Minimum-Threshold Crowbar for a Fault-Ride-Through Grid-Code-Compliant DFIG Wind Turbine

Graham Pannell, David J. Atkinson, and Bashar Zahawi, Senior Member, IEEE

Abstract—Doubly fed induction generator (DFIG) technology is the dominant technology in the growing global market for wind power generation, due to the combination of variable-speed operation and a cost-effective partially rated power converter. However, the DFIG is sensitive to dips in supply voltage and without specific protection to “ride-through” grid faults, a DFIG risks damage to its power converter due to overcurrent and/or overvoltage. Conventional protection is via a sustained period of rotor-crowbar closed circuit leads to poor power output and sustained suppression of the stator voltages. A new minimum-threshold rotor-crowbar method is presented in this paper, improving fault response by reducing crowbar application periods to 11–16 ms, successfully diverting transient overcurrents, and restoring good power control within 45 ms of both fault initiation and clearance, thus enabling the DFIG to meet grid-code fault-ride-through requirements. The new method is experimentally verified and evaluated using a 7.5-kW test facility.

Index Terms—Doubly fed induction generator (DFIG), induction generators, power conversion, wind power generation.

I. INTRODUCTION

Wind power is gradually becoming a more significant part of worldwide electrical generation with significant engineering challenges for its assimilation and operation within mature transmission networks [1]. Large wind farms need to contribute to the stability and reliability of the transmission grid if they are to form a robust component of the generation network [2]. This includes providing grid support during grid faults or voltage dips. Revised grid codes now require wind farms to remain dynamically stable during a voltage dip and to supply active and reactive power into the network. This can be achieved at wind turbine level, by engineering the individual wind turbines to provide the required response, as described in this paper.

Many wind turbines incorporate a doubly fed induction generator (DFIG) to permit variable rotor speed operation and provide independent control of active and reactive power output. A DFIG comprises a wound-rotor induction generator, where the stator windings are connected to the grid and the rotor windings are connected to a bidirectional power electronic converter (see Fig. 1). The partially rated converter offers considerable cost savings and lower losses than a directly connected full-rated converter topology [3].

Fault ride through (FRT) refers to the capability of generation plant to remain connected, dynamically stable, and offer network support throughout a serious voltage disturbance on the transmission network. Although the voltage dips associated with grid faults may last for only a few cycles, they can bring about certain undesirable characteristics of induction-machine-based generators, including uncontrolled active and reactive power and continued voltage suppression, failing grid-code FRT requirements.

The standard DFIG system is sensitive to dips in supply voltage. The induction generator very quickly loses internal magnetization in proportion to the lost voltage. The demagnetization produces large outrush currents on both stator and rotor circuits—typically far greater than the ratings of the converter’s power electronic devices [4]. The converter must either be temporarily disconnected to “ride-through” grid faults, or specific protection measures must be provided to avoid damage to the DFIG power converter devices and dc-link capacitors.

Conventional protection is via a sustained period of rotor-crowbar application during which the rotor phases are connected together through a resistor, diverting current from the rotor-side converter, and rapidly deenergizing the rotor. Unfortunately, control is lost while the crowbar is applied and...
the induction machine must draw its magnetization from the stator side, thus producing a high-slip reactive power demand that works to suppress the stator voltage. In this paper, a new “minimum-threshold” method is developed in which crowbar application is released by current threshold and feedback control carefully restored to optimize the resumption of power control to meet grid-code requirements. The method is experimentally demonstrated using a 7.5-kW laboratory DFIG test rig operating through various fault tests.

II. DFIG FRT AND THE ROTOR CROWBAR

Fig. 2 shows a typical connection between a single DFIG wind turbine in a wind farm and the transmission network. If a three-phase-to-ground fault is assumed to occur on one of the double-circuit transmission lines nearest the wind farm, the transmission system experiences zero voltage at the point of fault and a near-zero voltage at the 132 kV/275 kV transmission substation until the line is cleared. After clearance of the faulted line, the wind farm is connected to the grid by a single healthy transmission line; the local voltage will rise to a significant, but subrated magnitude until the faulted section of transmission line can be reinstated.

