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Influence of DFIG Reactive Current Injection during a Voltage Dip on the Operation of Wind Turbine Circuit Breaker

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***Abstract*-- This paper deals with an issue that has not received much attention in literature. The aim of the study is to investigate the influence of doubly fed induction generator (DFIG) reactive current injection during a voltage dip on the operation of a wind turbine circuit breaker. The study is done using a novel hardware-in-the-loop test environment constructed using two real time simulators (dSPACE and RTDS) and commercial protection relay. It is found in this study that the reactive current injection enhances the operation of wind turbine protection since the zero crossing of the circuit breaker currents is achieved earlier. This action may prevent from failed auto reclosing and other safety hazards.**

***Index Terms*--Circuit breaker, DFIG, Fault Ride Through, reactive current injection.**

I. Introduction

In the doubly fed induction generator (DFIG) wind turbine concept, the stator of the generator is directly connected to the grid while the rotor is connected to the grid through a partially rated frequency converter. The use of DFIGs in wind turbines has been popular since the size and costs of the power electronic components are smaller compared to the full-power converter design. However, the response of the concept to the network voltage dips is considered to be problematic.

The penetration of wind generation has increased in many areas to a remarkable level. In such areas, the wind turbines are not allowed to operate independently from the rest of the power system. For example, the power system stability may be endangered if many wind turbines are disconnected as a result of a voltage dip. [1] Thus, the system operators have created grid codes that insist the wind turbines to be able to tolerate deep voltage dips. In addition, the grid codes demand that wind turbines should be able to inject reactive power to the network during the voltage dip in order to support the grid voltage. [2] The specifications that determine the requirements for the operation of the wind turbine units during grid disturbances are called as the fault ride through (FRT) requirements.

A. Fault Ride Through of DFIG Wind Turbine

The amplitude of the rotating magnetic flux of the DFIG is proportional to the stator voltage. A voltage dip in the stator terminals decreases the amplitude of the rotating flux of the generator instantaneously. However, the total flux cannot change instantaneously. The difference between total flux and the rotating flux is called a transient flux or a natural flux as defined by Lopez *et al*. [3]. The transient flux is not rotating and it appears only if there is a sudden step in the stator voltage. In addition, the transient flux gets its maximum value at the beginning of the voltage step. However, the transient flux decays to zero according to RL time constant of the stator.

The induced voltage to the DFIG rotor is proportional to the stator to rotor turns ratio of the generator and angular slip frequency i.e., the difference between the synchronous angular frequency of the flux and the rotor electrical angular speed. Due to the presence of the non-rotating transient flux on the airgap of the generator during the fault, very high voltages may be induced to the generator rotor circuit. [3] These high voltages saturate the rotor side converter (RSC) control system since the DC-link voltage is limited. As a result, the RSC cannot control the rotor current and the currents can't be limited. In such situations, the crowbar, i.e., a set of resistors, is typically connected to the rotor circuit in order to protect the power electronic switches and to decrease the rotor currents. The crowbar can be switched off after the induced voltage on the rotor circuit is decreased so much that the current of the RSC is controllable. When the crowbar is switched off the wind turbine can start to inject reactive current to the network. This is important since the latest grid codes insist the injection of reactive current during a voltage dip.

During the voltage dip, the stator flux contains rotating and non-rotating parts. Due to the non-rotating transient flux, the DC-component appears on the stator currents during the grid voltage dip. [4] Naturally, this DC-component is present also in the DFIG circuit breaker current. This DC-current may be harmful in the cases when the wind turbine should be disconnected from the network since it can delay the current breaking of the circuit breaker.

B. Relay Protection and Circuit Breaker Operation

The wind turbines are equipped with LOM protection relay in order to prevent islanding and protect the turbine during very harsh situations e.g. the fault in the point of connection. When the LOM protection relay detects abnormal operation it sends a trip command to the circuit breaker to disconnect the turbine from the grid. However,

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the circuit breaker can break each of the phase currents only when the current crosses zero. [5] In other words, if there is no zero crossing on the circuit breaker currents, an arc will maintain the current path even while the circuit breaker attempts to open. This consequently delays the disconnection of the wind turbine, which can be very harmful for the use of fast automatic reclosing (AR).

The fast AR is meant for removing temporary faults automatically without causing an extended interruption to the power supply. This is done by opening the feeder circuit breaker connecting the faulted feeder to the supplying network for a short period of time, usually from 0,2s to a couple of seconds. In the case if the fault is temporary, the fault arc usually extinguishes during this short de-energized period. It is, however, necessary that all the generating units connected to the faulted feeder are disconnected within the open time of the circuit breaker. Otherwise the generating units would maintain the voltage at the fault location and would prolong arc extinguishion. Thus, the AR sequence fails. Even short delays in the disconnection of the generating units can cause the AR sequences to fail. This is an important issue because the majority of faults on overhead lines are temporary in nature and thus clearable with the help of the fast AR. [6] Moreover, the out of phase reclosing which causes dangerous stresses to the generating unit, can occur if the disconnection of the generating unit is delayed considerably. [7]

