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Coordination between Fault-Ride-Through Capability and Over-current Protection of DFIG Generators for Wind Farms

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Abstract: Fault Ride-Through (FRT) capabilities set up according to the grid codes may affect the performance of related protective elements during fault periods. Therefore, in this paper the coordination between the FRT capability and over-current protection of DFIG Wind Generators in MV networks is investigated. Simulation test cases using MATLAB-Simulink are implemented on a 365-MW wind farm in AL-Zaafarana, Egypt. The simulation results show the influence of the FRT capability on the protective relaying coordination in wind farms, showing that the FRT may work in situations where is were expected not to work, and then disabling the over-current protection, which should have worked in this situation.

Key words: Wind farms protection, dynamic modeling, MATLAB-Simulink, fuse, doubly-fed, induction generators.

1. Introduction

The wind energy has increased a lot and new grid codes have been set up giving new issues to be solved related to stability, reliability and security, among them considerations regarding coordination of different protection schemes and fault ride through possibilities.

The essential benefits from a dedicated protection functions are to avoid possible local damage resulting from incident faults and minimize the impact of these abnormal conditions on the other sound parts of the network [1-3]. This reduces the associated negative impacts of the faults on the service continuity and the system stability. Consequently, it enhances the reliability and dependability of the overall grid performance. Wind farms still utilize surprisingly simple and none-integrated protection methodologies [4-6]. Also, research efforts regarding wind farm protection are still limited in the literatures as reported by Bauscke, et al. in Ref.[2], different levels of damage were recorded resulting occasionally from the drawbacks of the associated protection system.

Conventionally, wind turbines were separated from the grid following grid faults leading to loss of an undesirable portion of power generation. Hence, utilities nowadays require Fault Ride-Through (FRT) capability for grid-connected wind farms. FRT aims mainly to enable the wind farm to withstand severe voltage dips at the connection point resulting from the occurring grid faults. Hence, the wind farm is required to remain grid-connected during grid faults for a certain time so that it can directly contribute with active power to the grid. This supports the overall system stability. This is nowadays essentially required by almost all known grid codes for modern variable speed DFIG [3]. DFIGs have nowadays the superiority for wind farms as compared with conventional IGs. This is mainly

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because these units are distinctive with different advantages including ability to control voltage and reactive power, low short circuit contribution and in this way the ability to support the system stability. The grid codes were issued mainly to define the basic requirements of wind turbines during grid faults considering their operation modes and control strategies.

On the other hand, different problems arise for the associated generator / converter protection and control issues. During the voltage dips, the delivered active power to the grid by the farm is remarkably reduced. Consequently, the mechanical power exceeds the delivered active power resulting in an increased rotor speed. Then, the control scheme of the DFIG variable-speed wind turbines embraces both the wind turbine control for preventing over-speeding of the wind turbine and the control and protection of the power converter during and after the grid faults [4].

Although the FRT enable the overall system to restore its stability without losing large amounts of power generations after fault clearing, these control strategies may influence the related protective elements. Relay miss-coordination or miss-operation may occur due to the resulting changes of fault current profile. Therefore, the aim of this paper is to investigate the behavior of the over-current protection used with wind generating units during the operation of the FRT procedure.

2. Conventional Protection System for Wind Farms

Fig. 1 shows a schematic of a typical wind farm consisting of (n) units of wind turbines. Nowadays, modern wind farms include 20 to 150 units with typical size from 0.5 MW to 3 MW wind turbine generators. Larger sizes up to 5 MW are recently available in the market, in which they were successfully installed in some European countries. The use of induction generators in wind farm installations is today a standard practice, due to its suitable characteristics for the wind turbines.

The typical generator terminal voltage may range from 575 to 690 V with a frequency of 50 (or 60) Hz. The generator terminal voltage is stepped up to the Collector Bus system with a typical voltage of 22 to 34.5 kV. The step up transformer is normally oil cooled, pad mounted unit located at the base of the wind turbine unit. Sometimes, the step up transformer is mounted in the turbine nacelle. These transformers are usually victims to remarkable vibrations due to the wind load hitting the wind turbine. Certain considerations should be applied for avoiding harmonic effects. The transformer tanks have vertical and horizontal reinforcements to reduce vibration and resonance. Also, the core / coil assembly will be highly clamped and secured in the tank, restricting any movement in any of the three dimensions. The typical wind farm collector system consists of a distribution substation collecting the output of the distributed wind turbine generators through the incoming feeders. Usually some reactive power compensation units are provided by a collection of switched capacitors. Finally, the collected power is transferred to the utility side via an interconnection step up transformer.

