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***Abstract*—Voltage stability is a key issue to achieve the uninterrupted operation of wind farms equipped with doubly fed induction generators (DFIGs) during grid faults. This paper investigates the application of a static synchronous compensator (STATCOM) to assist with the uninterrupted operation of a wind turbine driving a DFIG, which is connected to a power network, during grid faults. The control schemes of the DFIG rotor- and grid-side converters and the STATCOM are suitably designed and coordinated. The system is implemented in real-time on a Real Time Digital Simulator. Results show that the STATCOM improves the transient voltage stability and therefore helps the wind turbine generator system to remain in service during grid faults.**

***Index Terms*—Doubly fed induction generators (DFIGs), real-time implementation, static synchronous compensator (STATCOM), wind turbine.**

I. Introduction

THE WORLDWIDE concern about environmental pollution and a possible energy shortage has led to increasing interest in technologies for the generation of renewable electrical energy. Among various renewable energy sources, wind power is the most rapidly growing one in Europe and the United States.

With the recent progress in modern power electronics, the concept of a variable-speed wind turbine (VSWT) equipped with a doubly fed induction generator (DFIG) is receiving increasing attention because of its advantages over other wind turbine generator concepts [1]–[4]. In the DFIG concept, the induction generator is grid-connected at the stator terminals; the rotor is connected to the utility grid via a partially rated variable frequency ac/dc/ac converter (VFC), which only needs to handle a fraction (25%–30%) of the total DFIG power to achieve full control of the generator. The VFC consists of a rotor-side converter (RSC) and a grid-side converter (GSC) connected back-to-back by a dc-link capacitor.

When connected to the grid and during a grid fault, the RSC of the DFIG may be blocked to protect it from overcurrent in the rotor circuit [1], [3], [4]. The wind turbine typically trips shortly after the converter has blocked and automatically reconnects to the power network after the fault has cleared and the normal operation has been restored. In [1], the author proposed an uninterrupted operation feature of a DFIG wind turbine during grid faults. In this feature, the RSC is blocked, and the rotor circuit is short-circuited through a crowbar circuit (an external resistor); the DFIG becomes a conventional induction generator and starts to absorb reactive power. The wind turbine continues its operation to produce some active power, and the GSC can be set to control the reactive power and voltage at the grid connection. The pitch angle controller might be activated to prevent the wind turbine from fatal overspeeding. When the fault has cleared and when the voltage and the frequency in the utility grid have been reestablished, the RSC will restart, and the wind turbine will return to normal operation. However, in the case of a weak power network and during a grid fault, the GSC cannot provide sufficient reactive power and voltage support due to its small power capacity, and there can be a risk of voltage instability. As a result, utilities, typically, immediately disconnect the wind turbines from the grid to prevent such a contingency and reconnect them when normal operation has been restored. Therefore, voltage stability is the crucial issue in maintaining uninterrupted operation of wind turbines equipped with DFIGs [1]. With the rapid increase in penetration of wind power in power systems, tripping of many wind turbines in a large wind farm during grid faults may begin to influence the overall power system stability. It has been reported recently [5] that integration of wind farms into the East Danish power system could cause severe voltage recovery problems following a three-phase fault on that network.

The problem of voltage instability can be solved by using dynamic reactive compensation. Shunt flexible ac transmission system (FACTS) devices, such as the static var compensator

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TABLE I
SYSTEM PARAMETERS (ON 3.6-MW 4.16-kV BASES)

Wind turbine		Induction generator		Power network	
Rated capacity	3.6 MW	P_{rated}	3.6 MW	r_{l1}	0.14
Cut-in wind speed	3.5 m/s	$V_{s,\text{rated}}$	4.16 kV	x_{l1}	0.8
Cut-out wind speed	27 m/s	r_s	0.0079	r_{l2}	0.14
Rated wind speed	14 m/s	r_r	0.025	x_{l2}	0.8
Number of blades	3	L_{ls}	0.07939	Z_L	$0.7+j1.5$
Rotor diameter	104 m	L_{lr}	0.40		
Swept area	8495 m^2	L_m	4.4		
Rotor speed	8.5-15.3 rpm	pf	-0.9 ~ +0.9		

(SVC) and the static synchronous compensator (STATCOM), have been widely used to provide high-performance steady-state and transient voltage control at the point of common coupling (PCC) [6]. The application of an SVC or a STATCOM to a wind farm equipped with fixed-speed wind turbines (FSWTs) and squirrel-cage induction generators (SCIGs) has been reported in [7] and [8] for steady-state voltage regulation and in [1] and [8] for short-term transient voltage stability. However, compared with the FSWT with a SCIG, the operation of the VSWT with a DIFG, particularly during grid faults, is more complicated due to the use of power electronic converters, and it has not yet been studied with the use of dynamic reactive compensation.

This paper investigates the application of a STATCOM to help with the uninterrupted operation of a VSWT equipped with a DFIG during grid faults. The STATCOM is shunt connected at the bus where the wind turbine is connected to the power network to provide steady-state voltage regulation and improve the short-term transient voltage stability. The DFIG and STATCOM control schemes are suitably designed and coordinated. The system is implemented in real-time on a Real Time Digital Simulator (RTDS).

II. POWER NETWORK MODEL

In a real power system, a large wind farm generally consists of hundreds of individual wind turbines. It has been reported in [1] that with well-tuned converters, there is no mutual interaction between wind turbines in a wind farm, independently from the conditions of the power grid. Therefore, in this paper, only one wind turbine is used to represent the wind farm.