The consensus of newly revised grid codes that govern the connection, planning, and operating procedures for all transmission system users, including minimum FRT capabilities for transmission-connected generation, is that new generators, notably wind turbines, must remain connected and stable for a range of defined “credible” grid faults. These faults are defined by transmission voltage-dip profiles; worst-case profiles include 0% volts for 150 ms (Germany) [5] and 15% volts for 625 ms (Ireland) [6]. During the fault and for a period of fault recovery, the plant must provide reactive power to support the local voltage. Following fault clearance, active power must be delivered in a matter of seconds. In Great Britain, generators are required to provide active power in proportion to the retained voltage and deliver “maximum-available” reactive power [7].

Induction generators, including DFIGs, inherently lose a proportion of their magnetization during a grid fault, thus producing very short-period transient overcurrents and temporarily losing power control. A DFIG must therefore take self-protective action during fault transients to protect its power converter from the ensuing rotor overcurrents; during this period, vector control can be lost with a resulting loss of control of active and reactive power. The length and nature of this protective action, together with the speed with which vector control can be resumed, are critical issues with regards to the FRT response of DFIG wind turbines [8], [9].

A comprehensive FRT technique should therefore cover the following three broad aims.

1) Minimize the voltage drop at the generator: A technique that minimizes the voltage drop experienced by the generator will minimize the resulting demagnetization, aiding FRT, and expanding the range of faults for which protective action can be avoided. Notably, this is the most common approach in tackling FRT on a wind-farm level, using, for example, static VAR compensation (STATCOM) equipment to raise the fault voltage [10].

2) Divert or negate rotor overcurrents: Any FRT scheme must ensure that the currents carried by the insulated gate bipolar transistors (IGBTs) remain below the surge capability of each IGBT in the power converter. Furthermore, it is the transient rotor overcurrents that force a dc-link overvoltage. A scheme that successfully diverts or reduces the rotor overcurrents can also prevent a dc overvoltage event.

3) Produce appropriate power output during faults: The dynamic response of the DFIG controller will limit the rate at which apparent power control can be restored after the transient periods of fault initiation and recovery, and hence, determine the grid-code compliance of the turbine. What is clear is that instances of fault initiation and clearance impose very strenuous disturbances on a standard feedback-control scheme; this entails some instability and temporary loss of vector-control orientation. However, during the plateau of a grid fault, it is possible to safely deliver power in proportion to the residual balanced voltage and (up to) rated current’s worth of reactive power support.

Any proposed FRT scheme must restore active and reactive power control very swiftly following fault initiation and clearance in order to contribute to system frequency stability and improve the fault response of other locally connected equipment. Neither can be controlled by a DFIG in the immediate transient period after fault initiation. Specific regulations notwithstanding controlled export of power within 2–3 cycles (40–60 ms) of a serious voltage disturbance would represent a very favorable fault response.

A. DFIG FRT Control Limitations

In a comprehensive approach to FRT control, Xiang et al. [4] proposes precise positioning of the rotor converter voltage to negate or at least minimize the effects of machine flux decay. Experimental verification was however limited to no-load conditions, and the prefault voltage supply was required to be below 85% of rated voltage.

The importance of field orientation in the controller’s response was stressed by Yikang et al. [11] with slight improvements reported in a MATLAB/Simulink model. The same software is used by Serban et al. [12], where reduced overcurrents are reported for a simulated controller that throttles back the reference current demand. However, reactive power appears to dominate the voltage-recovery process with a period of 1.5 p.u.
VAr absorption. Rathi and Mohan [13] reports reduced overcurrents using “$H_\infty$ control synthesis,” although dc-link voltage deviations appear dangerously to extend to 100% above-rated and 50% below-rated. Improved performance against unbalanced voltage faults has also been demonstrated [14]. Yao et al. showed increased stability of the dc link under grid voltage dips [15], but made only a limited contribution to DFIG stability during fault periods.

