New method and hardware for grid-connection of wind turbines and parks

by

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Keywords

Fault handling, stress release, turbine protection, grid connection, innovative solution of technology

Abstract

The paper describes a novel method and a cost-effective hardware—Transient Booster—to handle wind turbines and parks during grid faults. The drive-train is released from mechanical stress during faults. At the same time, collection and transmission grids are released from electrical stress during grid faults. The method and hardware are especially attractive for emerging park demands. They form also a basis for reviving existing turbines at sea as well as on land to fit with new or expanded grid code. Both system performance and conversion efficiency are kept normal during hitherto controlled operation.

1. Introduction

Several grid connection requirements, grid-codes, for wind turbines exist today in DK, UK, DE, IE, … Some grid codes are described in references [A - F]. They are under harmonization in EU. It is known that there is sincere lack of simple and reliable solutions to codes covering grid faults when connecting large wind turbines and parks to mains, i.e., transmission and distribution, T&D, power networks.

1.1 Problem description

Problem 1: Avoiding wind power generation park disconnection during grid voltage dips is the main one. This problem can be expanded as: "*to drive-through wind turbines at grid-faults*" and "*to release collection & transmission (C&T) grids from electrical stress*".

Problem 2: Avoiding excessive mechanical drive-train stress in wind turbines during various grid faults is the second one. It can be expanded as "*to release their drive-trains from mechanical stress due to three-phase faults or two-phase faults*". The 2nd problem is judged to be beneficially solved with same hardware as the hardware to solve the 1st problem. The 2nd problem is overseen by most actors in wind power generation because the utilities have promoted the 1st problem: risks for park disconnection.

1.2 Problem solution

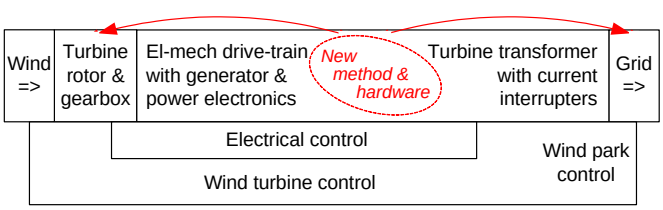

Fig. 1: A box-type overview of Transient Booster.

The new method & hardware is based on low-voltage control- & switch-gear. It is high-performance products. They are reliable with 1000s to 100 000s of maneuvers, and opening within a few milliseconds. They are well-nigh loss-less when closed. It is nearby to use such contactors and protection circuit breakers as switches in a new device to solve both problem 1 & 2.

The new method and hardware—Transient Booster—is promising. Its box-type diagram is shown in Fig. 1. Its realization and function is covered in more details later in this paper. The picture indicates:

- that existing AC & AC/DC/AC hardware is kept with the new method and hardware &
- that the impact of the new method and hardware stretches *in to* the turbine rotor through the mechanical drive-train and *out to* the collection grid; see the arrows in the picture, Fig. 1

The main demand on all solutions is that the electrical system shall be cost-effective, reliable, available and efficient. Efficiency is seen over a long period of operation. So, there can be temporary losses in the electrical system as long as it is negligible energy loss. Solutions which are improper in motor drives can be used as long as they are cost-effective, reliable and available in generating units.

The solution is technically visualized in Fig. 2 for a 2-Φ fault on the terminals of the wind turbine.