C. *Purpose of the Study*

In this paper, the influence of reactive current injection of the DFIG during a voltage dip on the functioning of the wind turbine circuit breaker is analyzed. This issue has not received much attention in the literature. A comparison between two alternative operation methods during a fault is done. In the first method, the DFIG protection relies on the passive crowbar protection and no reactive current is fed to the network for voltage support purposes. In the second method, an active crowbar is connected only during the first instants of the fault. After the currents on the rotor side are decreased enough, the RSC is connected back in operation and the reactive current is supplied by the generator to the network. In addition, the grid side converter feeds reactive current to the network during the whole fault period. [8][9]

The aim of the study is not to investigate the effectiveness of the used FRT strategies but to show the existence of interactions between the reactive current injection and the operation of the circuit breaker. It is found in this study that the reactive current injection and proper crowbar resistance selection enhances the operation of wind turbine protection since the zero crossings of the circuit breaker currents are reached earlier. This action may prevent from the failed auto reclosing and other safety hazards.

II. DFIG AND NETWORK MODELING

The space-vector based equivalent circuit of the modelled DFIG is presented in Fig. 1. The stator of the generator is directly connected to the grid while the rotor circuit is connected to the grid via a frequency converter. The variables with superscript ‘ are reduced to the stator. The transformer describes the rotor to stator turns ratio of the generator.

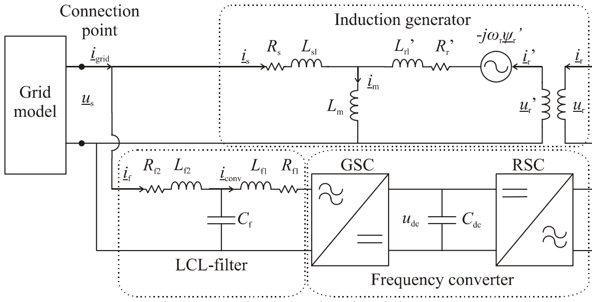

Fig. 1. Equivalent circuit of the DFIG.

The parameters of the generator, DC-link capacitor, LCL-filter and transformer are depicted in Table I. Both the RSC and the GSC are assumed to operate in the linear modulation area. In addition, the both converters are assumed to execute their voltage reference ideally i.e., the switching performance is not modelled in order to save the calculation resources. The transformer saturation is not taken into account in this study.

TABLE I
PARAMETERS OF DFIG AND TRANSFORMER

Parameter	Value	Parameter	Value
P_n	1700 kW	L_m	3.8 mH
$u_{s\ ll}$	690 V	Turns ratio N_r/N_s	2.73
R_s	0.0027 Ω	Pole pairs	2
L_s	0.089 mH	u_{dc}^{ref}	1100 V
R_r	0.0026 Ω	C_{dc}	22 mF
L_r	0.092 mH	L_{f1}	190 μH
R_{f1}	15 mΩ	L_{f2}	125 μH
R_{f2}	5 mΩ	C_f	70 μF
Transf. S_n	1.75 MVA	Transf. X_k	6%
Transf. R_k	1%		

The grid model is presented in Fig. 2. The network model used in the simulations is a greatly simplified model of a real Finnish distribution network.

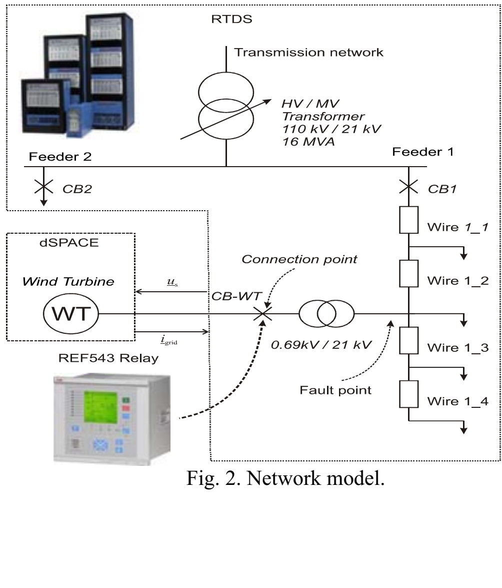

Fig. 2. Network model.

The distribution network model consists of two radial feeders, which is fed by a 16 MVA rated 110 kV/21 kV transformer. The WT is connected to the network through a circuit-breaker which is controlled by a real physical protection relay. The circuit breaker is modeled such that the current path on each phase can be interrupted only when the current crosses the zero.

III. CONTROL SYSTEM

The control system of the wind turbine consists of three parts. The control system of the grid side converter (GSC) controls the DC-link voltage to a constant value. The control system of the RSC adjusts the speed of the wind turbine and contributes on the voltage control by controlling the reactive power exchange with the grid. [10] Also the GSC can control its reactive current. In this study, the GSC injects reactive current to the network during a grid fault. The pitch control system is used to curtail the wind power production during high wind speeds in order to reduce the load of the mechanical and the electrical parts of the turbine system. The pitch control system used in this study is presented in the reference [11].

