Practical Implications of Low Voltage Ride Through Requirements on Windturbine Power Conversion

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***Abstract*—Practical challenges and implications of low voltage ride through (LVRT) requirements on design of windturbine (WT) power conversion system are discussed in this paper. Main focus and main challenges lie in retrofitting existing turbines that are not LVRT compliant and in designing new doubly fed systems bearing LVRT in mind. This is contrasted to full conversion (FC) which is best suited for this application. Certification process is briefly reviewed for completeness.**

***Index Terms*—Low voltage ride through (LVRT), wind energy converter (WEC), windturbine (WT), power converter, certification.**

I. Introduction

THE ratio between renewable energy sources to conventional sources is steadily increasing in many electric energy systems. This leads to introduction of more stringent rules to connection of these facilities to the grid. Wind energy conversion is the most mature and the most widespread of renewable technologies at the moment, and therefore receives the most attention from regulatory bodies as well as from the manufacturers and end users. In order to integrate wind farms into the grid, they are requested to follow directives from a dispatch center and participate in frequency control rather than to produce as much power as dictated by available wind [1]. Reactive power and voltage control requirements are also becoming more stringent, as well as fault tolerance requirements like low voltage ride through (LVRT).

All grid code requirements are defined for point of connection to the grid and in some cases can be satisfied with additional equipment like static compensators. A more economic approach is sought through making individual WTs dispatchable within a wind farm. Steady tightening of LVRT requirements makes wind farm level solutions absolutely impractical and must be handled on an individual-WT basis. Interdependency between power conversion technology and LVRT requirements is the most pronounced and that is why it is selected as a focal point of this paper.

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Nowadays, power rating of individual WT is ranging 2MW up to 6MW. At these power rating and with tendency to increase effectiveness and efficiency, all recent developments are based on variable speed technology. It is well known that wind energy curve for a given blade design depends on the third power of wind speed and a power coefficient which is dependent on blade tip speed and wind speed ratio [2]. Resulting wind power curve is highly nonlinear with four distinct regions for variable speed design. The first region is below cut-in speed when WT is out of production. The second region is operation with constant pitch angle which corresponds to optimal rotor efficiency. The third region is nominal power region, and the last one is excessive winds speed region where WT has to be taken off line. Constant speed turbines can efficiently exploit wind only at the corner point between regions two and three. In all other operating points rotor efficiency is significantly deteriorated if at all possible. This is why additional complexity related to variable speed and variable pitch designs is widely accepted. All the key auxiliary systems, like pitch, have also to be considered when designing an LVRT compliant WT, but in this paper main focus will remain on core power conversion.

An overview of available WT power conversion topologies is given in section II and it includes constant speed turbines whose retrofitting to fulfill LVRT requirements is mandated by some grid codes, like Spanish P.O. 12.3 [3]. General requirements for LVRT and certification procedures are briefly discussed in sections III and IV respectively. Section V is dedicated to a description of retrofitting solutions, while section VI discusses challenges related to new designs of DFIG systems for LVRT compliant design. Section VII briefly reviews advantages of full conversion systems with respect to LVRT.

II. Power Conversion Technology for WTs

The purpose of this section is to review the available power conversion technologies without a tendency to follow any established classification. Differentiation between constant and variable speed topologies is based on the most usual combinations and does not mean that different combinations are not possible.

A. Nearly Constant Speed WECs

Constant speed turbines are also known as stall turbines as they exploit aerodynamic effect called stall. Stall automatically sets in because shaft speed is constant and thus limits turbine aerodynamic efficiency at high wind speeds. This means that fixed blades can be used for rotor construction. Combined with directly connected squirrel cage induction generators (SCIG) this comprises the most inexpensive WT technology, Fig. 1.

SCIG technology typically includes a soft starter to limit connection transients and is bypassed during steady state operation. Power factor is maintained using banks of shunt capacitors. Limitation of the single wind-speed operation can be mitigated using double speed generators.

Stall-controlled turbines alone are not limited to operate at only one speed. If paired with wound rotor induction generator (WRIG) and variable rotor resistance control (RCC – rotor current control) these turbines can be utilized over a speed range of approximately 10%, Fig. 2. Rotor resistance adjustments correspond to slip variations of 0.6 – 10%. These turbines would still come equipped with soft starters and switched shunt capacitors. RCC is typically implemented as rotating equipment.

B. Variable Speed WECs

The enabling technology for variable speed WTs is a electro-mechanical drive-train which enables connection to fixed frequency grid. As stated above, even stall turbines can operate in wide speed range. The main difference is that variable pitch turbines extend speed range for nominal power operation (the third range) from a single point to a range of speeds.

Configuration of electro-mechanical drive-train in Fig. 3 is based on doubly-fed induction generator (DFIG). WRIG used in this application are equipped with slip-rings. DFIG configuration is considered relatively inexpensive due to a lower, typically 1/3, rating of frequency converter to the rating

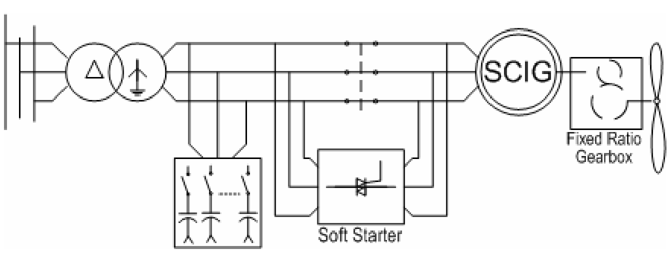


Fig. 1. Directly Connected Squirel Cage Induction Generators.