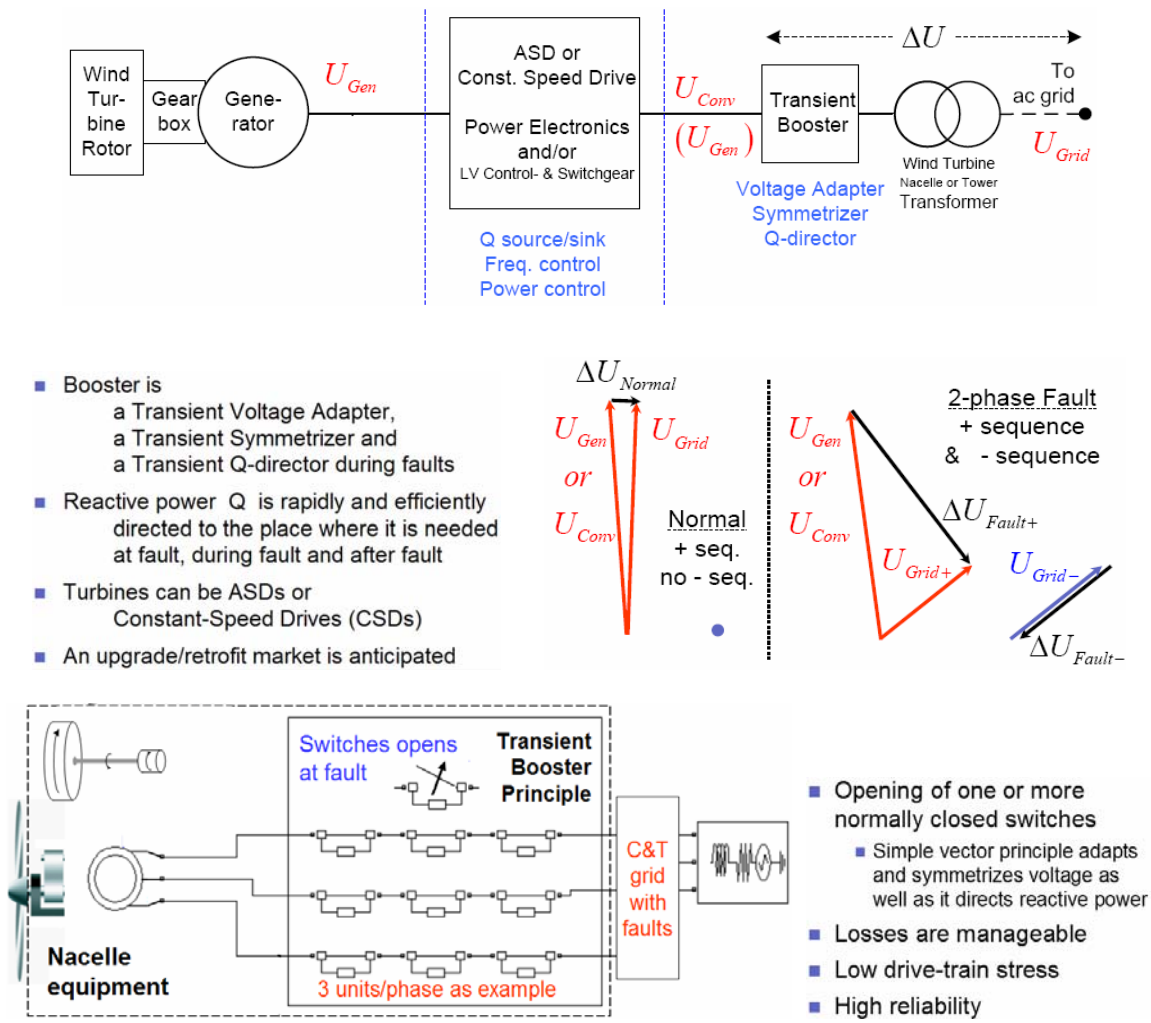

Fig. 2: Principles of Transient Booster; Top: Block circuit diagram
Middle: Left: Explanation as dotted statements; Right: Voltage phasor diagrams
Bottom: Left: Principle circuit diagram; Right: Comments as dotted statements

The principle is established from a synthesis approach. It is a clear intention to keep the main circuits and efficiency during normal operation. During faults, it is necessary to boost up the positive sequence voltage and to boost down the negative sequence voltage to create close to symmetrical voltages for all turbine equipment. A requirement is to keep the actual power flow from the turbine rotor in order to be able to stay "in synchronism" during faults for all main circuits that are marketed today or marketable in the future. Another requirement is to cope with non-bolted and bolted faults of all types.

2. Background

A fault can appear anywhere from the transformer's medium-voltage terminals and out to the point of connection; even in the transmission grid. A wind turbine shall stay connected for most of these faults. An original fault in a C&T network or a T&D grid with a temporary low voltage will be cleared by protective circuit breakers within "some hundred milliseconds". After that, the grid voltage will grow within "a few seconds" up to normal level. This is due to reactive power exchange with the C&T/T&D system connected to the generators. The time period and the shape depend on type of generator, stiffness of the shaft in the turbine drive-train, etc. and, now on Transient Booster.

Fig. 3 is a picture from Vladislav Akhmatov's PhD-thesis [1]. It shows a number of wind turbines connected via collection grids to traditional transmission & distribution, T&D, grids. Depending on where a fault appears, there will be different regions with T&D or C&T interconnections that will temporarily get outside the operational voltages. During the Akhmatov dissertation procedure, it was stressed that his focus was on the utility aspect, i.e., on drive-through, "Problem 1" in this paper. The mechanical drive-train stress was modeled by him but with less evaluation. "Problem 2", inside nacelle, was no major issue as in most publications with electrical power system aspects, e.g., [A - F].