The characteristic overcurrent rise time at fault initiation and recovery is a fraction of the transient time constant of the rotor circuit [4], and faster than the controlled rise-time response of the rotor converter’s current controller. It therefore seems that control alone cannot adequately curtail the overcurrents caused by a closeup fault.

B. Rotor Circuit Crowbar

Crowbar operation is a temporary measure developed as a rotor circuit protection device, long before the advent of wind turbine grid-code regulations. The term describes any device that connects together the rotor windings of a wound-rotor machine in a closed circuit through a designated resistance, diverting current from the rotor-side converter, and rapidly deenergizing the rotor. The crowbar absorbs the initial energy outflow from the machine, while the resistance shortens the effective decay timescale of the rotor flux decay, hence hastening the demagnetization process. Conventionally, the crowbar is applied for an extended duration to fully demagnetize the rotor [16], [17]. A crowbar activation period typically lasts about 120 ms. Unfortunately, this can lead to a 100-ms postfault period of at least 50% reactive power absorption and associated voltage suppression, and thus, failure to meet grid-code FRT requirements.

At least as important as the structure of the crowbar is the approach of the DFIG controller in restoring control after the crowbar is released [18]. Xie et al. reset the integral components of the rotor’s feedback PI controllers to zero before the crowbar is released to restrict windup of the controller’s integrators [19]. Morren and de Haan forced the feedback PI controllers to restart with a current reference equal to the last measured current, after which a soft restoration of control can be achieved by gradually altering the current demand [20].

When the crowbar is engaged, vector control is lost and the DFIG resembles a high-resistance singly fed machine, operating at very high slip [21]. This temporary configuration is a worst-case combination of poor torque output and very high reactive current demand. This reactive power absorption can only occur on the stator, acting to suppress the local fault voltage. The poor torque output worsens the mechanical stability. It is therefore necessary that crowbar application periods are minimized. The failure of a DFIG system to meet FRT requirements when using a crowbar for periods of 100 ms or more has been reported [22].

Other more complex FRT techniques have also been suggested. For example, Kasem et al. [23] presented a simulation study of a scheme employing a crowbar circuit in conjunction with an additional series static switch to reconfigure the rotor circuit on fault detection. In this arrangement, the rotor-side converter is totally isolated from the rotor circuit for the duration of the fault and connected in parallel with the supply-side converter to inject reactive power into the supply. Because of the isolation of the rotor converter, however, the DFIG cannot provide active power in proportion to the retained balanced fault voltage. Furthermore, the crowbar is applied and the machine is left uncontrolled for the duration of the fault. This means that the potential benefits of the reactive power export from both converters would, to a large extent, be cancelled by the reactive power requirement of the crowbar-activated induction machine operating at high slip. Any practical implementation of such a scheme would also suffer from higher on-state losses and higher costs compared with a standard crowbar system because of the inclusion of the static series switch and the current-sharing reactances needed to reduce circulating currents during the periods in which the two converters are connected in parallel.

III. MINIMUM-THRESHOLD CROWBAR METHOD

In this paper, a new minimum-threshold rotor crowbar is developed to reduce the length of crowbar application periods and optimize the resumption of power control as an FRT tool for wind turbine DFIGs. The crowbar circuit used in this investigation is formed of a three-phase rectifier, power resistor, and series IGBT switch, as shown in Fig. 3. The swift turn-off ability of an IGBT is necessary for the new minimum-threshold crowbar control method described in this paper. The application of the minimum-threshold crowbar was designed to allow the controller to smoothly resume vector control of a partially energized machine so that the length of the crowbar application periods could be minimized to meet grid-code requirements without the need for any additional circuits or devices. The development of the new technique is detailed in the following sections, but first, a brief description of the test rig used in the experimental investigation is presented.

A. Test Rig

The test rig, as shown in Fig. 4, comprised four main elements: a DFIG system, a wind turbine simulator, a grid fault emulator, and a control hardware assembly.

