

Low Voltage Ride Through with high current injection

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Abstract—Large scale electric generating units supplied by renewable resources shall stay connected to the grid and continue stable operation when the actual course of each of the three phase-to-phase voltages drops to a value between 0% and 90% the nominal voltage for a certain time.[1]

In European standards a fault current contribution of 100 % the nominal current is state of the art for large scale solar power plants. In some countries like UAE (United Arabian Emirates) a current of 120 % the nominal current is required [1]. Especially in grids with long distances between the producing and consuming hubs such an expanded fault current contribution could be reasonable. The current injection ability has to be adapted accordingly. During development of inverters able to deliver higher currents during FRT, the manufacturer is facing two main difficulties:

1. Handling additional stress for the power electronic components
2. Provide appropriate test equipment to run the test. (Especially for large inverters this is one of the main challenges).

SMA solved these problems for the 2.5 MVA inverters and can provide data from a test program regarding those issues.

Keywords-component; fault ride through; low voltage ride through (LVRT); standards; test results; test equipment; current injection; ancillary services

I. INTRODUCTION USING THE EXAMPLE OF GERMANY

The relevance of PV-energy for the electric energy supply is increasing: Current situation in Germany: 37 GW PV installed base. 40-50% of the load is covered under some cases at noon (Fig. 1).

The present plan for grid development counts with 50-60 GW for 2030. This seems to be rather conservative considering the ability to install 200 to 300 GW roof top solar in Germany. → Even with such a scenario a couple of hours with dominating PV supply can be considered at noon. (Fig.2). In case PV dominates generation, PV has to generate sufficient ancillary services to keep the entire electric power grid working under such conditions.

Regarding the question: “How ancillary services for the power grid can be characterized”, we can find some answers in reference [5]. We can distinguish between established function (blue) and future functions (red), between local and global zones of influence and last but not least between functions running autonomous in the devices or running coordinated from a high level management function. (See Fig 3)

The established functions are:

- Static voltage support
- Dynamic voltage support also called LVRT (low voltage ride through)
- Frequency support in case of over frequency

Future functions for grid connected PV:

- Active power reserve
- Coordinated reactive power management
- Coordinated black start

To achieve these goals the aggregated operation of many distributed PV-plants and the implementation of batteries for the so called active power reserve is necessary.

In light blue color of Fig. 3 - the objective of this paper, the dynamic voltage support, is highlighted. Importance of FRT provision from renewable sources had been investigated in reference [2]. Especially the ability to offer higher fault ride through currents beyond state of the art had been discussed in this paper.