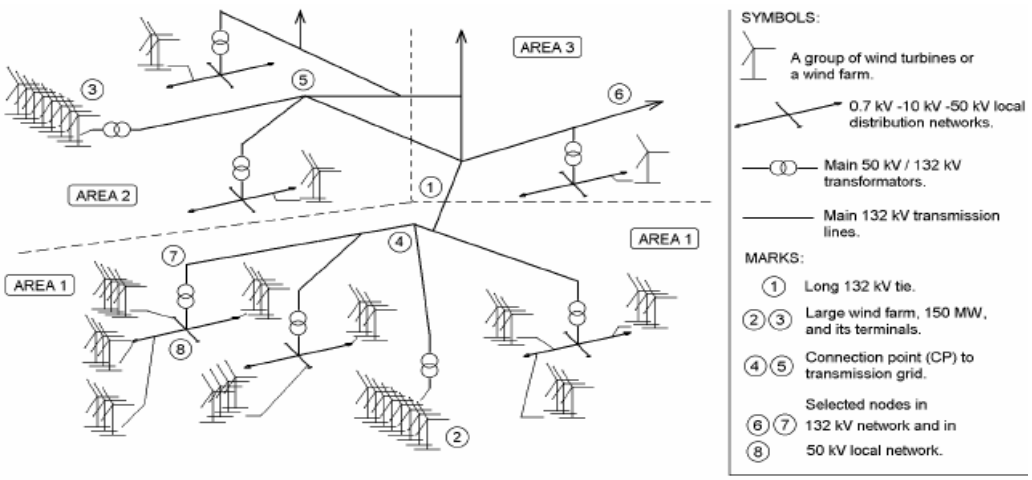

Fig. 3: Sketch of a large power system comprising several wind power generation parks, [1, Fig. 11.2]

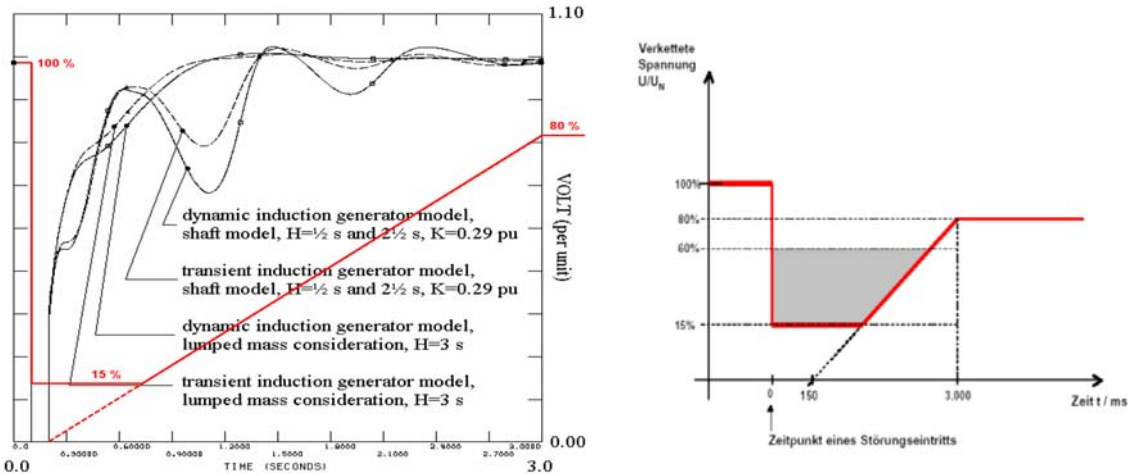

Fig. 4: Left: Simulated voltage recovery, [1, Fig. 4.4]; Right: E•ON's demand for drive-through. The demand curve (right) is also added on the simulated curve (left).

Fig. 4 shows Akhmatov's comparison [1, Fig. 4.4] of simulated grid voltage recovery of a large power system—due to drain of reactive power—comprising several wind power generation parks. Simulations

were made with different models of induction generators and drive-trains in fixed-speed wind turbines. The utility E•ON's demand [C] for drive-through is added here, both in Akhmatov's figure Fig. 4 (left) and as original picture from E•ON Fig. 4 (right). Akhmatov's curves shows influence of modeling weak drive-trains and of generator models far from worst-case demands, by E•ON's and others.