The 7.5-kW DFIG system represented the wind turbine’s DFIG, including a 7.5-kW wound-rotor induction machine and a custom 415-V, 50-A-rated back-to-back IGBT power stack employed as a bidirectional power converter, as illustrated in Fig. 5. Test rig induction machine parameters are given in the Appendix.

The induction machine’s rotor was wound to produce rated converter voltage at a maximum operating slip of ±30% and rated stator voltage. The vector-controlled converter was

![Crowbar circuit](image-url)
overrated to permit a range of grid fault tests without adversely affecting normal operation. Similarly, the electrolytic dc-link capacitors were selected for their additional surge capability, permitting short-term excursions of up to 1100 V \text{dc}.

An LC-type filter was chosen for the line-side converter with a 1200-Hz cutoff frequency. A small three-phase choke was added to the rotor circuit to minimize the impact of pulsewidth modulation (PWM) switching. A resistor set was included in series with the line-side connection (with a bypass circuit) to limit the inrush current when precharging the dc link. After a 3-s delay, the resistors were bypassed by a timer-controlled contactor.

The crowbar circuit connects the rotor phases together through an external resistor, as described earlier. The test rig crowbar IGBT was enabled by either of two triggers: a hard-wired error signal (enabled by gate driver error or a measured current exceeding 45 A), or a software-enabled trigger. When the crowbar was engaged, the rotor-side converter switches were turned OFF.

The crowbar contained a 25-Ω, 0.6-kW resistor chosen to reduce the rotor time constant to 10 ms, roughly a quarter of its original value. The relatively low thermal power rating is acceptable because the crowbar is used for such short periods. A 10-kW dc motor and its drive provided a torque input to the DFIG. Together with a simulated mechanical two-mass shaft model and blade-pitch control model (see Appendix) executed by the control hardware, this replicated the torque input from a variable-speed wind turbine rotor to represent the blade-pitch control action of the turbine. The final torque demand was applied to the dc motor by a 75-A dc-drive. A 5000-line optical encoder on the rotor shaft provided detailed rotor position information.

The grid fault emulator permitted a range of balanced voltage-dip profiles to be applied to the terminals of the DFIG via a 1:1 Y–\text{\&}–\text{\&} isolation transformer. Three independent voltage levels (healthy, fault, and recovery) were prepared in parallel on three three-phase variable autotransformers. The three outputs were connected by a set of back-to-back IGBT switches controlled from a central electronics board. A fault test was performed by switching the voltage applied to the generator from one source to the next in sequence. A single line diagram of the grid fault emulator setup is shown in Fig. 6.

The IGBT switches were rated for 55 A each and were protected by a series of fast-acting 30-A semiconductor fuses. The status of the switched voltage sources was dictated by a command signal dispatched from the dSpace controller. The dedicated switch-control board logic precluded short-circuiting the variacs via simultaneous engagement of multiple switches. The grid fault voltage and recovery voltage magnitudes were manually preset before each test.

A grid transformer, connecting a wind farm to the grid, possesses considerable reactance. Additionally, each wind turbine typically has a dedicated step-up transformer and interconnecting cabling. Included in the grid fault emulation kit, therefore, was a set of three-phase reactors, selected as a representative lumped connection impedance for a wind turbine in a large wind farm [24]. A wind turbine’s transformer is most commonly wound in star-delta form; this arrangement was reproduced by a three-phase star-delta wound 1:1 isolation transformer connected in series between the reactors and the DFIG.

Test cases were chosen to reflect grid-code requirements, as discussed in Section II. Results are presented in this paper for two of the most onerous cases: a 15% voltage enduring for 500 ms and a 0% voltage enduring for 140 ms, each with a 90% recovery-period voltage. The dc motor’s wind turbine torque simulator was set up to produce a prefault speed of 112% (of synchronous) in each case, representing a high wind speed of 10 m/s and an electrical output of 5 kW [1]. Less severe voltage dips and low-speed test cases proved to be less onerous. Fault test were not synchronized to correspond to any given point-on-waveform.
and repeated tests did not show any marked difference in the results.