A. Control System of Grid Side Converter

The GSC control is done in the reference frame oriented to the positive sequence component of the connection point voltage $\underline{u}_s$. The positive sequence component of the voltage is extracted using a dual second order generalized integrator–frequency-locked loop (DSOGI FLL), Fig 3. [10] The DSOGI is a bandpass filter. The outputs are v_α' and v_β' which are the filtered versions of the grid voltage components in the stationary reference frame as well as qv_α' and qv_β' which are the inquadrature versions of v_α' and v_β', respectively. The output signals are used to calculate the positive and the negative sequence (PNS) components of the grid voltage. The PNS components can be estimated very accurately as long as the filter resonance frequency ω' corresponds to the grid frequency. However, the grid frequency is not constant. The FLL is used to modify the filter resonance frequency to the grid frequency. Thus, the DSOGI-FLL is a filter adapted to grid frequency which outputs can be used to detect the PNS components of the grid voltage.

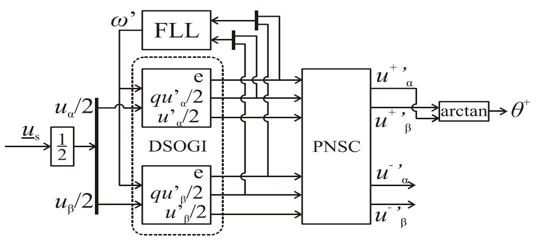

Fig. 3. Schematic diagram of the DSOGI-FLL.

The control system of the GSC is illustrated in Fig. 4. The fast inner loop controls the converter current $\underline{i}_{conv}$. The aim of the DC-link voltage controller is to keep the constant DC-link voltage u_{dc}, thereby ensuring the active power balance between the RSC and the GSC. The output of the DC-link voltage controller is the reference of the converter current x-component $i_{conv,x}$*. In the normal operation, the reference of the converter current y-component $i_{conv,y}$* is set to zero and GSC does not contribute to the reactive power control. However, during a network voltage dip, the current reference is increased in order to inject reactive power into the grid. The reference is calculated so that the converter current capacity is fully utilized. The output of the control system is the reference for converter voltage $\underline{u}_{conv}$*.

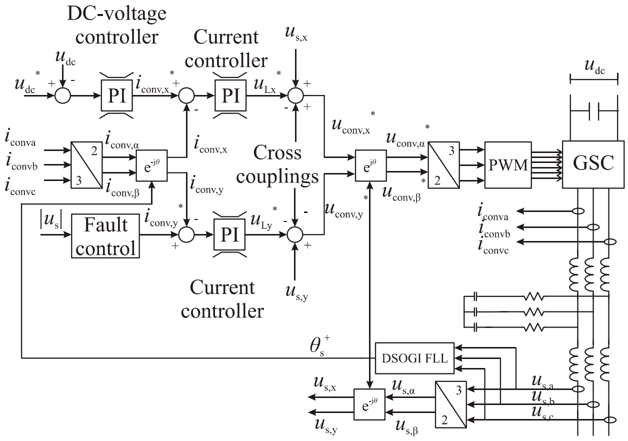

Fig. 4. Control system of the GSC.

B. Control System of Rotor Side Converter

The control system of the RSC is illustrated in Fig. 5. The control is based on the vector control in a reference frame that is oriented to the estimated positive sequence of the stator flux linkage. The stator flux linkage is first calculated from the measured stator voltages and currents. Then, the PNS components of the stator flux linkage are estimated using the DSOGI-FLL.

The RSC is controlled to extract the maximum power from the wind by optimizing the ratio between the blade tip speed and wind speed. The output of the speed controller is the reference for the torque t_e^*. The torque controller gives the reference value for the rotor current y-component. The reactive power controller enables the control of the reactive power exchange with the grid. The controller gives the reference for the rotor current x-component. The cross coupling compensation terms are added to the output of the current controller and the reference for rotor converter voltage $\underline{u}_r^*$ is achieved.

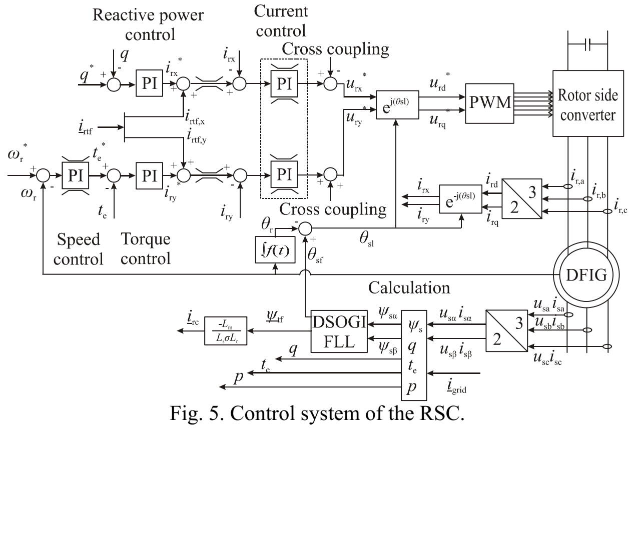

Fig. 5. Control system of the RSC.

C. Control of DFIG during a Fault

In this paper, two different operation strategies of DFIG wind turbine during a grid fault are used. The aim is to investigate the influence of the DFIG operation on the zero crossings of the circuit breaker currents and, thus, on the circuit breaker operation.