Already in 1977, there were studies of wind generators with today's ratings of wind turbines, [2]. The electro-dynamic torque stresses were simulated during various faults for 0.5 MW and 4.2 MW induction generators. Table I shows calculated results, peak values for torque & currents, for bolted short circuit faults on the electrical terminals of an asynchronous generator. The table shows that two-phase bolted short-circuit, SC, faults are the most severe ones to stress the drive-trains.

	P_{2N} = 0.5 MW Asea MF 500L		P_{2N} = 4.2 MW Asea MBE 1000/S	
Fault type	$\lvert i \rvert_{max}$ [pu]	$\lvert T_e \rvert_{max}$ [pu]	$\lvert i \rvert_{max}$ [pu]	$\lvert T_e \rvert_{max}$ [pu]
3ϕ SC	6.6	4.0	7.0	4.2
2ϕ SC (w/o*)	6.3	5.4	6.6	5.6**
2ϕ SC (with*)	6.1	4.8	6.5	5.0
1ϕ grounded	4.6	3.9	4.6	4.0

* without (w/o) & with ground contact; ** 2.6 – 5.6 pu depending on fault angle

Table I: Calculated maximal currents and electro-dynamic torques for two power ratings and four types of bolted short-circuit, SC, faults, [2]

Lower stress values can be gotten, depending on fault angle, i.e., where a bolted short-circuit fault happens during the time period of the AC system.

The values in Table I and their associated time curves are now reused to validate models in SimPowerSystems-MatLab/SimuLink.

In the 1977 studies, weak shafts were disregarded. Stiff connections were used between the turbine rotor and the generator.

From the 1977 studies, it was found that the pu-values are well-nigh the same, independent of the ratings 0.5 and 4.2 MW, see Table I. So, 2 MW which is 2005's major sales are suitable for new computer simulations to synthesize electrical and mechanical behavior in wind turbines with and without the new method and hardware: Transient Booster.

Judged to be scaleable at least <0.5 MW and >5 MW, the wind turbine simulations in this paper focus wind turbines with 2 MW induction generators and with weak shafts in the drive-train. Backlash etc. in the gearbox are still disregarded for simplicity.

The torsion mode of the weak shaft systems in large wind turbines is due to a shaft relaxation process, commonly with resonance in the range of 1-2 Hz, not seen with stiff shafts (lumped mass consideration). It is close to typical values of the electric power grid eigenfrequencies. There is thus a risk of oscillation between the wind turbines and the entire network. Such phenomena are atypical compared to previous T&D systems and installations with only conventional power plants where the large synchronous generators are equipped with damping windings to damp the 1-2 Hz eigenfrequencies.

The largest mechanical stress on the components in the drive-train system appears at 2-Φ/2-Φ-0 faults, as can be seen in the table above. Such 2-Φ/2-Φ-0 faults appear fairly frequently in rural medium-voltage, MV, distribution networks, e.g., when two overhead lines start to swing towards each other and hit themselves. Similar sparking 2-Φ faults can appear at low voltage, LV, inside the turbine but would normally cause the actual turbine to trip and disconnect.

The problem is non-linear. It can be seen in following simulations Fig. 7 that two short (0.2 second) 2-Φ faults during a second can cause a 2-speed wind turbine to disconnect and to brake. If not disconnected and braked, there will be severe over-speed and high torsional drive-train stress as result.

As summary of problem description and background so-far:

- Existence of 3-Φ faults that stress the utility's power system is paid most attention so-far
- Shaft relaxation process in the drive-trains has impacts on voltage recovery and drive-through
- 2-Φ faults are most likely more common and more devastating what regards the mechanical drive-train in a wind turbine
- 2-Φ faults can—within parts of a second—develop to 3-Φ faults due to ionization in the LV cable terminations, recently observed by DKABB
- 2-Φ faults, that oscillates between fault & non-faults via oscillating & colliding MV overhead lines, were also indicated by DKABB as severe fault cases

3. Simulations

Simulations are made in SimPowerSystems-MatLab/SimuLink on a wind turbine with a 2 MW induction generator and with a weak shaft in the drive-train. Backlash in the gearbox is neglected. Shaft relaxation process in the weak shaft drive-train is programmed and added to the standard package.

