A Prototype 3.2 MW Flux-Switching Permanent Magnet Drive for Large Wind Turbines

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***Abstract*—Previous papers have presented proof-of-concept results for using a flux-switching permanent magnet (FSPM) machine combined with a parallel connection of converter modules as a drivetrain topology for direct drive wind turbines with high power ratings. This paper presents results of our continued investigations, including experiments done on a 3.2 MW rated prototype system. Test results for the prototype demonstrate that this system can easily master low-voltage ride-through events. Further characteristics of the new drivetrain topology are: a strictly modular structure, high efficiency, and high availability due to fault-tolerance, while maintaining low cost.**

I. Introduction

Currently, wind turbine manufacturers are pursuing cost-effective drivetrain technologies for increasing the power ratings of individual turbines, for increasing turbine reliability, and for standing up to ever more stringent grid codes. Market data up to and including 2015 shows that wind turbine drivetrains with direct-drive and full-power converters are steadily gaining market share [1]. While in Europe DFIG systems have been continually losing on popularity due to high renewables penetrations levels and strict grid codes, they remain popular in North America and Asia. Amongst the higher power wind turbines, there is a clear trend toward reducing gear stages or entirely eliminating the gearbox. The steadily falling costs of power electronics converters continue to increase the benefit of using full power converter systems. Several prominent turbine manufacturers are pursuing modular drivetrain components due to the many benefits this provides, including for transportation, installation, and maintenance [1].

As described in [2], the drivetrain solution with a novel flux-switching permanent-magnet (FSPM) generator coupled with a modular, parallel-connected full-power converter has great potential for addressing these pressing issues. The design of a 500 kW demonstrator unit was presented in [3]. Latest technological advances have been achieved by the design, construction, implementation and tests of a 3.2 MW prototype, a system designed for a light-wind location (see Fig. 1). These tests were successful and cast the FSPM machine in a positive light regarding its potential for use in future high-powered wind turbines.

Using an FSPM generator has several advantages for a high-power, high-torque, low-speed generator, these include:

- *Segmentation*: Easily accomplished for both rotor and stator; Provides convenient and inexpensive manufacturing and logistics; Enables segment-swapping for on-location repairs
- *All active materials in stator*; Improved cooling; Easy encapsulation in epoxy–excellent corrosion protection
- *Embedding of magnets in stator pockets*; Physical protection of magnets; Improved magnet cooling

Myriad sources cite the benefits of modularity for constructing a power converter (e.g. [4]). The modular parallel multilevel converter here is unique due to a special type of multilevel modulation; its particular benefits include:

- *Inexpensive and technologically mature low-voltage IGBTs*
- *Innovative multilevel modulation*: Low IGBT switching frequency; High line-side control and current ripple frequency; Fast reaction to grid disturbances; Filter-less operation (increases availability, reduces cost, losses and space requirements)
- *Intelligent distributed control electronics*: Very high failure tolerance; Fast reaction to grid disturbances

This paper gives an overview on the 3.2 MW prototype system. Section II describes the FSPM generator including its structure, optimization, and characterization. Section III describes the converter and its control system. In section IV, experimental tests results are presented for the 3.2 MW

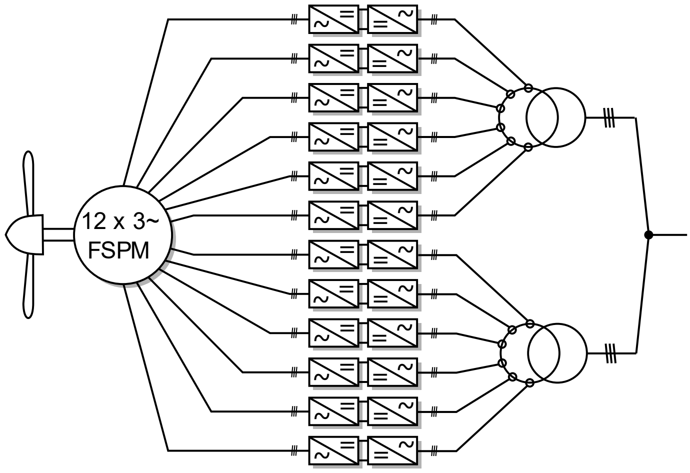

Fig. 1: Block diagram of the 3.2 MW wind turbine drive system with FSPM generator, 12-module modular converter, and dual multi-winding transformers.

prototype converter and generator, attained at a high power nacelle testing facility [5].