Fig. 1 shows the single-line diagram of the power system used for this paper. In a real power system, a large power plant is normally connected to the power network by multiple parallel power lines with certain capacity redundancy, not only because of the thermal limits of each single power line but also to increase the reliability of the power transmission in the case of the outage of one power line. As in this paper, a 3.6-MW DFIG driven by a wind turbine [9] is connected to a power grid through a transformer and two parallel lines. A three-phase balanced electric load at the sending end bus is modeled as a constant impedance load Z_L. A STATCOM is shunt connected at the sending end bus for steady-state, as well as transient, voltage support. The parameters of the system components are given in Table I.

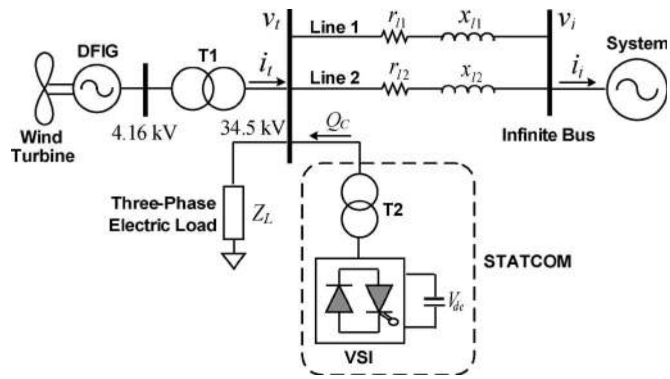

Fig. 1. Single-line diagram of the power network.

III. MODELING AND CONTROL OF DFIG

The basic configuration of a DFIG driven by a wind turbine is shown in Fig. 2. The wind turbine is connected to the DFIG through a mechanical shaft system, which consists of a low- and a high-speed shaft with a gearbox in between. The wound-rotor induction machine in this configuration is fed from both stator and rotor sides. The stator is directly connected to the grid while the rotor is connected to the grid through a VFC. In order to produce electrical power at constant voltage and frequency to the utility grid for a wide operating range from subsynchronous to supersynchronous speeds, the power flow between the rotor circuit and the grid must be controlled both in magnitude and in direction. Therefore, the VFC consists of two four-quadrant insulated-gate bipolar transistor (IGBT) pulse width modulation (PWM) converters connected back-to-back by a dc-link capacitor [10]. The crowbar is used to short-circuit the RSC in order to protect it from overcurrent in the rotor circuit during transient grid disturbances.

Control of the DFIG is achieved by control of the VFC, which includes control of the RSC [4], [10]–[12] and control of the GSC [10]. The objective of the RSC is to independently regulate the stator active and reactive powers, which are represented by P_s and Q_s, respectively. The reactive-power control using the RSC can be applied to keep the stator voltage V_s within the desired range, when the DFIG feeds into a weak power system without any local reactive compensation. When the DFIG feeds into a strong power system, the command of Q_s can be simply set to zero. Fig. 3 shows the overall vector control scheme of the RSC. In order to achieve independent control of the stator active power P_s and reactive power Q_s (Fig. 2) by means of rotor current regulation, the instantaneous three-phase rotor currents i_{rabc} are sampled and transformed to d–q components i_{dr} and i_{qr} in the stator-flux-oriented reference frame. The reference values of i_{dr} and i_{qr} can be determined directly from Q_s and P_s commands, respectively. The actual d–q current signals (i_{dr} and i_{qr}) are then compared with their reference signals (i^*_{dr} and i^*_{qr}) to generate the error signals, which are passed through two PI controllers to form the voltage signals ν_{dr1} and ν_{qr1}. The two voltage signals (ν_{dr1} and ν_{qr1}) are compensated by the corresponding cross-coupling terms (ν_{dr2} and ν_{qr2}) to form the d–q voltage signals ν_{dr} and ν_{qr}. These are then used by the PWM module to generate the IGBT gate control signals to drive the rotor-side IGBT converter.

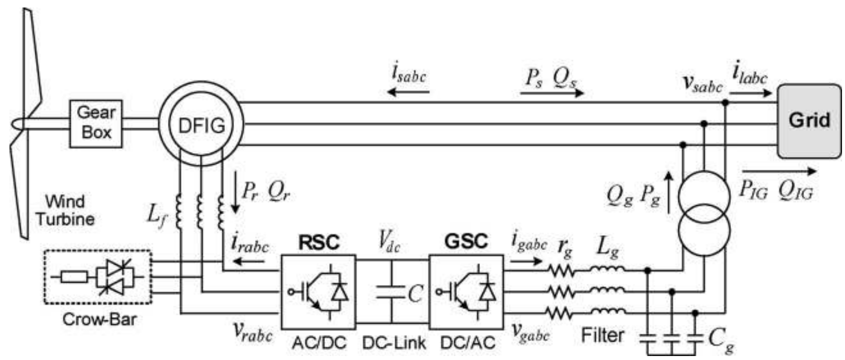

Fig. 2. Configuration of a DFIG wind turbine.

