus, given procedures are adopted subsequently. This work shows test results for FW22 and VW52 in the functions domain. The FW22 test result is shown in Figure 3. The EuT shows a hysteresis when returning from high/low frequencies to nominal frequency. It shows reverse power flow operation mode from charging (negative power) to discharging (positive power), and vice versa. The measurement points marked with starpoints show a perfect match with the reference curves, therefore accurate and stable operation is provided.
Test results of the VW52 domain are shown in Figure 4. The EuT does not follow the piecewise linear reference curve in a perfectly matched way at the first run. For the purpose of calibration, a measurement offset correction of the EuT was effectuated by the manufacturer. After the elimination of the offset, the second and third attempt measurement delivered better results. It shows that acceptance criteria are needed in the future to maintain precise operation at critical grid situations.

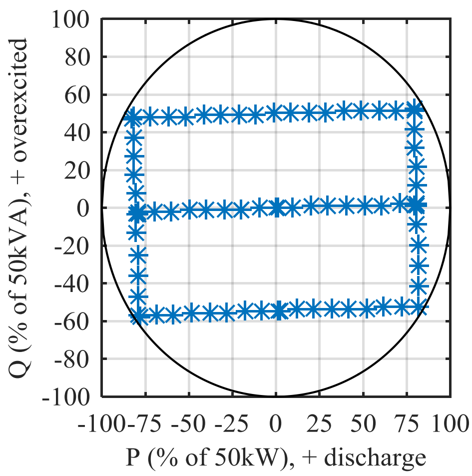

Figure 2: PQ-Active / Reactive power chart of EuT

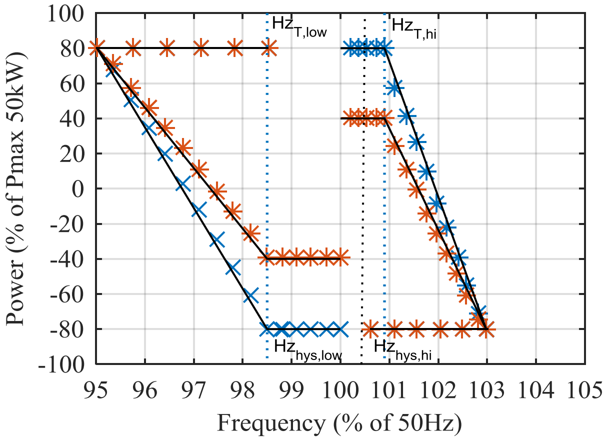

Figure 3: FW22 domain test with tie-line parameters $HZ_{T,low}$, $HZ_{T,high}$. ,hysteresis and recovery frequency $HZ_{hys,low}$, $HZ_{hys,high}$

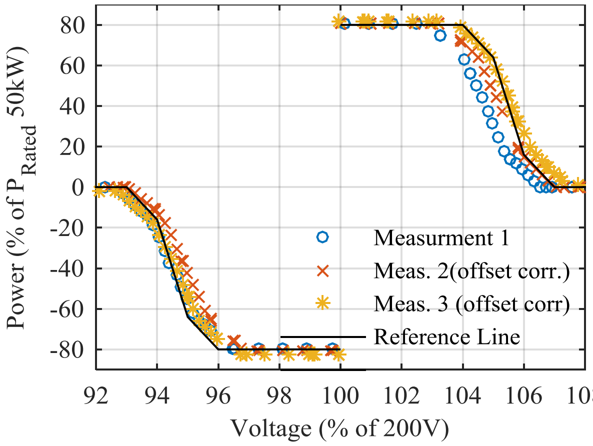

Figure 4: VW52 domain (positive power means discharge)

Time Domain

All timing parameter of the EuT have been tested individually according to the SIRFN draft test protocol. Additionally, a FW22 test with all parameter activated is done and shown in Figure 5. The test sequence consists of 10 decreasing frequency steps and 6 increasing frequency steps. The EuT decreases its charge power to 0 W with decreasing frequency and starts discharging operation, because the frequency still decreases. The applied time intervals shown in Figure 5, are described in Table 4. The test confirms the proper functionality of the EuT with respect to the provision of correct time delays and ramp rates.

It should be mentioned at this stage, that equivocality in definitions of the timing parameter can be found. The definition of a ramp-rate increase and decrease may be misleading for BESS with bidirectional power flow. In case the power reverts from charging to discharging, a decrease will be an increase after changing the quadrant. The definitions in the technical documents do not always declare, whether a timing parameter is only executed once or multiple times after a voltage/frequency deviation until default operation is allowed again. Several grid codes use the parameter time delay and recovery time, but IEC and SunSpec information models use only the time-window and recovery ramp parametrization.