II. Generator

A. Flux-Switching Permanent Magnet Machines

Fig. 2 shows the basic construction of a flux-switching permanent magnet (FSPM) machine. This type of machine has been described in several publications to date (e.g. [6], [7]), but it will be briefly described here as a reference to the reader. Both rotor and stator have salient teeth. The stator is made of stacks of U-shaped laminations; in between these stacks are permanent magnets, magnetically oriented in alternating tangential directions. The windings are realized as concentrated windings around each tooth. The rotor consists of laminated steel sheets. As the rotor rotates, the rotor teeth serve to channel the flux from the permanent magnets, causing the flux linkage through each winding to alternate, approximately sinusoidally, between negative and positive peaks ("bipolar flux principle"), which induces a voltage on the winding terminals.

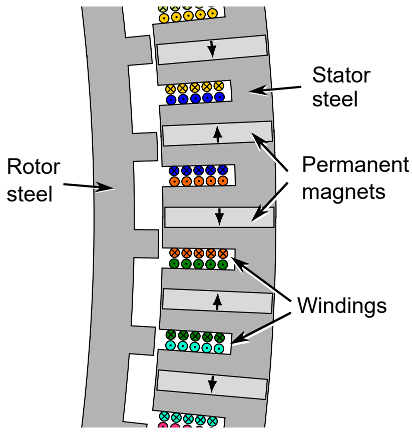

Fig. 2: Basic cross section of the large diameter FSPM machine.

The frequency f_e of the generated emf and current are a product of rotational speed n_g in rpm and rotor tooth number N_r per

$$f_\mathrm{e} = N_\mathrm{r} \cdot \frac{n_\mathrm{g}}{60} \quad (1)$$

The phase relationship between the emf of each tooth is dictated by the ratio of rotor to stator teeth; by connecting windings with the same or similar phases in series, the amplitude can be increased. Three-phase systems can be established by selecting three winding groups with phase separations of 120 degrees and connecting one end of each winding to a form a star point.

The multiphase FSPM machine is currently gaining momentum for use in large direct drive turbines due to its technically comparable performance to the more established permanent magnet synchronous machine (PMSM) coupled with several important advantages. Some well established advantages include the simple, robust rotor, the improved cooling capability for the stator-bound magnets, low short circuit current, and reduced copper weight and losses due to the small end windings.

One further advantage relates to the air gap. Since the permanent magnets of an FSPM machine are placed inside stator pockets by design, they are extremely well protected against mechanical damage and corrosion. With a conventional PMSM, the magnets must be mechanically affixed to the rotor in a very stable way, which means that some portion of the air gap will necessarily be sacrificed for mechanical attachment (e.g. adhesive), which can be foregone with the FSPM. Furthermore, in a PMSM, the size of the air gap is important for the cooling of the magnets; in an FPSM the magnets are cooled by conduction via the stator back iron. First investigations show that the air gap of a large-diameter FSPM can be roughly 20-30% smaller than an equivalent PMSM, which has a significant effect on the developed torque and torque density (specific thrust).

At first glance, the FSPM seems to have a significant drawback with its relatively low power factor, which is a result of the comparatively high inductance of the machine compared to an equivalent PMSM (found for example in [8] and confirmed by the authors). For this reason, the current-carrying capability of the generator-side power converter must be increased to accomodate the reactive current draw. However, when a holistic approach is taken to optimizing the investment cost of the drive system including both converter and generator, the slight increase in converter cost is quickly outweighed by a much higher decrease in generator investment and operating cost. Furthermore, power converter price is generally expected to continue falling as the technology matures, whereas generator cost will remain largely a function of raw material prices.

B. 3.2 Megawatt Prototype Generator

The 3.2 MW prototype generator was designed using finite element analysis (FEA) to determine its electromagnetic properties. A Pareto multi-parameter optimization method was used to select an optimal design based on a trade-off of low permanent magnet material weight, low copper losses, power factor, and high torque density (see [3]). Table I shows the data from the 3.2 MW prototype machine.

TABLE I: Data from the 3.2 MW prototype generator.