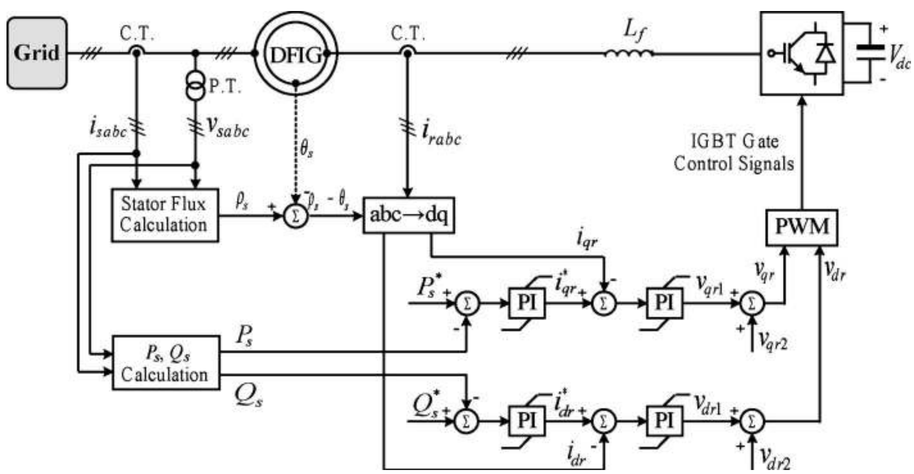

Fig. 3. Overall control scheme of the RSC. $\nu_{dr2} = -s\omega_s\sigma L_r i_{qr}$; $\nu_{qr2} = s\omega_s(\sigma L_r i_{dr} + L_m^2 i_{ms}/L_s)$.

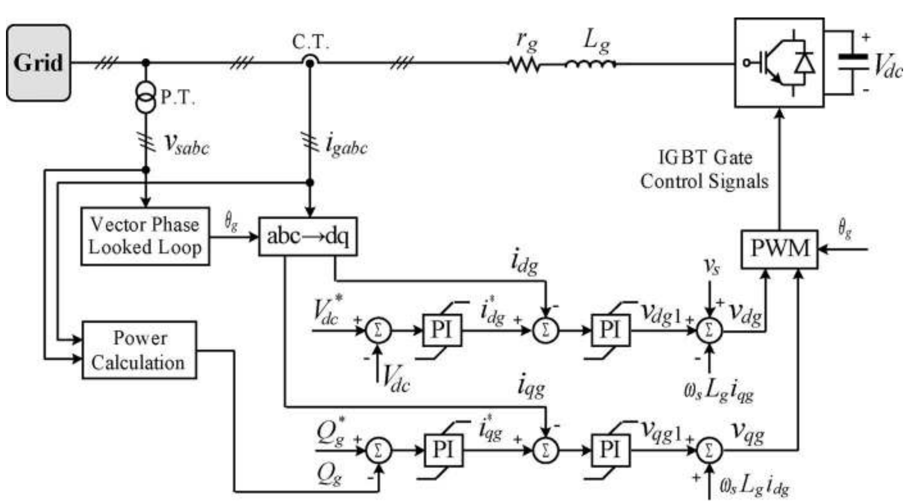

Fig. 4. Overall control scheme of the GSC.

The objective of the GSC is primarily to keep the dc-link voltage constant regardless of the magnitude and direction of the rotor power. In this paper, the GSC control scheme is also designed to regulate the reactive power Q_g exchanged between the GSC and the grid. During normal operation, the GSC is considered to be reactive neutral by setting $Q_g^* = 0$. This consideration is reasonable because the VFC rating is only 25%–30% of the generator rating and because the VFC is primarily used to supply the active power from the rotor to the power grid. However, the reactive-power controllability of the GSC can be useful during the process of voltage reestablishment, after a grid fault has been cleared and the RSC has been blocked. Fig. 4 shows the overall control scheme of the GSC. The actual signals of the dc-link voltage and the reactive power (V_{dc} and Q_g) are compared with their command values (V_{dc}^* and Q_g^*) to form the error signals, which are passed through the PI controllers to generate the reference signals for the d- and q-axes' current components (i_{dg}^* and i_{qg}^*), respectively.

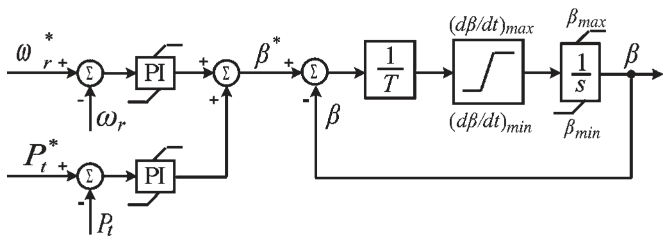

Fig. 5. Wind-turbine pitch angle controller.

The instantaneous ac-side three-phase currents of the GSC are sampled and transformed into d–q current components i_{dg} and i_{qg} by applying the synchronously rotating reference frame transformation. The actual signals (i_{dg} and i_{qg}) are then compared with the corresponding reference signals to form the error signals, which are passed through two PI controllers. The voltage signals (ν_{dg1} and ν_{qg1}) are compensated by the corresponding cross-coupling terms to form the d–q voltage signals ν_{dg} and ν_{qg}. They are then used by the PWM module to generate the IGBT gate control signals to drive the grid-side IGBT converter.

