Improvement of PGU Simulation Models based on FRT Test Rig with adjustable Voltage Vector and Short-Circuit Power

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***Abstract*—This paper shows influences on the behaviour of power generating units due to variations in the grid impedance. In order to investigate these effects, an alternative transformer based test equipment has been developed that allows for simultaneous voltage vector magnitude and angle jumps. A complex transformation ratio is defined to prove electrical equivalence of the test systems in combination with additional impedances. It is assumed, that simulation models can be improved by including additional measurements into the validation process which are not part of the prototype measurements yet.**

I. INTRODUCTION

Riding through voltage dips without tripping is one of the most crucial requirements for distributed generators (DG) such as wind energy converters (WEC). In order to get meaningful results out of fault-ride-through (FRT) testing, the test equipment has to reproduce real FRT conditions as adequate as possible. Otherwise, successfully riding through the tests would not necessarily result in successful ride-through events in ”real” fault situations and system stability may be harmed.

Testing – especially when it comes to field tests – is always a compromise, because the test equipment has to be transportable (thus robust), affordable and should have a low impact on the upstream network. The first test equipment that fulfilled these requirements was based on inductive voltage division and is still state of the art nowadays. This kind of test equipment will be referred to as standard test equipment in this paper.

In the last years in Germany a couple of grid situations occurred, which were followed by a subsequent and significant loss of DG. This led to more attention regarding the conditions during FRT events. As a consequence FRT requirements in the German grid codes [3] were specified more precisely.

This paper deals with some effects that have been observed during several years of measurements – mainly the influence of short-circuit power and phase angle jumps. These effects influence the test results of low-voltage ride through testing but depend on the site specific grid situation. Simulation models that validate these measurement data may not show realistic values in deviating grid situations. The severeness of these possible deviations should be considered in future discussions.

II. EXPERIENCES GAINED FROM SEVERAL YEARS OF MEASUREMENTS

FRT testing are standard procedures within the wind industry since many years. Nowadays these measurement are applied to different power sources such as photovoltaics or combined heat and power systems. The following sections will show examples for deviating behaviour of power generating units (PGU) connected to the grid, based on both inverters or electrical machines. Firstly the conditions during grid faults will be extended by two more variables, that is, the short-circuit power and the phase angle of the voltage vector.

A. Effects of sudden changes of the grid impedance

The effect of sudden changes of the grid impedance $\underline{Z}_{\text{grid}}$ (which for simplification reasons is already included in $\underline{Z}_{\text{series}}$) does not just occur while utilising the standard test equipment. “Real” grid faults such as short-circuits, split up the grid impedance as well, resulting in a sudden change of the magnitude of the remaining $\underline{Z}_{\text{grid}}$ between the point of connection (POC) of the DG and the fault location. Since the R/X-ratio differs between the voltage levels this “split” of $\underline{Z}_{\text{grid}}$ will also result in a varied R/X-ratio.

So two effects (in addition to the reduced voltage) occur during grid faults for the downstream connected DG:

1) The different magnitude of $\underline{Z}_{\text{grid}}$ will result in a change of short-circuit power.
2) The difference in the R/X-ratio will force the voltage vector of the remaining voltage to a angle jump. The jumps sometimes have a magnitude of more than 30°.

The FRT-stability of a network is highly dependent on the capability of the power generating units (PGU) to handle these uncommon, however, sensitive grid situations. Both effects are currently not part of the standard testing of DG and, thus, not part of the EUT’s simulation model.

B. Influence of short-circuit power variations

Regarding inverters, the output filter typically produces a short current spike on fault-entry. Figure 1 shows a symmetric low-voltage ride through on an inverter based generator including a current spike of appr. 10 times the current’s nominal value.