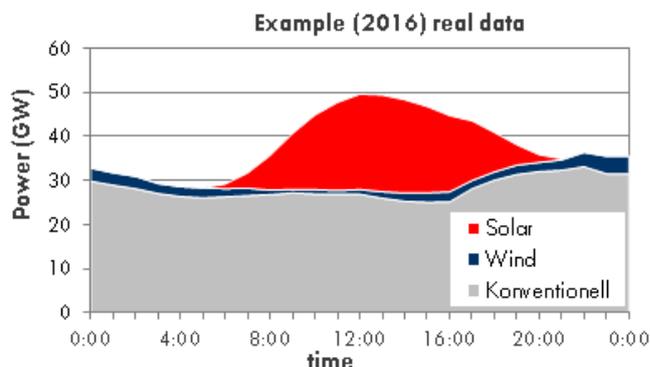


Figure 1: Contribution of PV energy to a present load curve

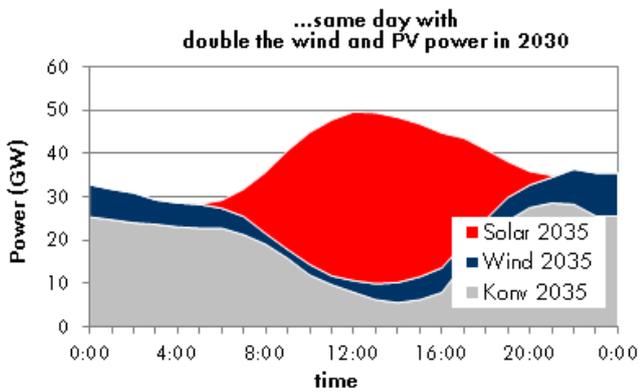


Figure 2: Contribution of PV energy to a load curve in the future

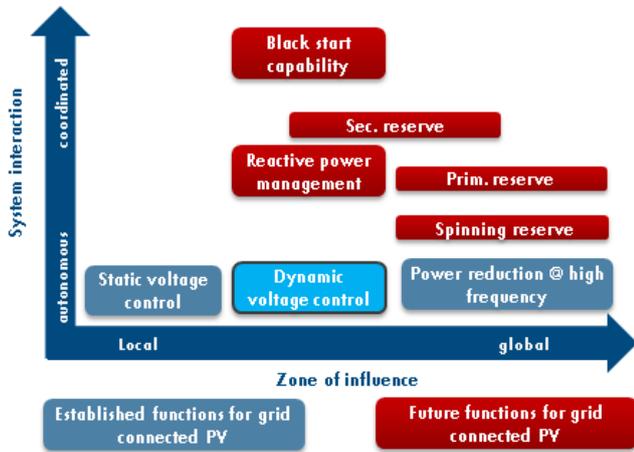


Figure 3: Contribution of PV energy to a load curve in the future

II. LVRT REQUIREMENTS

What reason we could have to require more than 100 % the nominal current as reactive current during LVRT?

Higher FRT currents expand the degree of freedom while installing large solar and/ or battery equipment:

- Voltage support effect is proportional to the current flowing during FRT. Thus an FRT current of **120% to 130% the nominal current** helps to keep the voltage up. (e.g. during switching on of VAR-compensation-units)
- Flexibility in design of protection devices for electric installations → higher current for triggering protection units (e.g. circuit breaker).
- Support in starting large motors in weak grids.
- Premise to install grid supporting or grid building battery inverters. Especially in voltage control mode of battery inverters, a higher current helps to handle critical grid situations. ⇒ Experiences of solar inverters can be replicated to battery inverter design.

UAE authorities (the Regulatory & Supervisory Bureau) launched the "Renewables Standards", version 1.0, November 2013. The generating unit shall stay connected to the network and continue stable operation when the actual

course of each of the three phase-to-phase voltages at the connection point remains within the blue hatched area defined in Figure 9 of the standard (here Fig. 4).

Consider that operation with 10% or even 0% of nominal voltage can be guaranteed with a stable DC Source only. VAR-compensation units (reactive power compensation units) cannot be operated during such states; because the active power necessary to run the equipment cannot be extracted from the grid.

During the LVRT event the PV voltage rises to no load voltage because there is no energy transfer to the grid during the event. Thus the power electronic components are stressed not only by a high current but by a high voltage too [6].

Further requirements:

- Below 42% of retained voltage, reactive current shall be supplied not less than 1.2pu (see Fig. 5)
- Additional reactive current up to 0.6pu must be provided within 20 ms (response time) (see Fig.6)
- The full range of additional reactive power must be provided no later than 60 ms (settling time).

Critical values are the reaction time and the requirement of an LVRT current of 120% the nominal current.

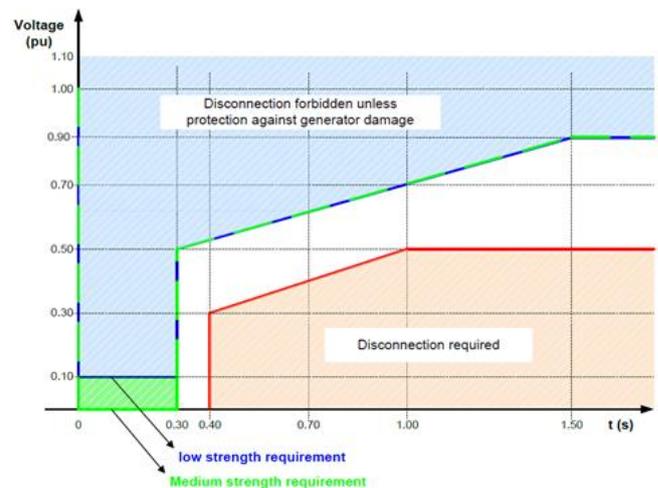


Figure 4: Figure 9. from "Renewable Standard"