3.1 Results from simulations

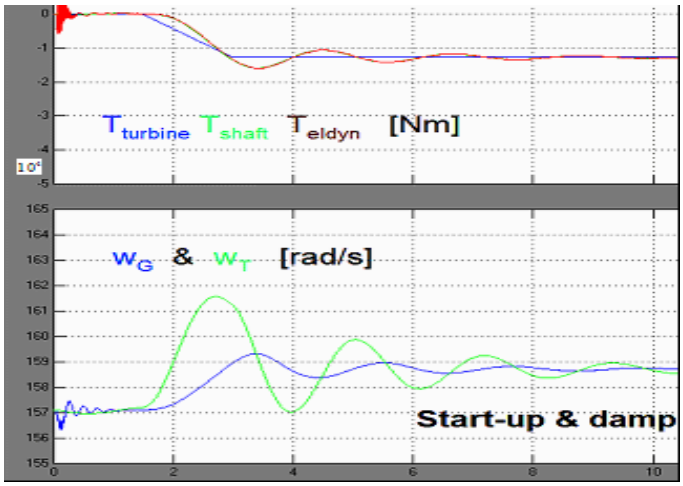

Fig. 5: Electrical energizing at synchronous speed. Ramping on torque through a damped weak shaft

In Fig. 5, it is simulated that the turbine is first electrically connected at synchronous speed.

The nominal torque is then applied as a ramp via the high-inertia rotor through the weak shaft to the generator's lower-inertia rotor as a mechanical torque, stationary in balance with the generator's electro-dynamic torque.

When applying the torque ramp there appears a damped transient showing the drive-train's resonance frequency.

After 10 to 12 sec, the transients are damped so that there is a close to stationary operation.

Discussions between the authors who have long experiences from machines, power electronics, power apparatus, power grids, etc. and good contacts with wind turbine manufacturers and utilities resulted in

- that there are some risks associated with the fault characteristics behind the graphs in Fig. 4,
- <u>but</u> that there are more devastating risks loosing the turbine's operation in "synchronism" with the grid when there are mixes of positive-sequence and negative-sequence components as results of intermittent grid faults.

The hitherto traditional grid-code 3-Φ faults are therefore replaced with repetitive 2-Φ and 2½-Φ[1] "bang-bang-type" faults, graphically shown in Fig. 6 (right) for simulations in this paper.

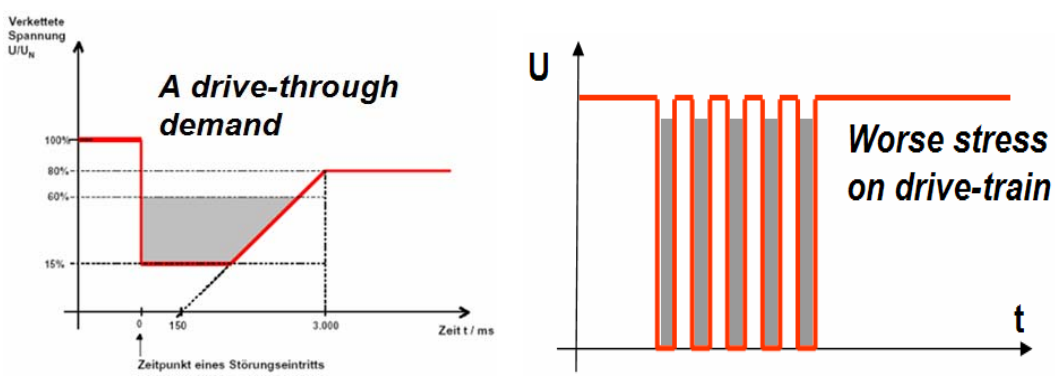

Fig. 6: Left: E•ON's voltage demand curve [C] for drive-through; Right: Worse voltage demand curve, energizing resonance in the drive-train with a damped weak shaft

[1] 2½-Φ denotes a close to 3-Φ fault but it is a so-called simultaneous line-to-line and line-to-ground fault.