With exception of the short-circuit power, the generator is measured under the same measurement conditions as shown

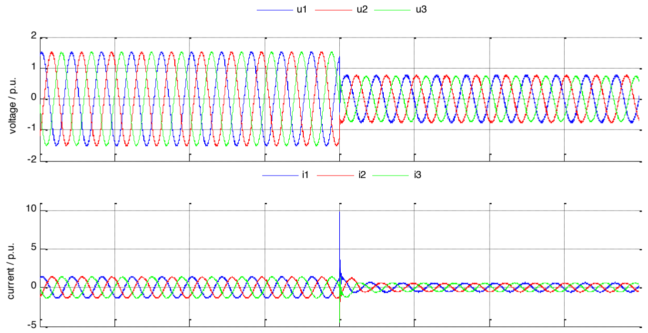

Figure 1. Inverter based generator during LVRT test at a connection point with high short-circuit power. Note the current spike of $10 \cdot I_\mathrm{r}$.

in Figure 2. The different short-circuit power completely avoids the current spike. While in Figure 1 the ratio of the short-circuit power to the generator's apparent power is 3 in Figure 2 this ratio is 33. So both measurements fulfill the requirements of FGW TR3. [1]

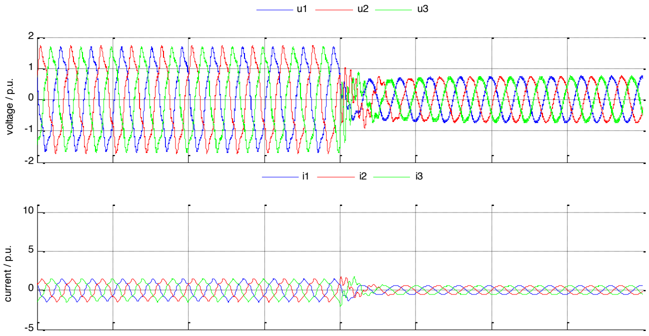

Figure 2. Inverter-based generator during LVRT test at a connection point with low short-circuit power

Different behaviour cannot only be observed on fault-entry but on voltage recovery as well. Figure 3 shows the behaviour of an inverter-based generator on voltage recovery, while the available short-circuit power is high. The inverter immediately starts to ramp up current and, thus, power again.

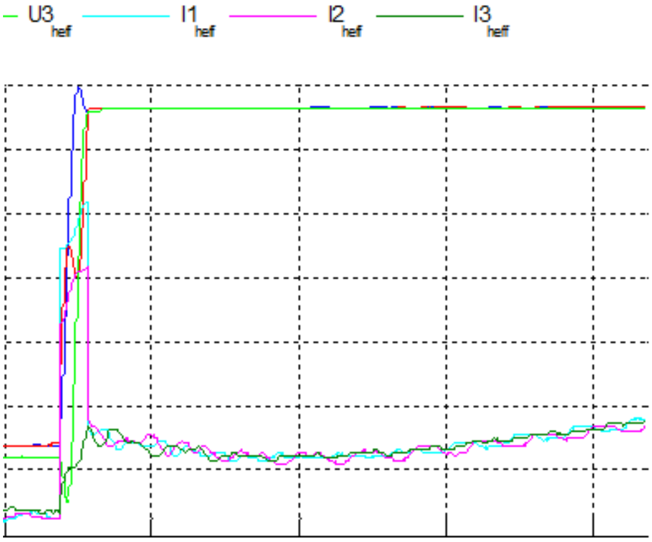

Figure 3. Inverter based generators during voltage recovery, high S_SC

Figure 4 shows the same inverters on voltage recovery to the same kind of voltage drop. The available short-circuit power is significantly lower than in the first case. In contrast to Figure 3, in Figure 4 the inverters' current control is not working properly and a power ramp up cannot be identified.

