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Challenges and rationale for laboratory research of offshore grids

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Abstract

Offshore power systems will be characterized by a large penetration of power electronics converters and power cables, resulting in complex behaviors that can be quite different from traditional AC systems. Analyzing such systems is challenging due to their complexity and the relative lack of experience. In this context, performing laboratory tests in scaled down model network have significant relevance to verify simulation models and to test equipment and control methods in a controlled environment. The design of the laboratory needs to be a compromise between the capability to accurately reproduce the real system behavior and the practical constraints on ease of use, equipment size, cost and safety. This paper summarizes the main design considerations for a laboratory infrastructure dedicated to research of future offshore grids and the possible challenges. The laboratory facility developed jointly by NTNU (Norwegian University of Science and Technology) and SINTEF Energy Research is described with examples of the experimental possibilities.

Keywords: Offshore Grids; Laboratory Testing; Power Electronics, Model verification.

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1. Introduction.

In the last years the initiatives promoting the development of offshore grid infrastructures have been gaining a growing support worldwide. The plans for a North Sea Offshore Grid are probably the more concrete example within Europe [1].

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The transmission backbones for offshore grids rely on the HVDC technology since it represents the only viable candidate for transmission of high power with cables over long distances, and the grids will likely incorporate local AC and DC clusters. Thus, these power systems will be characterized by a large penetration of power electronics converters and of power cables resulting in complex behaviors that can be quite different compared to the traditional AC systems [2]. The dynamics of the system can be faster and its behavior during faults and interactions between components may not be easily predictable. The operation of such a complex infrastructure represents still a major challenge since no similar configurations are in operation today and only a limited experience is available. In addition, standard methods and tools for the analysis and operation of conventional AC transmission grids cannot be directly transposed to hybrid HVAC/HVDC cable-dominated grids due to their substantial differences.

Although numerical simulations are an essential analysis tool, performing laboratory tests in scaled down model network is a complementary method that can be used to verify simulation models and to test equipment and control methods in a controlled environment. However, the design of the laboratory needs to be a compromise between the capability to accurately reproduce the real system behavior and the practical constraints on ease of use, equipment size and cost, and safety.

The paper summarizes the main elements that should be considered for the development of a laboratory infrastructure dedicated to the research of future offshore grids and the possible challenges. In particular, considerations on the scaling factors and their influence are reported. Moreover, the laboratory facility developed jointly by NTNU (Norwegian University of Science and Technology) and SINTEF Energy Research is described as an example in the last sections; this description provides details on the structure of the laboratory, the characteristics of part of the equipment and examples of the experimental possibilities.

2. Simulations versus laboratory experiments

In the past decades numerical simulation has become an essential tool for the analysis of power systems since reliable results can be obtained with a relatively low effort. Software environments and simulation models have been developed and tuned to match the observed phenomena in the real systems. The validity of present numerical simulations is also the product of this extensive practical experience. The introduction of hybrid AC/DC systems and AC systems with a high penetration of converters raises doubts about the validity of current tools and methods since the power converters exhibit behaviors that are not present in rotating machines.

Any simulation-based investigation is based on mathematical models of the real physical objects to be studied. These models can never be true representations which reproduce every aspect of the real object, but they include only the properties that are assumed to be relevant for the actual investigation. Proper insight of the physics of the objects that are modeled and the consequences of the assumptions and simplifications that are made are crucial in order to get trustworthy simulation results. It is also crucial to know the validity limits of the models, when and where the deviation between the model and the real object becomes significant. This leads to necessity of cross validation of the models by means of experimental tests. Laboratory testing can give unexpected results, reveal that factors that were considered to be negligible or have been overlooked completely have significant effects, or that some of the assumptions that simulation models are based on are stretched outside their validity area. It may also reveal unexpected phenomena, especially when there is interaction between different components in a complex grid. These considerations are especially relevant when applied to complex systems on which only limited experience have been acquired [3].

Full scale experiments provide the most reliable results, but may not be feasible due to economic and safety issues, or simply because some components are not yet available at full scale. Laboratory experiments on scaled down physical models may be an alternative to reduce costs, size and risks. Downsized models can replicate the behavior of their full size counterpart, provided that simplifications in the scale model are correctly chosen.

3. Scaling effects

When a scale model system is designed it is important to know how the reduction of the rated values introduces scaling effects and changes the properties of the system. The choice of scaling factors is a compromise between conflicting requirements. The scaling effect of some of the major parameters is discussed in the following paragraphs:

3.1. Power

The power rating is directly linked to the price, size and cost of the equipment. It also affects the ease of handling and modifying the system. Low power systems with equipment rating in the 10 kW range can be modified quickly and easily, while high power systems in the MW range tend to require additional efforts and costs for preparation, rigging and modification. They also tend to be less flexible restricting the range of setups and experiments that can be easily performed. Short circuit power level and the amount of stored energy determine the damage potential in case of component failure, affecting the safety requirements.