Manufacturer	Venpower GmbH
Stator segments	24 (2 segments per 3-phase system)
Rated electrical power	3.2 MW
Rated speed	12.4 min^{-1}
Rated torque	2.6 MNm
Power factor at rated power/speed	0.63
Rated voltage (line-line, rms)	670 V
Rated electrical frequency	52 Hz
Cooling	liquid

The choice was made to construct the stator using 24 segments. Two segments (a "segment pair") generate one three-phase electrical system, and are connected to one of the twelve converter modules. The segments were designed to have a mass of less than one Metric ton to simplify transportation, installation, and handling; furthermore, they were manufactured at a facility with relatively small room

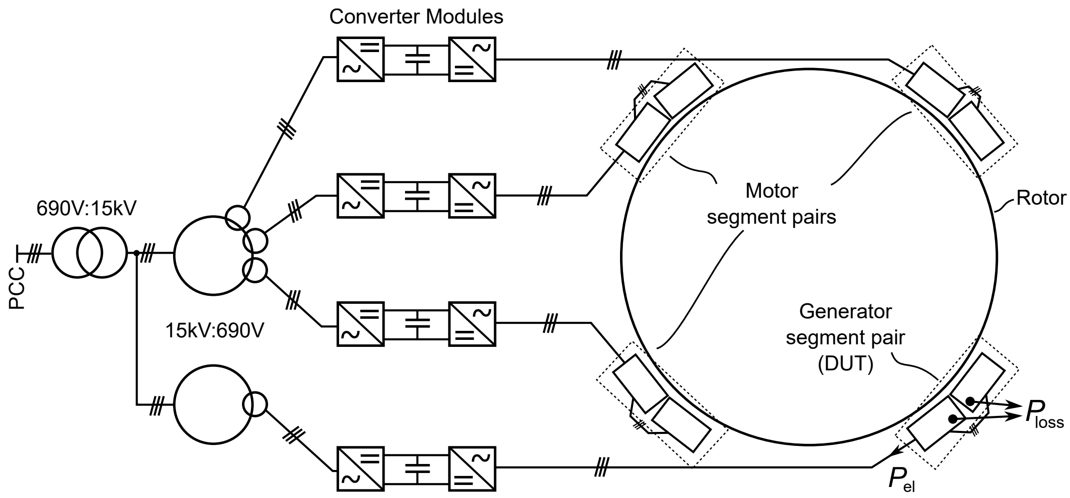

Fig. 3: Test setup for generator characterization experiments.

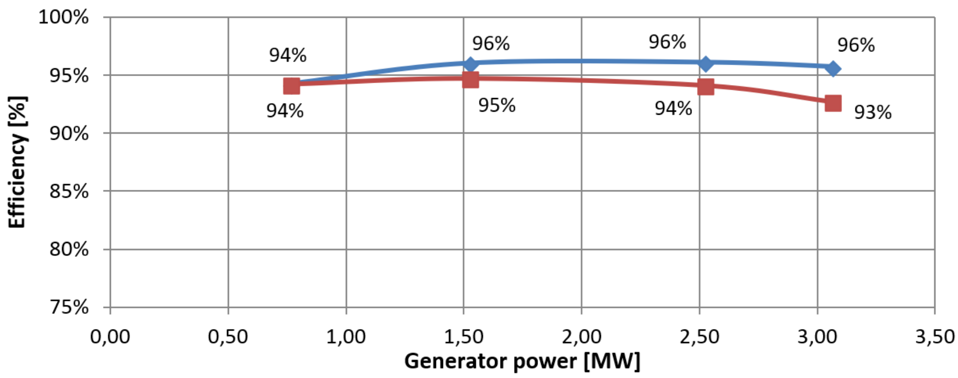

Fig. 4: Measured efficiency Vs. electrical power (at terminals) of the 3.2 MW prototype FSPM generator (red: measured; blue: estimated efficiency of a new winding design for reduced proximity effect).

size and low ceiling height. Each segment is equipped with water cooling, which allows heat withdrawal to occur with a very close coupling to the permanent magnets: the most heat-sensitive components. This is in stark contrast to a conventional permanent magnet synchronous generator with the magnets affixed to the inner or outer rotor where only air cooling is possible.

C. Characterization of FSPM: Efficiency and Thermal Performance

A unique quality of the modular system was leveraged in order to test the generator segments at rated power. By operating a number of generator segment pairs as motors, the rotor speed can be adjusted and controlled without any additional external driving motor. Then, other segment-pairs can operate in generator mode to “load” the machine. These generator segment pairs and the corresponding converter modules are thus operating under rated conditions and can be investigated by way of “heatrun” experiments. Fig. 5 shows this setup with 3 motoring segment pairs and one device-under-test (DUT) segment pair.

