High Voltage Ride Through - Challenges of a 66 kV FRT Test Equipment

Rainer Klosse, EESYST Energie Elektrische Systemtechnik GmbH,
Blumenstr. 4, 26382 Wilhelmshaven, Germany, rainer.klosse@eesyst.de
Gregor Krause[1], Rayk Grune[2], R&D Test Systems A/S,
Großbeerenstraße 2-10, 12107 Berlin, Germany, [1]grk@rdas.dk, [2]rgr@rdas.dk
Sascha Heinecke, R&D Test Systems A/S,
Sigma 3, 8382 Hinnerup, Denmark, sah@rdas.dk

Abstract—

High-voltage power equipment like offshore wind farms is exposed to grid faults within its supplying high-voltage power network. It is desirable to perform standardized grid code testing directly on site including all turbine components.

The herein presented test equipment is capable to emulate the required undervoltage and overvoltage grid faults on the 66 kV high-voltage level without the need for additional transformers. Its mobile design allows the use at various test sites. Fully installed high-voltage wind turbine systems can be tested without further adjustments and under real environmental conditions.

Description of the test setup

A. Connection of an air autotransformer

Before and after an emulated fault event, the coils in each phase act independently of each other as series impedances between grid and turbine, compare figure 5. They are coupled via power switches during fault events to act as autotransformers. Undervoltage or overvoltage faults are generated depending on the autotransformer terminal connections.

The required switch gear consists of high-voltage devices. It is placed outdoors, but its layout and installation maintain overall mobility. It is designed and explicitly tested to withstand the demanding high voltage characteristics.

The test equipment is capable to perform free field measurements of undervoltage and overvoltage ride through (UVRT, OVRT) events. Multiple residual voltages can be generated in the range down from 0% up to 150% residual voltage. Balanced and unbalanced fault ride through (FRT) test sequences are realized by two-phase or three-phase synchronous closing of event switches. The clearance of a FRT test sequence conforms the opening characteristics of a standard circuit breaker. The contact of the phase with the first current zero crossing opens first. The contacts of the other two phases follow in the subsequent current zero crossings.

The characteristic of faults generated by the autotransformers' voltage divider and their clearance by circuit breakers is similar to real short circuits.

The coil design comes without an iron core which would be prone to saturation effects according to its nonlinear magnetic characteristics. The magnetic field passes air only. Therefore, faults can be emulated without additional saturation or inrush effects introduced by the test equipment.

B. Special challenges

A completely new transformer has been developed for this test facility. Basically, it is similar to a Peterson Coil used for arc suppression in distribution networks. However, due to the electrical and magnetic requirements this coil is much bigger in size. Standard dimensioning and layout tools do not cover coils of such sizes.

In contrary to conventional medium voltage FRT containers, the coils are placed outdoors and they must be weather protected. Coil cooling systems must span longer distances.

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

II. INTRODUCTION

Principally different test devices have different motivations for high-voltage FRT test systems. Conceptually, a distinction is made between medium voltage (below 36 kV) and high voltage (above 36 kV). The considered devices under test (DUT) are basically subdivided into onshore or offshore applications. In this article, a wind farm connected to the high-voltage network and a single wind turbine in a 66 kV offshore application are used as representative examples. However, the basic statements also hold for other decentralized power generation systems, battery storage systems and potentially also for consumption systems that are particularly relevant to the supply network (large consumers) or need special attention on security of supply (e.g. hospitals, emergency power for tunnel systems).

A. Onshore Wind Park:

Wind turbines are grouped into wind parks. From certain sizes, they have their own substations or share them with neighboring wind farms. In the onshore area, a common network is characterized by the gradation of extra high voltage, high voltage and medium voltage grids as shown in Figure 1. Usually transformers with the vector group of star - star (Yy) are connected between the extra high to high voltage grid. Whereas transformers in delta - star (Dy) connection are used to connect high and medium voltage grids.