The wind farm protection system is usually divided into different protection zones including the wind farm area, the wind farm collection system, the wind farm interconnection system and the utility area. The induction generator protection is typically accomplished via the generator controlling system co-

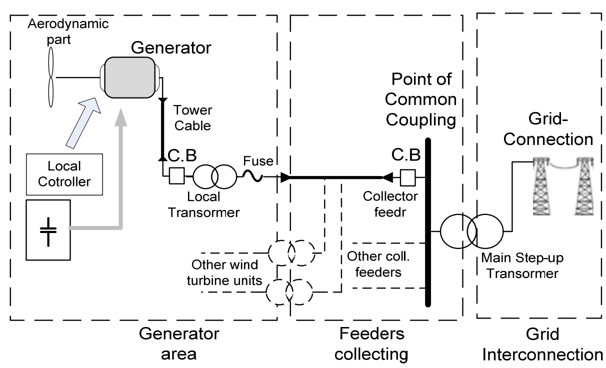


Fig. 1 Schematic of the conventional protection system.

vering some certain protection functions such as under / over voltage, under / over frequency, and generator winding temperature (RTDs). The generator control system does not contribute to the interconnecting system or the utility zone. The generator is protected against short circuits with its circuit breaker, which is practically dimensioned to 2-3 times the generator rated current. The generator step up transformer is usually protected with fuses dimensioned to 2-3 times its rated current. The collector feeder protection is simplified considering it as a radial distribution feeder using over-current protection (50 / 51). A basic challenge arises due to the distributed generators connected together to the radial feeder in determining the minimum faulty zone. That is in order to keep the remaining sound parts of the farm supplying the power. On the other hand, the protection of the wind farm substation collector bus and main power transformer consists of a multi-function numerical relay system including main transformer differential relay, transformer backup over-current relay, collector bus differential relay and breaker failure relay. Further details are available in the literatures [5-7]. It should be considered, that the wind farm interconnection would be to the MV distribution network, HV system, etc. Therefore, the coordination of utility relays and the wind farm will be quite different. Communication systems with dedicated SCADA are quite important for the wind farm operation. Nowadays, the data from each wind generator control is transmitted via optic cables and spread to the main substation for general control

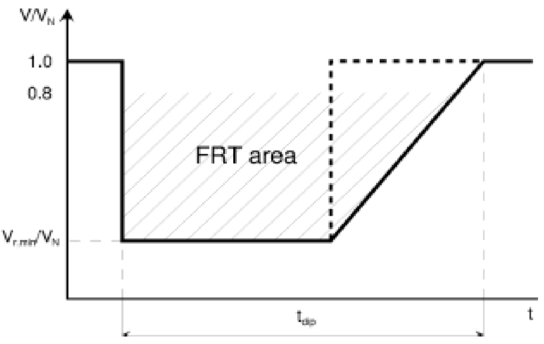


Fig. 2 FRT capability curve profile.

and monitoring purposes. This provides an ideal situation for providing them with an integrated monitoring and control system.

3. Problem Identification

3.1 Fault-Ride-Through Fundamentals for DFIGs

Historically grid codes allowed the wind turbines to be disconnected instantaneously at voltage sags below 0.8 per unit. In 2003, E.ON and VET (Germany) introduced the first FRT code requirements. Later, other international wind energy associations introduced their similar codes as well. Generally speaking, the grid codes required, that grid connected wind turbines should withstand voltage dips on any or all phases in the transmission system as long as the voltage measured at the high-voltage terminals of the grid-connected transformer, or in other words at the common coupling point (CCP), remains above a predetermined level in the grid code [8-12]. Different benefits are expected to be gained with FRT capabilities including enhancing the system stability and fast restoration of system service if the fault is cleared during the allowable time. These capabilities can be achieved by an adapted control strategy.