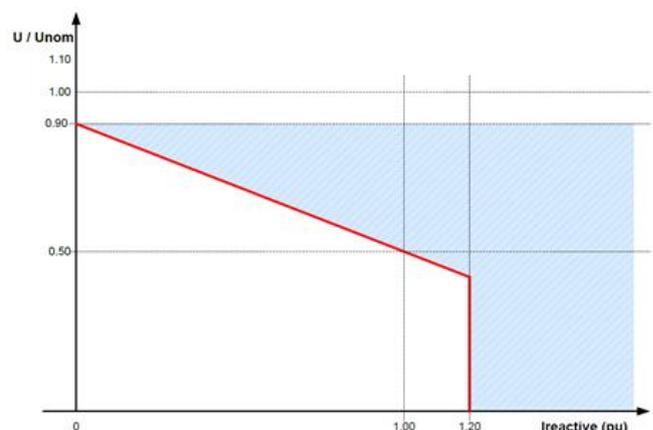


Figure 5: Reactive current injection during fault, Figure 10. from "Renewable Standard"

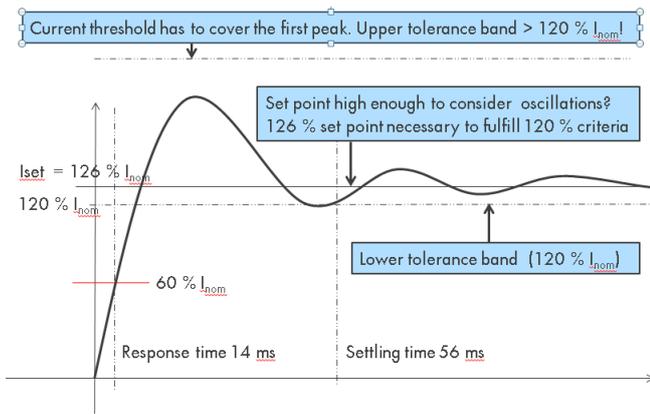


Figure 6: RMS value of LVRT current during entering phase (realistic values from SMA experiences)

III. K-FACTOR ADJUSTMENT

The k-factor adjustment is described in the new German standard VDE-AR-N4110 for the grid connection of generating units on medium voltage level [4]. This is a standard in discussion (draft level). The k-factor describes the gradient of current increase with dropping grid voltage. For renewable energy sources coupled to the grid with power electronic components normally a k-factor of 2 is chosen.

Reference [4] gives a hint, that a factor above 2 (e.g. 2.15) should be chosen to compensate the voltage drop of MV-transformer (power electronic components normally have a voltage measurement on LV-side). See Fig. 8 for calculating the k-factor.

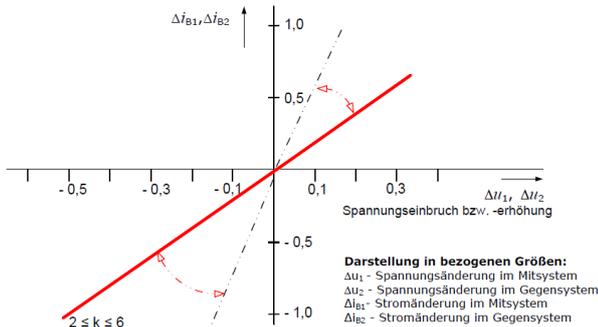
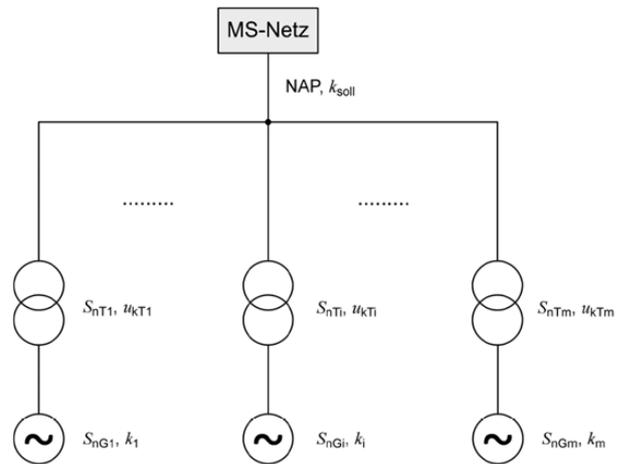