The relative inherent damping caused by electrical and mechanical losses tend to increase as the power is scaled down, because the relative amount of resistance and friction tend to increase. This effect, which is especially pronounced at low power ratings, below 1 kW, makes low power systems more stable than high power systems. Increased resistance also gives shorter damping time constants in small electrical machines compared to large counterparts with similar design. This can be seen when data for 50 kW and 50 MW synchronous machines are compared.

The influence from measurement devices increases as the power is scaled down. Current drained by voltage measurements, and voltage drop caused by current measurements may influence the behavior of low power (1 kW) systems, especially when secondary effects, like ground fault handling in non-grounded power is studied. Power drawn by auxiliary circuitry, control electronics, fans etc. may be noticeable too when the power level is scaled down. The effect of this load can be removed from the model by using a separate auxiliary power supply system. This also allows undisturbed operation when the voltage in the model circuitry is severely disturbed.

3.2. Voltage

High voltage systems are potentially hazardous and require very stringent safety procedures and personnel qualification demands. The potential hazard is reduced when the system voltage is scaled down to the low voltage region. As long as electrostatic or insulation issues are not part of the investigation, scaling down the system voltage does not introduce large scaling effects, as long as the power level is scaled down similarly.

There are some natural choices for system voltage. The safe voltage threshold of 28V AC / 60V DC is an obvious limit for very low power (100W), bench-top equipment. The mains voltage level of 230V

/400V is a natural choice for medium power systems since all sorts of components and equipment for this voltage level are readily available off-the-shelf.

Passive components can normally be scaled linearly, while semiconductors may require more attention, as the voltage drop across power semiconductors tend to be fairly constant, in the 1.5- 4V range regardless of the rated voltage. This means that the relative effect of the voltage drop in semiconductors increases when the voltage level is scaled down. Another effect is that high-voltage semiconductors (1700V and more) tend to be significantly slower than low voltage semiconductors (600V and 1200V).

4. Components

Small versions of electrical machines as transformers and synchronous machines are readily available. A critical part of a converter model is its control system, which must operate very close to how the real one does in order to have a satisfactory representation of it. This is important in converter dominated grids as converter behavior is crucial to the system performance. A model grid should also have some form of centralized control that represents the real grid control system. As a real system control system has significant delays in measurement and control signal transmission, this delay should be represented in the model system too.

4.1. Power lines

True replicas of power lines or cables are usually not feasible in a laboratory setup, but line equivalents made with passive components can be used instead. Using inductors to represent the line inductance is sufficient in many cases. Line resistance can be represented either by the winding resistance or by additional resistors. An important aspect about these inductors is their saturation current that must be higher than the maximum peak transient current expected in the model setup.

For very high-voltage overhead lines and for long cables the effect of the line capacitance may be considered to be significant. This can be represented by a single PI equivalent, which consists of an inductor and shunt capacitors at the two line ends. When wide band frequency behavior is considered to be important, or when a very long cable is emulated, it can be represented by a cascade of PI-equivalents, each representing a small section of the line. This may be required when transient overvoltages and resonances in long cables are being investigated.

In multi-pole lines and cables there are mutual coupling between the lines; current in one conductor induces voltages in the neighboring conductors. Proper representation of this requires more complex networks containing coupling transformers and capacitors [4]. Similarly, accurate representation of the impedance seen by ground currents may be obtained by common mode inductors, which actually is a form of combined coupling transformer and inductance. Attention to magnetization currents and saturation is required, as the ground currents may contain both low, sub-synchronous frequency components and DC components.

4.2. Prime movers, motordrives

As real diesel engines, wind turbines, etc. may not be very practical in a laboratory scale model, induction motors and inverters can be used to represent the prime movers which drive synchronous and induction generators. Scalar control mode is not a good choice as inverter control method, as it does not give precise control of the torque, even though it can keep the speed fairly stable. Vector control mode is instead preferred as it gives fast and stable control of motor torque. The motordrive must have a speed limiter function, because a vector control drive does not have any natural maximum no-load speed. The torque reference signal is given by a more or less complex outer control loop that emulates the behavior of a prime mover and its governor. As the motor speed is crucial for this control loop it is usually necessary to mount a speed sensor, a pulse encoder to the motor axle, in order to get a good speed signal. A basic speed regulator may be sufficient for the outer control loop many cases. It has two main control signals: Speed reference and maximum torque limit. Droop control is usually required in order to control the torque when a PI regulator governs the speed of a synchronous generator that is connected to a large grid.