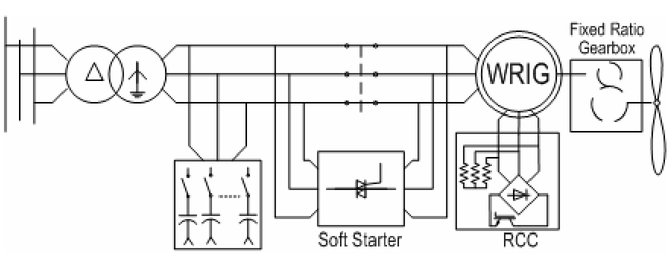


Fig. 2. Wound Rotor Induction Generator with Variable Rotor Resistance.

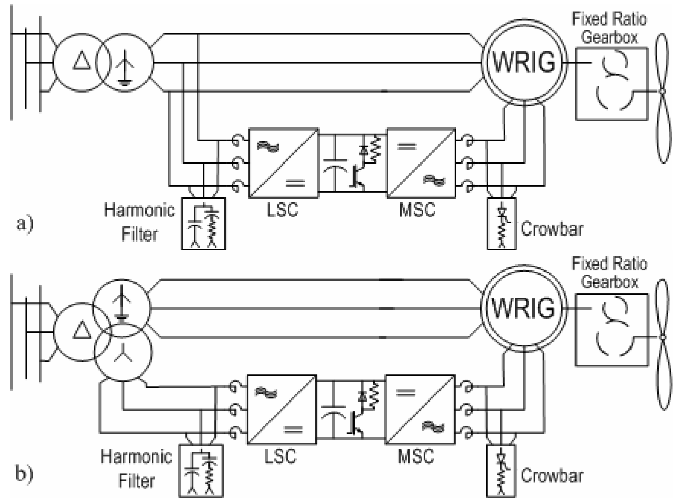


Fig. 3. Doubly Fed Induction Generator Topologies.

of the generator. This is possible due to the fact that induced emf on the rotor windings is function of not only winding transfer ratio but also slip frequency. Rotor voltage under locked-rotor condition (slip = 1) is usually on the order of 2000Vrms line-to-line while typical frequency converter voltage is 480Vrms or 690Vrms. Under normal operating conditions slip frequency varies by not more than 10-15Hz. Voltage compliance between the frequency converter and rotor becomes an issue under fault conditions and therefore a crowbar circuit must be present to isolate the converter from the machine.

The frequency converter must be capable of four quadrant operation to support both subsynchoronous and supersynchronous operation. In subsynchronous mode generator speed is slower than synchronous and the power must be supplied to the rotor circuit through frequency converter. Net generation is difference between power out of the stator and the one into the converter. Supersynchronous operation is when the rotor speed is higher than synchronous and the frequency converter also draws power from the rotor, and the total generated power sum of the power from stator windings and the converter.

Reactive power control is linear and utilizes frequency converter. Line side converter (LSC) can be used to directly inject or draw reactive current from the grid or machine side converter (MSC) can be used to over/under excite the machine.

Implementation in Fig. 3 b is used if frequency converter voltage needs to be lower than stator voltage. This may be a limiting factor in LVRT retrofitting of older turbines of such a design.

Full-scale power conversion (Full Conversion = FC) topologies are shown in Fig. 4. The name comes from the fact that full rated power is transferred through frequency converter from generator to grid. The generator can be any electric machine. SCIG, wound field synchronous generators (WFSG), and permanent magnet synchronous generators (PMSG) can be found in practical turbines.

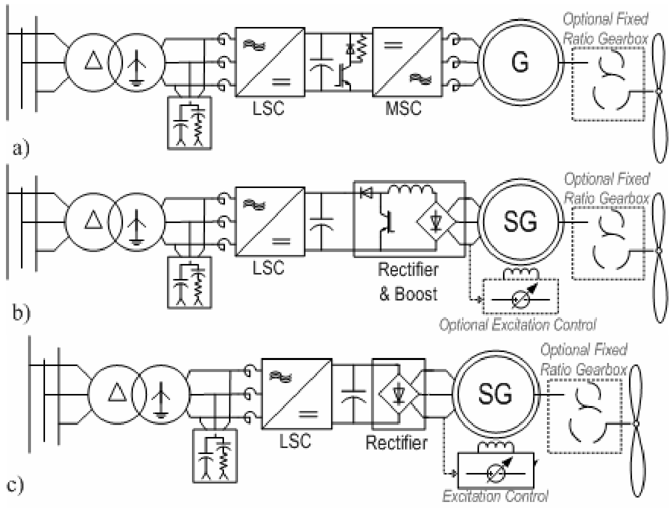


Fig. 4. Full-Scale Conversion topologies.

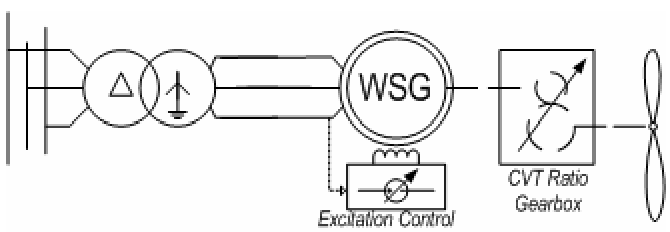


Fig. 5. Directly Connected Syncrhous Generators.

The generator is completely decoupled from the grid in this configuration. Power flow is therefore unidirectional and two quadrant power converters can be applied (Fig. 4 b and c), except with SCIG where MSC is used to properly magnetize the machine (Fig. 4 a). WFSG require additional circuitry to control field current, but the rating of these devices is very small due to integrated exciter winding and rotating rectifier on the rotor. An adjustable field is desirable to either eliminate boost stage in DC bus circuit or to optimize efficiency by adjusting excitation with respect to load. High harmonic content of diode rectifier currents may impose additional requirements on generator design and diminish benefits of elimination of the MSC. MSC can also be used for field weakening operation of PMSG if this is desired to extend operating speed range or maximize efficiency.