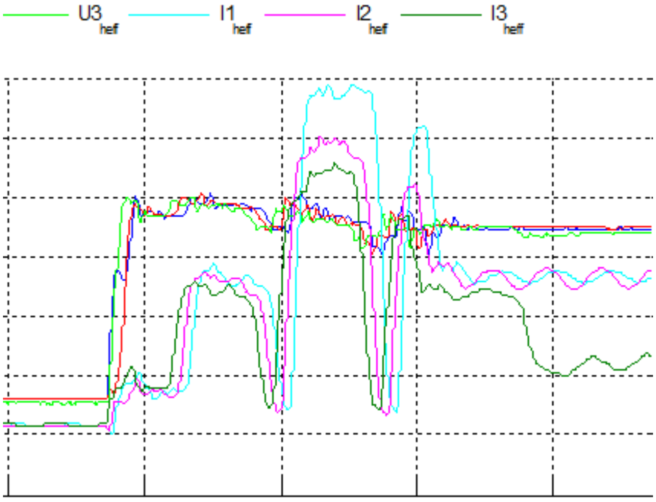

Figure 4. Inverter based generators during voltage recovery, low S_SC

The standard test equipment (see section III for details) requires a large series impedance in order to limit the short-circuit current I_SC when switch S_2, see Figure 7, is closed. The available short-circuit power at the terminals of the Equipment Under Test (EUT) is significantly reduced. Additionally to the jump in the short-circuit power S_SC, another effect occurs, that is described in the following section.

C. *Influence of vector angle jumps*

As described in the previous section, the series impedance of standard test equipment causes a significant reduction in S_SC. On the other hand, this impedance influences the R/X ratio at the terminals of the EUT. So the series impedance does not just influence the magnitude of the voltage drop across the grid impedance (from the EUT's point of view). In addition, it influences the phase angle of the voltage drop resulting in a vector angle jump in the terminal voltage.

Figure 5 shows a LVRT test sequence using standard test equipment on an electrical machine. In the second plot of Figure 5 it can be seen that the active power in the positive sequence P_pos shows oscillations every time when the switching state of S_1 or S_2 changes. It should be noted that the largest magnitude of this oscillation occurs when the bypassing switch S_2 is closed again.

Applying different vector angle jumps leads to different output currents. In Figure 6 the current response of an electrical machine is shown during a 3-phase LVRT test. In the upper plot (77 % residual voltage) no vector angle jump is applied. In the middle and lower plots (both 70 % residual voltage) a vector angle jump of appr. 19° lagging and leading is applied. On the one hand, the maximum amplitude of the current response is lower when no vector angle jump is applied. On the other hand the times when the maximum/minimum values of the damped oscillations occur is different and the maximum values are higher.

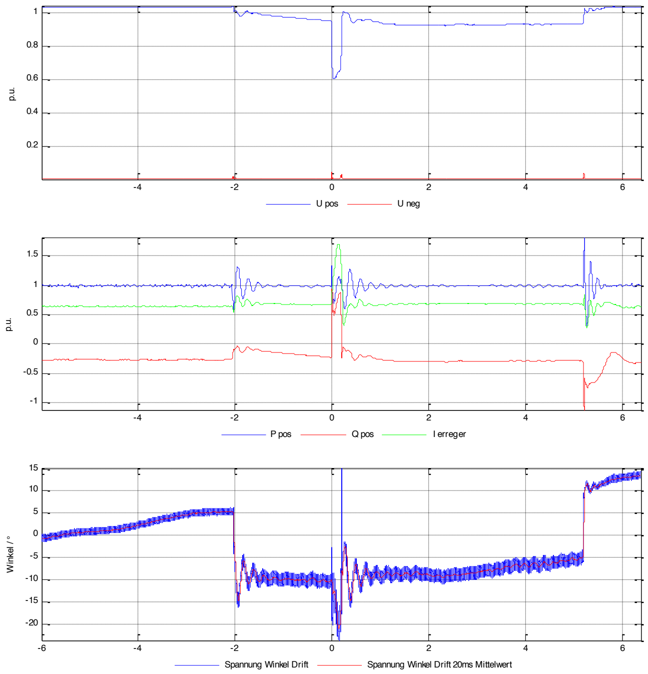

Figure 5. Test sequence voltage drop to 60 % residual voltage including opening and closing of by-passing switch S_1. Upper plot: Positive sequence voltage. Middle plot: Real, reactive and apparent power. Lower plot: Angle drift in relation to fixed 50,0 Hz.