IV. Wind-Turbine Model

The aerodynamic model of a wind turbine can be characterized by the well-known C_P–λ–β curves. C_P is called power coefficient, which is a function of both tip-speed ratio λ and the blade pitch angle β. The tip-speed ratio λ is defined by

$$\lambda = \omega_t R / \nu_w \tag{1}$$

where R is the blade length in meters, ω_t is the wind-turbine rotor speed in radians per second, and ν_w is the wind speed in meters per second. The C_P–λ–β curves depend on the blade design and are given by the wind-turbine manufacturer. Given the power coefficient C_P, the mechanical power extracted by the turbine from the wind is calculated by [1], [9]

$$P_m = \frac{1}{2}\rho A_r \nu_w^3 C_P(\lambda, \beta) \tag{2}$$

where ρ is the air density in kilograms per cubic meter; $A_r = \pi R^2$ is the area in square meters swept by the rotor blades.

At a specific wind speed, there is a unique value of ω_t to achieve the maximum power coefficient C_P and thereby extract the maximum mechanical (wind) power. If the wind speed is below the rated (maximum) value, the wind turbine operates in the variable-speed mode, and the rotational speed is adjusted (by means of active-power control in the DFIG) such that the maximum value of C_P is achieved. In this operating mode, the wind turbine pitch control is deactivated, and the pitch angle β is fixed. If the wind speed is above the rated value, the rotor speed can no longer be controlled within the limits by increasing the generated power, as this would lead to overloading of the generator and/or the converter. In such a situation, the pitch control is activated to increase the wind turbine pitch angle to reduce the mechanical power extracted from the wind. Fig. 5 shows the structure of the pitch angle controller [1], [9]. $P_t (= P_s + P_r)$ is the total output active power from the DFIG.

V. STATCOM Model

A STATCOM [6], [13], also known as an advanced SVC, is a shunt-connected FACTS device. It generates a set of balanced three-phase sinusoidal voltages at the fundamental frequency, with rapidly controllable amplitude and phase angle. A typical application of a STATCOM is for voltage support. In this paper, the STATCOM is modeled as a gate turn-off thyristor (GTO) PWM converter with a dc-link capacitor. The objective of the STATCOM is to rapidly regulate the voltage at the PCC in the desired range. It can enhance the capability of the wind turbine to ride through transient disturbances in the grid. The overall control scheme of the STATCOM is shown in Fig. 6.

VI. Uninterrupted Operation Feature of the Wind Turbine During Grid Faults

The idea behind this uninterrupted operation feature is that the wind turbine does not trip when the RSC has blocked during a grid fault. During the RSC blocking, the rotor circuit is short-circuited by a crowbar, which is simply implemented by connecting an external resistor across each phase of the rotor circuit. The value of the external resistance is chosen as $R_{\text{ext}} = 20 \cdot r_r$, as recommended in [14]. The wind turbine continues its operation, with the DFIG rotor short-circuited. During such an operating condition, the controllability of the RSC is naturally lost, and there is no longer any independent control of active and reactive powers in the DFIG. The DFIG becomes a conventional induction generator, which produces an amount of active power and starts to absorb an amount of reactive power. In order to prevent the wind turbine from overspeeding, the pitch angle controller can be activated to keep the speed around the predefined value.

When the RSC is blocking, the GSC can be set to control the reactive power exchanged between the DFIG and the grid. This controllability of the GSC, however, is limited due to the small capacity of the converter. In a weak power network, as a result, there can be a risk of voltage instability and the subsequent tripping of the wind turbine generator. To avoid such a contingency, a STATCOM is used to provide transient voltage support to help the DFIG ride through grid faults. The STATCOM can also be used for steady-state voltage regulation and power factor control of the DFIG.

During the RSC blocking, the RSC control system continues monitoring the rotor current, the terminal voltage, the active and reactive powers, and the generator rotor speed. When the fault has cleared and when the terminal voltage and the rotor current return to their predefined ranges, the RSC starts synchronization [1]. At synchronization, the RSC starts switching, and the external resistance is disconnected; the d–q components of the RSC voltage source (Fig. 3) are set to $\nu_{dr} = i_{dr} \cdot R_{\text{ext}}$ and $\nu_{qr} = i_{qr} \cdot R_{\text{ext}}$, which are used by the PWM module to generate the IGBT gate control signals to drive the IGBT converter. When the synchronization seems to be complete, the control system of the RSC switches to the regular control system, as shown in Fig. 3, and the RSC restarts. When the RSC has restarted, the DFIG again has independent active- and reactive-power controls, and the wind turbine returns to normal operation.

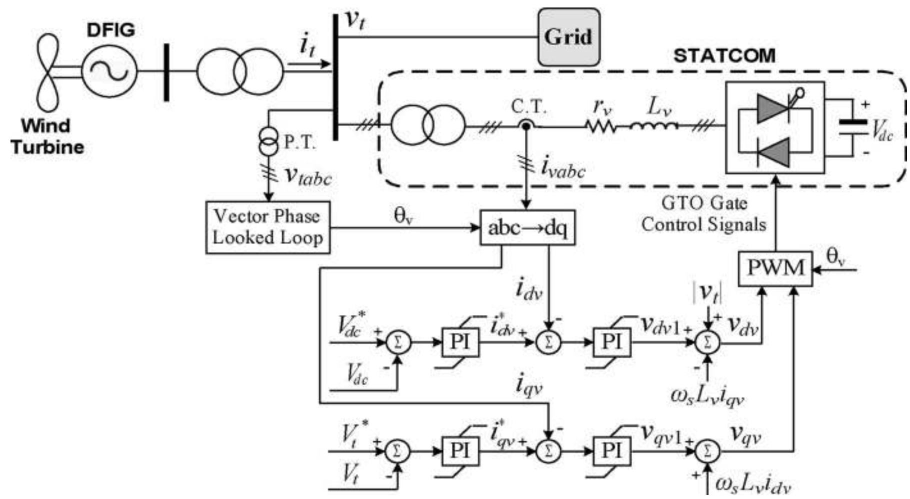

Fig. 6. Overall control scheme of the STATCOM.