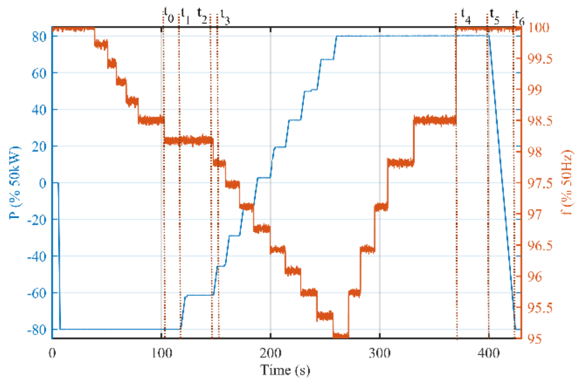

Figure 5: Time domain test of the EuT. (positive power means discharge)

Table 4: Timing parameters of the test shown in Figure 6

Time	Symbol	Name	Value
t_1 - t_0	t_D	Time delay	15 s
t_2 - t_1	r_{RD}	Ramp Rate decrease	4.4 $\%P_{max}$
t_5 - t_4	t_{REC}	Recovery Time delay	30 s
t_6 - t_5	r_{REC}	Recovery Ramp Rate	6.6 $\%P_{max}$

The SIRFN draft test protocol describes the ramp time and recovery ramp time parameter as relation to the ramp-rate, e.g. $t_{REC} = 1/r_{REC}$ and $t_r = 1/r_r$. This statement is only valid for a power step with maximum power, because r_r and r_{rec} are defined as gradient of $\%P_{max}\cdot s^{-1}$.
The implementation of the time delay for VV11, VW51/52 and WP41/42 in the EuT differs from FW21/22. It activates only a delay for sending the function enable command and parameter settings. No time delay is executed at the moment when the function gets activated due to a potential exceptional grid state. Therefore, a better definition for a function or mode which is enabled or disabled - activated or deactivated because of an exceptional grid state - would be helpful in future documents.

Priority of Functions - Combined Tests

Tests are done with multiple activated functions at the same time. Depending on the power capability of the EuT, conflicts may occur if the BESS operates at a capability limit and must prioritize active or reactive power provision. Priority regulations are required if two functions control the same output variable. Control stability must also be guaranteed, if two functions with different dependent variables as FW and VV operate at the same time. A test is done with both functions activated and shown in Figure 7. The BESS changes its output power whenever the grid frequency changes.

Due to the activated line impedance, a change in output power also impacts the grid voltage. As an aggressive Volt-Var curve is used for this test, the BESS reacts immediately to this voltage change with reactive power provision. No stability issues are observed for this EuT, however, further analysis is required for the validation of proper functionality with multiple functions.

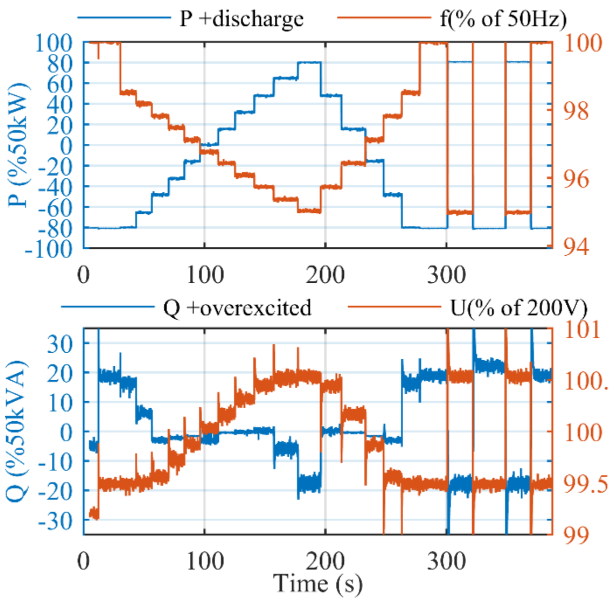

Figure 7: Combined FW22 and VV11 test

CONCLUSION

Validation of advanced interoperability functions of BESS with concerns to function definitions and test procedures is done. Deficiencies in definitions of timing parameter are found and a further harmonization and adaption for BESS is required. Functions descriptions for VV or VW, which use the voltage as independent variable need an additional parameter if the three-phase average or maximum voltage is used as reference. Both options are found in current grid codes.

The SIRFN draft test protocol should be extended with test procedures for a BESS capability test. Knowledge about power limits of the EuT is important, especially when multiple functions are activated at the same time.

Test methods should be introduced for voltage-watt (VW51/52) and watt- power factor (WP41/42), as well as the commonly used FW21 function. New testing methods and priority regulations for multiple activated advanced interoperability functions are required to guarantee stable operation of BESS supporting the electricity grid.

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