The first operation strategy relies on the passive crowbar. During the crowbar activation the rotor windings are short-circuited by crowbar resistors by firing the thyristor in Fig. 6. As the DFIG senses the voltage dip on the network, the crowbar is activated and both the RSC and the GSC stop modulation. After the crowbar activation the DFIG is operating like an induction generator with the increased rotor resistance. The use of the passive crowbar protection has been the common practice in older DFIG wind turbines due to the simplicity of the control and the effectivity of the converter protection. However, the main drawback of the fault control strategy is that the wind turbine is always disconnected from the grid after the crowbar activation. Hence, the latest grid codes are not fulfilled. [8]

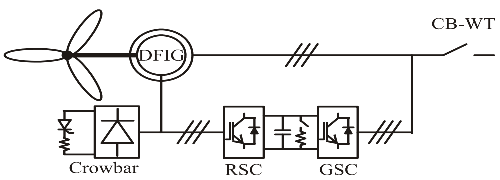

Fig. 6. Passive crowbar protection.

In the second case, the operation strategy during a fault relies on the active crowbar protection, Fig. 7. In addition to the crowbar activation, the reactive current is injected to the network during the fault for voltage support.

After the voltage dip is sensed the GSC starts to feed reactive current to the network immediately. The x-axis current is prioritized in order to keep the DC-link voltage in the desired value. However, the difference between the GSC current capacity and the x-axis current is set as the reference to the y-axis current component in Fig. 4.

As explained earlier, high and uncontrolled rotor currents start to flow as a result of a deep network voltage dip. The crowbar protection is activated and the RSC stops modulation if the rotor currents exceed the current capacity of the RSC. After the rotor currents are decreased under the current capacity the crowbar is deactivated and the RSC is activated. In the FRT method, the RSC starts to feed transient flux compensation current and reactive current after the crowbar removal.[8][9][12] The DSOGI-FLL is used to calculate the positive sequence component from the stator flux. The transient flux linkage $\boldsymbol{\psi}_{tf}$ is the difference between the total stator flux linkage $\boldsymbol{\psi}_s$ and the positive sequence component of the flux linkage $\boldsymbol{\psi}_{s+}$.

$$\boldsymbol{\psi}_{tf} = \boldsymbol{\psi}_s - \boldsymbol{\psi}_{s+} \quad (1)$$

The stator and the rotor flux linkage can be expressed using Equations:

$$\boldsymbol{\psi}_s = L_s \mathbf{i}_s + L_m \mathbf{i}_r \quad (2)$$

$$\boldsymbol{\psi}_r = L_r \mathbf{i}_r + L_m \mathbf{i}_s \quad (3)$$

where $\boldsymbol{\psi}_r$ is the rotor flux linkage, L_s and L_r are the stator and the rotor self-inductances, respectively, and L_m is the magnetizing inductance. The stator and rotor currents are $\mathbf{i}_s$ and $\mathbf{i}_r$, respectively. The rotor flux linkage can be expressed using Equations (2) and (3):

$$\boldsymbol{\psi}_r = \frac{L_m}{L_s}\boldsymbol{\psi}_s + \frac{L_r}{L_s}\mathbf{i}_r + \frac{L_m^2}{L_s}\mathbf{i}_r = \frac{L_m}{L_s}\boldsymbol{\psi}_s + \sigma L_r \mathbf{i}_r \quad (4)$$

where σL_r is defined as the rotor transient inductance. The current that oppose the stator flux can be calculated using Equation (4) and setting $\boldsymbol{\psi}_r$=0.

$$\mathbf{i}_r = -\frac{L_m}{L_s \sigma L_r}\boldsymbol{\psi}_s \quad (5)$$

The transient flux compensation current $\mathbf{i}_{rtf}$ is the current that oppose the transient flux $\boldsymbol{\psi}_{tf}$.

$$\mathbf{i}_{rtf} = -\frac{L_m}{L_s \sigma L_r}\boldsymbol{\psi}_{tf} \quad (6)$$

The idea behind the FRT concept is to use the RSC current capacity to minimize the effect of transient flux on the rotor. Thus, the transient flux compensation current, which is also called as the demagnetizing current [8], is prioritized. The transient flux causes uncontrolled oscillations on the currents around their references. These oscillations may activate repititive crowbar activation when reactive current is attempted to maximize. [9] However, the transient flux decays quite rapidly and when the calculated $\mathbf{i}_{\mathrm{rtf}}$ is smaller than the current capacity of the RSC the rest of the capacity is utilized for reactive current injection to the grid. In other words, the x-component of the rotor current is maximized while the y-component is set to zero in Fig. 5. It should be noted that after the transient flux is cancelled the current $\mathbf{i}_{\mathrm{rtf}}$ is zero and the whole current capacity of the RSC is utilized for the reactive power injection.

As explained above, when the wind turbine senses the deep voltage dip on the network it immediately starts to execute its FRT process. However, in some cases the turbine should be disconnected from the grid for example in order to prevent unwanted islanding. The wind turbine LOM protection relay determines whether the turbine should be disconnected from the grid or not.

When the wind turbine should be disconnected from the grid the LOM protection relay sends the trip command to the wind turbine circuit breaker. The trip command is also sent to both the RSC and the GSC as a signal to stop the modulation of both converters.

