Transformer Based FRT Test Unit Becomes Common

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***Abstract*—**

Three medium voltage transformer-based test units for Fault Ride Through (FRT) tests are already in operation. Others are in planning or in process of building. The new users are impressed of the wide range of possibilities for testing with a smarter test device.

The increasing requirements of accuracy in model validation of the devices under test (DUT) caused the requirements that as well the test unit itself needs a better description. This paper will serve mathematic approaches how to handle this kind of network fault generator in the computer simulation area.

FRT test devices in general were taken to demonstrate that real wind turbines or other DUT are able to handle grid faults. In this context a grid fault is a 2 or 3 phase instantaneous voltage drop or rise over some 100 ms up to not more than 3 s usually.

The way how a DUT has to handle this grid faults is postulated in the grid codes of each system operator or in general country grid codes. In Europe the network code requirements for generators and in Germany the VDE AR N 4105, -4110 and -4120 in conjunction with the measurement procedures of FGW technical guideline TR 3 and DIN VDE 0124-100 are setting the standards.

Compared to previous years, not only voltage drops need to be simulated but also overvoltage events up to 150%voltage. Long term measurements with voltages of 115% or 85% have a test duration of up to 60 s. The new IEC 61400-21-1 proposes to measure not only the requirements according to the grid codes. The suggestion of the new IEC 61400-21-1 is, to simulate the maximum capabilities of the wind turbines. These capabilities can be far beyond the mentioned test. To meet these new requirements a new generation of FRT test equipment was developed.

Keywords-component; HVRT, OVRT, LVRT, UVRT, FRT, test unit, voltage dip, grid fault, voltage divider, autotransformer, air coils, grid codes, model validation, transient.

I. INTRODUCTION

The discussed transformer-based test system simply consists of some auxiliary components, out of a customized auto transformer and conventional switch gears. All components fit in one ISO Standard Container. Therefore, that realization got a high attention at the first presentation in the last wind integration workshop. The legitimate question about the disadvantages will now be discussed by presenting new more accurate computer models of the test device.

After some theoretical estimations in WIW 2009 [5] and experience with low voltage test devices in, WIW 2015 [3], in WIW 2016 [2] WindGuard Certification GmbH has started to build and delivered one medium voltage test unit in 2018 and two in 2019. The first experience with the test unit of GE Renewable Energy were shared in the presentation of WIW 2019 – 240 [1]. GE has bought also a second test unit for the US American business unit. Windtest Grevenbroich a measurement laboratory joined the development team in 2018 and received their new FRT container in spring 2019. After a first long measurement campaign at a GE prototype wind turbine the FRT test unit was rent to INNIO, a gas engine manufacturer. With other gas engine test projects of Windtest, experiences were gathered also at this kind of power production with their typical high dynamic behaviour.

The three pictures Figure 1 up to Figure 3 show the different test devices at wind turbine test sides.

Figure 1: First auto transfomer based test devices installed close to multi megawatt wind turbine.

Figure 2: First auto transfomer based test devices in USA at test side of GE. With this test device probably the first medium voltage OVRT test on a turbine level in America was succesful carried out in May 2019.

Figure 3: The first medium voltage auto transfomer based test device ownd by an independed test laboratory. Windtest Grevenbroich uses this frequently for many different power generation units.

In general, the measurements are used for a comparison with mathematically generated unit models in different time scales. The actual guidelines have requirements according to the kind of voltage drops. In part of impedance behavior, it is proposed to compare test devices with common voltage divider. Therefore, the way of estimation of impedances are discussed. Three different circuit diagrams will be presented.

II. PRINCIPAL CIRCUIT DIAGRAMM OF THE AUTO TRANSFORMER IN USE FOR OVER AND UNDER VOLTAGE RIDE THROUGH TESTS

Inside the test unit, medium voltage coils with multiple number of possible connections are mounted, compare WIW 240- 2018 [1]. Up to now these coils have no iron core in use. Therefore, a lot of characteristic values for different settings were collected out of low voltage measurements. Nonlinear effects out of higher voltage were not expected. Out of no-load measurements, some settings were also validated at medium voltage.