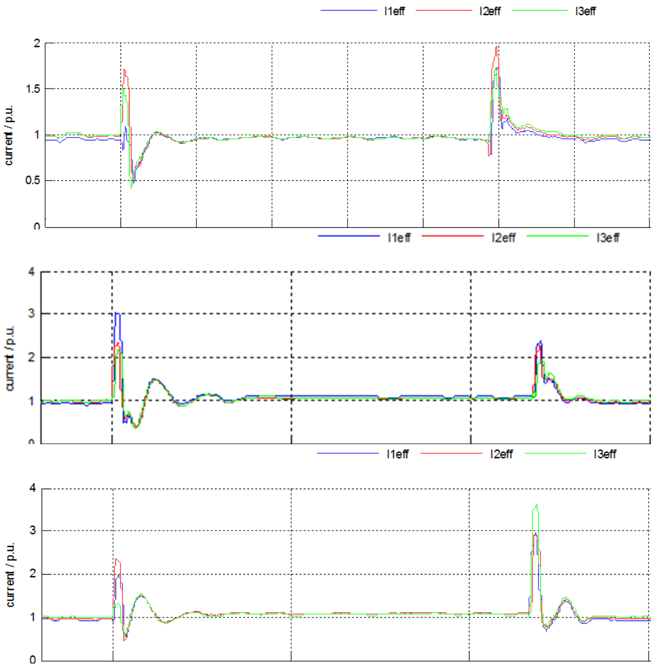

Figure 6. Current response of an electrical machine during a 3-phase voltage dip. Upper plot: without additional vector angle jump, 77 % residual voltage. Middle: vector jump 19° lagging, 70 % residual voltage. Lower: vector jump 19° leading, 70 % residual voltage.

III. STANDARD TEST EQUIPMENT

The standard test equipment for testing low-voltage-ride-through events is based on the principle of inductive voltage division. In IEC 61400-21 [2], regarding field-testing of wind turbines, it is described with the explicit indication that it is an example. But especially regarding field testing wind turbines this principle is still state of the art. This test rig consists of two inductances, $\underline{Z}_{\text{series}}$ and $\underline{Z}_{\text{fault}}$. $\underline{Z}_{\text{series}}$ is combined with a bypassing switch S_1 while $\underline{Z}_{\text{fault}}$ is completed with a series switch S_2, see Figure 7.

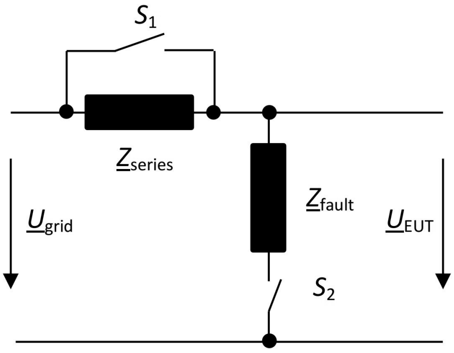

Figure 7. Conventional test equipment

During normal operation (NOP) S_1 is closed, S_2 is open and the equipment under test (EUT) is not confronted with deviating conditions. The test procedure starts by opening S_1 and closing S_2 subsequently. When S_2 is closed, the fault event (FEV) is started. $\underline{Z}_{\text{series}}$ will limit the short-circuit current that will flow from the grid while S_2 is closed. The ratio between $\underline{Z}_{\text{series}}$ and $\underline{Z}_{\text{fault}}$ will determine the residual voltage for the EUT.

IV. INTERMEDIATE CONCLUSION

The effects described in the previous section imply that there are more effects than the depth of the voltage dip that should be considered during LVRT measurements.