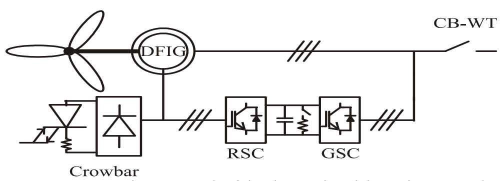

Fig. 7. Fault ride through with active crowbar.

IV. Experimental Setup

The study is done using a hardware-in-the-loop test setup shown in Fig. 8. The test setup consists of a dSPACE DS1103 controller board, a Real-Time Digital Simulator (RTDS), a REF 543 relay by ABB and an Omicron CMS 156 amplifier. The RTDS is used to simulate the power system model while the wind turbine model is simulated using the dSPACE, Fig. 2.

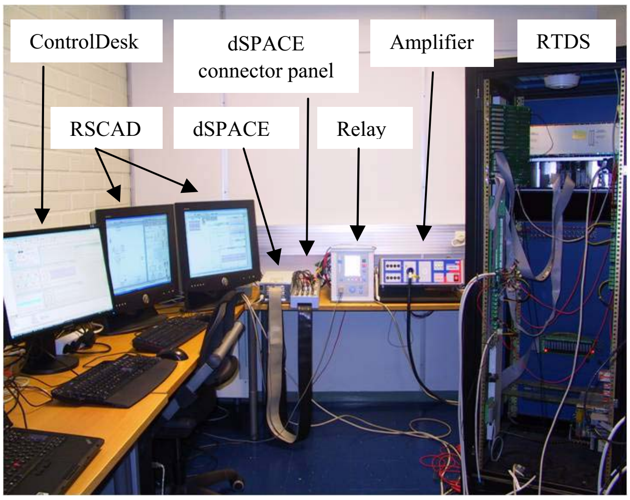

Fig. 8. Hardware-in-the-loop test setup.

The combination of the RTDS and the dSPACE provides an excellent environment for wind turbine and network interactions studies with minimized simulation time. Since a real protection relay is included as a part of simulation system, the influence of the wind turbine fault current on the circuit breaker operation can be studied. Additional benefit of the environment is the possibility to share calculation power between two simulators.

A. Practical Implementation

The block diagram of the RTDS/dSPACE implementation is shown in Fig. 9. The dSPACE simulates in real time the functioning of the DFIG, which is modeled in Simulink. The ControlDesk program is used to control and observe the simulation. The power system model is created in the RSCAD Draft mode. The RSCAD Runtime mode is used to control the real time simulation that is performed by the RTDS. The data transmission between the real time simulators is done through analog signals. In other words, first the digital signals of the simulator are converted to analog signals which are converted back to digital signals when fed to the other simulator. The dSPACE receives the connection point voltages $u_{s(a,b,c)}$, an interruption signal and the information on whether the relay is open or closed from the RTDS and gives the connection point current $i_{grid(\alpha,\beta)}$ back. From the RTDS viewpoint, the wind turbine is modeled as a current source. The interruption signal *int* is used to synchronize the calculations of the dSPACE and the RTDS. The transformer secondary side voltage measurement, i.e. the connection point voltage, is fed from the RTDS to the relay via an amplifier. The amplifier is needed since the voltage of the signals provided from the RTDS digital to analog converter card is not sufficient for the relay.

V. Simulation Results

Three phase short circuit occurring on the primary side of the wind turbine transformer, Fig. 2, is simulated. This is modeled as the full three phase voltage dip on the fault point which lasts 250ms. This is comparable to the real case where the feeder overcurrent protection opens the feeder circuit breaker CB1 after 50ms from the beginning of the fault and the feeder circuit breaker is automatically reclosed after 200 ms from the breaker opening. The feeder overcurrent protection relay and its automatic reclosing function were not included in the simulations due to the lack of the real relay. In the first simulation, the FRT method of the DFIG relies on the passive crowbar protection and no reactive current injection for voltage support is provided. In the second case, the FRT strategy includes the active crowbar protection and the reactive current injection. The crowbar resistances in the both cases were selected to be 0,4 p.u.