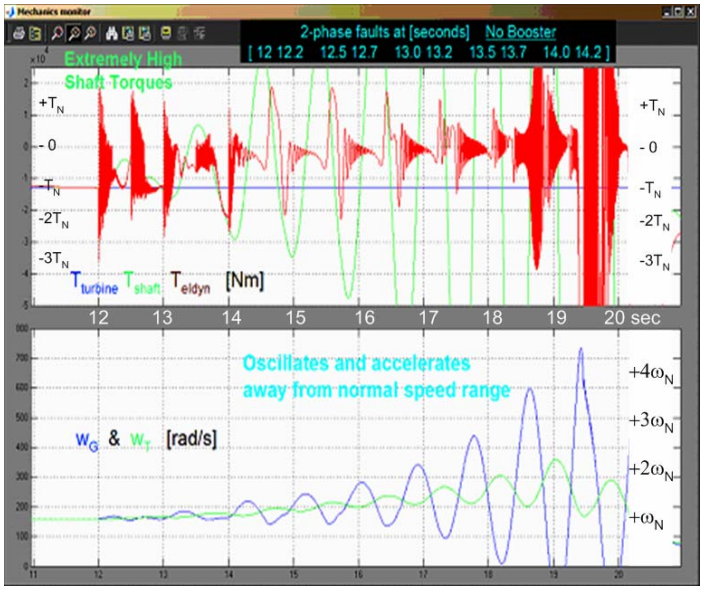

Fig. 7: Graphs of torques and speeds for repetitive 2-Φ faults
Wind turbine without Transient Booster

A simulation of a 2-speed turbine is shown in Fig. 7, left. 2-Φ faults are made at 12.0 - 12.2 s, 12.5 - 12.7 s, 13.0 - 13.2 s, 13.5 - 13.7 s, and at 14.0 - 14.2 s.

The simulation starts at steady-state rated torque operation at four-pole speed from a previous ramp with a damp-out as in Fig. 5. Motor operation references are used in simulation and graphs.

- Three torques are shown as top graph with a display of $+2 \cdot T_N$ and $-4 \cdot T_N$ where $-T_N$ (blue line) is nominal generator torque
- Two speed curves are shown as bottom graph with a display of $0 \cdot \omega_N$ and $+5 \cdot \omega_N$, i.e., <u>0 - 500 % speed</u>

The simulation shows, already at the second 2-Φ fault (12.5 - 12.7 s), a generator speed high above the speed corresponding to pull-out torque. As a consequence, it results in a "loss of capability" to get back to previous "synchronism" with normal operation's few percent slip.

The bottom graph in Fig. 7 shows also that the turbine rotor speed reaches ≈130 % of the nominal one within 3 s after the first fault. The generator has thus limited capability to get back and generate an electro-dynamic torque. This is due to reactive power drain out of the machine in the generating unit out to the collection grid. It can also be seen in the graph that the turbine rotor speed would become some 200 %, before the influence of the chosen repetitive bang-bang fault transient ends, and the turbine should have been synchronized again. All with omitted protection and constant turbine torque.

Previous after-effects to faults disappear with Transient Booster: "a Q-director during faults". So, shaft relaxation process in the weak shaft drive-train is eliminated. This is discoursed based on Fig. 8 and 9.

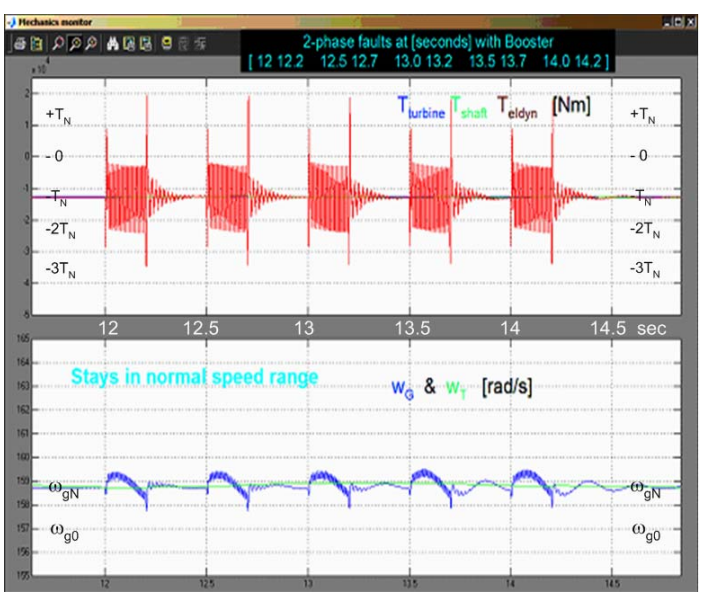

Fig. 8: Graphs of torques and speeds for repetitive 2-Φ faults
Wind turbine with Transient Booster

Torque and speed curves are given as time graphs. They are resulting from five repetitive 2-Φ and 2½-Φ, faults at the same events as above

- Three torques are shown as top graph with the previous torque display $+2 \cdot T_N$ and $-4 \cdot T_N$.
- Two speed curves are shown as bottom graph with a display of $\approx 0.98 \cdot \omega_N$ and $\approx 1.05 \cdot \omega_N$, i.e., <u>99 - 105 % speed</u>

An immediate response e.g. to over-current initiates Transient Booster and <u>keeps the reactive power inside the turbine and at the same time the negative-sequence voltage outside the turbine's LV circuits</u>.