3.2 Crowbar System Protection

The crowbar system protection comprises thyristors, that short-circuit the rotor winding and hence thereby limit the rotor voltage and provides an additional path for the fault current. When a disturbance is introduced, high currents are induced into the rotor circuit from the stator side affecting the dc-link voltage as well. Then, the dc-link over-voltage protection will stop the rotor converter / inverter unit, meanwhile it turns on the crowbar control thyristor. Similarly, the crowbar can be triggered based on an occurring over-current through the rotor circuit. The rotor is now connected to the crowbar and remains connected until the main circuit breaker disconnects the stator from the grid [13, 14]. After clearance of the fault the generator can be line-synchronized again and started in a normal oper-

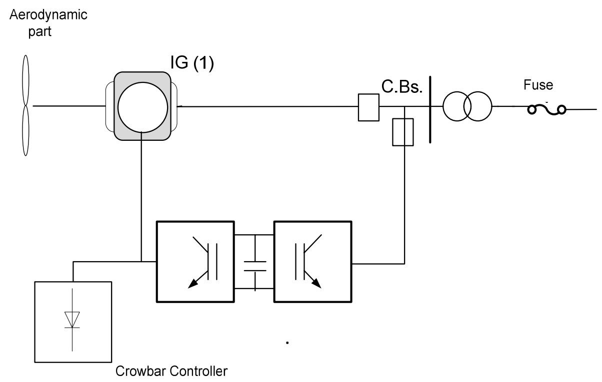


Fig. 3 Crowbar protection system for DFIG units.

ation mode.

The core of the crowbar operation was described by Akhmatov, Xiang, Holdsworth, Ekanyaki and Niiranen as reported in [9-17]. Technically, two types of crowbar systems are known including passive and active ones. For passive ones, the crowbar consists of a diode bridge that rectifies the rotor phase currents and a single thyristor in series with a resistor *Rcrow*. The thyristor is turned on when the DC link voltage *Udc* reaches its maximum value or the rotor current reaches its limit value. Simultaneously, the rotor of the DFIG is disconnected from the rotor-side frequency converter and connected to the crowbar Fig.3. The rotor remains connected to the crowbar until the main circuit breaker disconnects the stator from the network. When the grid fault is cleared, the rotor-side converter is restarted, and after synchronization, the stator of the DFIG is connected to the network. In contrast to a conventional passive crowbar, the active crowbar is fully controllable by means of a semiconductor switch. This type of crowbar is able to cut the short-circuit rotor current whenever needed and thus the DFIG wind turbine is able to ride through a network disturbance. If either the rotor current or dc link voltage levels exceed their limits, the IGBTs of the rotor-side inverter are blocked and the active crowbar is turned on. The crowbar resistor voltage and dc link voltage are monitored during the operation of the crowbar. When both these voltages are low enough, the crowbar is turned off. After a short delay for the decay of the rotor currents, the rotor-side inverter is restarted and the reactive power is ramped up in order to support the grid.

3.3 FRT Behavior during Disturbances

Fig. 4 shows different fault locations occurring on either the wind farm MV distribution network or the HV transmission system connecting the farm to the grid. These fault positions are designated with (A), (B), (C) and (D) respectively. Ideally, successful FRT operation is restricted to the faults that occur outside the wind farm in order to support the system stability. For those faults occurring inside the farm, the FRT scheme should not operate in order to enable the associated protection system to respond correctly. Referring to Fig. 4, solid three phase faults at positions (A) and (B) are normally characterized with larger voltage dips (down to 10% of the nominal voltage) which may be localized below the FRT characteristic edge. Hence, these faults may not trigger the FRT mechanism to operate. On the other hand, other external faults such as those ones at positions (C) and (D) are characterized with relatively smaller voltage dips (about 30% of the nominal voltage). Then, the FRT mechanism should operate correctly.

Since, the core for the crowbar mechanism depends mainly on the occurring rotor over-current to start, the aforementioned behavior of the FRT is expected to function properly for solid three phase faults as described earlier. This however, can not be guaranteed for non-solid faults or for unbalanced ones.