Voltage compliance question can be raised with respect to use of PMSG and possible overspeed operation. It turns out that the voltage under these conditions does not exceed normal safety margin and a crowbar is not required.

Reactive power control is solely based on LSC which has to be sized accordingly.

The last variable speed topology is based on continuously variable transfer ratio gearbox which enables constant speed operation of a directly connected WFSG. Only WFSG can be used as the excitation control is the only possibility to regulate reactive power. There is no frequency converter in this configuration. All the complexity is moved to a mechanical gearbox.

III. General Requirements for LVRT

Grid codes define requirements for the point of common coupling. The most basic of the requirements is that the turbine must remain connected to the grid during voltage sags. A number of particular system level requirements can be derived from this simplest general requirement mandated by a grid code. Some turbine systems that are typically omitted in papers on LVRT are critical for operation of the turbine. Some of those are pitch subsystem and system controller. These critical subsystems must be protected by an uninterruptible power supply (ups). An alternative approach is to connect all auxiliary loads downstream from ups.

The power rating of critical WT auxiliary loads is such that a UPS is a feasible and simple solution. The energy rating of the UPS must consider voltage sag durations which is discussed next.

A. Voltage Sag Anvelope

Every grid code will contain a definition of voltage sag based on remaining voltage in affected phase and its duration. A number of these curves from different grid codes and available LVRT turbines are shown in Fig. 6. Worst-case curve connecting maximum sag durations for given remaining voltage is also shown in Fig. 6 and denoted ‘world-wide’. ‘Retrofit’ curve from the same picture corresponds to a commercially-available retrofitting solution discussed in section V-B. The turbine may trip if the duration of the voltage sag exceeds the duration specified for the corresponding remaining voltage.

The same voltage sag envelope is typically used for both balanced and unbalanced sags. In case of unbalanced sags, the remaining voltage is the lowest percentage value between all line-to-neutral and line-to-line voltages. This may be significantly lower than remaining positive sequence voltage, e.g. positive sequence voltage for 0V remaining line-to-line fault is 50%.

B. Power Curves

Power curves, if defined in a grid code, are as significant for LVRT definition as the voltage anvelope and much harder

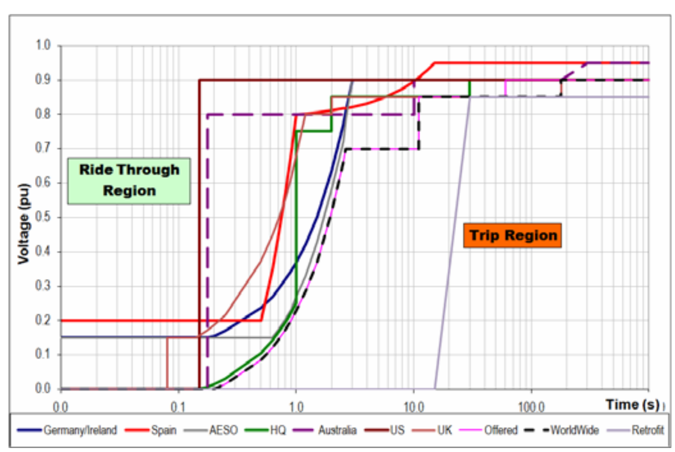


Fig. 6. Summary of LVRT Envelopes.

to satisfy than the basic requirement that the turbine must stay on line.

The significant phases in the voltage sag are sag inception transients, 'steady state' LVRT run, voltage recovery transient, and active power recovery period. These phases of voltage sags are indicated in Fig. 7. Different requirements for power curves should be defined for each of these four stages.

It is impossible to generalize power curve requirements as they vary a lot from an instance to another. For example [3] requires that injection of capacitive current during sag is proportional to active power draw from the grid, while [4] requires that capacitive current is scaled in opposite proportion to remaining voltage during sag.

Figure 7 shows ideal power curves in bold black lines and some arbitrary tolerances and non-ideal response curves. In general, power must not be drawn from the grid, voltage must be supported by capacitive current injection, and realities of real system response must be recognized and acceptable relaxed margins defined.

C. Implications

The grid codes are supposed to prescribe requirements which are best suited for the grid and equivalent to requirements imposed to existing conventional generation based on synchronous generators. The first criterion may be correct, but the second is questionable.

Examination of LVRT durations in some grid codes shows what appears to be unrealistically long time for real faults in transmission system and unrealistically deep for faults in distribution systems. Speed of reaction in reactive power control is unrealistically fast for synchronous generator systems depending on excitation system and rotor time constants.

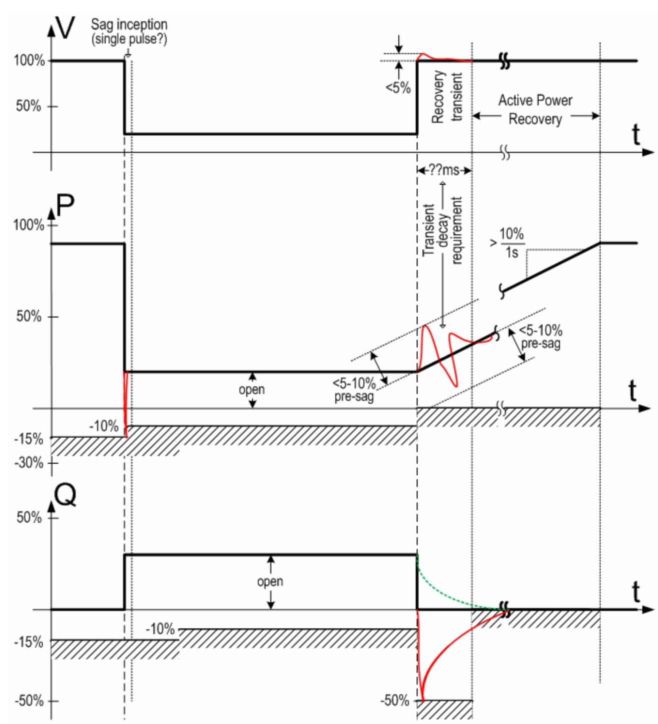


Fig. 7. Example Power Curves.