The connection point voltages of the simulations are

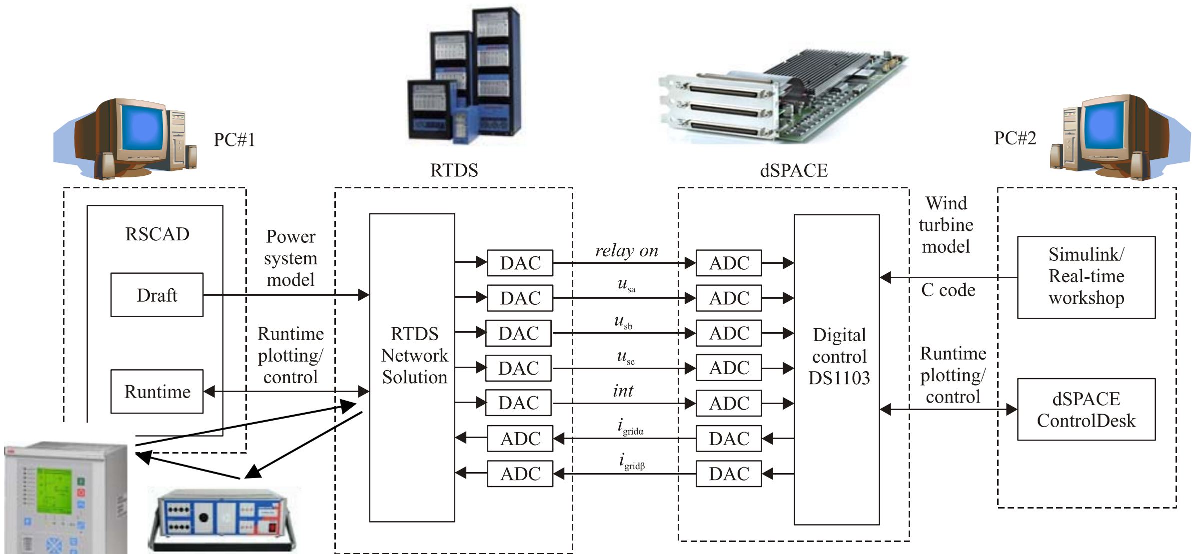

Fig. 9. Practical implementation of the research environment.

shown in Figs. 10a and 10b, respectively. In the first case, the three phase voltage dip occurs at 7.5s. The voltage dip induces high rotor voltages due to the transient flux and saturates the control system of the RSC. Thus, the currents in the rotor windings cannot be limited. The passive crowbar is activated when the peak value of the rotor current exceeds the current capacity of RSC which is in this case 900 A rms (peak value 1270). The rotor currents and the crowbar activation are shown in Fig. 11a. The high rotor currents activate the passive crowbar that stays connected as long as the currents flow in the rotor circuit. The frequency of the rotor current corresponds to the angular slip frequency. During the voltage dip the transient flux causes the rotor current frequency to increase since the synchronous angular frequency of the transient flux is zero.

Since the fault occurs on the wind turbine feeder, the protection LOM relay controlling the wind turbine circuit breaker operates. After 200ms from the beginning of the fault the LOM relay sends a trip command to open the wind turbine circuit breaker. The currents through the circuit breaker are shown in Fig. 12a. It can be seen that the DC-component caused by the transient flux appears in the currents. Although the LOM relay sends a trip command, the circuit breaker cannot interrupt the currents due to the absence of the currents zero crossings.

The DC-component delays the current interruption of the wind turbine circuit breaker. The delay can be very harmful for the use of fast automatic reclosing and can cause additional wearing of network components. In this case the circuit breaker currents were not zero when the automatic reclosing occurs after 250ms from the beginning of the fault. Thus, the automatic reclosing fails. Thus, in reality, the voltages cannot be restored to the wind turbine connection point. However, the voltages appear although the autoreclosing fails in Fig. 10a. This is because the AR sequence is modeled as the three phase voltage dip in the fault point which lasts 250ms and the real operation of feeder circuit breaker is not modeled. In addition, it is worth noticing that even if the LOM relay had tripped considerably faster than 200ms, the current interruption of the circuit breaker would still have occurred exactly at the same time.

In the second case, the FRT strategy includes active crowbar and reactive current injection to the grid in order to fulfill the grid codes. The identical fault compared to previous case occurred at 7.24s. The fault increases the rotor currents and crowbar protection is activated as shown in Fig. 11b. When the currents in the rotor windings are decreased under the RSC current capacity the crowbar is turned off at 7.32s using GTO (Gate turn-off thyristor). After crowbar removal the RSC controls the operation of the DFIG and starts to feed demagnetizing current as well as reactive current. When the LOM relay sends the trip command at 7.44s to the circuit breaker the modulation of the RSC is stopped.

The circuit breaker currents and the LOM relay operation are shown in Fig. 12b. During the time when

a) b)

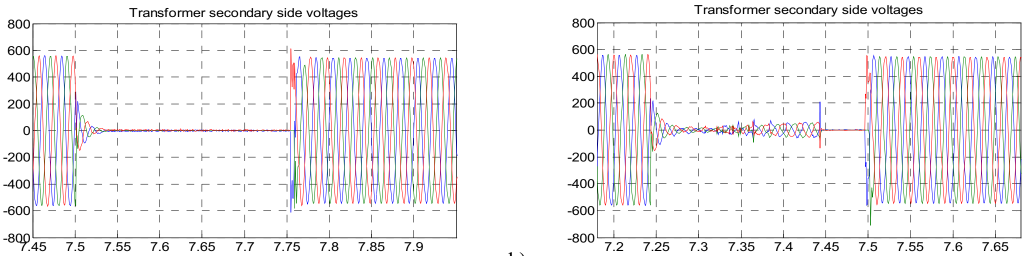

Fig. 10. Connection point voltage: a) DFIG without reactive current injection, b) DFIG injecting reactive current.

a) b)

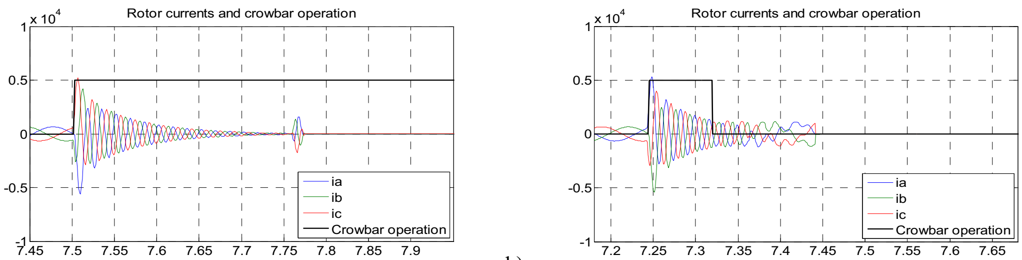

Fig. 11. Rotor current and crowbar operation: a) DFIG without reactive current injection, b) DFIG injecting reactive current.