4. Development of the System Model

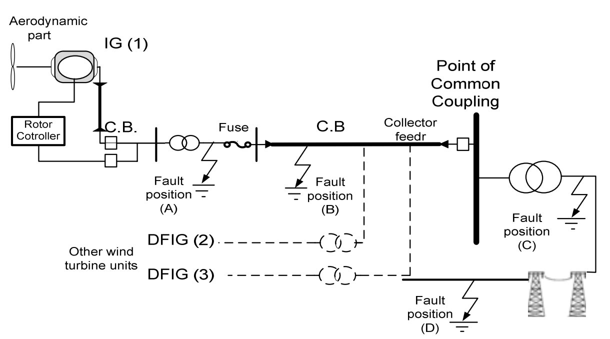
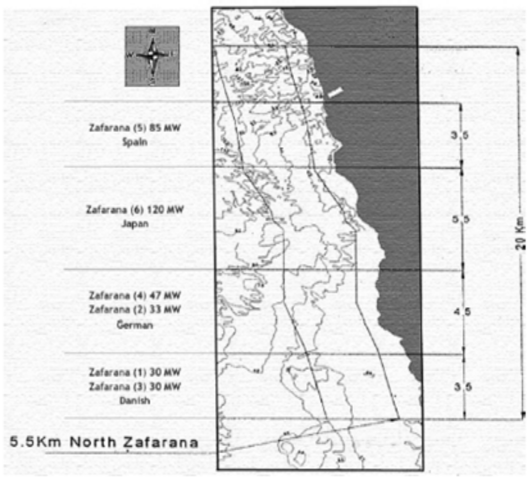
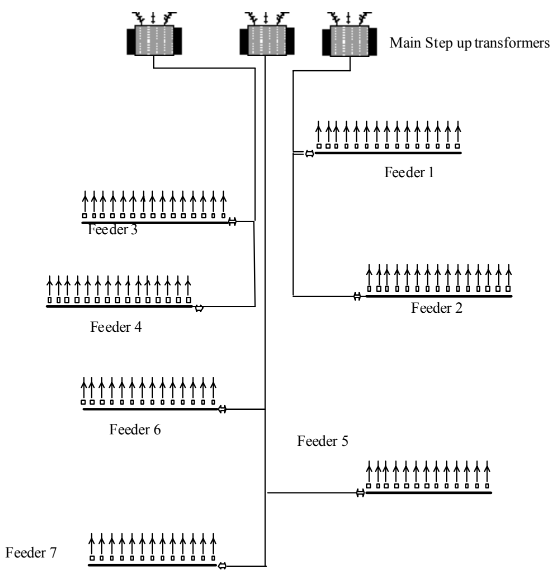


Fig. 4 Fault positions during faults for wind generating unit.



a



b

Fig. 5 Description of the fifth stage of Al-zafarana farm (a) geographical distribution of Al-Zafarana farm; (b) Schematic of the fifth stage of Al-Zafarana farm.

Modeling of DFIGs is well described in the literatures [15-17]. A 365-MW wind farm was recently established in Al- Zafarana (220 south east of Cairo, Egypt) and connected to the Egyptian 220 kV grid. This area is distinctive with different features such as an average annual wind speed of 9.5 m / s. The farm was structured through seven stages of 30, 33, 30, 47, 80 and 85, 120 MW respectively as described in Fig. 5(a). Except the latter two stages, other stages are with fixed speed and variable pitch operation. The fifth stage of the farm is selected as a simulation example in the paper. It consists of 100 wind turbines (with a 850 kW DFIG units for each turbine) providing a total power of 85 MW The DFIGs are distributed at seven feeders as illustrated in Fig. 5(b). Each wind turbine is connected to a 690 V:22 kV local step-up transformer. The collected power are then fed to the 220 kV network through three 75 MVA, 22 / 220 kV step-up transformers.

The turbine operation is characterized by the wind speed, the generator speed and its individual pitch control, the nominal wind speed being assigned to 9.5 m / sec "*the annual average wind speed at its corresponding location*" and the "cut-in" wind speed assigned to 4.5 m / sec. Each wind turbine is modelled by its induction generator model based on the asynchronous machine built-in model in MATLAB [18]. The operation of the crowbar is modeled by deactivating the converters upon detection of a rotor current magnitude above the current protection limit and then short-circuiting the generator rotor.