During 3-phase voltage drops the following effects can be observed in theory:

- The voltage dip during the fault will cause on fault-entry and fault clearance a jump in the voltage vector. This jumps affect both magnitude and angle.
- The vector angle jump will be leading or lagging dependent from the jump of the R/X-ratio between normal and fault operation.
- The resulting grid impedance during the fault is not only depending on the parallel connection of $\underline{Z}_{\text{series}} + \underline{Z}_{\text{grid}}$ with $\underline{Z}_{\text{fault}}$. It will depend on the impedance between the junction to $\underline{Z}_{\text{fault}}$ and the terminals of the EUT. This impedance includes e. g. transformer and cabling.
- EUTs tend to be tested on (too) weak grids so that capacitor discharging effect are disregarded.
- If the ratio of the nominal power of the test equipment and the EUT is high the stability of the EUT will not be tested adequately.

During unsymmetrical (e. g. 2-phase) voltage dips, in addition, the following effect occurs:

- The vector group of the transformer(-s) cause fundamental changes on the components of the voltage vector at the terminals of the EUT.

It has been shown so far that there are more influencing parameters during grid faults. The standard test equipment is not able to give proper consideration to all of the above mentioned effects. However, these effects have a strong influence on measurement results and, thus, the design of simulation models of the EUT. So it should be questioned if at least some effects could be taken into account using alternative test equipment.

In the next sections, on the one hand, will be shown that it is possible to configure the transformer based test equipment equally to the standard test equipment or simplified grid models. On the other hand it will be shown that the transformer based test equipment is capable of additional features.

Two switching states will be considered (no-load condition):

1) Pre- and post-fault conditions, (normal operation, index NOP):
   Standard test equipment: Switches S_1 and S_2 are open, see Figure 7
   Transformer based equipment: Initial transformation ratio, see Figure 13
2) Fault event (index FEV):
   Standard test equipment: Switch S_1 is open while S_2 is closed, see Figure 10
   Transformer based equipment: Altered transformation ratio, see Figure 14

V. TRANSFORMER BASED TEST EQUIPMENT

Transformer based test set-ups are not widely spread but some test laboratories use this kind of equipment since many years.

Mainly the transformer based test equipment consists of a transformer which offers as many taps as necessary on the secondary winding. By switching between the taps the transformation ratio is changed and voltage jumps are applied to the EUT, see Figure 8.

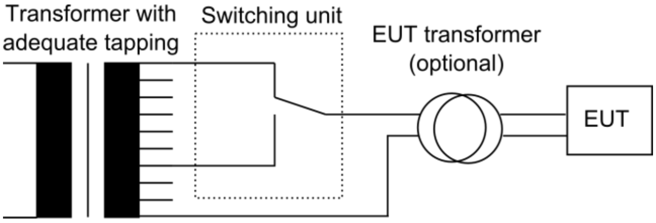

Figure 8. Schematic diagram of transformer based test equipment [4]

A. Advantages of autotransformer based test equipment

One of the main advantages in comparison to the conventional test equipment are reduced system perturbations to the upstream network since it is not loaded with short-circuit current during the voltage drops [4]. The available short-circuit power S_{SC} can be applied to the EUT and varied by additional series impedances.

Besides low-voltage ride through events, high-voltage ride through events can be easily achieved. So requirements that have been defined in up-to-date grid codes can be fulfilled.

Since occurring currents and, hence, losses are low transformer based equipment is more efficient. So LVRT, or HVRT events, respectively, can be applied for longer times than usual. The maximum ride through times of EUTs can be easily determined.

Utilising additional winding sections a large variety of transformations can be realised. Tests can be carried out on low-voltage level since vector diagram that are result of the vector group of the EUT's transformer can be directly modeled by the test setup

B. Additional options of transformer based test equipment

When modifying equations 7 and 8 one can see, that transformer based test equipment is able to produce test situations that cannot be achieved in real (and operating) grids. But by choosing adequate values, worst-case scenarios can be applied to the EUT.