More elaborate models of the prime mover, as the turbine and governor characteristics, the waterway dynamics for a hydropower plant or the aerodynamic properties of a wind turbine can be used when a more accurate representation of its dynamics is required. This function can be performed by some form of process controller that gives torque reference signal to the motordrive converter. In such a system the total signal propagation time through the control loop is an important factor that may limit its performance.

The inertia of the motor- generator set should match the inertia of the prime mover it represents. Emulation of additional inertia can be done by the prime mover emulator, provided that the control loop is fast enough. The prime mover–governor model gets its reference signal from a higher level control system in the same way as in the real case.

Inverters with diode rectifiers are not able to handle bidirectional power flow. When braking capability is required a brake chopper and resistor must be added, in order to handle short braking transients. Using an active rectifier instead of a diode rectifier allows for continuous braking operation.

5. The Renewable Energy System Laboratory at SINTEF Energy Research and NTNU

A Renewable Energy System Laboratory has been established jointly by SINTEF Energy Research and NTNU. It is essentially a power grid laboratory and has been developed gradually during several years, and is still being extended and upgraded with new equipment. A main design target has been to make the system as versatile as possible, suitable for research in a wide range of fields. Parts of the system are made as fixed installations, while other parts are made as movable items that can easily be rearranged.

Figure 1 Some of the equipment in the laboratory.

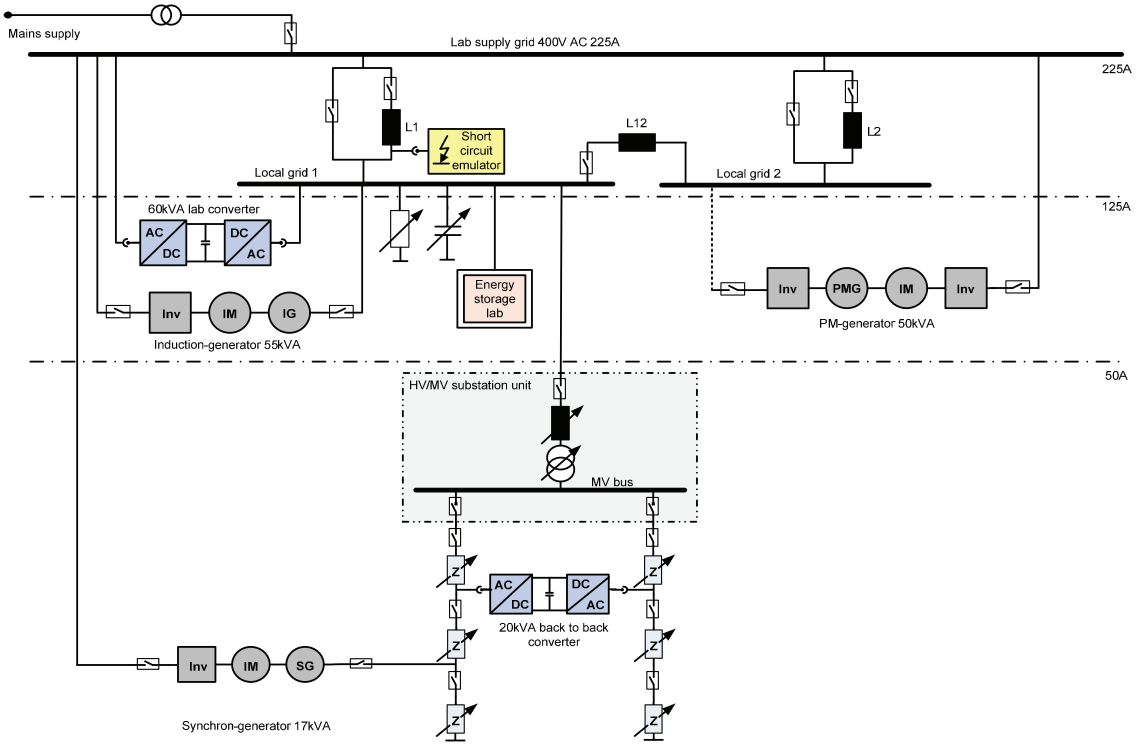

Figure 2 Laboratory network overview

Examples of component oriented research are test running of electrical machine prototypes and experiments with control methods for grid connected converters. Examples of power grid related research are transient and fault handling in power systems, fault ride through for various loads and sources, and network operation and protection during weak grid and islanding conditions. The laboratory can also be used for experiments regarding operation and fault handling in converter dominated systems, with little or no rotating machines, and for multiterminal HVDC systems as models of a North Sea offshore transmission system connecting offshore wind farms, oil and gas installations and multiple countries.