Fig. 6 shows the detailed schematic diagram of each wind turbine unit constructed with the built-in wind turbine model in MATLAB. The relatively large number of wind turbine units, in which each of them was constructed with different individual items "Turbine, generator, local transformer, feeding cable, …" increased remarkably the corresponding source of code. This is characterized with a huge operation time (around 305 min for each single run on a 3.2 GHz, 2 GB-RAM machine). This resulted in an impractical testing profile for the simulation purposes, that are characterized with huge amounts of simulation cases. Moreover, the aforementioned problem is significantly exaggerated for larger systems. Therefore, a need for reducing the overall wind farm model is obvious. On the other hand, the reduced model should be conditioned with the following restrictions:

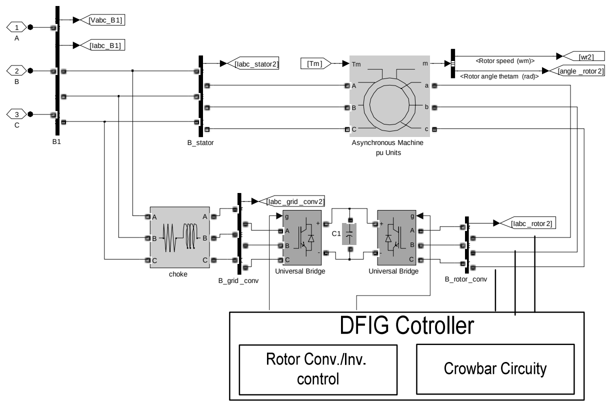


Fig. 6 Simulink-based diagram of a single unit.

Model accuracy for each individual power system element should be kept in its higher level.

The essential concepts for distributed generation must be satisfied.

Equivalence of currents for each individual unit as well as overall farm currents for both detailed and reduced model should be realized.

Equivalence of the generated power for each individual unit as well as for the overall farm for both detailed and reduced model should be realized.

Total power losses (due to connecting cables) should be considered.

Fig. 7 illustrates the proposed reduced model for the fifth stage of the Al-Zafaranna wind farm. The first six collecting feeders are lumped with their power equivalency with total lumped equivalent generators for each feeder respectively. For the latter collecting feeder, 10 generators are represented with their equivalent lumped generator, whereas the rest ones (the first, second and last units) are represented individually for keeping the distributed generation concept. For the lumped units, cable lengths were considered for keeping the total power losses equal to those resulting from the corresponding detailed model. The response of the reduced model is validated compared with the corresponding detailed one via different simulation examples for both faulty and non-faulty operating conditions. Details for the proposed modeling methodology were fully addressed in Ref. [7].

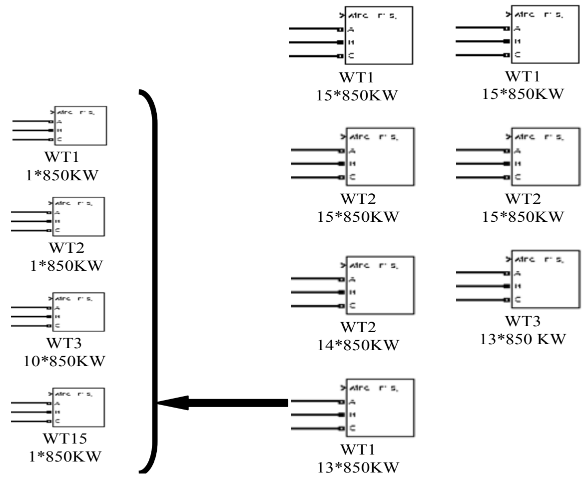


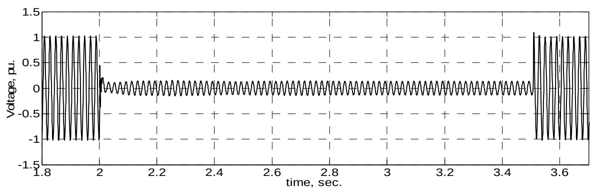
Fig. 7 Schematic of the reduced wind farm model.

5. Simulation Results

Depending on the developed reduced model in the preceding section, the behavior of the DFIG units in conjunction with the related FRT mechanism is thoroughly investigated under various faulty and non-faulty operating conditions. These cases are applied on the seventh collecting feeder as described in Fig. 4. Four different fault locations are considered: beyond the local step-up transformer (position A), along the connecting cable (position B), beyond the grid-connecting transformer (position C) and along the HV transmission line (position D). For each case, voltage and current quantities for both stator and rotor circuitries are recorded as described in the following sub-sections.