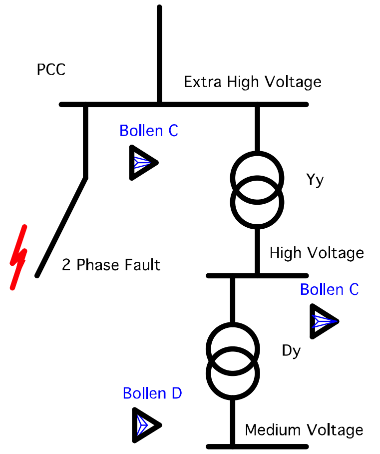

Figure 1: Unsymmetrical 2-phase fault at extra high voltage level

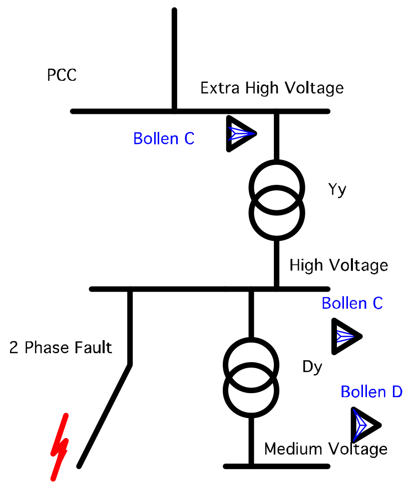

Figure 2: Unsymmetrical 2-phase fault at high voltage level

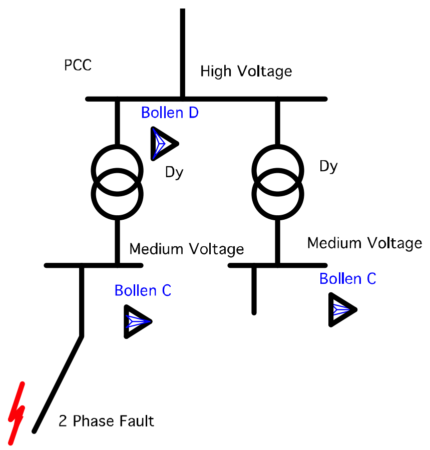

Figure 3: Unsymmetrical 2-phase fault at a nigbour medium voltage grid

If asymmetrical faults occur in the extra-high voltage network, like in Figure 1, they appear in the high-voltage network in a very similar way. The Bollen classification [17] is often used to describe the fault voltage vectors. See Figure 1 and Figure 2. Asymmetrical faults in the high and extra high voltage network can be classified as Bollen C based on the facts considered here. In contrast, the vector image changes from Bollen C to Bollen D when it is transferred between the high to the medium voltage network (Dy transformer). A 50% two-phase fault in the high voltage grid has a minimum line to line voltage of 66% in the medium voltage grid. Using symmetrical components for analysis, this corresponds to a negative sequence phase rotation by 180° of the voltage. while the positive sequence voltage decreases only in amplitude without any phase rotation.

From a traditional view, the 180° phase shift does not have any effect on synchronous machines. However, power electronic converters and protection systems are freely programmable. Systems need to be retested after each update. This fact alone does not justify the need for a high voltage test system. Even with passive medium-voltage test devices, i.e. test devices with the main components shown here, configurations can be found that generate equivalent voltage patterns in a more complex way. The difference is in the simultaneous change in the grid impedance. With medium-voltage systems, these cannot be represented in such a way that they resemble the high-voltage test equipment or the real faults. However, a converter-based system can control currents or voltages, and thereby consequently a referenced fundamental frequency impedance. The control performance of those converter-based grid emulators determines the achievable dynamic behavior.

Medium-voltage grids are mostly operated in radial switching position. If a fault occurs, the entire path is selectively switched off, if possible. Thus, the German grid code for medium voltage VDE AR-N 4110 has recognized that wind turbines do not have to remain connected to the grid in the event of voltage drops to near zero voltage. The high-voltage network has enough power to clear this kind of fault with sufficient safety margin. When the wind farm detects a fault close by, it should switch off. The aim of the general grid codes is to ensure that there is no fault-escalation in the network in the event of a dynamic grid fault.