Fig. 8 and 9 shows generator speeds staying well below the speed corresponding to pull-out torque.

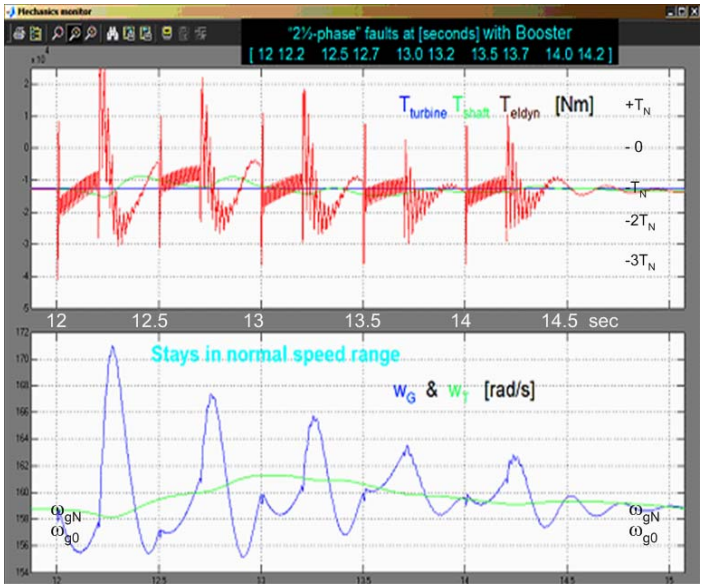

Fig. 9: Graphs of torques and speeds for repetitive 2½-Φ faults
Wind turbine with Transient Booster

Some more simulations were made with various delays for detection of faults in order to form a basis for discussion of how to adapt ABB's control- & switch-gear like contactors and protection circuit breakers for sensing the faults and to be triggered for their new task with various main circuits in the turbines. The manufacturing units judge that breakers and contactors will open in less than ten milliseconds.

The reactive power, kept inside the turbine, leads to a close to nominal positive-sequence AC voltage at the generator terminals.

With a short reaction time, there is still reactive power available to magnetize a traditional induction generator (IG) and to create a well-nigh symmetrical stator voltage for a constant-speed IG with its power factor correction capacitor bank. It should also keep any power electronic converter—for any adjustable-speed drive (ASD), rated due to stationary needs—in operation with its associated generator of any type.

3.2 Initial conclusions based on simulations

Transient Booster is capable of keeping wind turbines and wind power parks to stay connected without draining reactive power out of the turbine as well as without draining reactive power out of the neighboring power network. It was furthermore found from an initial discussion with an FMEA[2]-thinking that existing protective circuit breakers must be embodied with two settings as the short current levels are lowered inside the turbine circuitry when Transient Booster is engaged.

Transient Booster can operate on-off-on-off-... for any type of fault. It can also stay "on" during a long period, say ten seconds; if a temporary "surplus power control circuit"—an electric brake [3 - 6]—is arranged in the low-voltage main circuitry. Transient Booster solutions are cost-effective and with marginal, temporary losses, < 10 kWh/event, manageable with hundreds of kilograms in the turbine.

It is judged discerning to rely on the simulated time graphs above and similar ones as well as on accompanying voltage-current-curves for discussing the new technology with turbine manufacturers, with utilities that provide grid codes and with all other actors in wind power.

4. Technology and market aspects

For investments in wind power parks as well as in single turbines, there is a sincere lack of simple and reliable solutions to grid code demands and drive-train stresses due to grid faults. Therefore, ABB disseminates Transient Booster at Copenhagen Offshore Wind Conference 2005. A basic, technology & market communicative picture for that event is Fig. 1. Transient Booster is intended for new installations and for already installed wind-turbines due to:

1. changing grid-codes,
2. emerging demands on replacing gearboxes at a certain age, and
3. hitherto unknown possibilities to release the collection & transmission (C&T) wind power park grids from electrical stress during faults.