5.1 Grid Faults

During the three phase grid fault, the fault resulted in a sufficient drop in the phase voltage so that the associated crowbar mechanism is initiated to protect the rotor windings from the excessive fault current. As illustrated in Fig. 8, both the rotor and stator windings suffered by increased currents, resulting from the solid 3-phase grid fault occurring at position (C). On the other hand, the crowbar mechanism resulted in shorting circuiting the rotor winding rapidly after the fault inception (at 2 seconds) as well as deactivating the rot-



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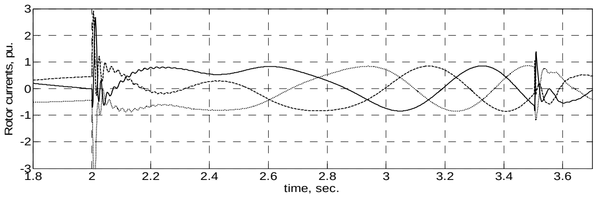

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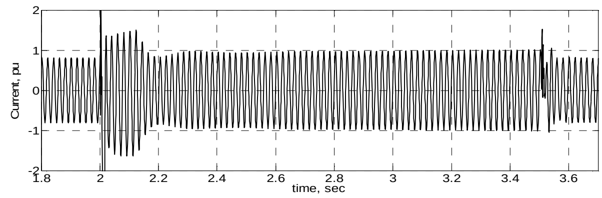
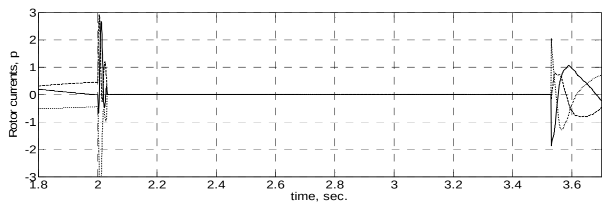


(c)

Fig. 8 Simulation response due to a solid 3-phase grid-fault at position (c) without crowbar initialization.

(a) Stator phase voltage, pu; (b) Rotor phase currents, pu; (c) Stator phase current, pu.



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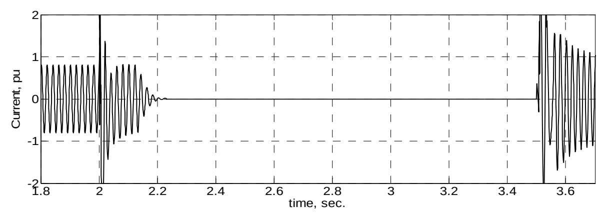
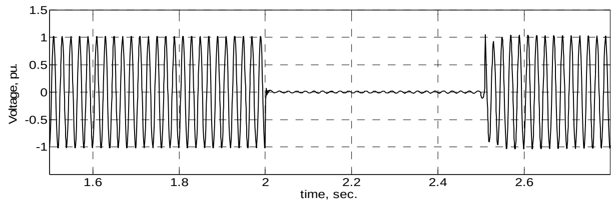


(b)

Fig. 9 Simulation response due to a solid 3-phase grid-fault at position (c) with crowbar initialization.

(a) Rotor phase current, pu; (b) Stator phase current, pu.

or controller as seen in Fig. 9, meanwhile the DFIG reacts similarly to the conventional single infeed machines. The rotor currents are decreased to zero avoiding possible winding damage, whereas the stator currents are decreased to zero due to the loss of reactive power compensation. This was fully addressed for three



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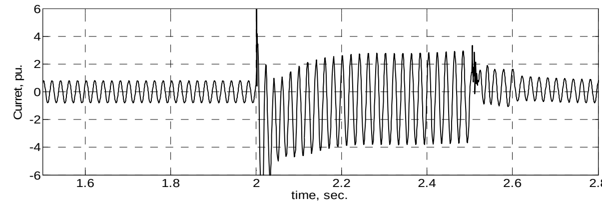

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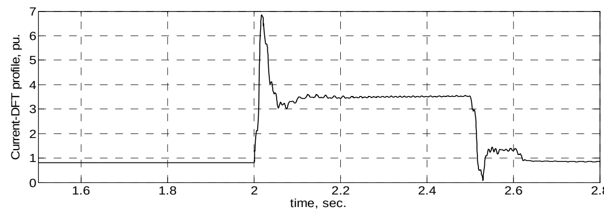


(c)

Fig. 10 Simulation response due to a solid 3-phase fault at position (B) without crowbar initialization.