The principal circuit diagram for one configuration looks like an auto transformer, for OVRT compare Figure 4, for UVRT compare Figure 5. Out of the need that the impedance between grid and device under test (DUT) should be as low as possible and the impedance between DUT and Event, as well Grid and Event should be as high as possible, the characteristic values are far away from standard autotransformer just for energy transport. To get the first impression the coil impedances can be measured by voltage and current measurement between Grid-DUT, Grid-Event and DUT-Event.

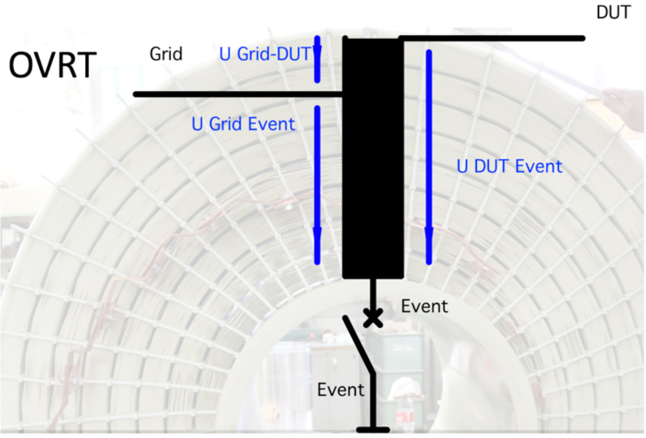

Figure 4: Principal circuit diagramm of the auto transformer in over voltage configuration with a picture of one multi pole coil. Event connection close to the inner winding and DUT connection at the surface of the coil.

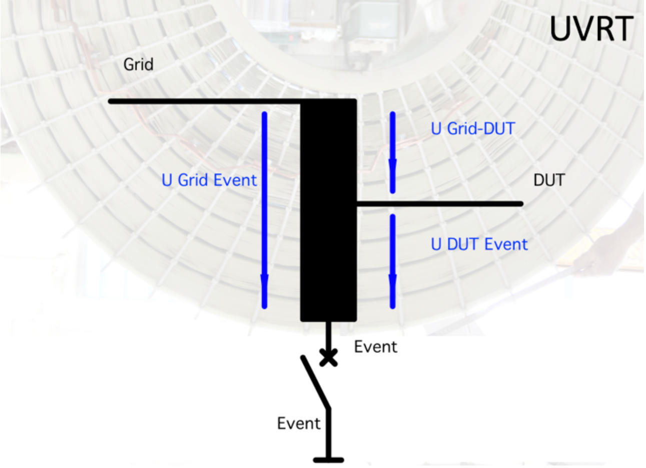

Figure 5: Principal circuit diagramm of the auto transformer in under voltage configuration with a picture of one multi pole coil. Event connection close to the surface of the coil and Grid connection at the inner winding of the coil.

III. BASIC VALUES OF CALCULATION

To get the impedances for the following calculation, the current and voltage were measured between DUT to Event, DUT to Grid and as well between Grid to Event.

The resistance of the impedance was calculated out of the material values. Due to the fact that the resistance is much lower than the inductance of the coil, the impedance is set to the inductance. ($R \ll X_L \rightarrow Z_L \approx X_L$)

The transmission rate r_{winding} is principally given by the numbers of the windings between the connection points. Also, in a no-load measurement the effects of the leakage inductance are too high so that the transmission rate cannot be measured directly. The measured transmission rate is named as the real transmission rate. For a high number of settings this real transmission rate was measured. The remaining not measured real transmission rates were interpolated out of neighboring measurements.

In this state a phase shift out of the transmission rate of the coil itself is assumed to be negligible and was not considered. A phase shift of a transmission rate could be provided out of connection settings, but they are not discussed here, compare [3].