Using this test setup, temperature sensors were used to monitor the temperatures at several spots within the DUT. The electrical output power of the DUT segment pair was measured using a calibrated power measurement device. Information on segment losses was measured calorimetrically by leveraging the measured ingress and egress temperatures of the cooling water, as well as its flow rate, in conjunction with thermal simulations using Solidworks. The red line in Fig. 4 shows the measured efficiency at five operating points. The slight reduction of efficiency as the power increases up to its rated values is due mainly to an increase in copper losses due to excessive proximity effect.

D. Lessons Learned

Of course, many lessons were learned with the 3.2 MW prototype machine. Adaptations to machine geometry cause the torque density to increase from 40 kN/m^2 to 60 kN/m^2 with only a slight increase in the amount of permanent magnet material. Also, due to geometrical design, the cogging torque is reduced from 3% to around 0.3%, which could be reduced even further by skewing the rotor or torque ripple compensation via current control (see [9]). By modifying the winding design the proximity effect can be reduced, increasing the efficiency as shown with the blue line in Fig. 4.

III. Modular Parallel Multilevel Converter System

Since the FSPM generator can so readily be constructed to output energy via multiple isolated three-phase electrical systems, it is quite natural to extend the same degree of modularity to the converter system, as achieved by the Modular Parallel Multilevel Converter (MPMC). The basic idea of this converter is, as described in [2], that each three-phase winding system of the generator is equipped with its own back-to-back, 3-phase, low-voltage, voltage-source IGBT converter module which is responsible for transferring the harvested energy to the power grid. On the grid side, the respective phases of the parallel converter modules are connected to each other over an inductance; if this inductance is derived from the stray inductance of the secondary windings of a multi-winding transformer, then the system can operate with no grid filter. This is very advantageous, since the high cost, instability, and low reliability of grid filters can be eliminated.

The control system is highly distributed; each converter module is equipped with a local FPGA/DSP control platform. Redundant central control platforms which communicate directly with the local units using dedicated 100 Mbps Ethernet lines (see [10]). On the generator side, each converter bridge is controlled independently by one of the local controllers; this is possible, since the three-phase systems are electromagnetically independent of each other. A torque reference is realized via a stationary dq-frame current controller with pulse-width modulation.

On the grid side, a voltage-oriented control scheme is computed in the central control platform, and the grid-side IGBTs are modulated as a multilevel converter. A system with n parallel converter modules can generate output voltages with $2n - 1$ levels.

A proprietary multilevel modulation technique was used whereby the grid-side current controller cycle frequency f_{ctrl} is a multiple of the average grid-side IGBT switching frequency $f_{\text{sw,grid}}$ per

$$f_{\text{ctrl}} = n \cdot f_{\text{sw,grid}}. \tag{2}$$

For example, with $f_{\text{sw,grid}}$ = 2.5 kHz and n = 6, a control frequency f_{ctrl} of 15 kHz results. In contrast to other published methods like phase-shifted PWM, this technique provides much higher control dynamics due to the boosted control frequency. This enables the system to easily react to disturbances like the grid voltage step of a voltage dip. Despite retaining very high control dynamics, the semiconductor switching frequency remains low.

As seen in Fig. 1, the 12 converter modules are arranged into two “converter systems”: groups with 6 converter modules each. Each converter system is associated with one dry multi-winding transformer. By using two transformers, each rated at half of the total system power, further fault-tolerance is attained. One of the converter systems is shown in Fig. 6a. Data on the converter modules and multi-winding transformer is given in Table II.

TABLE II: Power converter system data.

Converter Module (each)	
Manufacturer	Venpower GmbH
Rated power	650 kVA
Voltage, DC-link	1150 V
Gen.-side switching frequency	1-2.4 kHz
Grid-side switching frequency	1-4 kHz
IGBT Modules	650 A, 1700 V
Multi-Winding Transformer	
Manufacturer	Starkstrom Geraetebau GmbH
Rated power	1650 kVA
Number of secondary winding groups	6
Rated primary voltage (line-line, rms)	15 kV
Rated secondary voltage (line-line, rms)	690 V

IV. Experimental Test Results

Extensive testing of the generator and converter was conducted at the Fraunhofer IWES DyNaLab facility [5]. At this facility, entire wind turbine nacelles can be installed in an indoor test rig. A high-power wind simulator motor is mounted to the rotor of the nacelle-under-test, and the medium voltage cables which export the harvested energy to the grid are connected to a high-power multi-level grid simulator converter. Highly reproducible wind profiles can thus be used to type-test the drivetrain, as well as other inner-nacelle components. Data on the nacelle testing rig is shown in Table III. Fig. 6 shows the 3.2 MW FSPM prototype being installed at DyNaLab.