The advantages of this uninterrupted operation feature include the following: 1) The wind turbine continues supplying the active power to the power network, and therefore, the demand for immediate power reserves is reduced, and 2) the wind turbine can contribute to maintaining the frequency in the power network during a transient state.

VII. Real-Time Implementation Setup

The RTDS is a fully digital electromagnetic transient power system simulator capable of continuous, sustained real-time operation [15], i.e., it can solve the power system equations fast enough to continuously produce output conditions that realistically represent conditions in the real network. The RTDS has been widely accepted as an ideal tool for the design, development, and testing of power system protection and control schemes. Considering that the solution is in real time, it can be connected directly to the power system control and protective relay components.

The RTDS is a combination of advanced computer hardware and comprehensive software, as shown in Fig. 7. It has a custom parallel-processing hardware architecture assembled in modular units called racks. Each rack contains both processing and communication modules. The mathematical computations for individual power system components and for network equations are performed using processor modules. The RTDS uses a user-friendly graphical interface—the RSCAD Software Suite—as the user's main interface with the RTDS hardware. The software is comprised of several modules designed to allow the user to easily perform all of the necessary steps to prepare and run a simulation and to analyze simulation output.

The RTDS hardware has a number of different types of processor cards available, including the Triple Processor Cards (3PCs), the RISC Processor Card (RPC), and the Giga Processor Card (GPC). The 3PC contains three Analog Device ADSP21062 (SHARC) processors, each operating at 80 MHz. The 3PC is typically used to perform the computations required to model the user's power system and control systems with a typical time step of 50 μs. The RPC contains two IBM PowerPC 750CXe RISC processors, each operating at 600 MHz. The most recent GPC contains two IBM PowerPC 750GX RISC processors, each operating at 1 GHz. In addition to the network solution and the simulation of standard components, the GPC can also be used to provide small timestep $(<2\ \mu s)$ simulations of voltage source converters with a high switching frequency. The RTDS provides a specially designed *small-dt* module to perform the small timestep simulations on the GPC card. In this paper, the VFC of the DFIG contains two PWM IGBT converters with switching frequencies of 2 kHz each and therefore is simulated on the GPC card using the *small-dt* module. The power network model and the STATCOM are simulated on the 3PC and RPC cards, respectively. The control systems are simulated on the 3PC cards. Fig. 8 shows the RTDS modules and the processor assignments for a real-time implementation of the system in Fig. 1. In RTDS, an interface transformer

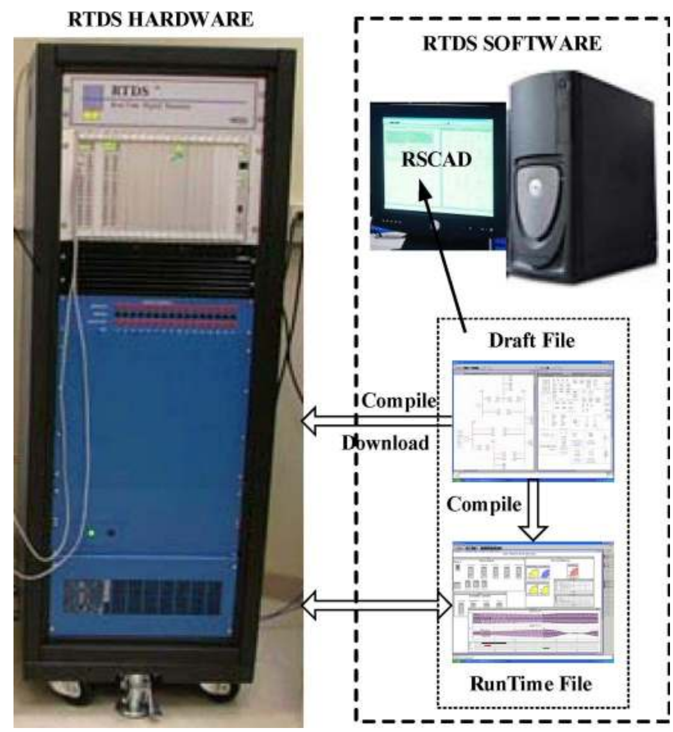

Fig. 7. Real-time implementation setup using RTDS.

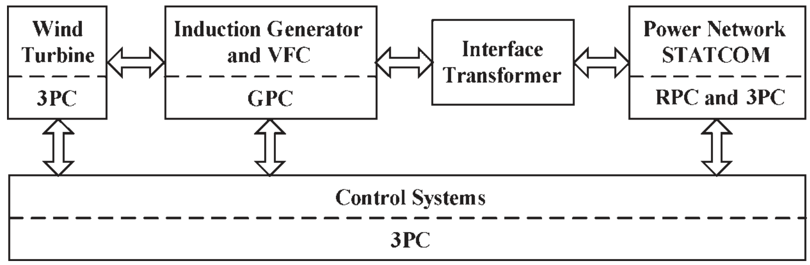

Fig. 8. RTDS modules and processor assignments for real-time implementation.

is used to connect the small-timestep power system module ($< 2\ \mu$s) to the large-timestep ($50\ \mu$s) power system module.