Figure 7: k-Factor



$$k_i = \frac{c_k}{\frac{1}{k_{soll}} - u_{kTi} \cdot \frac{S_{nGi}}{S_{nTi}}}$$

See also:
VDE-AR-N 4110, draft, March 2017 (Technical requirements for the connection of customer equipment to MV-grid)

Figure 8: Compensation of k-Factor

IV. LVRT TEST SETUP

SMA designed a special test setup to execute LVRT test with reasonable effort. Therefore the so called “back to back” mode with two inverters is chosen. The losses for both inverters are covered via a rectifier unit from the grid. The rectifier unit supplies the common DC-bus of both inverters. One inverter works as a sink and voltage source and the equipment under test works as a current source and behaves like a PV-inverter. The EUT (equipment under test) is localized in a test chamber controlling the ambient temperature to 50° C. Both devices operate some hours before the test starts to keep the temperature in the power electronic components to maximal temperature level. During an LVRT event the sink shifts the AC-voltage to a desired voltage dip during the event. The EUT device injects the current as specified.

SMA performed 310 no. of LVRT tests a 50° C ambient temperature and 1250 V DC-bus voltage to achieve a realistic test scenario. During those tests the equipment works properly, no failures occur. Sink and source are still in operation for further tests. The test was performed with currents between 126% and 130% of the nominal current to cover tolerances and effects regarding settling time.