a) b)

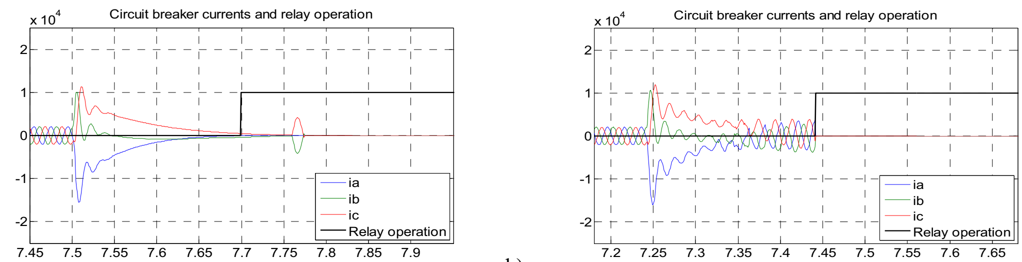

Fig. 12. Circuit breaker current and relay operation: a) DFIG without reactive current injection, b) DFIG injecting reactive current.

the crowbar is in operation the circuit breaker current shows some oscillations compared to Fig. 12a. These oscillations are caused by the reactive current feed by the GSC. The current capacity of GSC was selected to be 600 A rms (peak value 848 A).

When the crowbar is turned off the oscillations are increased further since the reactive current is injected from both the GSC and the RSC. These oscillations are beneficial since the current zero crossing on each phases is attained earlier. Hence, the circuit breaker is able to break the current as soon as the LOM relay sends the operation command. In this case, the circuit breaker would have had capability to disconnect the turbine from the grid even much earlier. However, the time of disconnection is determined by the settings of the LOM protection relay.

Effect of Crowbar Resistance

In next simulations, the crowbar resistance was selected to be 0.05 p.u. In the first case, passive crowbar protection is used. The connection point voltage drops at 7.57s as shown in Fig. 13a. The rotor currents are higher compared to situation where the higher crowbar resistance is used as shown in Fig. 14a. The peak value of the rotor current is approximately 7500 A while in the previous case the maximum peak current was approximately 5200 A. It should be noted that the rotor voltages are lower during the crowbar connection when the lower crowbar resistance is selected.

The circuit breaker currents and the LOM relay operation are depicted in Fig. 15a. When the low crowbar resistance is used very high circuit breaker currents are generated. The peak value the currents are slightly less than 21000 A. In the case when the 0.4 p.u. crowbar resistance was used the corresponding value is about 16000 A. The DC-component appears in the currents as in the previous case. However, it can be seen that also large oscillations appear. Due to these oscillations the circuit breaker current zero crossing is attained earlier. Thus, from the operation of the circuit breaker viewpoint the low crowbar resistance is beneficial.

The connection point voltage in the case where the active crowbar and 0.05 p.u. resistance is used is depicted in Fig. 13b. Low crowbar resistance makes the rotor currents to decrease rapidly from the high starting value under the current capacity value of the RSC as shown in Fig. 14b. This deactivates the crowbar and activates the RSC. However, as the RSC is reconnected the rotor currents increase again over the limit causing the crowbar to re-activate. This is because the transient flux has not disappeared and due to the flux the current oscillates around its reference.[9] Repetitive crowbar activation could be avoided for example by increasing the crowbar connection time.

Since there are great oscillations in the circuit breaker currents the zero crossings are attained earlier than the LOM relay operates, Fig. 15b. Thus, the circuit breaker can disconnect the wind turbine without problems in both

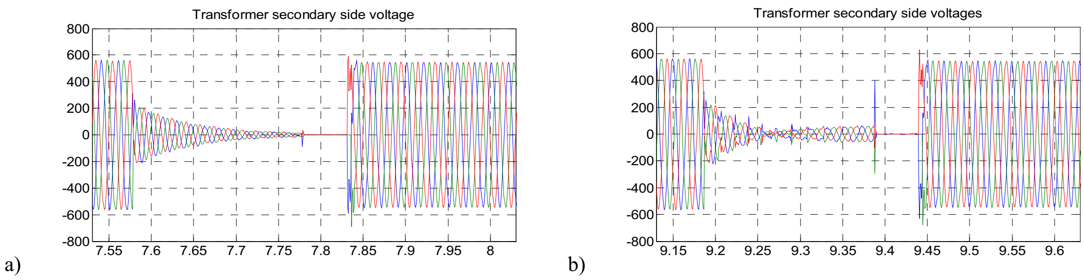

Fig. 13. Connection point voltage: a) DFIG without reactive current injection, b) DFIG injecting reactive current.