IV. CALCULATION OF CHARACTERISTICAL VALUES OF TWO VOLTAGE SOURCE MODEL

Out of the base values estimated from measurement and interpolation a two-voltage source model can be calculated, compare Figure 7. This model can only be used in mathematic simulations. The switch moves from one to the other position without any moment of no connection to one of the contacts.

The upper position “Not disturbed Grid” represents the situation that a part of the auto transformer is in chain between the grid and the DUT. The event switch at the real test set up is still open.

The bottom position “Event Grid” represents the full active auto transformer were the event switch in the real test set up is closed.

The impedance from the view of the DUT at “Not disturbed Grid” can be taken directly from the basic values of the measured coil, compare chapter before. The impedance of the short circuit power, when the test device is connected, has to be added to the test device impedance, compare Figure 6. This overall impedance can be named as well as length impedance. The ideal voltage source is assumed to the voltage at the no load situation before the test and before the DUT has started.

At closed event switch in parallel to the length impedance, the impedance between DUT and Event has to be added. By using this impedance, the voltage source has to be reduced by the measured transmission ratio. It is assumed that both voltage sources have the same phase angle.

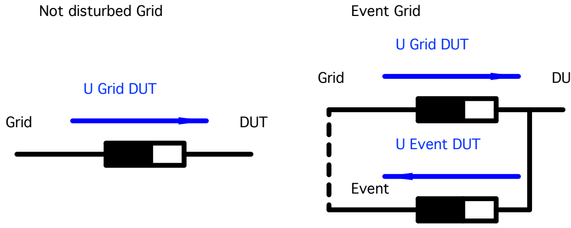

Figure 6: Estimation of the impedance of the two sources model of UVRT.

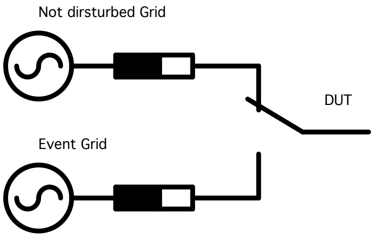

Figure 7: Two voltage sources model to discribe the behavior of FRT test system between the two switching possitions.

V. CALCULATION OF CHARACTERISTICAL VALUES WITH ONE CIRCUIT BRAKER AS EVENT SWITCH FOR COMPARISON TO CONVENTIONAL VOLTAGE DIVIDER

The two-voltage-sources model can be transferred into a circuit diagram which looks similar to a conventional voltage divider including the length impedance from a power generation unit transformer, compare Figure 8. In the new circuit diagram, the voltage source has the same amplitude and the same phase position as the “Not disturbed Grid” voltage source. It has to be considered that the grid impedance is not only the impedance of the test device. In principal all impedances are complex values, but out of the much higher inductance comparing the resistance, the resistance can be nearly neglected.

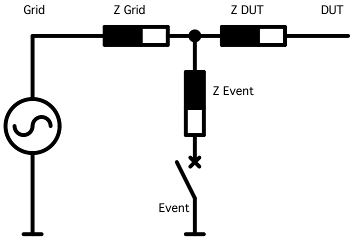

Figure 8: Circuit diagram of the test device including the short circuit impedanc calculated out of the two source equivalent.

As a rough estimate in a 50% UVRT test it was found that with the same longitudinal impedance the short-circuit current of this auto transformer system is 50% lower compared to a conventional test system. Based on the example of a conventional distribution with $X_{L\ Grid} = X_{L\ Event} = 10\ \Omega$, the new test facility must have $X_{L\ Grid} = X_{L\ Event} = 20\ \Omega$. However, in order to obtain the same longitudinal impedance, assuming $X_{L\ DUT} = 0\ \Omega$ of the conventional test equipment, the DUT side impedance of the new test system must have negative values $X_{L\ DUT} = -10\ \Omega$. In terms of technical equipment, a capacitor with $X_{C\ DUT} = 10\ \Omega$ is thus connected in series. In the same way this results also into a negative active component in the DUT impedance. With practical use of this power source, it becomes clear that some grid calculation programs do not provide components for this purpose. Problem seems to be that negative effect resistances are prevented. Negative resistances are also not simple voltage or current sources.