TABLE III: Data on the DyNaLab nacelle testing facility.

Wind Simulator Motor	
Manufacturer	Lloyd Dynamowerke GmbH & Co. KG
Rated power	10 MW
Peak power	15 MW
Rated torque	8.6 MNm
Peak torque	13 MNm
Grid Simulator Convenrter	
Manufacturer	ABB
Rated power	44 MVA
Voltage	up to 33 kV

While there are many grid codes which a wind turbine must satisfy, including harmonic content, power controllability, and power characteristics as a function of frequency and voltage, the sudden voltage “dips” of the low-voltage ride-through (LVRT) requirements are one of the most challenging. In order to prevent wide-spread grid destabilization during grid disturbances for increasing levels of distributed energy generation, distributed generating units are required to stay connected to the grid and inject reactive current for short-duration faults (for most grid codes, durations up to around 2 seconds). In particular, the DyNaLab facility has an excellent capability for testing and simulation of grid faults (similar to [11]). Since the “grid” is generated entirely by a power converter, it has very high flexibility.

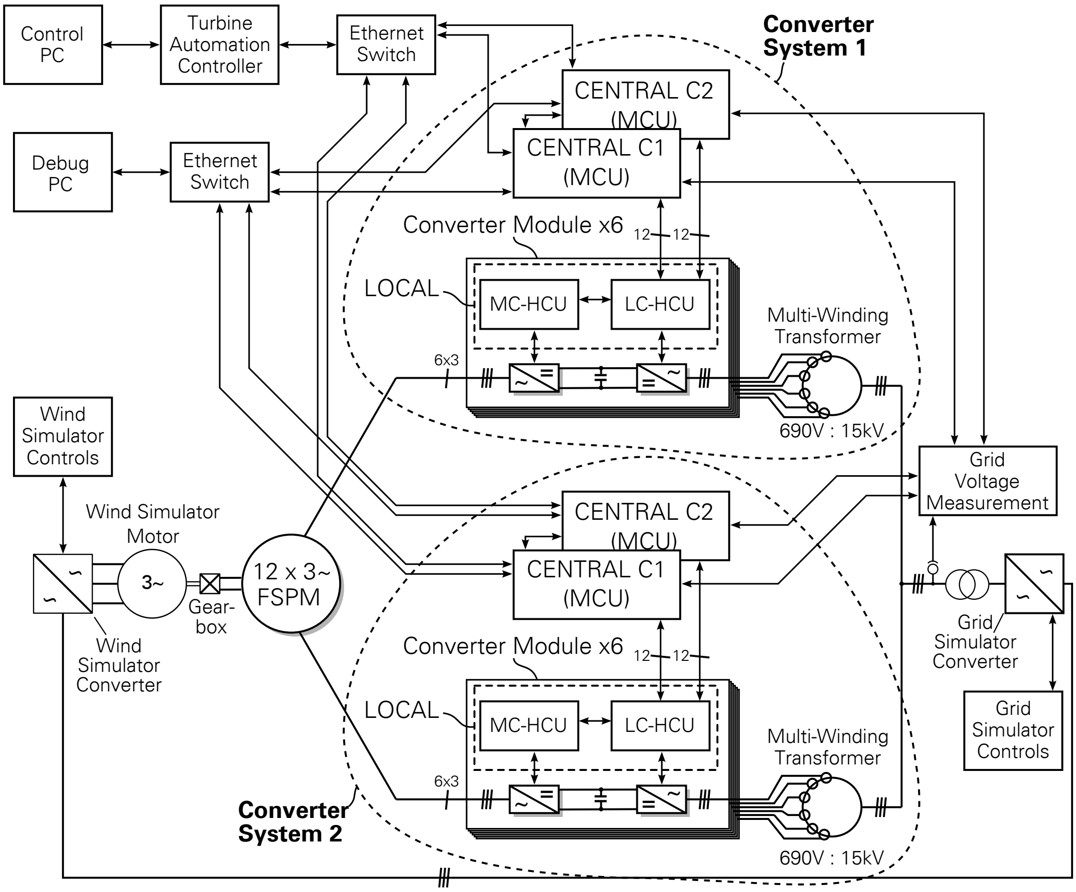

Fig. 5: Block diagram of system under test at the DyNaLab nacelle testing facility (source: [12]).