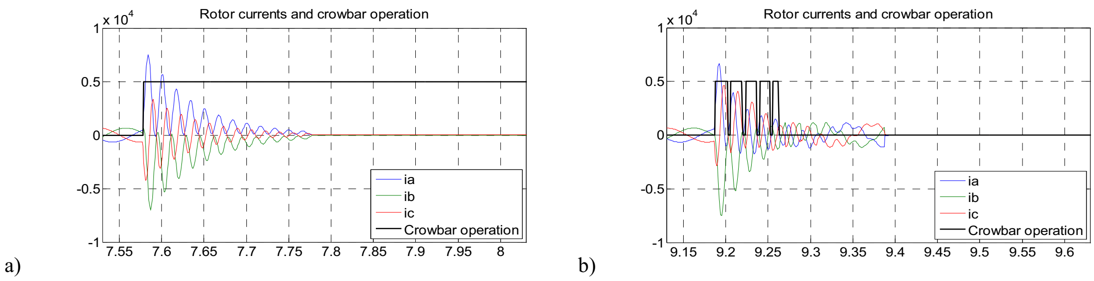

Fig. 14. Circuit breaker current and relay operation: a) DFIG without reactive current injection, b) DFIG injecting reactive current.

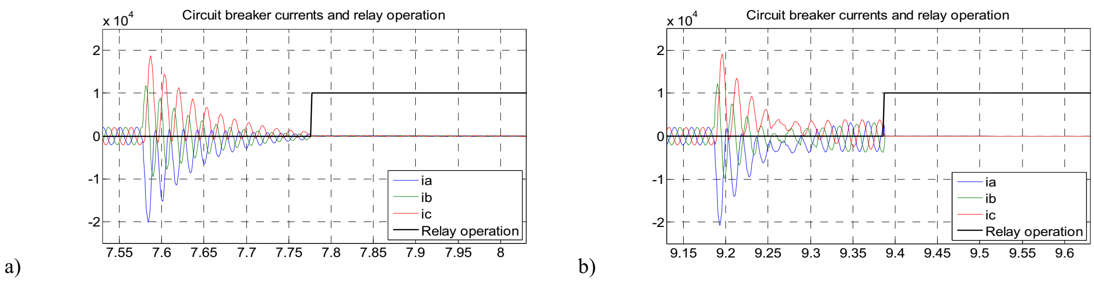

Fig. 15. Circuit breaker current and relay operation: a) DFIG without reactive current injection, b) DFIG injecting reactive current.

the passive and the active crowbar cases.

VI. Discussion

In this paper, the influence of reactive current injection during a voltage dip on the operation of wind turbine circuit breaker is evaluated. Based on the simulations it is found that if the passive crowbar protection utilizing high crowbar resistance is used the zero crossing of the circuit breaker current is delayed. This fact has influence on the operation of the circuit breaker since the breaker can interrupt the current only when the current crosses zero.

If there is no zero crossing an arc will appear between the breaker contacts. In the simulation model, the arc was modeled such that the current path is interrupted only as the current crosses zero. However, the resistance of arc was not taken into account and in that sense the simulation results represent the worst case scenario. In reality, the arc has resistive behavior. Especially at medium voltage levels the zero crossing of the current will be attained earlier due to the resistance of arc. If the wind turbine would be connected to the high voltage level and the fault near the turbine occurs the arc resistance is not so effective in decreasing the delay of the currents zero crossings. [5]

It should be noted that every time the circuit breaker attempts to interrupt the DC-current the arc will cause additional stress to the circuit breaker which decrease its lifetime. In addition, too long lasting arc may destroy the circuit breaker. The arcing time depends not only on the voltage level of the generator connection but also on the resistance and reactance in the fault path. Typically the generators and the transformers are designed to have minimized losses. This trend decreases the resistance and thus delays the current zero crossings. [5]

Although the resistance of the arc in the medium voltage network accelerates the zero crossings even a short delay in the disconnection of the generating units may cause problems when using the fast AR. Actually, it is not even enough that the arc is fully extinguished before the feeder breaker reclosing. Without sufficient time delay to allow the ionized gas created by the fault arc to disperse the arc will start conducting again after the AR. Thus, the fast AR will fail.[13] In that sense, it is vital that the circuit breaker can interrupt the currents as soon as the LOM relay sends the trip command.

The grid codes nowadays insist that wind turbines should inject reactive current to the grid during a voltage dip. It is shown by the simulations that reactive current injection adds additional oscillations on the circuit breaker currents. These oscillations accelerates the current zero crossings and thus improves the operation of circuit breaker.

VII. Conclusion

In this paper, the influence of the DFIG fault ride through method and reactive current injection to the operation of the wind turbine circuit breaker is studied. Due to the presence of non-rotating transient flux on the airgap of the generator the DC-component occurs on the stator currents during a grid voltage dip. This DC-component delays the zero crossing of the current that flows through the circuit breaker. Fundamental property of the circuit breaker is that it can interrupt the current only when the current crosses the zero.

The study is done utilizing the real-time simulation environment with protection relay-in-the-loop. Simulation results show that the reactive current injection for the voltage support creates AC oscillations to the DFIG grid currents which have DC-component. In addition, the selection of low crowbar resistance increases the AC oscillations. These oscillations advance the grid currents zero crossing. This improves the current interrupting capability of the wind turbine circuit breaker.

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