The bottom-line implication is that only systems which rely on frequency converters are capable of meeting these requirements.

IV. Validation and Certification

Grid codes may be too brief in describing LVRT requirements. Since LVRT certification is typically required and regulated, the certification protocols and procedures can provide additional insight and even extend prescribed requirements. The basis for LVRT validation and certification in the field is so called sag generator – equipment for simulation of grid faults. The principal design of a sag generator, its insertion into the circuit, and power measurement details are specified in IEC 61400-21 [5] and cited or copied over into national grid codes.

A Sag generator is nothing else but a voltage divider which is inserted into medium voltage feed to an individual WT, Fig. 8. Photographs of an example sag generator are given in Fig. 9.

Per [5], the sag generator must be configured such that the short circuit current does not cause significant disturbance for the upstream windpark installation and that the short circuit power is at least three times rated power of the test turbine (1). This is adjusted by Z1 in Fig. 8, while Z2 adjusts the remaining voltage level. Desired voltage during sag is defined for no-load condition and tested with test sag prior to starting WT which then affects the actual voltage during normal operation and sag. Tolerances for the sag voltage as well as timing are also defined in [5]. Voltage tolerance prior and during sag is ±5%. It is increased to ±10% upon voltage recovery. Timing of sag inception and voltage recovery may be delayed by 20ms.

$$S_{sc} \geq 3S_r;\ X/R > 3. \quad (1)$$

Voltage sag types per remaining voltage profile are shown in Fig. 10. Typically only one sag profile is applied during certification process. In author's practical experience it would be either single sag or double sag with lower then higher

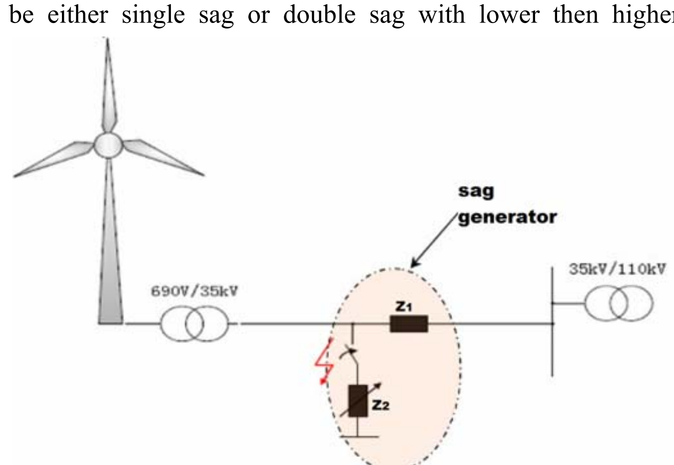


Fig. 8. Sag generator insertion into medium voltage feed.

remaining voltage. A double sag is obviously designed to test system reaction to faults on high voltage lines that do not clear before automatic reclosure is attempted.

The certification process consists of a number of test points. High-wind and low-wind conditions (i.e. high and low production) are required to be tested per [5]. High production is defined as higher than 90% rated and low is between 10% and 30% of rated power. The system has to be tested for balanced and unbalanced sags. In some cases only the deepest sags are considered, while some certification protocols require testing for a number of different sag depths and durations along appropriate voltage anvelope in Fig. 6.

The unbalanced sag that is applied during certification is line-to-line on medium voltage side. This corresponds to the most common transmission level fault which is line-to-ground and transformation through Delta-to-Wye transformer [6]. This is again seen as single phase-to-ground sag on low voltage side of WT transformer.

In addition to technical certification requirements there are a number of procedural requirements that must be followed. For example, every test point must be repeated twice. If one of the attempts fails it must be followed by two successive successful runs. Two failures may completely annul all the successful testing thus far. Needless to say, no adjustments to the system, including a parameter change, are allowed during certification.

Fig. 9. Photographs of a sag generator.

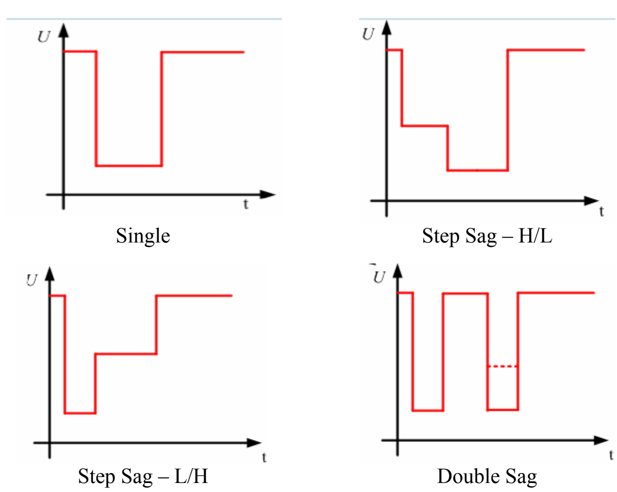


Fig. 10. Test voltage sag types.