VIII. Real-Time Implementation Results

This section presents the real-time implementation results of the system in Fig. 1 at the following operating conditions: 1) The wind speed is constant during the simulation (this assumption is reasonable for investigating short-term voltage stability [1]); 2) the DFIG is running at a supersynchronous speed with the generator rotor speed at about 1.2 per unit (p.u.); and 3) the DFIG does not exchange reactive power with the power system when applying the STATCOM, namely, the reactive power commands of both RSC and GSC are set to zero.

A. Steady-State Voltage Regulation

The voltage command of the STATCOM controller V_t^* (Fig. 6) is step changed from 0.92 to 1.02 p.u. at $t = 2$ s and back to 0.92 p.u. at $t = 5$ s. Fig. 9 shows the steady-state voltage regulation result and the corresponding reactive power Q_c compensated by the STATCOM. Without any reactive compensation, the initial steady-state value of the PCC voltage V_t (Fig. 1) is 0.92 p.u., which is below the lower limit value of 0.95 p.u. With the STATCOM inserted for reactive compensation, the PCC voltage is kept at the desired value of 1.02 p.u. The response of the STATCOM to the step change of the voltage command is fast and smooth.

B. Three-Phase Short Circuit Test: RSC Not Blocking

Grid faults, even if far away from the location of the wind turbine, can cause voltage sags at the connection point of the wind turbine. Such a voltage sag results in an imbalance between the turbine input power and the generator output power, which initiates the machine stator and rotor current transients, the converter current transient, the dc-link voltage fluctuations, and a change in speed.

A temporary three-phase short circuit is applied for 200 ms to the infinite bus in Fig. 1 at $t = 2$ s. The protective system of the wind turbine and the DFIG is disabled in this test. Fig. 10 shows the rotor current I_r response with and without the STATCOM. In the case of no STATCOM, the reactive power command of the RSC is set to 0.28 p.u. in order to regulate the PCC voltage at 1.02 p.u. These results show that during the fault and post-fault transient states, the rotor current exceeds its limit value (1.0 kA) in both cases. Therefore, the RSC must be blocked to avoid being destroyed by the overcurrent in the rotor circuit.

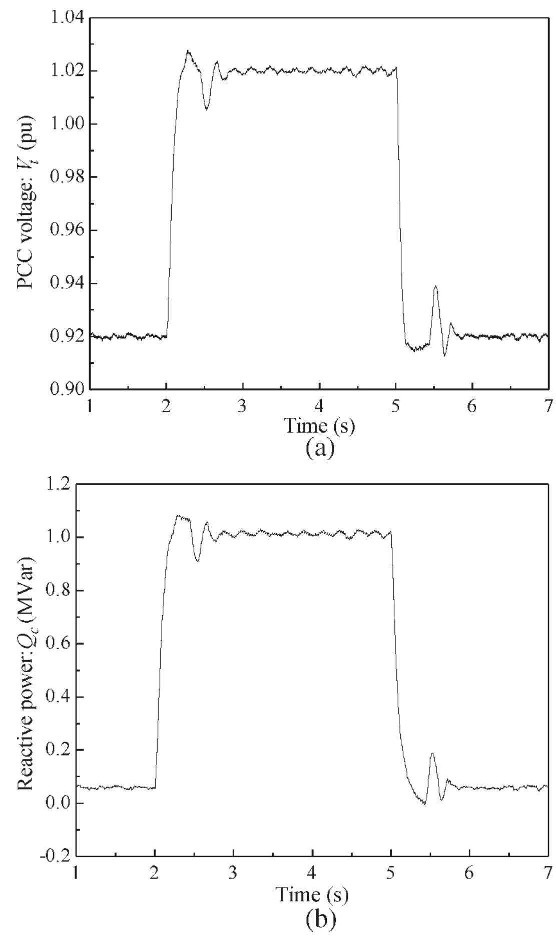

Fig. 9. Steady-state voltage regulation result of STATCOM at PCC: V_t and Q_c, when the reference V_t^* has a step change.

C. Three-Phase Short Circuit Test Without the STATCOM: RSC Blocking

The same three-phase short circuit test as in Fig. 10 is applied at $t = 2$ s without using the STATCOM; this time, however, 30 ms after applying the fault (at $t = 2.03$ s), the RSC is blocked to protect it from overcurrent in the rotor circuit. Fig. 11 shows the voltage profiles at the PCC. The curve GSC indicates the result with the reactive compensation by the GSC (the reactive power command of the GSC is set to the maximum value of 0.25 p.u. instead of zero) from 2.03 s, and the curve NC indicates the result without any reactive compensation from 2.03 s. In both cases of GSC and NC, the reactive power command of the RSC is set to 0.28 p.u. instead of zero before applying the fault in order to regulate the PCC voltage at