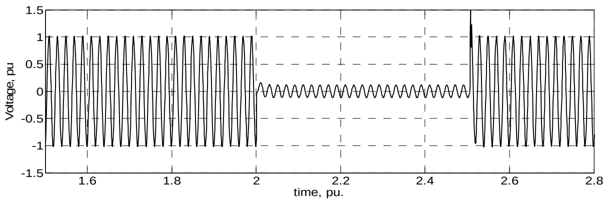
(a) Stator phase voltage, pu; (b) Stator phase current, pu; (c) Stator phase current peak profile with DFT.

phase faults for single infeed machines in Ref. [7]. When the fault is cleared at 3.5 seconds, the DFIG is restarted again. This means, that in this case the FRT operate as it should.

5.2 Solid Wind Farm Faults

In order investigate the behavior of the DFIG equipped with crowbar mechanism, a solid 3-phase fault is then applied before the local transformer at position (B). As illustrated in Fig. 10, the resulting low voltage condition at the generator terminals inhibited the crowbar operation. This is owing to the relatively larger voltage drop located lower than the FRT edge in the shown characteristics in Fig. 2.

Similarly, the DFIG response for a 2-phase solid fault at the same position beyond the local step-up transformer at position (B) is investigated and is shown in Fig. 11. As seen from the results, the voltage drop in this case initiated the crowbar mechanism, even though the fault position is inside the wind farm area. As noted from Fig. 11(c), the resulted stator fault current was kept below the predetermined setting of the utilized fuse element selected typically from 2 to 3 times the rated current, this means that the over-current protection in this case is disabled. Repeating, the same



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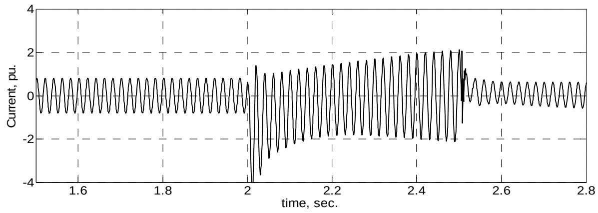

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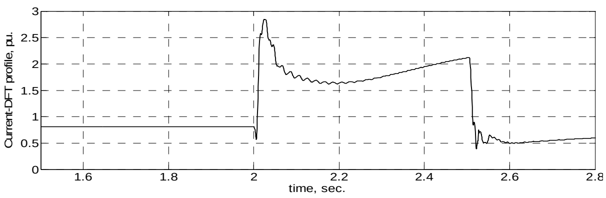
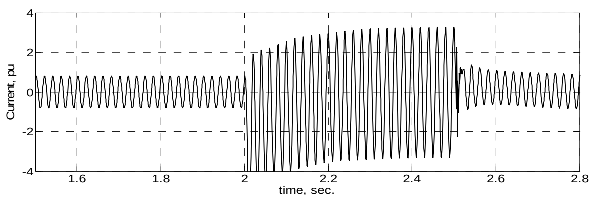


(c)

Fig. 11 Simulation response due to a solid 2-phase fault at position (B) with crowbar initialization.

(a) Stator phase voltage, pu; (b) Stator phase current, pu; (c) Stator phase current peak profile with DFT.



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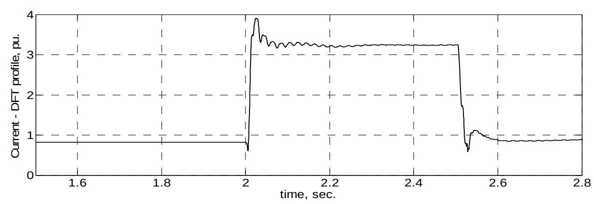
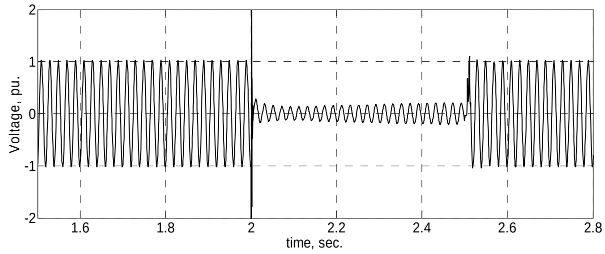


(b)

Fig. 12 Simulation response due to a solid 2-phase fault at position (B) without crowbar initialization.

(a) Stator phase current, pu; (b) Stator phase current peak profile with DFT.