[2] Failure Mode and Effects Analysis is an easy to use and yet powerful pro-active engineering quality method that helps to identify and counter weak points in the early conception phase of products and processes See, e.g., IEC 60812

5. Conclusions

Transient Booster is a cost-effective, well-nigh loss-less, element. It is temporarily engaged as a series device to *"stay connected"* with wind turbines, Fig. 2. It is preferably embodied at low-voltage inside the nacelle. Transient Booster's task is to *"eliminate reactive power drain from the generator as well as from the grid"* during and after grid faults. The *positive sequence voltage is boosted up while the negative sequence voltage is boosted down*. Transient Booster has also a capability *"to release wind turbines' drive-trains from excessive mechanical stress during faults"*.

If the engagement time period is long, there might appear a need to engage a temporary surplus power control circuit, a brake. Dynamic electric brakes are known since decades [3 - 6] to support transmission line dynamic stability as well as generator plants' run-through. Brakes are shunt devices engaged to dissipate temporary surplus energy.

A savvy[3], cost-effective hardware-based method to drive-through is introduced.

- The main circuits and efficiency are kept during normal operation.
- Both the system performance and the conversion efficiency are kept normal during hitherto controlled operation.
- The drive-train—e.g. the gearbox—is released from mechanical stress during and after faults.
- At the same time, collection and transmission grids are released from electrical stress during grid faults.
- Reactive power compensation equipment in turbine is directed. Ratings are kept or lowered.
- Power electronics rating is rated due to stationary needs.
- Upgrade/retrofit markets are anticipated.
- The method and hardware
  are especially attractive for emerging park demands but
  are also a basis for reviving existing turbines at sea
  as well as on land to fit with new or expanded grid codes.

Acknowledgements

At Copenhagen Offshore Wind 2005, this paper is accompanied by two other papers from ABB: Bo Normark, Erik Koldby Nielsen: *Advanced power electronics for cable connection of offshore wind*, and, Stefan G. Johansson, Jutta Hanson, Johan Karlström, Fleming Krogh, Lars Liljestrand: *AC cable solutions for offshore wind energy*.

The conference website is http://offshore.windpower.org

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[3] By "savvy", it is characterized by keen awareness, sharp intelligence, and some sense of the practical.

National codes are, e.g., described in [A –D] while [E – G] holds comparisons, analysis and reviews.

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All web-addresses above were checked June 21, 2005

Appendix

On asynchronous machines at voltage dips

There are synergies between induction generators and motors in the megawatt range. The assumption, that voltage sag is rectangular or trapezoidal at short circuit faults, does not hold.

- Motors decelerate during the short circuit. After fault-clearing, motors will accelerate again, drawing a high reactive current from the supply, causing prolonged post-fault voltage sag.

  See E•ON's 3 seconds ramp and, e.g., Bollen, M.H.J., ***The influence of motor re-acceleration on voltage sags***, Industry Applications Society Annual Meeting, 1994, 2-6 Oct. 1994, Conf. Record, Pages: 2235 – 2242, vol. 3
- Generators accelerate during fault. After fault-clearing, generators will decelerate consuming high reactive current.
- Shaft relaxation process has impacts on these phenomena, see [1].

On SimPowerSystems

SimPowerSystems extends MatLab/SimuLink with tools for modeling and simulating basic electrical circuits and detailed electrical power systems; www.mathworks.com/products/simpower/. These tools let modeling the generation, transmission, distribution, and consumption of electrical power, as well as the conversion to/from mechanical power.

"Wind-Turbine Asynchronous Generator in Isolated Network" is an early demo example from HQ/IREQ documented inside the package. It is also documented www.transenergie-tech.com/pdf/demoeoliennes.pdf as an open report.

www.mathworks.com/access/helpdesk/help/toolbox/physmod/powersys/windturbine.html models a wind turbine. The web page has links to SimPowerSystems drive-trains, "Wind Turbine Induction Generator" and "Wind Turbine Doubly-Fed Induction Generator", both modeled with stiff shaft drive-train.

For this Copenhagen Offshore Wind 2005 paper:

- Basic models of electrical machines and electrical circuits were used for this paper's simulations. www.mathworks.com/access/helpdesk/help/toolbox/physmod/powersys/asynchronousmachine.html#2393493
- Shaft relaxation process in the weak shaft drive-train was developed and added to the package.
- Wind model is here as simple as constant input torque to the turbine rotor during the faults.