VI. COMPARISON BETWEEN STANDARD AND TRANSFORMER BASED TEST EQUIPMENT

A. Thevenin equivalent of standard test equipment

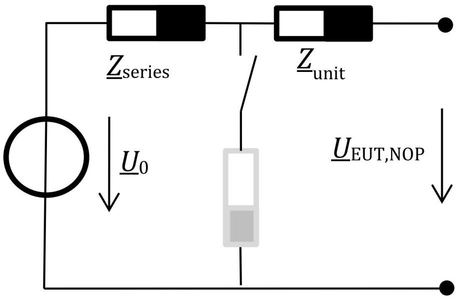

Figure 9. Standard test equipment during normal operation (NOP), switching state 1

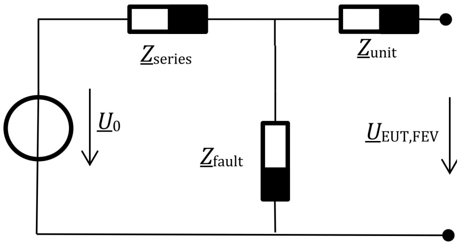

Figure 10. Standard test equipment during fault condition (FEV), switching state 2

Both states can be simplified into their Thevenin equivalent circuits with a resulting voltage source and a series impedance.

$$\underline{U}_{\mathrm{EUT,NOP}} = \underline{U}_{0,\mathrm{NOP}} \overset{!}{=} \underline{U}_0 \tag{1}$$

$$\underline{Z}_{\mathrm{NOP}} = \underline{Z}_{\mathrm{series}} + \underline{Z}_{\mathrm{unit}} \tag{2}$$

Impedances $\underline{Z}_{\mathrm{series}}$ and $\underline{Z}_{\mathrm{unit}}$ are without effect on the result of equation 1 due to no-load condition of Figure 9.

$$\underline{U}_{\mathrm{EUT,FEV}} = \underline{U}_0 \frac{\underline{Z}_{\mathrm{series}}}{\underline{Z}_{\mathrm{series}} + \underline{Z}_{\mathrm{fault}}} \quad (3)$$

$$\underline{Z}_{\mathrm{FEV}} = \frac{\underline{Z}_{\mathrm{series}} \cdot \underline{Z}_{\mathrm{fault}}}{\underline{Z}_{\mathrm{series}} + \underline{Z}_{\mathrm{fault}}} + \underline{Z}_{\mathrm{unit}} \quad (4)$$

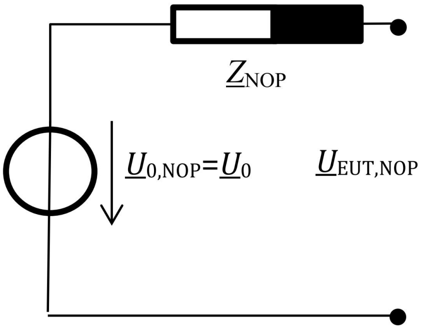

Figure 11. Thevenin equivalent circuit during normal operation, switching state 1

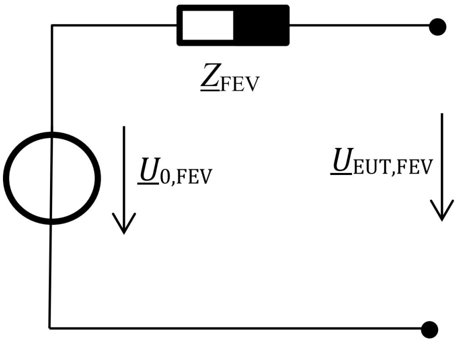

Figure 12. Thevenin equivalent circuit during fault condition, switching state 2

During no-load condition the test rigs are configured in a way that a certain ratio $\underline{V}$ between both voltages – representing the depth of the voltage dip – is reached.

$$\underline{V} = \frac{\underline{U}_{\mathrm{EUT,FEV}}}{\underline{U}_{\mathrm{EUT,NOP}}} = \frac{\underline{Z}_{\mathrm{fault}}}{\underline{Z}_{\mathrm{series}} + \underline{Z}_{\mathrm{fault}}} \quad (5)$$

It should be kept in mind that the voltage vector jumps in case that the R/X-ratio of $\underline{Z}_{\mathrm{fault}}$ is different to the R/X-ratio of $\underline{Z}_{\mathrm{series}}$ and, thus, this ratio represents a complex value.