V. Retrofitting Solutions for IG Turbines

An approach to retrofitting existing windfarms for LVRT that may seem attractive is to add shunt connected static compensators (STATCOM) to support voltage for the whole windfarm. This solution has been successfully applied for industrial applications and has been applied for some windfarms. However there are some limitations related to this approach.

STATCOM systems are sluggish in their response time due to the nature of their operation. Maximum voltage build-up is limited to 50% to 60% and even this requires a weak connection of the protected circuit to the grid. It is also more difficult to validate statcom based solutions. Individual WT retrofits are therefore preferred.

A. Series Compensators

Series compensators or dynamic voltage restorers are obvious candidates for LVRT support of WTs (Fig. 11) and are successfully implemented in practice. Their main advantage is at the same time their main disadvantage. Series compensator inverters must run at all times to pass current through series inserted transformer. This gives a chance to continuously run a voltage regulator which would automatically react to voltage sag, without a need to run a special sag detection algorithm. The reaction time is very fast and continuous. Drawback of this is that the transformer must be sized for full rated power, while the compensator inverter must be rated in proportion to desired voltage build up, e.g. 70% for operation down to 20% rated. All this corresponds to increased losses as well.

Back-to-back inverters are used (although not explicitly shown in Fig 11) to support reactive current and power flow demands during LVRT. The active power delivery to the grid is limited by remaining voltage and current rating of the equipment, while the generator output is limited only by available wind power per requirement that the retrofit

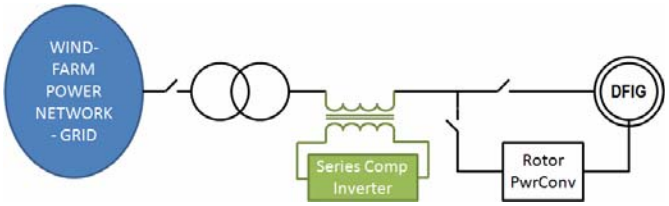


Fig. 11. Insertion of a series compensator.

solutions shall not require any modification in the existing WT controls. Therefore excess power must be dissipated within the restorer.

Modified control strategy is proposed in [7] to further improve system response and minimize converter rating. The approach is not to restore the voltage but to demagnetize IG in proportion to remaining voltage. However, this approach does not lend itself to a retrofitting application, as the protection circuits and critical auxiliary loads would have to be modified.

B. Transient Rated Full Conversion (TRFC)

A cost- and efficiency-optimized solution for LVRT retrofitting of WTs is shown in Fig. 12 and Fig. 13. It consists of a back-to-back power converter which is transient rated, mainly meaning that active cooling is not required. The Static Switch (SS) is the main power component which is rated for steady state power. The SS enables quick reconfiguration of the system from its original topology, most commonly SCIG as in Fig. 12 a, into temporary FC turbine.

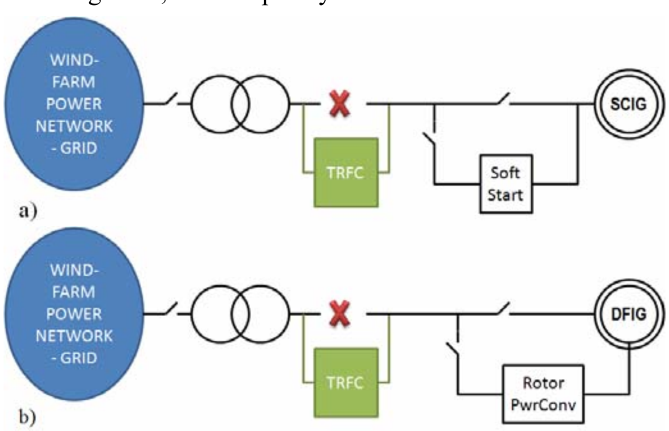


Fig. 12. Retrofitting a WT with a TRFC system.

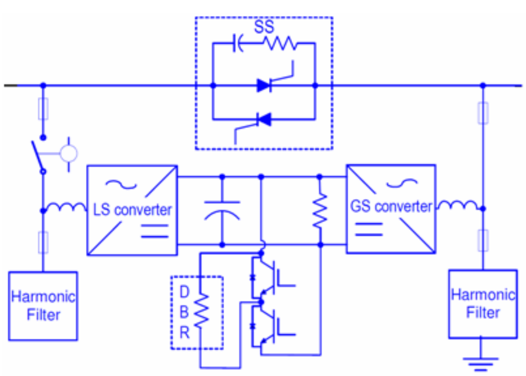


Fig. 13. Single line diagram of a TRFC.

During normal operation, power converter is in stand-by mode. Only control circuitry, harmonic filters, and DC bus are energized while whole power is transferred through the SS. Efficiency of the TRFC is extremely high as it utilizes rectifier grade thyristors. High efficiency also means simple cooling of the SS, which is very important as preferred location for installation of these systems is tower base.

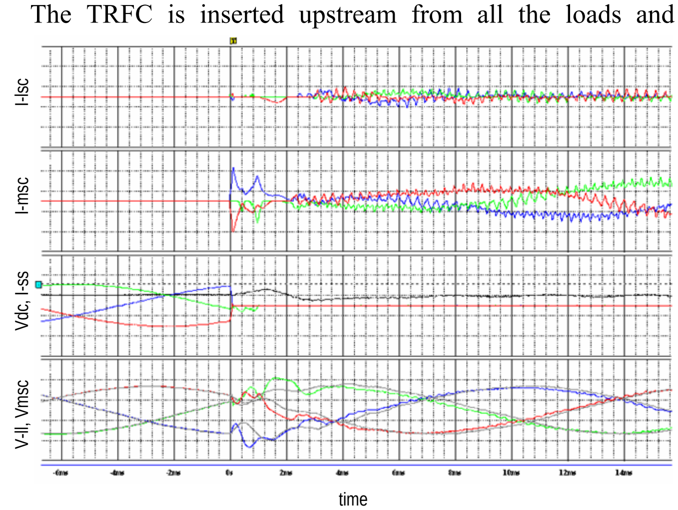
Once voltage sag is detected the SS opens and the converter starts actively regulating voltage on the generator terminals and active and reactive power at grid side. Again, active power is limited by remaining voltage and shall not be limited on the generator side, so excess has to be dissipate in a hefty dynamic break resistor (DBR), Fig. 13.