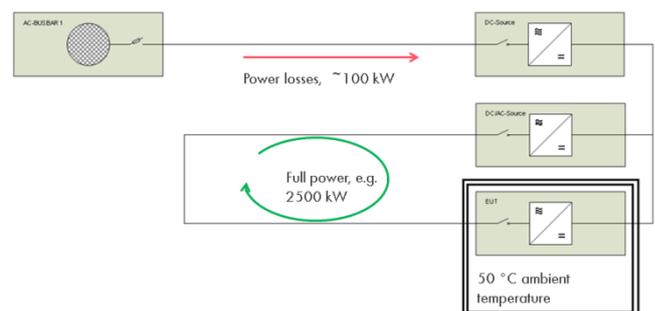


Figure 9: SMA test setup

V. RESULTS SYMMETRICAL VOLTAGE DIP

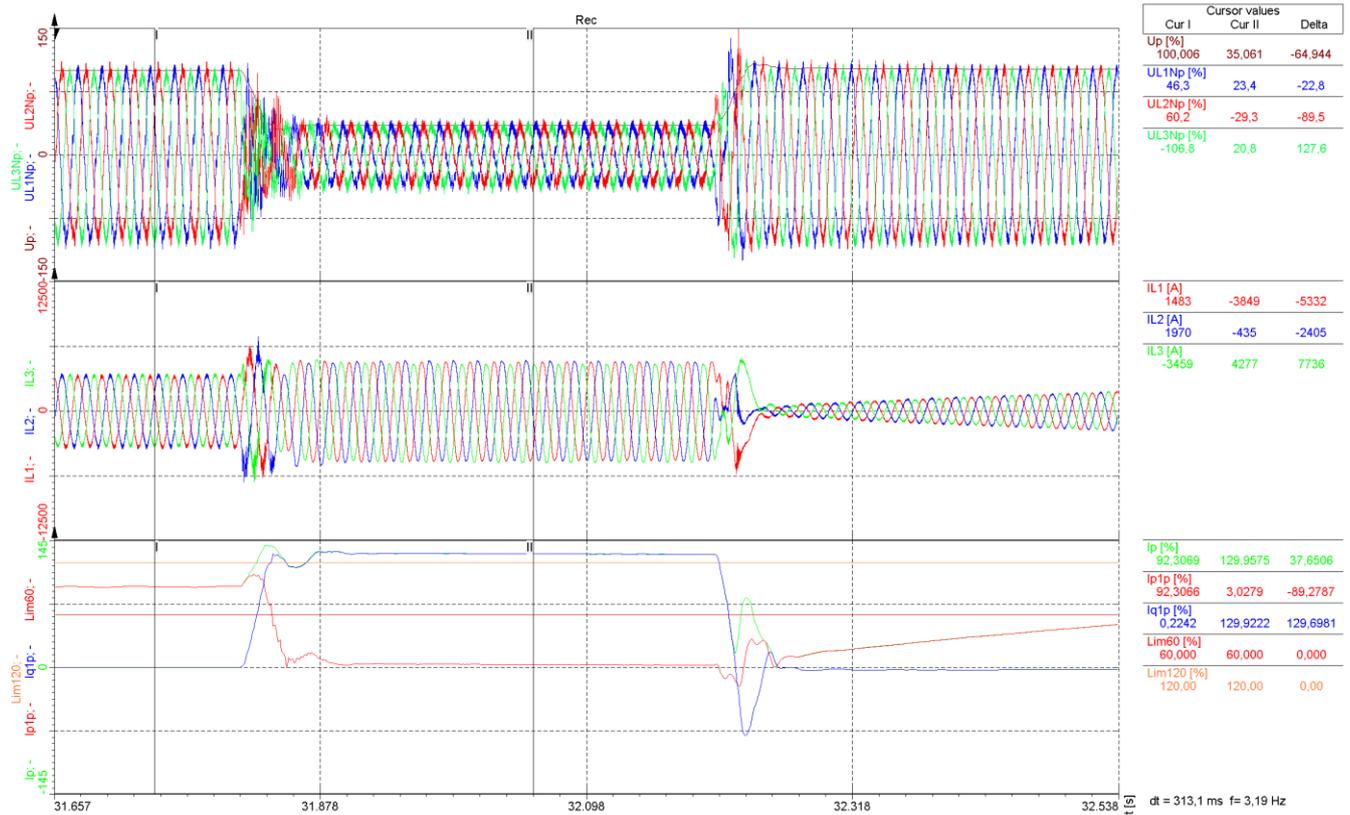


Figure 10: Test results symmetrical failure

Test with symmetrical voltage dips are presented in Fig. 10. Voltage drops to 35% of nominal voltage during an operation at 2.2 MW and 50° C. Voltage dip lasts for 400ms. As in [1] the device should stay minimum 300ms and maximum 400ms connected. So the test had been performed with 400ms to cover worst case scenarios.

- After the voltage dip the current ramps up as required in the standard.

Explanations:

- First curve: Phase to neutral voltage during voltage dip. At the right side one can see the instantaneous voltage at cursor location I and II. Voltage dip is visible
- Second curve: Phase current during voltage dip. At the right side one can see the instantaneous current at cursor location I and II. Current increases during voltage dip to about 1.3 the nominal current
- Third curve: RMS current values during voltage dip. At the right side one can see the RMS current at cursor location I and II. Reactive current increases during voltage dip to about 1.3 the nominal current and active current falls to zero.
 - Green: apparent current
 - Red: active current
 - Blue: reactive current