Transmissions from neighboring medium-voltage networks can still cause visible faults in the wind farm, but the residual voltages remain above 70% of the pre-fault voltage. Asymmetrical faults propagate through the Dy interconnection of the transformers twice and fall back to the fault pattern according to Bollen C in the medium-voltage network of the DUT. The magnitude of the series impedance of such faults is usually smaller, so that a high-voltage test device in Bollen D connection still delivers good results with regard to the impedances.

B. Offshore wind turbine.

In offshore wind farms, electrical energy is usually transmitted from wind turbines to the grid on 66 kV level, which is classified as high-voltage network. The individual wind turbines are interconnected by rather short cable connections until the maximum power capability of the cable is reached. The individual cable strands are then brought together at a collection point. There, the power is transmitted to the consumers either via an AC link using a standard transformer or via a HVDC link.

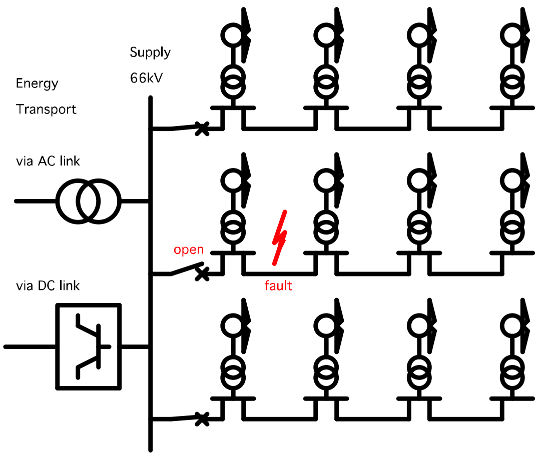

Figure 4: Fault in an offshore wind farm. Transmission to shore via AC transformer or HVDC line

No matter if connected through long lines of AC connections or through HVDC transmission systems, the short-circuit power is rather small compared to onshore connections. The individual strings are connected to their protection relays via their own circuit breakers. If the distribution system is disturbed at one point by a short circuit, this fault can be switched off quite selectively. Until the fault has been eliminated, the voltage in the entire offshore wind farm collapses considerably, mostly close to zero. This example shows the importance of the ZVRT. FRT tests down to low residual voltages can also be generated with passive test equipment at the medium voltage level. The voltage can then be brought to the connection terminal of the wind turbine via a step-up transformer (33kV/66kV). A ZVRT can also be generated without a load. If the wind power installation feeds the fault via a step-up transformer, a rise of voltage across the transformer occurs. Thus, the wind turbine itself ensures that there is always a residual voltage. However, the frequency is not linked to the feeding grid and can drift away. The phase drift will remain low due to the short time. But it can be significant in the test setup. Despite the voltage drop no real power is drawn by the dominantly inductive components.

In order to trim the medium-voltage test setup as close as possible to a ZVRT, the step-up transformer can be designed with a particularly low impedance. However, as a consequence the amount of iron in the step-up transformer practically increases. Increasing inductive charge effects will lead to additional inrush currents and non-linear voltage change. Probably depending on the quality of the overall grid and test simulation module this effect can be considered, but it is certainly not trivial. In simulations, different results between high-voltage test devices are therefore expected directly at the connection terminals of the wind power plants compared to a medium-voltage test device that is fed via a step-up transformer.

III. Implementation of the FRT Test Facility at High Voltage Level

A. *MV switchgear for HV requirements and challenges*

The principal circuit diagram of the FRT test system is shown in Figure 5. The entire medium voltage test system fits into a single ISO 40 feet container [1]. A HV test system is even bigger. The dimensioning of an outdoor realization is comparable to a more complex substation, see figure 6. Alternatively, a gas-insulated switchgear system would require several containers or a larger building, compare figure 7. Not only certification issues, but also cost differences, delivery times and technical factors must be considered.