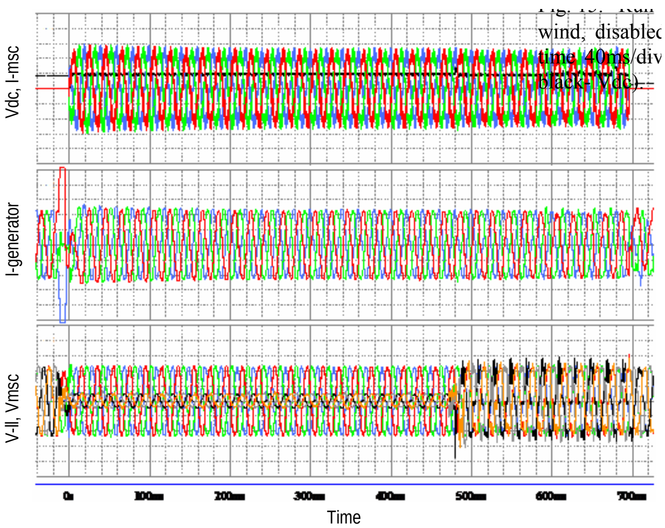
Reaction speed of TRFC obviously depends on sag detection speed and commutation of SS in the first place. Fast sag detection algorithms can utilize natural reaction of a generator, like it was in test cases presented in Fig. 15 and Fig. 16, or instantaneous sequence component voltage measurements. Special care must be taken to the extraction of sequence components if the latter approach is used.

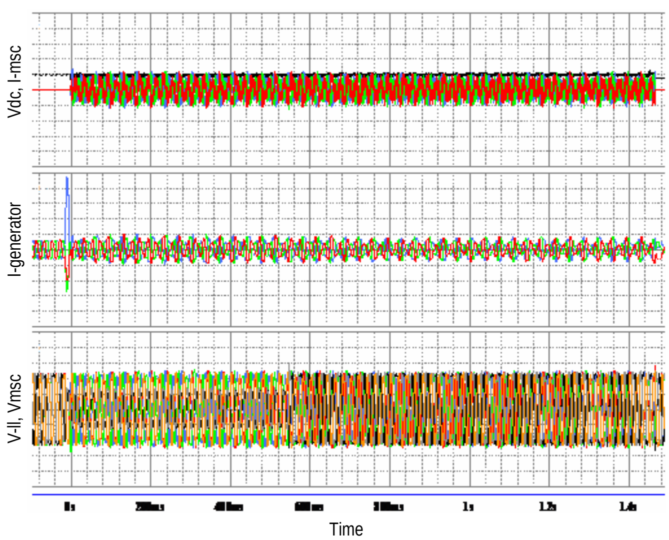
Forced commutation of SS is required for application of TRFC with DFIG turbines. Forced commutation can be accomplished by using both LSC and MSC to extinguish SS currents, Fig. 14. Forced commutation times that are fraction of a millisecond long are realistic.

Example LVRT runs in Fig. 15 and Fig. 16 are obtained on SCIG turbines where forced commutation was not used as it proved to be unnecessary. Initial transients in generator currents are used to detect sags. Resynchronization to the grid and reclosure of the SS is virtually seamless, although it may be delayed by up to several hundred milliseconds to avoid miss-detection of voltage recovery, and to ensure smooth transition. Active power delivery can be almost immediately restored upon voltage recovery as the generator and the turbine do not change their operating mode. There is no difference in performance between balanced and unbalanced sags as the generator always sees balanced voltage.

The TRFC is inserted upstream from all the loads and







production of WT and therefore provides steady power supply for critical and non-critical auxiliaries. As a result retrofitted turbines can run through much longer voltage sags than required by typical grid codes. The only limitation to the sag duration is energy capacity of the DBR and thermal capacity of transient cold plates inside the converter.

Converter operation is always stable due to the fact that complete power generation passes through the converter during LVRT. There is always enough energy to maintain DC bus voltage. Zero volts ride through is also possible with only small changes in LSC control code.

The only drawbacks of the TRFC are its cost and small, but still-present efficiency penalty.

VI. LVRT Compliant DFIG Turbines

LVRT compliance can be achieved with DFIG turbines without significant overrating of frequency converter and expensive additional equipment. Key components in LVRT compliant DFIG design is to design it on system level and to adopt a crowbar design which enables extinction of high transient crowbar currents, Fig. 17 b and c. Standard crowbar design in Fig. 17 a cannot be used for LVRT as it requires that rotor currents naturally die out. Design in Fig. 17 b exploits fact that frozen flux causes rotor current pulsations at rated frequency for balanced and twice rated frequency for unbalanced sags. These higher frequency current components will eventually cause zero crossing and lead to natural commutation of crowbar thyristors. Design in Fig. 17 c basically duplicates design of DBR which is suboptimal solution.

Basic idea for frequency converter operation in LVRT compliant DFIG turbines is to continue normal operation as long as possible. Appropriate actions are taken only if necessary to protect and restore normal operation of the converter. This is why nuisance sag detections are acceptable in this system. On the one hand, this makes sag detection less of a challenge. On the other hand, sag detection must be based on line voltage measurements and cannot be based on machine response to sag. Voltage recovery still must be reliable as it was the case in retrofitting systems.