VI. RESULTS ASYMMETRICAL VOLTAGE DIP

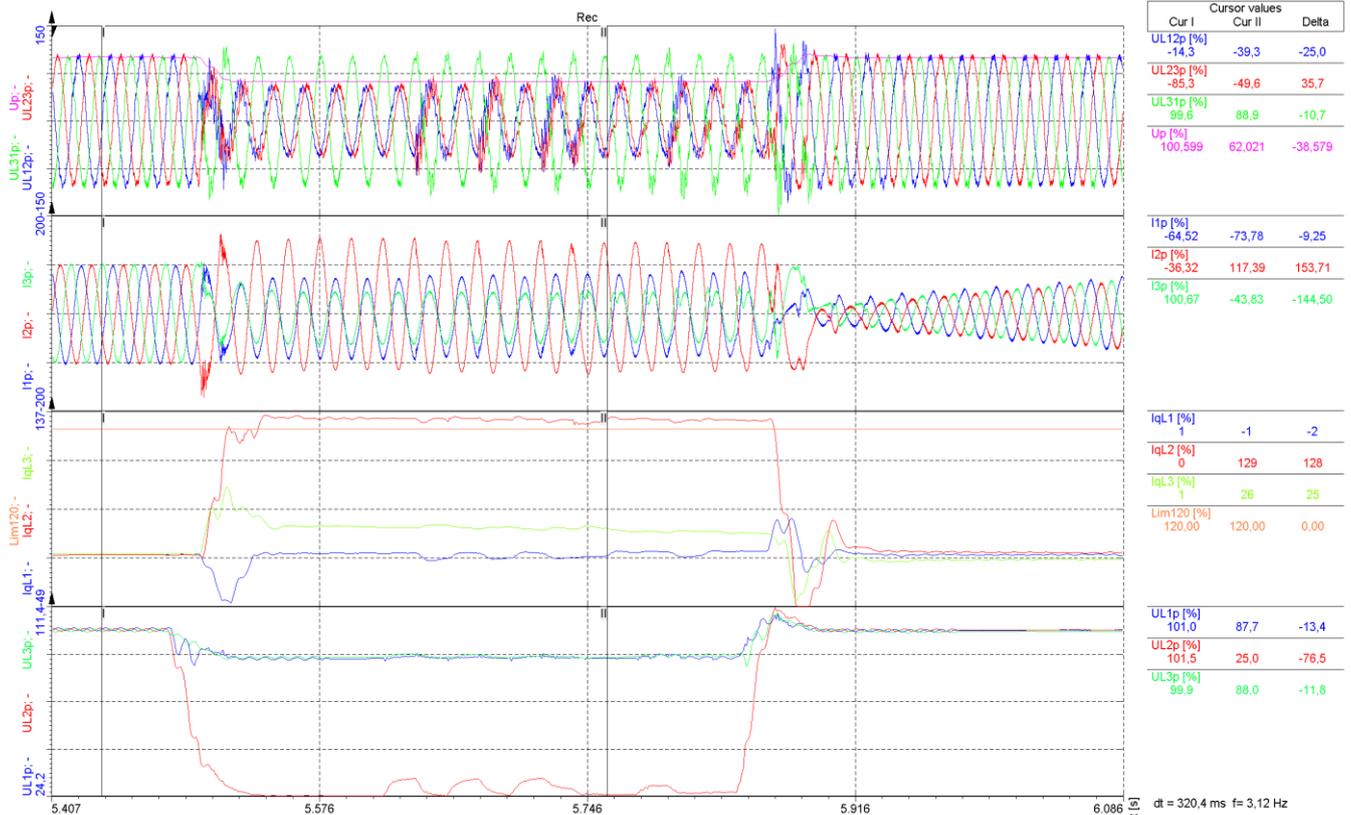


Figure 11: Test results asymmetrical failure

Test with asymmetrical voltage dips are presented in Fig. 11. Voltage between two phases drops to 15% of nominal voltage during an operation at 2.2 MW and 50° C. Voltage dip lasts for 400ms. As in [1] the device should stay minimum 300ms and maximum 400ms connected. So the test had been performed with 400ms to cover worst case scenarios.