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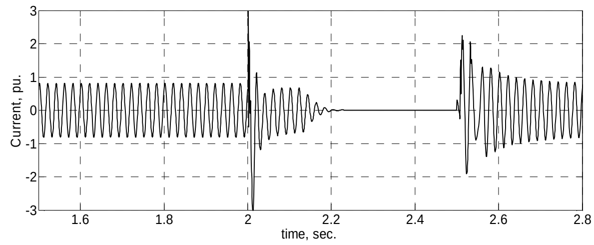

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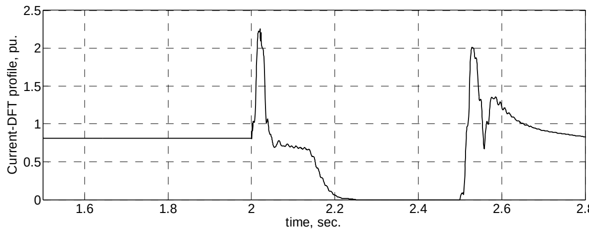
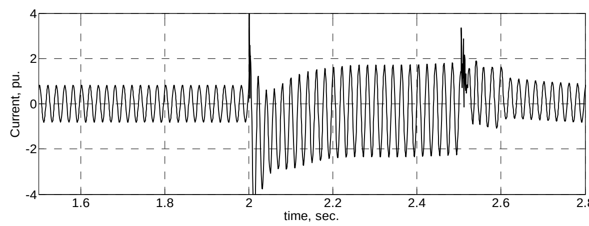


(c)

Fig. 13 Simulation response due to a 3-phase fault at position (A) with crowbar initialization and fault resistance of 2 Ω.

(a) Stator phase voltage, pu; (b) Stator phase current, pu; (c) Stator phase current peak profile with DFT.



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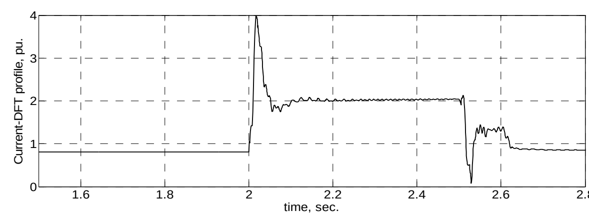

(b)

Fig. 14 Simulation response due to a 3-phase fault at position (A) without crowbar initialization and fault resistance of 2 Ω.

(a) Stator phase current, pu; (b) Stator phase current peak profile with DFT.

fault but with deactivating the crowbar mechanism is illustrated in Fig. 12(a) and (b), in which the fault resulted in a relatively larger fault current as noted from the associated Discrete Fourier Transform (DFT)-based peak detector of the fault current. These aforementioned results raise the effects of the FRT mechanism on the performance of employed over-current protection with DFIG machines equipped with FRT mechanisms.

5.3 Non-solid Wind Farm Faults

At non-solid faults usually the fault current decreases due to an increased fault resistance. These faults should be considered for evaluating the behavior of the DFIG machines equipped with FRT mechanisms. When a fault resistance is inserted in the fault current path, the decrease of the fault current is accomplished with a decrease of the voltage drop at the generator terminals. Consequently, the FRT mechanism may incorrectly be initiated for faults occurring inside the wind farm. This results in inhibiting the operation of the related over-current protection due to the reduced fault current. This is illustrated in Fig. 13 for a 3-phase fault through a 2 Ω fault resistance occurring at position (A) with utilizing the crowbar operation. Whereas the DFIG response, for the same fault condition, when deactivating the crowbar mechanism is shown in Fig. 14. Seen from both results, the crowbar operation reduces the fault current rapidly, whereas the fault current is kept at a remarkable level without the FRT operation. Hence, the impact of the FRT operation on the performance of over-current relays for such situations is obvious.

6. Conclusions

DFIG generators represent nowadays the most common generator type for wind farms using either onshore or offshore turbines. Owing to the increasing penetration of wind farms into power system grids, FRT capabilities is recently required by all known common grid codes. Common FRT strategies for DFIGs are usually performed with shorting the rotor winding of the faulted DFIG and deactivating the rotor converter immediately after detecting the occurring fault. The DFIG behaves, therefore, exactly as conventional SFIGs during the fault period. This results in lower levels of fault currents as compared with continuous DFIG operation during the fault. This consequently affects the behavior of the conventional over-current protection elements against network faults occurring in the local connecting circuitry of the wind farm. Fault resistance in conjunction with FRT strategies, even with small values, shows a significant effect perturbing the performance of the over-current protection as well. The results corroborate the need for new or modified coordination rules for over-current elements incorporated with DFIGs and FRT capability tools.

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