Some of the most interesting and most challenging aspects of LVRT DFIG design are discussed in following subsections.

A. *Voltage Collapse and Voltage Compliance Issues*

Existence of subsynchronous operating mode makes LVRT challenging due to possibility of collapsing DC bus voltage. If the MSC draws energy from the DC bus and LSC is not capable of drawing this energy from the grid, then the DC bus voltage inevitably will drop. On the other hand, disabling MSC would prevent the DC bus voltage collapse for some limited time, and at the cost of lost control over generator and inability to meet power curve requirements. Zero voltage ride through under subsynchronous operation would definitely create conditions for DC bus voltage collapse.

On the other hand, lack of voltage compliance in DFIG design makes crowbar circuits necessary. Frozen flux at the sag inception is stationary while the rotor rotates at speed

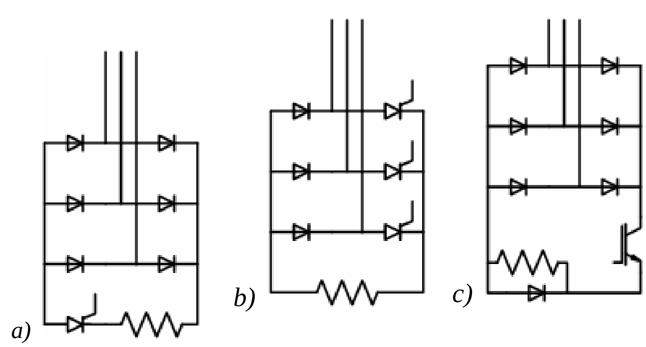


Fig. 17. Crowbar power circuits.

which is close to synchronous speed. This generates high voltage and tends to push the converter outside the safe operating area (SOA).

The voltage compliance issue is even more pronounced in unbalanced sags, where reflected negative sequence voltage has frequency of twice the rated frequency and reflects with twice the transfer ratio. Even for shallower (and therefore less unbalanced sags) where crowbar triggering is avoidable, these reflected negative sequence voltages cause control issues. The MSC voltage command could be reaching voltage limit, Fig. 18, which makes it impossible to suppress negative sequence currents. The negative sequence currents do not have to be suppressed as they do not have adverse effects per [5]. This is contrary to many scientific papers and patents which are based on suppression of these current components or compensation of the unbalance. The standard converter design for DFIG application does not have enough DC bus voltage margin to apply these algorithms. Also, voltage compensation is based on voltage drops on upstream impedance which is typically 6% for WT transformer. Complexity of those methods is disproportional to very limited benefits.

A superior approach to deal with unbalanced sags is to control instantaneous power to stabilize DC bus voltage, or even to simply ignore higher frequency components and automatically avoid steady state control error which may result from the voltage compliance issue, Fig. 18.

B. System Level Approach

Auxiliary loads of DFIG WT must be supplied through their own UPS systems since there is no possibility to restore voltage seen by them. The voltage inevitably sags for all systems. This is especially important if zero voltage ride through is desired.

Abrupt changes in generator load cannot be always avoided as some sags will cause crowbar to trigger. This may lead to turbine overspeed, and must be prevented by fast pitch reaction. Fast pitching may affect tower movement and has to be carefully tuned. Since fast pitching is not optional, it may as well be used to relieve converter torque control action.

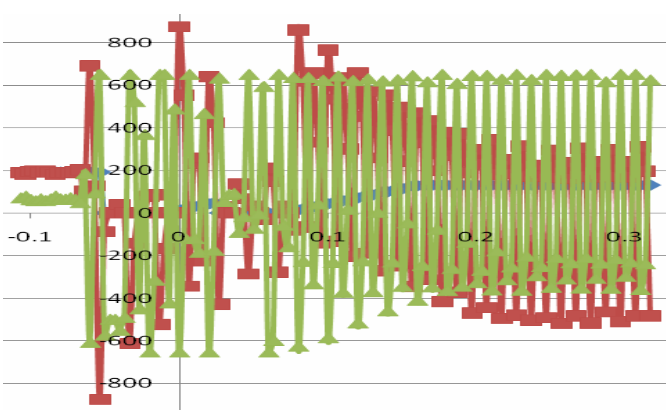


Fig. 18. Example of voltage compliance issue caused be reflected negative sequence component (red- current feedback; blue- current reference; green- voltage command).

Power recovery after voltage restores must not be too quick as this cannot be followed by regular pitch and tower movement control. This is why a slow steady ramp is desired.

C. Power Curves

One of the biggest challenges in DFIG design for LVRT is to match power curve requirements discussed in section III B. This is sharp contrast to the retrofit systems which automatically satisfy the most stringent power curves if the sag detection is fast enough and the whole system is deployed on time. In DFIG turbines it is not so hard to make the turbine stay connected to the grid, but it is much harder to accomplish sufficient command tracking to produce power curves like the ones shown in Fig. 19.

The required condition to accomplish power controls from Fig. 19 is to avoid triggering the crowbar. Simulated LVRT relying solely on crowbar is shown in Fig. 20. Here very high peaks of instantaneous active and reactive power are seen along with negative average reactive power draw during LVRT run and very high reactive power draw at voltage recovery. Subsynchronous operation would result in active power draw in addition.