The system voltage is 400V, 50 Hz three-phase without neutral conductor. Nominal unit rating is chosen to be 50 kW. A corresponding rating of 70 kVA allows for equipment with low power factor. This gives an equipment grid connection rated for 125 A. Power supply and grid busbar cabling are designed for the combined power of two units, ca 150 kVA. This is obtained by a power supply and busbar rating of 225 A. Short-circuit current at the intake is estimated to 4 kA. That gives a 50 Hz short-circuit impedance of 3%, related to a 70 kVA unit rating.

Various types of equipment are connected to the busbars in the lab. Some of the main equipment is:

- Water cooled resistor bank. Adjustable in steps from 2 kW to 55 kW.
- Capacitor bank for reactive compensation. 5x 10 kVA
- Induction generator. 55 kW. This type was used in fixed speed wind turbines. Connected to one of the busbars via a thyristor soft starter, which can be replaced by a full power VSC converter set which allows for emulation of a variable speed generator.
- Small synchronous generator with brushless magnetization. 17 kW. It has exciter and protection equipment that is typical for small (1-10 MW) hydropower plants.

- 50 kW low speed (30 rpm) permanent magnet synchronous generator. It is mounted on a machine test bed, and is driven by an induction motor via a gearbox. This is a scaled prototype for a direct drive wind turbine generator.
- Short circuit emulator, consisting of large (1400A) antiparallel thyristors and inductors. It can expose the system for low ohmic voltage dips that starts at a specified phase angle, and lasts for a specified time. The depth of the voltage dip is determined by the ratio between the inductors [5]

Attached to one of the local grid busbars is a distribution grid model. It consists of a model of a 66kV/22kV transformer station with a 25 kVA transformer and protection equipment typically found in such transformer stations. Two outgoing lines are represented by inductors, capacitors and resistors that represent sections of overhead lines. The 17 kVA synchronous generator is connected to one of these branches, representing a remote hydropower plant connected to a countryside distribution line.

5.1. Converters

Four 60 kVA DC/AC converters and one 20 kW back to back AC/DC/AC converter are available in the lab. These consist of an IGBT transistor converter core, LCL smoothing filters, switchgear and control electronics. The use of an in-house developed control system allows full insight into all details of the control system, with no black boxes [6,7]. The control system, which runs on a processor system that is embedded in FPGA (Field-Programmable Gate Arrays), is highly configurable. Active current is controlled either directly by a reference current signal, by a DC link voltage regulator, or by an AC grid frequency regulator. Reactive current can be proportional to the active current or governed by an AC grid voltage regulator operating as a static compensator. A motordrive variant of the control system is used for generator control. Active current is here given by torque or speed control, and reactive current by magnetization control. CAN bus is used for communication between converters and a higher level control system, in order to transfer measurements and status signals to the control system, and reference values and commands to the converter.

5.2. Instrumentation

Busbar voltage and current on most of the busbar connection are being measured mainly by Hall element based sensors. Their ability to measure DC components properly was preferred to the precision that could be obtained by measurement transformers. Measurement signals are both available at BNC connectors for oscilloscope investigation and as signals to a set of distributed data acquisition units. Signals from these are gathered in a PC running a LabView-based data acquisition and presentation system. This system is also used to control the model network, since it provides control signals to the main circuit breakers, commands and references to the prime mover emulating inverters, and the power electronics converters in the system, resembling the function of a centralized supervisory and control (SCADA) system for the laboratory network. The PC based system can also be extended and supplemented by other modules, which can perform tasks as emulating wind turbine models etc. accurately. Elspec voltage quality monitoring instruments are installed at selected points in the system, in order to give continuous monitoring of the state and of events in the system similar to a real power grid.

5.3. Future extensions

The laboratory infrastructure is upgraded, and new equipment are purchased or built in order to extend its experimental capabilities according to the requirements of the research projects that use the laboratory. Examples of future extensions that are already planned are:

12 pulse thyristor HVDC link, with transformers, filters and control systems as found in large HVDC links. This can be used to investigate power flow in complex systems, and interaction between various types of converters, and hybrid HVDC systems containing both current and voltage source converters.

50 kW synchronous generator. It would allow experiments on load flow and frequency management when multiple non-synchronous networks are connected.

A 16 kW photoelectric solar panel is installed at a south facing wall of a building in the vicinity of the laboratory. Power from this solar panel is normally fed into the grid but a cable that connects the solar panel inverters to one of the laboratory grid busbars is going to be installed.

A low voltage transformer, with 400V TN-S secondary circuit will be connected to the distribution line model. Various types of loads will be connected, as resistor loads, induction motors, and rectifiers.

6. Conclusions

Laboratory experiments can be used to as a complement to simulations, in order to verify models, and to explore areas that are not well covered by existing simulation models. The difference in power and voltage rating between real world system and the scale model introduces scaling effects that must be observed, and handled properly.

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