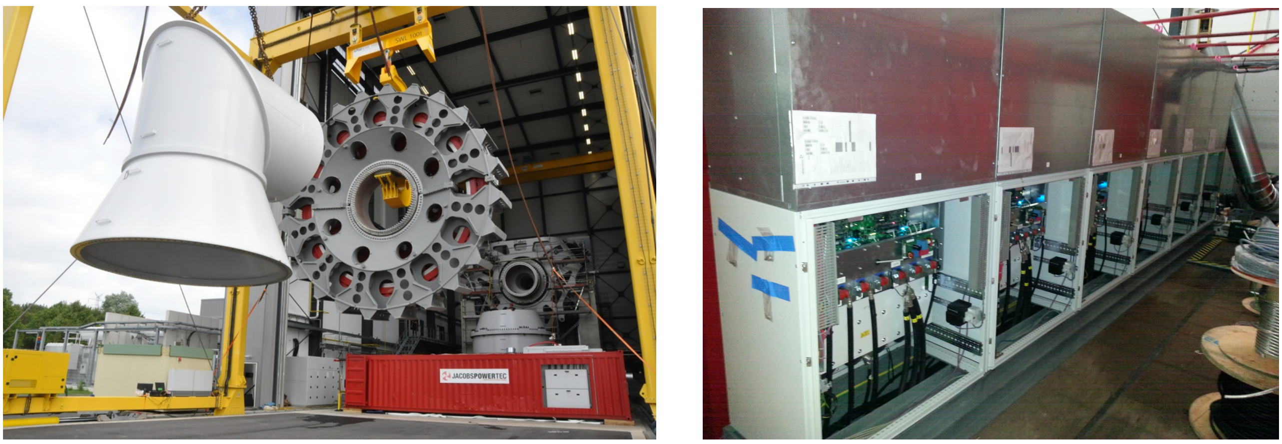
Fig. 6: (left) Assembly of the 3.2 MW prototype at the DyNaLab facility. (right) One “converter system” with 6 converter modules.

When the grid voltage drops, the grid-side currents rise rapidly since the voltage drop over the grid-side inductivity is high. There is a finite delay for the propagation of voltage measurement, to when the controller detects the dip. Once this has taken place, the grid-side controller has the ability to react, but the reaction to this grid-voltage step function will usually take several control periods to adjust gate pulse duty cycles.

Fig. 7 shows measurement results for two different operating points. On the right diagram, at around t=0.05 s, a converter fault was simulated by artificially triggering a converter module critical error. As is seen, the remaining modules continued operating with no pause in operation. It should be noted that all testing was done with no grid-side filter: only the fairly low inductance of the multi-winding transformer between the converter and the grid was used.

Due to the boosted control frequency of the prototype multilevel modular converter system, this reaction can be very fast. One, two, and three-phase voltage dips of varying durations and depths were readily mastered. Figs. 8 and 9 shows the result of two LVRT tests.

V. Conclusion

First results were presented for a novel 3.2 MW prototype drive for a wind turbine. The drive features a flux-switching permanent magnet (FSPM) generator with highly modular construction and a parallel connection of low-voltage IGBT back-to-back 3-phase converter modules. The results show that the prototype generator has an efficiency of 93-96 %. Testing done on the DyNaLab test rig show how it easily mastered low-voltage ride-through testing, and how the systems fault-tolerance was proven in action.

VI. Acknowledgments

This work was supported by European Regional Development Fund, the State of Brandenburg, and the Federal Republic of Germany. The authors would like to thank JacobsPowertec and Fraunhofer IWES for their support for testing the prototype drive.