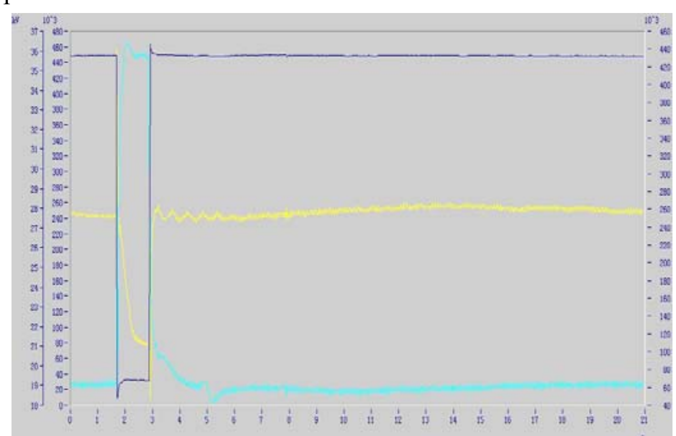


Fig. 19. Example measured power curves – 50% balanced sag, low wind (dark blue- voltage anvelope; light blue- reactive pwr; yellow- active pwr).

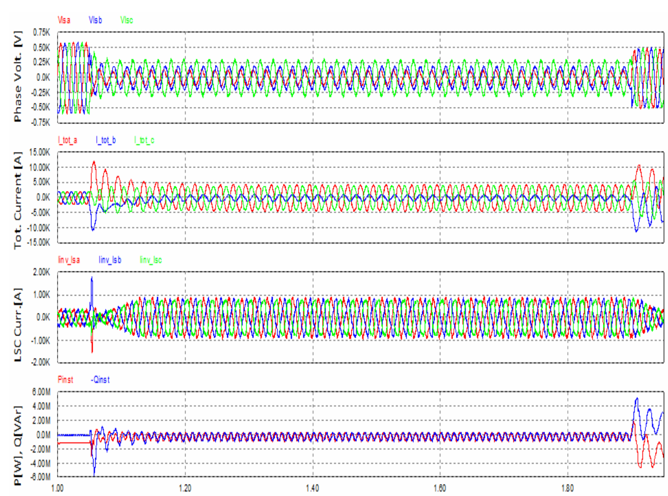


Fig. 20. Simulated LVRT with exclusive use of crowbar – unbalanced, full load.

One approach to minimize crowbar triggering during sags is to maximize effectiveness of DBR circuit. In many cases it is acceptable to trigger crowbar for very deep sags like in Fig. 21. Crowbar must trigger immediately upon sag inception to ensure reactive power production instead of consumption. This is opposing argument to maximizing effectiveness of DBR circuit. The crowbar must turn off within time allowance for inception transients, e.g. 150ms in [3]. Recovery transient is much less severe and can be limited by DBR only in Fig. 21.

VII. Full Conversion

FC turbines are always configured as TRFC during LVRT run, such that all the benefits mentioned in section V, subsection B apply here as well. In addition, there are no transients related to switching operating modes like there is in TRFC. Only transients in FC LVRT come from control system reaction to step change of the voltage which is disturbance for current regulators. The step response of the converter in FC can be improved by advanced control techniques since there is no voltage compliance nor DC bus voltage collapse issues in this case.

Some system-level interaction between frequency converter controls and pitch is desirable to minimize DBR energy ratings. Sag detection would only be used for this and adjustment of power curves per grid code requirements and therefore does not need to be extremely fast or sensitive.

Unlike TRFC, auxiliary power during normal operation and LVRT has to come from grid as generator frequency and voltage vary. This means that separate UPS must be provided just like in DFIG turbines.

VIII. Conclusions

Meeting LVRT requirements is a must for significant wind power installations integrated into power grids. How this is accomplished and to which extent heavily depends on electric power conversion topology. SCIG is not compliant without expensive retrofit systems which are defeating the purpose of building WT based on this technology. DFIG is the most challenging with respect to LVRT and the amount of effort and tradeoffs can hardly justify continuing to use this technology for newest designs. Full conversion lends itself as future WT technology mostly because of LVRT.

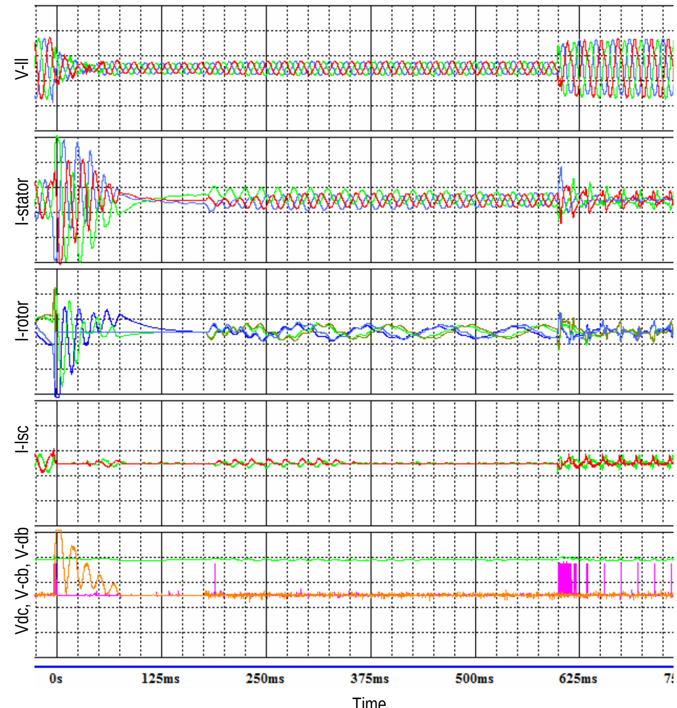


Fig. 21. Run through a balanced sag down to 20% remaining voltage – hig wind. Crowbar triggers at sag inception, than clears (Full scales for eac signal ±2kA/kV; time 40ms/div; red- Ixa or Vxab, green- Ixb or Vxbc, blu Ixc or Vxca, black- Vdc).

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