B. Timer Action Crowbar

The first step in understanding crowbar operation is to study the conventional safety-first timer-controlled crowbar in which the crowbar is engaged for a timed period, chosen to comfortably exceed rotor transients, after which the crowbar is disabled and the rotor converter is reengaged onto a rotor circuit with zero current.

Fig. 7 directly compares differing test results for a 15% fault applied to a DFIG with timer crowbar results on the right and a base scheme without crowbar action on the left. The timer action crowbar is activated when the magnitude of the rotor current exceeds a threshold value set for the stated maximum IGBT pulse current of 2.0 p.u. (i.e., when the rotor \( d-q \) current magnitude exceeds 2 p.u.). The crowbar then remains engaged for a fixed time \( \tau_{cb} \). While the crowbar is engaged, rotor-side pulsewidth modulation (PWM) is disengaged (all switches “OFF”). The rotor current and power PI controllers are all reset to zero output. The line-side converter’s controllers remain unaffected. After \( \tau_{cb} \) has elapsed, the crowbar is released. If a rotor overcurrent persists, the crowbar is reengaged for an additional \( \tau_{cb} \) period.

When the crowbar is released, rotor-side PWM and rotor current PI control are immediately resumed. Power control is resumed after a specified delay, to allow the current controllers to settle. In the meantime, the current controllers work with interim reference values, held constant to minimize the settling time. The power control delay is not onerous as the choice of interim reference currents will deliver a reasonable power factor and will not act to destabilize the controller. A key ploy for stability is to initialize the power/reactive power PI feedback controllers’ integral components with values set equal to the interim reference values. This helps to smooth the resumption of outer-loop feedback control. Further changes to the reference currents are rate-limited such that any sharp transitions cannot destabilize the inner current control loops.

The active power reference was held constant during the fault: \(-0.67 \) p.u. (5 kW) nominal generation, which implies that the \( d \)-component of interim rotor current was held at \(+0.67 \) constant. The \( q \)-component was smaller here because no offset has been added to magnetize the machine at zero voltage. This was a cautious approach assuming the possibility of zero voltage on the stator and set in order to minimize the current reference, noting that the rotor is completely deenergized after 120 ms of crowbar engagement.

As power/reactive power PI control is resumed, the rotor current reference value changes were rate-limited to not more than 1.50 p.u./s to ensure current feedback control stability. Finally, the reactive-current reference saturation limits had been set at \( \pm 1.0 \) p.u.

The main advantages and disadvantages of this crowbar action are starkly apparent from Fig. 7. On a positive note, crowbar activation immediately redirected the rotor currents. In these tests, the current sensors were placed at the output of the rotor-converter’s series filter chokes, between the crowbar and the converter. It is clear from this data that the converter leg currents were forced to zero throughout the crowbar period. The close-up graph of rotor current magnitude shows the 2 p.u. limit in effect. During the whole fault period, the peak rotor current never exceeded the calculated maximum limit of 2 p.u. (9.5 A corresponding to 3.35 A rotor rms current). The redirection of the transient rotor currents protects the dc link from dangerous overvoltages; the maximum dc-link excursion being 30 V compared with 90 V in the base test.

After the first crowbar action, the controller brought the \( d-q \) rotor currents toward the same values, as with the base scheme, at a controlled rate limit of 1.5 p.u./s. By fault clearance, power control was restored and the local voltage boosted to 25%, close to the voltage of the base scheme.

However, crowbar activation initially suppressed the local voltage to 13%, while the machine’s internal magnetization was demanded from the stator circuit. Worse still, on fault recovery, the machine absorbed more than 50% reactive power for the full 120 ms of crowbar activation. The local voltage was suppressed to 84% during this period.

After the second crowbar activation period, control is regained very quickly; active and reactive power levels returned to unity power factor and 5 kW generation within tens of milliseconds.