Explanations:

- First curve: Phase to neutral voltage during voltage dip. At the right side one can see the instantaneous voltage at cursor location I and II. Voltage dip is visible
 - Second curve: Phase current during voltage dip. At the right side one can see the instantaneous current at cursor location I and II. Current in one phase increases during voltage dip to about 1.3 times the nominal current
 - Third curve: Reactive RMS current values during voltage dip. At the right side one can see the RMS current at cursor location I and II. Reactive current increases during voltage dip for one phase to about 1.3 times the nominal current. The reactive current of the other phases remains small.
 - Red: reactive current phase one
 - Blue: reactive current phase two
 - Green: reactive current phase three
- Reactive current is injected into the affected phase only

- Forth curve: RMS voltages of the three phases (phase to neutral voltages)

In case an asymmetric failure occurs, reactive current injection into the not affected phases must be avoided. In case reactive current would be injected into the phases not affected, the voltage in those phases would be increased. This would result in increasing the negative sequence component and may lead to increased voltage stress for the isolation and all other components affected from a high phase to neutral voltage.

In reference [7] it was shown, that FRT requirement of Japanese grid code can be fulfilled with a two stage device (booster plus inverter). In the Japanese grid code, fault ride through with fast current feed in continuation after voltage recovery is required only (current recovery of 80 % the current before the failure within 100ms). A reactive current injection is not required.

Here it is demonstrated, that LVRT including high current injection is possible even with a one stage inverter. The method demonstrated here can be adapted to any grid code requiring a current injection during the fault smaller than 1.2 times the nominal current (see Fig. 10) and a current recovery time faster than 60ms (see Fig. 6).