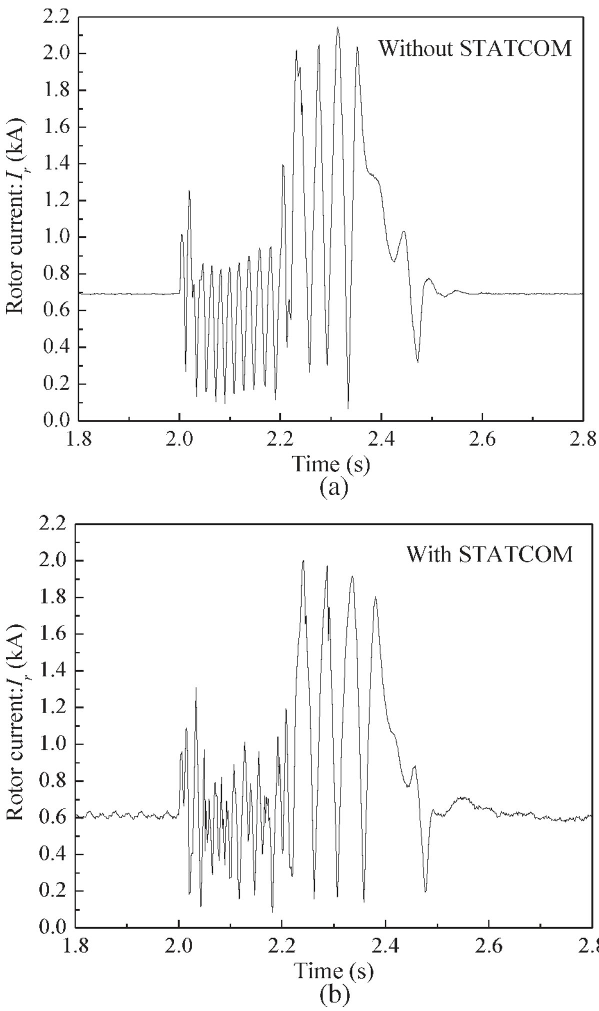

Fig. 10. RMS rotor current I_r during a 200-ms three-phase short circuit at the infinite bus, RSC not blocking.

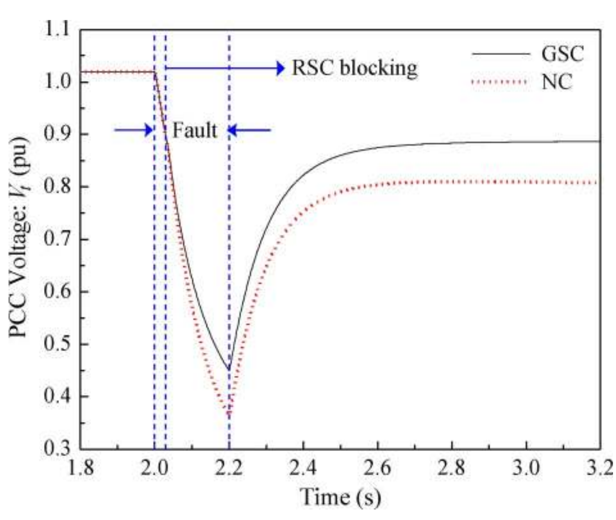

Fig. 11. 200-ms three-phase short circuit at the infinite bus, RSC blocking without STATCOM: PCC voltage V_t.

1.02 p.u. The fault is cleared at $t = 2.2$ s. However, the PCC voltage cannot be reestablished without the STATCOM or by only using the GSC. Therefore, the RSC cannot restart, and the wind turbine has to be tripped from the system.

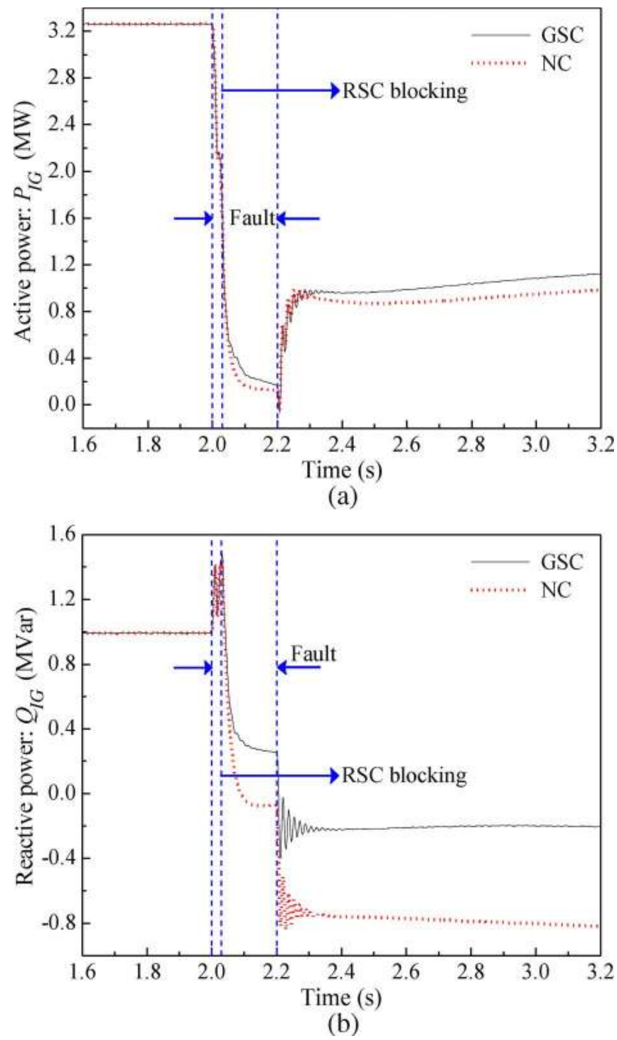

Fig. 12. 200-ms three-phase short circuit at the infinite bus, RSC blocking without STATCOM: P_{IG} and Q_{IG}.