In real constructions, similar partitions have been measured. The main deviation is due to the radial effect, in which the short circuit current from the grid can be further reduced. In this context, the active component reacts very sensitive to changes of X/R ratios of the individual components. The impedances have been converted only for the fundamental frequency. Thus, good results can be achieved with RMS models. Dynamic EMT models must continue to use the two-voltage-sources model.

At OVRT, capacitors appear in the event branch as in the conventional setup for boosting the voltage. The effect of the capacitor is then partly taken back from DUT point of view by an inductance in the DUT impedance. The same applies to the active components.

VI. CALCULATION OF CHARACTERISTICAL VALUES OF A TRANSFORMER CIRQUIT DIAGRAM

In the literature so far no equivalent circuit diagram for a standard auto transformer as it is used here was found. Especially with small FRT residual stresses, the main inductance with respect to the stray inductors becomes very small.

Also, for the fundamental, it is theoretically possible to derive complex impedances from the two-voltage-sources model for a standard auto transformer estimation diagram, compare Figure 9. Here, the transformation ratio was determined from the winding ratios of the coil sections.

$$1/r_{all} = 1 + 1/r_{trans\ U} \qquad (1)$$

$r_{trans\ U}$ → transformer ratio in the circuit diagram

r_{all} → ratio of the overall ideal auto transformer

In this model, the transformer can be considered without impedances of the short-circuit power or voltage source on its own.

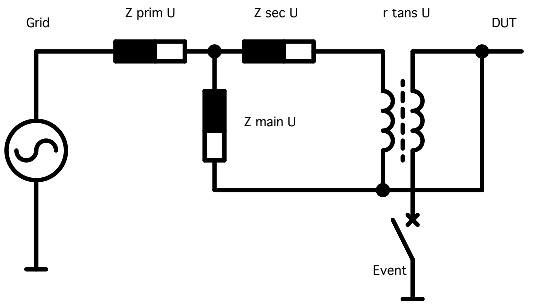

Figure 9: Auto Tranformer in UVRT Configuration

To make the equivalent circuit plausible, the simplified values of the chapter before with $X_{L\,Grid\text{-}DUT} = 10\ \Omega$, $X_{L\,Grid\text{-}Event} = 40\ \Omega$ and $X_{L\,DUT\,Event} = 10\ \Omega$ can be used. At 50% residual voltage ($r_{all} = 0.5$), a one-to-one transformer is used at a transfer rate of $r_{trans\,U} = 1$. During the event switch is open, no current flows over $Z_{sec\,U}$. This doesn't change even with the DUT starting to run. If the event switch closes in this example, the current through the event switch and the grid input do have the same current. By use of the one-to-one transformer in this case the current through $Z_{sec\,U}$ is as well equivalent. Due to the double current through $Z_{main\,U}$ this impedance then acts 4 times higher. For this simplified case, the distribution of main impedance is $X_{main\,U} = 10\ \Omega$ and the leakage inductances $X_{prim\,U} = X_{sec\,U} = 0$.

The radial effect results in the impedance being smaller than $X_{L\,Grid\,DUT} < 10\ \Omega$ when the event switch is open and $X_{L\,Grid\,Event} > 40\ \Omega$ during the event is closed. This can be seen in the equivalent circuit in the increasing importance of leakage inductance $X_{sec\,U}$. By lowering the main inductance X_{main} and increasing $X_{prim\,U}$, the balance results in real measured values. If the Auto Transformer is swapped in the same experiment Grid and Event, then $X_{prim\,U}$ with $X_{sec\,U}$ exchange with equal amounts with unchanged main inductance $X_{main\,U}$.

$$\underline{Z}_{Grid\text{-}Event} = \underline{Z}_{primU} + (1+r_{transU})^2\,\underline{Z}_{mainU} + r_{transU}^2\,\underline{Z}_{secU} \quad (2)$$

$$\underline{Z}_{DUT\text{-}Event} = r_{trans\,U}^2\,(\underline{Z}_{sec\,U} + \underline{Z}_{main\,U}) \quad (3)$$

$$\underline{Z}_{Grid\text{-}DUT} = \underline{Z}_{prim\,U} + \underline{Z}_{main\,U} \quad (4)$$

With Impedances according Figure 5 and Figure 9.