C. Minimum-Threshold Crowbar

Fig. 7 clearly demonstrates how the crowbar-engaged DFIG displays very poor active and reactive power output. A key development aim is therefore to minimize the length of time for which the crowbar is used. Reflecting on the FRT demands outlined previously, it may be acceptable to lose power control if control can be regained in not much longer than one or two system cycles (20–40 ms). Indeed, if good power control can be restored within roughly 50 ms, the DFIG could be said to contribute very positively to the grid for the majority of the fault duration [25].

It is proposed to trigger the crowbar release by the fall of rotor current magnitude below a set threshold, noting the single-peak decay characteristic of rotor fault current magnitude. The stator variables of the rotor current PI controller are suspended with last good values to increase stability on the resumption of feedback control, thus allowing for the significantly reduced rotor decay-time constant. The outer-loop power and reactive power PI controllers are suspended during crowbar engagement, and then, soft-restarted at crowbar disengagement over a period of 10 ms, a quarter of the natural rotor time constant, as a compromise between stability and fast recovery. This presents the minimum period of crowbar use for the safety of the rotor-converter’s devices, and allows full resumption of current and power control within approximately 20 ms, thus enabling the DFIG to meet grid-code FRT requirements.

Using this method, there are potential problems with releasing the crowbar close to its turn-ON threshold of current magnitude: the ac element from the stator flux decay, uncertainties in the grid voltage plus any kicks from feedback control resumption could all threaten to retrigger the crowbar. A 5% margin on
Fig. 7. Timer action crowbar experimental results for 15% fault tests; 2 p.u. threshold and 120 ms crowbar duration.
maximum current-limiting threshold is thus used on crowbar turn-OFF to ensure stability.

A number of simple control schemes (such as the introduction of a deadband period and the use of a constant interim current reference to the inner control loop) promised excellent control in simulation, but failed to deliver satisfactory test rig performance, where the vagaries of system noise and low-quality voltage supply imposed far tougher standards and the problem demanded further investigation.

Some of the instability following resumption of rotor current PI control lay in the stabilization of its state variables, i.e., the PI integral components. Rather than reset to zero, the PI states are “frozen” by immediately setting the input $d-q$ error signal to zero when the crowbar was triggered, which causes the PI integral components to remain constant. In light of the very short period of crowbar use in this method, this frozen prefault state is more appropriate in terms of smoothly resuming current control with the current near to its threshold limit. The PQ controllers were soft-restarted after crowbar turn-OFF by means of an error signal ramp, as shown in Fig. 8.

When the crowbar is engaged, the PQ PI controllers’ input error signals are artificially held at zero. Furthermore, at the instant, the crowbar is released, the PQ error calculation is restored. However, the PQ error signal is passed through a dynamic saturation limit process. This magnitude limit starts at zero and ramps up to a maximum of $\pm 1.0 \text{ p.u. at 10 sec}$. After 10 sec, the error limit is removed from the control process. When the crowbar is released, the PQ PI controllers’ integral components are artificially reset to output the most recent measurement of rotor current. As a result, the rotor current PI controllers restart with approximately zero-error input, minimizing any kick in current associated with the resumption of feedback control. Ten meter second was chosen for the ramp duration as a quarter of the natural rotor time constant and a value comfortably between the characteristic rise times of the two control loops (5 ms for rotor current control and 40 ms for PQ control).

Results obtained from the application of this minimum-threshold method to the DFIG test rig for a 15% grid fault are shown in Fig. 9. The rotor currents flowing through the converter remained below 2 p.u. for the whole test duration. The first instance of crowbar application was so quick that the
dc-link voltage barely registered the event. The second led to a safe excursion of only 30 V. The first application, 1.2 ms after the fault, lasted for 13.0 ms. The second crowbar application, 6.6 ms after fault clearance, lasted for 15.6 ms.

The $d$–$q$ rotor currents show that stable control is established no more than 10 ms following the first crowbar release. The PQ controller led the $d$-component to a +0.67 p.u. reference in a first-order lag-type response, showing the controller’s 40-ms characteristic rise time. The $q$-component rises to the maximum limit of −1.0 p.u., which was held throughout the fault plateau. As a result, active power rises from 2.5% to 22% generation after crowbar release. Reactive power during the fault leveled out at 33% generation (via the stator).