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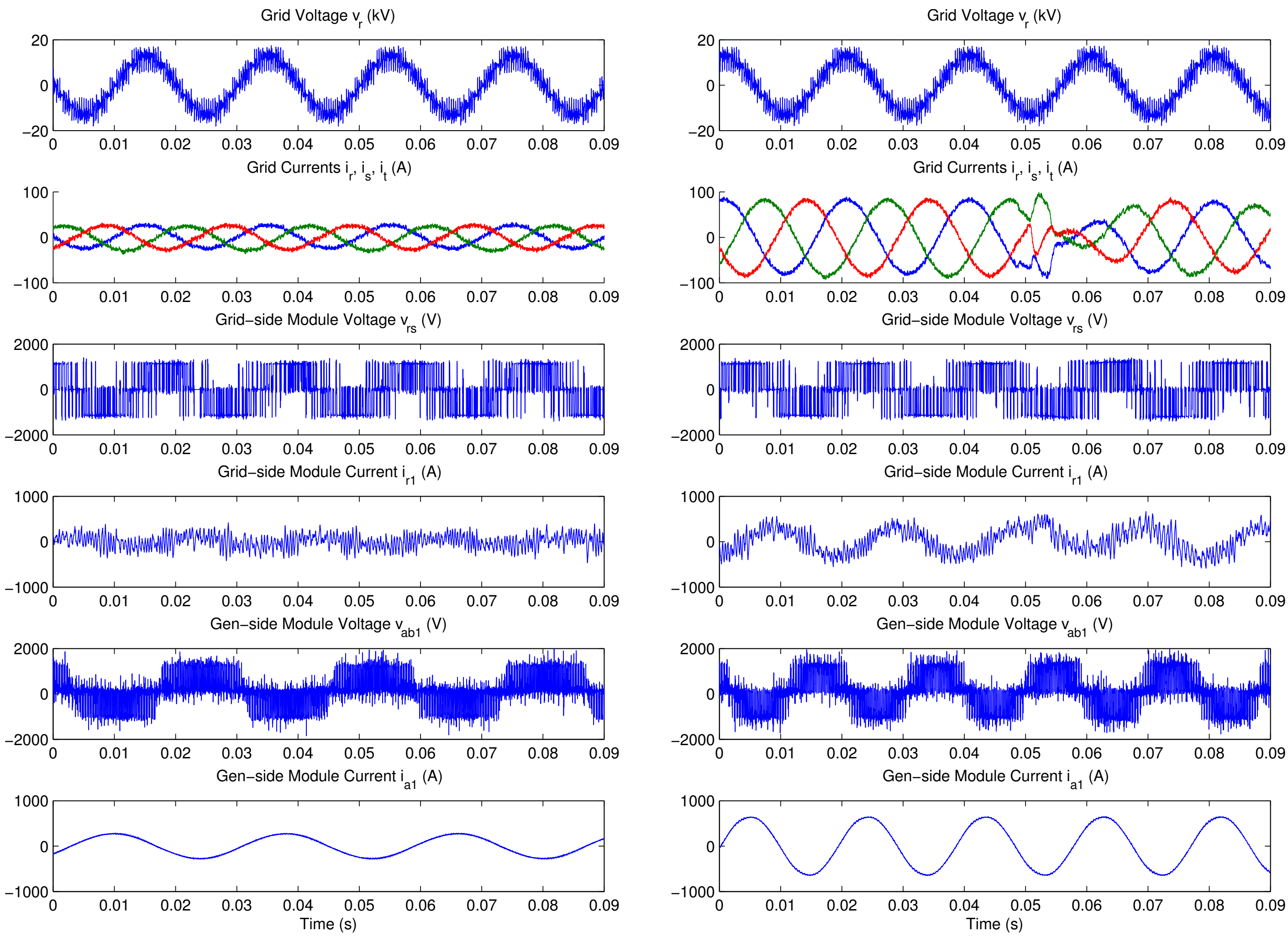

Fig. 7: Measurement results with one converter system, (left) 8.5 rpm, 650 kNm, (right) 12.4 rpm, 1500 kNm.