Out of this formula (2) up to (4) the no load transmission ratio r_{NL} can be calculated as in (5).

$$\underline{r}_{NL} = 1 - \underline{Z}_{primU}/\underline{Z}_{Grid\text{-}Event} - (1+r_{transU})\underline{Z}_{mainU}/\underline{Z}_{Grid\text{-}Event} \quad (5)$$

This formula has been checked by measurements with connected low voltage at main frequency.

For the OVRT configuration, the equivalent circuit changes in terms of longitudinal operation, that at idle, the total impedance is formed from the leakage inductances. Even when the event switch is open but under load, the main inductance contributes to the longitudinal impedance, unless $Z_{sec\,O}$ is also ineffective.

$$r_{all} = 1 + r_{trans\,O} \quad (6)$$

$$\underline{Z}_{Grid\text{-}Event} = \underline{Z}_{prim\,O} + \underline{Z}_{main\,O} \quad (7)$$

$$\underline{Z}_{DUT\text{-}Event} = (1+r_{trans\,O})^2\,(\underline{Z}_{main\,O} + \underline{Z}_{sec\,O}) \quad (8)$$

$$\underline{Z}_{Grid\text{-}DUT} = \underline{Z}_{prim\,O} + r_{trans\,O}^2\,\underline{Z}_{main\,O} + (1+r_{trans\,O})^2\,\underline{Z}_{sec\,O} \quad (9)$$

$$\underline{r}_{NL} = (1+r_{trans\,O})\,\underline{Z}_{main\,O} / \underline{Z}_{Grid\text{-}Event} \quad (10)$$

With Impedances according Figure 4 and Figure 10.

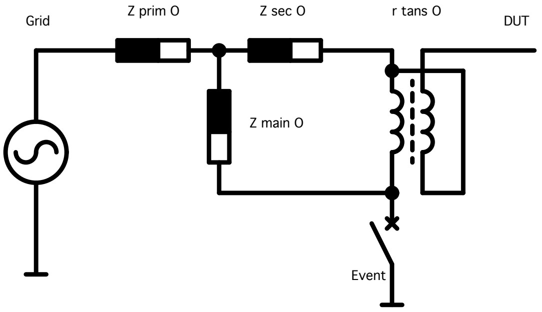

Figure 10: Auto Tranformer in OVRT Configuration

These transformer equivalent circuit diagrams have no simplifications regarding harmonics and can thus also be used for dynamic models.

VII. SUMMARY

This FRT test device based on auto transformer becomes more and more common. The test devices were used for validation processes not only at wind turbines, also in solar inverter unit and gas engine systems. The principal functionality was accepted in certification processes by different third-party certification bodies according the German validation processes.

In this paper three possible models for DUT model validation purpose were presented.

For general use the two-sources model can be used in any case but sometimes it is difficult to implement it in a standard model environment.

The "T" circuit diagram is close to the conventional used FRT test system based on simple voltage deviation of impedances. With this circuit diagram the equivalence to the proposal of the ICE 61400-21-1 as the international standard guideline can be discussed. As a feedback of the user the negative resistance, which are the results of the transformer effect, can often not be implemented in standard model environments as well. Further this model can only be used for RMS model validation.

The auto transformer model is closest to the physical structure of the test facility. The parameters transmission rate, main impedance and stray impedance can be found for two different equivalent circuits diagrams. From both models, however, the same no load transmission ratio can be derived.

VIII. OUTLOOK

It is assumed that a more accurate estimation of the basic Impedances gives a more precise model result. The autotransformer model needs to be investigated more also for the high frequency range in conjunction with capacity effects.

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