The rotor currents underwent a controller stabilization period of roughly 30 ms after the second crowbar application. After this period, the PQ controller brought the rotor current references to appropriate values for the voltage-recovery period. This unfortunately left a 30-ms postcrowbar release period where reactive power of up to 1 kVar was absorbed by the machine through vector-control misalignment. Overall, however, good power control was restored only 45 ms after the crowbar was triggered.

The stable control performance is reflected by the stable stator voltages, which are held up at 30%–31%, throughout the fault. After fault clearance, the 45 ms period before control was fully stabilized showed only a 3% relative voltage suppression, which was quickly removed.

Results are shown in Fig. 10 for a severe 0% grid fault test showing the same quality of fault response as the less onerous 15% test. Peak currents were high, but limited to a single peak each at fault initiation and clearance; at each voltage step, the rotor currents were successfully diverted through the crowbar. DC-link voltage excursions were limited to a drop of 30 V, a rise of 50 V, all the time within operational limits. Crowbar application periods were first 1.0 ms after the fault, lasting for 15.0 ms, and second, 8.4 ms after fault clearance, lasting for 10.8 ms.

Good control of rotor currents can be seen within 15 ms after the crowbar is first released. The PQ controller led the $d$-component toward a +0.67 p.u. reference over the proceeding 100 ms, while the $q$-component again marked the maximum limit of −1.0 p.u. Correspondingly, active power rises to 8.4% generation from a crowbar-release value at 3.9% of rated power. Reactive power during the fault rise from a respectable 21% to 25% export. On voltage recovery, the second crowbar period again led to a 30 ms period of control restabilization. However, here the reactive power incidentally held a position of roughly 1 p.u. export at exactly the moment the crowbar was released, and in the proceeding transient, no significant reactive power absorption ensued. Overall, good power control was restored 40 ms after the crowbar was retriggered.

Stable voltages were maintained at 18% through the fault, solely by local VAr generation. After fault clearance, the second crowbar period caused only a 1% relative voltage suppression, which was relieved within 40 ms.

For completeness, DFIG rotor speed is included (see Figs. 11 and 12), showing the excitation of the low-frequency natural resonance of the drive shaft [26]. The amplitude of the resonance...
PANNELL et al.: MINIMUM-THRESHOLD CROWBAR FOR A FAULT-RIDE-THROUGH GRID-CODE-COMPLIANT DFIG WIND TURBINE 9

resulting from the 15% grid fault does not exceed 5.5%, which for any turbine remotely close to normal operation prior to the fault would not pose a significant problem. The 0% grid fault conveys a relatively small impact due to its short duration; although the speed rises over 4% during the 0.14-s grid fault, this was partially offset by a 1.5% kick-down in speed associated with demagnetization energy dissipated from the machine at fault initiation. The resulting low-frequency speed oscillation was very small in magnitude.

IV. CONCLUSION

A minimum-threshold method has been developed in this paper to minimize the length of DFIG crowbar application periods during a grid fault transient and optimize the resumption of power control. This involved partial suspension of the rotor current PI controllers and a soft-restart function for the PQ outer-loop PI controllers. The crowbar was engaged and disengaged strictly according to the rotor current magnitude, thus taking advantage of a single-peak characteristic of the hastened crowbar-induced rotor flux decay. The new method has been demonstrated using a 7.5-kW DFIG test rig capable of emulating a wide range of supply fault scenarios.

In a range of fault tests, the new minimum-threshold crowbar method successfully diverted the overrated transient currents and presented good power output within 45 ms of each voltage step. The crowbar application periods were 11–16 ms in duration, once each at fault initiation and at fault clearance. During the brief settling period after crowbar release, the worst instantaneous reactive power was 1.0 kVAR import in fault recovery, causing a brief 3% suppression in stator voltage; unity power factor was restored in roughly 30 ms. During the fault period, the raised rotor reactive-current limit of 1.0 p.u. allowed 33% reactive power, and hence, 22% active power output (15% fault test).