- The space for an open field switchgear installation must be available.
- Requirements and constraints on portability, packaging dimensions, installation times, complexity of transport and the number of required heavy load trucks must be considered for such a HV setup.
- All components must be available for encapsulated setup and the configuration and combination of those must meet the test requirements.
- The risk of a component failure within a test campaign must be considered.
- Standard equipment is not designed for frequent switching operations in the first place. If a component fails, it must be accessible and quickly replaceable.

In the first high-voltage project, an outdoor system superseded any other option. However, this is still challenging considering the varying conditions.

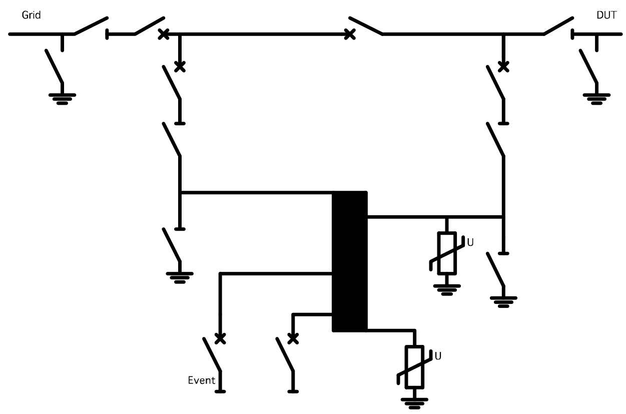

Figure 5: Principal Circuit diagram of FRT Test Unit

Figure 6: Outdoor substation components for High Voltage Test System

Figure 7: SF6 Gas isolated switch gear components for High Voltage Test System

B. Coil

Up to now passive FRT test devices reach rated voltages of up to 36 kV. In order to safely perform FRT events a sufficiently sized impedance is required. It fills one standard ISO container because of its physical dimensions [1].

If the grid connection voltage increases, from 33 … 36kV up to 66kV the impedance must increase by the square of the voltage increase - in this case by factor 4. Coils with iron core could be used. But they would cause non-linearities. Alternatively, air core coils are used. But their dimensions are significant and could in turn limit mobility, e.g. considering road bridge heights. The coil developed for this high voltage test system has a dimension that just meets European road traffic regulations and thus remains portable and also fulfills all requirements with regard to linearity.

C. Autotransformer

The test setup consists of three autotransformers, which are designed to generate amplitude jumps from 0% undervoltage to 150% overvoltage. No capacitors are required for the overvoltage test cases. A “clean” amplitude jump can therefore be expected in accordance with the grid connection measurement regulations. Oscillations in the network or a damped rise in voltage are not to be expected. With this test device, phase jumps can also be simulated combined with amplitude changes. Such experiments can be used to derive indications of grid forming characteristics of the DUT.

IV. Summary

New equipment for FRT testing of power generation units at high voltage level, based on an air-core autotransformer has been proposed. The presented FRT equipment is capable of testing high-power wind turbines and wind farms at 66 kV voltage level.

Several aspects of the design were presented and its challenges regarding the high voltage level were emphasized. Compared to similar FRT test systems for medium voltages, the total line impedance is very different during a fault event. Moreover, HV fault patterns not only comprise changing voltage amplitudes. They also include impedances and phase angle shifts.

The test equipment coil dimensions increase by the square of the voltage level of the device under test. The presented coil has never been developed and produced before. The air-core design provides a linear transmission behavior and prevents saturation effects like excessive inrush currents.

Whether the switchgear is designed for outdoor installation or for indoor installation using gas insulated breakers depends on many weighing parameters. Both realizations are conceivable.

V. Outlook

The test facility is expected to go into operation in 2021. A new dimension of onsite measurements is achieved once the tests succeeded and the equipment proofs to be reliable.

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