VII. DEPENDENCY OF FRT FROM TRANSFORMER CONFIGURATION

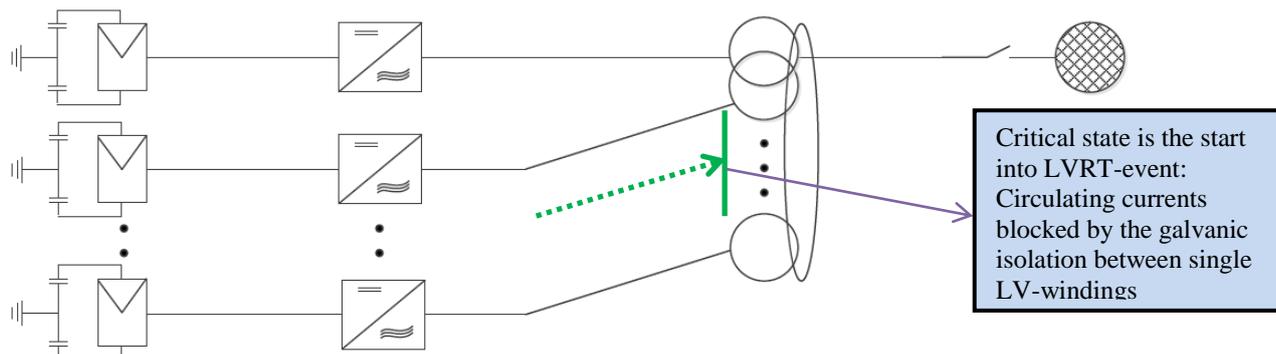


Figure 12: Topology with one transformer winding for every inverter

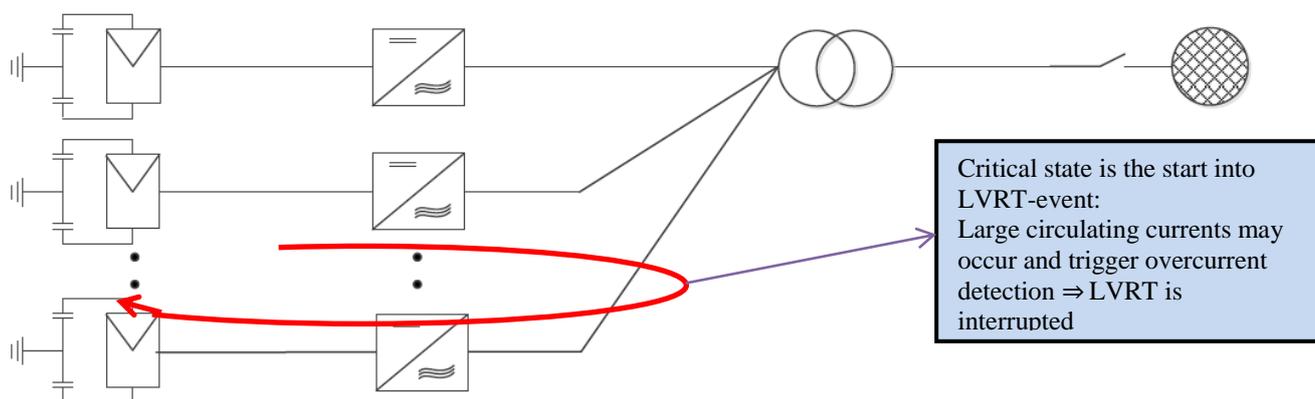


Figure 13: Topology with one transformer winding for multiple inverters

The behavior during LVRT depends on the transformer configuration. In case multiple inverters with separate DC-buses and sine wave filters without direct galvanic connection to the DC-bus (typical central inverter design) are connected to one winding of a medium voltage transformer (see Fig. 13), circulation currents with switching frequency can occur. Such currents are flowing via the parasitic capacitors from array to ground and occur in case the pulse pattern of the inverters connected to one winding differs. During entering into an LVRT-event such differences are obvious, because the voltage shape is totally unpredictable and control behavior has to be adapted accordingly. For the verification of the LVRT behavior of a system as in Fig.13 it is necessary to perform an LVRT test with the entire setup. This is very complicated considering verification under all circumstances can be achieved only in case numerous tests had been run under worst case temperature and voltage conditions.

In case a setup as in Fig. 12 had been chosen, the conditions during LVRT-event and for the meaningful verification are much better. In this case no circulation currents occur and the test results from a single inverter can be transferred to the behavior of the entire system.

VIII. SUMMARY

FRT is one of the pillars of ancillary services. Renewable energy sources have to offer, in case their contribution to the energy supply increases.

FRT current of 120% to 130% the nominal current is feasible for standard inverters. Test results have been presented here.

FRT is possible for symmetrical and asymmetrical voltage dips. Both configurations should be tested. Tests have been presented here.

In the initialization phase (voltage dips occur), a current overshoot and a damped oscillation has to be considered. The semiconductors in the inverters have to handle this state. Thus an endurance test with 310 no. of single FRT events had been performed and presented here.

FRT test should be performed with no load voltage and not with MPP voltage because the PV generator is unburdened during FRT (only reactive current is injected). In this case 1250 V/ DC @ 50° ambient temperature had been chosen.

If the grid voltage dip falls below a certain limit, FRT is feasible only in case a DC power source is available (PV-

generator or battery). VAR- compensation units cannot contribute in such a case.

Due to oscillations in the initialization phase, it may be necessary to choose a FRT current higher than the requested current to be sure to reach the nominal FRT-value in time.

In most of the cases a k-factor larger than 2 but smaller 2.5 has to be chosen. This is necessary to compensate the voltage drop on transformers and line inductors in the plant (inverter measurement is localized on LV-side and the inverter increases the measured voltage with his injected FRT current).

In case of multiple inverters connected to one LV-winding: FRT-Test should be performed for the entire set up. Test with one inverter only is not sufficient. This is important mainly in case the DC buses of the multiple inverters are not connected and sine wave filter on the AC side has no direct galvanic connection to the DC bus.

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BIOGRAPHICAL INFORMATION

Andreas Falk is born in Witten/ Germany 1963. From 1983 to 1988 he studied electrical engineering at "Ruhr_Universität Bochum".

He holds the title "Diplomingenieur Elektrotechnik" and worked in various positions in development and product management in SMA Solar Technology AG. Currently he holds the position of System Architect in the Business Unit Utility.

Mr. Falk joined the team which developed the first solar inverter produced in serial production in 1989. He published numerous papers regarding PV energy. Currently he is responsible for defining the next development steps for large scale PV-inverters and entire utility power systems.