The proposed minimum-threshold crowbar method meets all stated FRT design aims: diverting transient rotor overcurrents, swiftly restoring active and reactive power control, and providing local voltage support by delivering reactive power to the network.

APPENDIX

The parameters of the star equivalent, per-phase equivalent circuit of the four-pole induction machine used in the investigation are as follows.

Stator resistance = 0.68 Ω, rotor resistance (referred to the stator) = 0.46 Ω, stator leakage inductance = 9.04 mH, rotor leakage inductance (referred to the stator) = 9.04 mH, magnetizing inductance = 226 mH, and stator/rotor turns ratio = 0.32

The per-phase filter impedances used are as follows.

Rotor choke inductance = 0.4 mH, line-side inductance = 10.56 mH, line-side capacitance (star) = 1.5 mF

A two-mass model of the wind turbine was used, as described by the following torque equations:

\[ J_L \frac{d^2 \theta_L}{dt^2} + B_L \frac{d\theta_L}{dt} + D(\omega_L - \omega_m) + K(\theta_L - \theta_m) = T_L \]

\[ J_m \frac{d^2 \omega_m}{dt^2} + B_m \frac{d\omega_m}{dt} + D(\omega_m - \omega_L) + K(\theta_m - \theta_L) = T_r. \]

Turbine inertia \( J_L = 5.25 \) p.u., turbine friction \( B_L = 0.0 \) p.u., coupling stiffness \( K = 98 \) p.u., coupling damping \( D = 1.0 \) p.u., total DFIG high-speed shaft inertia \( J_m = 1.44 \) p.u., and DFIG high-speed shaft friction \( B_m = 0.12 \) p.u.

ACKNOWLEDGMENT

The authors would like to thank Dr. T. Abeyasekera for the valuable contribution and construction of the test facility.

REFERENCES


Fig. 11. Rotor speed variation during the 15% minimum-threshold crowbar experimental fault test.

Fig. 12. Rotor speed variation during the 0% minimum-threshold crowbar experimental fault test.

Authorized licensed use limited to: Newcastle University. Downloaded on August 13,2010 at 14:08:19 UTC from IEEE Xplore. Restrictions apply.


Graham Pannell received the B.A. degree in physics from Cambridge University, Cambridge, U.K., in 2001, and the Eng.D. degree in engineering from Newcastle University, Newcastle upon Tyne, U.K., in 2008. He was a Research Engineer at Econnect Ltd., Hexham, U.K., where he was engaged with doubly fed induction generator performance under grid-fault conditions. He is currently a Senior Engineer at AC Renewables Ltd., Hexham, where he is involved in advising on the grid integration of wind farms.

David J. Atkinson received the B.Sc. degree in electrical and electronic engineering from Sunderland Polytechnic, Sunderland, U.K., in 1978, and the Ph.D. degree from Newcastle University, Newcastle upon Tyne, U.K., in 1991. For 17 years, he was with NEI Reyrolle Ltd. and British Gas Corporation. Since 1987, he has been with Newcastle University, where he is currently a Senior Lecturer in the Power Electronics, Drives, and Machines Research Group, School of Electrical, Electronic, and Computer Engineering. His research interests include control of power electronics systems, including electric drives and converters for renewable energy systems.

Bashar Zahawi (M’96–SM’04) received the B.Sc. and Ph.D. degrees in electrical and electronic engineering from Newcastle University, Newcastle upon Tyne, U.K., in 1983 and 1988, respectively. From 1988 to 1993, he was a Design Engineer at Cortina Electric Company Ltd., a U.K. manufacturer of large ac variable-speed drives. In 1994, he was a Lecturer in electrical engineering at the University of Manchester, Manchester, U.K. In 2003, he joined the School of Electrical, Electronic, and Computer Engineering, Manchester, U.K. His current research interests include power conversion and the application of nonlinear dynamical methods to electrical circuits and systems.