B. Thevenin equivalent for transformer based test equipment

Since the standard test equipment is considered as state of the art every alternative test equipment has to prove that test conditions are at least equal to the standard equipment or even closer to real grid situations.

Following the approach of section VI-A, two switching states of the transformer based test equipment are considered. Figures 13 and 14 present these two switching states using the example of an autotransformer with tertiary winding.

The ratio $\underline{V}$ is defined by the no-load voltages of the two switching states.

$$\underline{V} = \frac{\underline{U}_{0,\mathrm{FEV}}}{\underline{U}_{0,\mathrm{NOP}}} \quad (6)$$

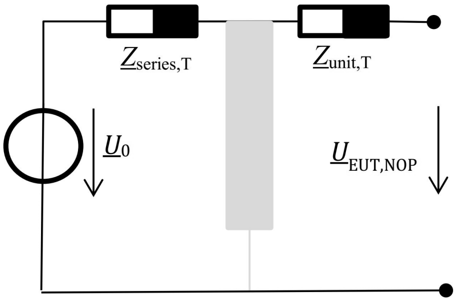

Figure 13. Autotransformer during normal operation (NOP), switching state 1

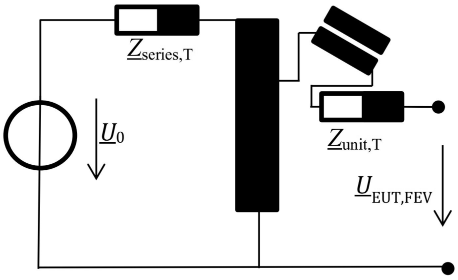

Figure 14. Autotransformer during fault condition (FEV), switching state 2

The impedances $\underline{Z}_{\mathrm{series,T}}$ and $\underline{Z}_{\mathrm{unit,T}}$ have to be chosen in such way that they are equal to the values of the Thevenin equivalents represented by equations 7 and 8.

$$\underline{Z}_{\mathrm{series,T}} = \frac{\underline{Z}_{\mathrm{NOP}} - \underline{Z}_{\mathrm{FEV}}}{1 - \underline{V}^2} \quad (7)$$

$$\underline{Z}_{\mathrm{unit,T}} = \underline{Z}_{\mathrm{NOP}} - \underline{Z}_{\mathrm{series,T}} \quad (8)$$

VII. CONCLUSION & OUTLOOK

From the shown examples it can be seen that with increasing series impedances, the tendency towards an oscillation or instability of the power generating unit increases. These effects can be triggered by voltage vector jumps. In electrical grids, vector angle jumps related to voltage dips are rather the rule than the exception. High short-circuit powers in the other hand, stimulate, amongst others, discharge effects that may result in significant current spikes. Using conventional test equipment, short-circuit power variation test can only barely be performed, as it reduces available short-circuit power due to required series impedances. Models of power generating units are utilised to verify, inexpensively, the unit on reliable behaviour, for grid situations not yet tested. The question remains whether or not a simulation model is sufficiently validated, if certain basic functionalities had never been tested by measurement.

The presented measurement data is the result of measurements utilising an autotransformer based test systems with nominal power of 11 kW. These autotransformer-based test systems offer multiple additional options to perform tests that are not part of standard prototype testing yet. The electrical equivalence to standard test equipment has been proven. In the next steps, test have to be carried out on PGUs with higher rated power.

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