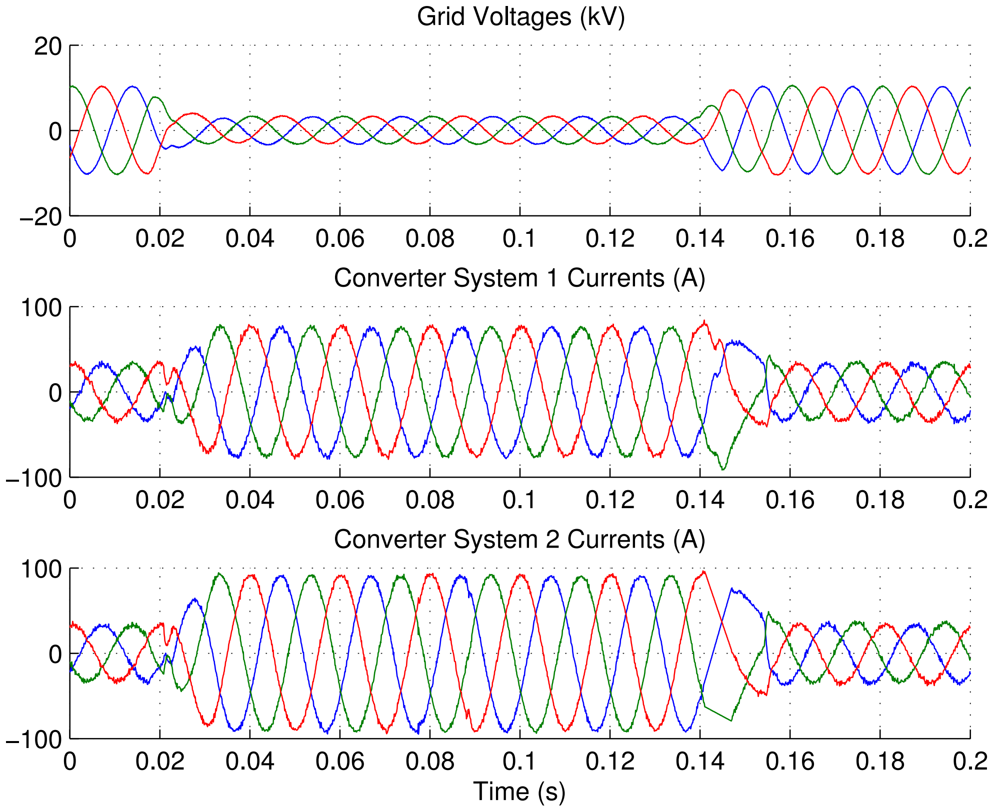

Fig. 8: Low-voltage ride-through (LVRT) test with both converter systems; generator off; dip down to 30% for 120 ms with 11 converter modules. Grid voltage is filtered, and the currents are the sums of the secondary-side currents measured by the converter, and scaled ($\cdot 690/15000$) in post-processing to be equivalent to the primary-side (phase shift is not compensated).

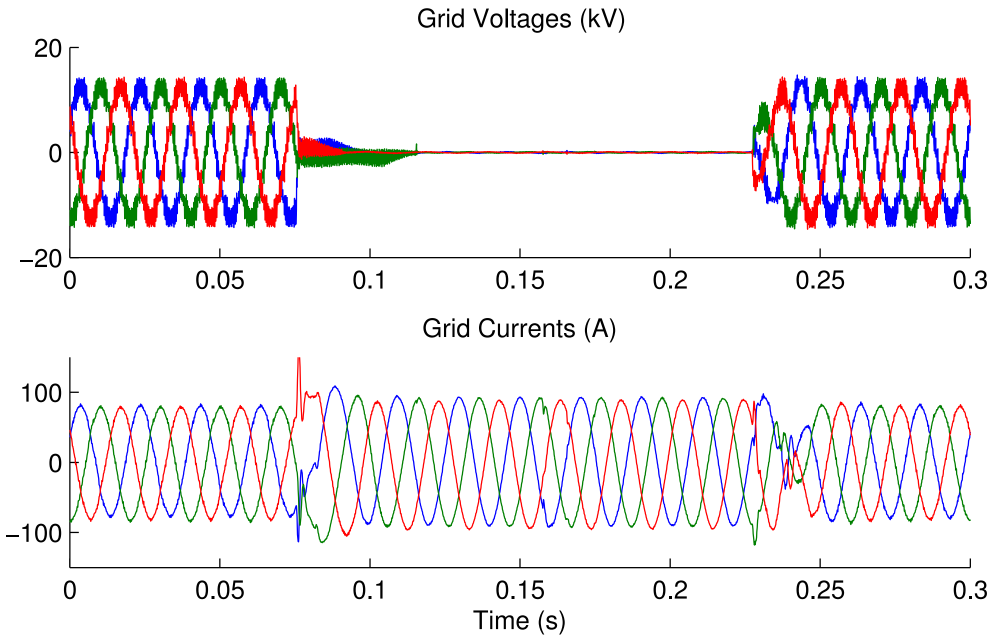

Fig. 9: Low-voltage ride-through (LVRT) test with only Converter System 2 (6 converter modules), dip down to 0% for 150 ms with 6 converter modules, each at rated real power.