Fig. 12 shows the total active power P_{IG} generated by the induction generator and the total reactive power Q_{IG} exchanged between the induction generator and the grid. During the RSC blocking, the active power generated by the induction generator reduces significantly for both the GSC and the NC. After the fault has cleared (at $t = 2.2$ s) but with the RSC still blocking, the induction generator absorbs some reactive power (negative values in Fig. 12) from the grid. However, compared with the case of NC, with the GSC providing reactive compensation, the induction generator produces more active power to the power grid, and the reactive power absorbed by the induction generator is reduced.

D. Uninterrupted Operation of the Wind Turbine With the STATCOM

A grid fault in the power network can be temporary or permanent. A permanent grid fault is normally cleared by disconnecting the power line on which the fault occurs from the system. Line tripping reduces the operational and stability margins of the power system and hence results in a relatively weaker power network. Therefore, a permanent grid fault with

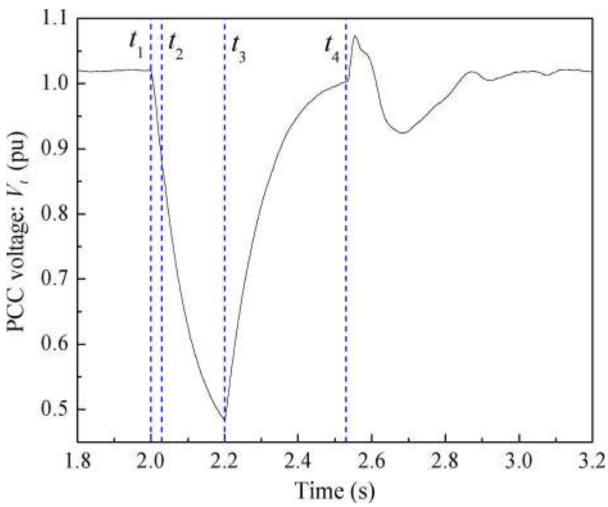

Fig. 13. Uninterrupted operation of the wind turbine with a STATCOM during a grid fault: V_t.

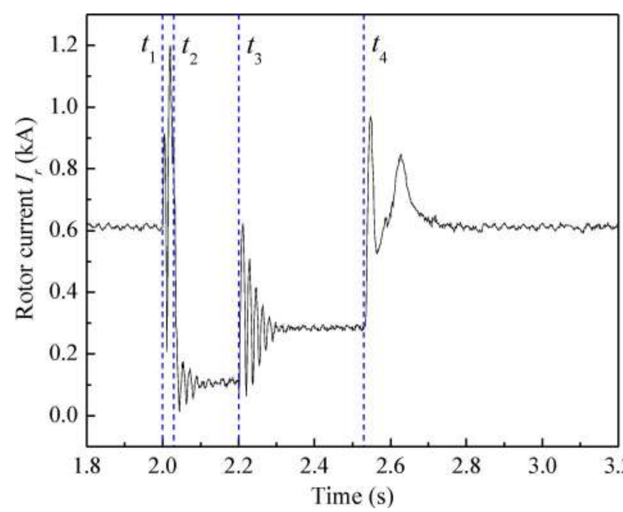

Fig. 14. Uninterrupted operation of the wind turbine with a STATCOM during a grid fault: I_r.

line tripping is more severe than a temporary fault without any line tripping for power system operation and stability.

To demonstrate the effectiveness of the STATCOM to help the wind turbine ride through grid faults, a three-phase permanent short circuit is now applied to the receiving end of line 1 at $t_1 = 2$ s and is cleared by tripping line 1. The STATCOM is now used to help achieve the uninterrupted operation of the wind turbine. During the entire test, the reactive power command of the GSC is set to $Q_g^* = 0$. Fig. 13 shows the voltage profiles at the PCC. Before $t = t_1$, the power system is at normal operation. Thirty milliseconds after applying the short circuit (at $t_2 = 2.03$ s), the RSC is blocked to protect it from overcurrent in the rotor circuit. Two-hundred milliseconds after applying the short circuit (at $t_3 = 2.2$ s), the fault is cleared, and line 1 is disconnected from the system. In contrast to the cases of no STATCOM, as shown in Fig. 11, with the STATCOM for transient voltage support, the PCC voltage is quickly reestablished shortly after the fault has cleared. When the PCC voltage returns to a predefined value, the RSC starts switching. Finally, 500 ms after blocking the RSC (at $t_4 = 2.53$ s), the RSC restarts successfully, and the uninterrupted operation of wind turbine is achieved.

Fig. 14 shows the magnitude of the rotor current I_r. Compared with Fig. 10, the rotor current transient is significantly reduced. During the RSC blocking, the rotor current magnitude is within its limit value (1.0 kA) by connecting a suitably selected external resistance to the rotor circuit. In addition, with a proper restarting procedure and a suitably designed control system, the RSC successfully restarts with only a small transient in the rotor current.

Fig. 15 shows the total active power generated by the induction generator P_{IG} and rotor active power P_r. During the RSC blocking from t_2 to t_4, the total active power generated by the induction generator is reduced, and there is no active power flowing through the rotor circuit ($P_r \approx 0$). However, compared with the results without the STATCOM in Fig. 12, with the STATCOM now connected, the induction generator generates more active power to the power network when the fault has cleared (between times t_3 and t_4).

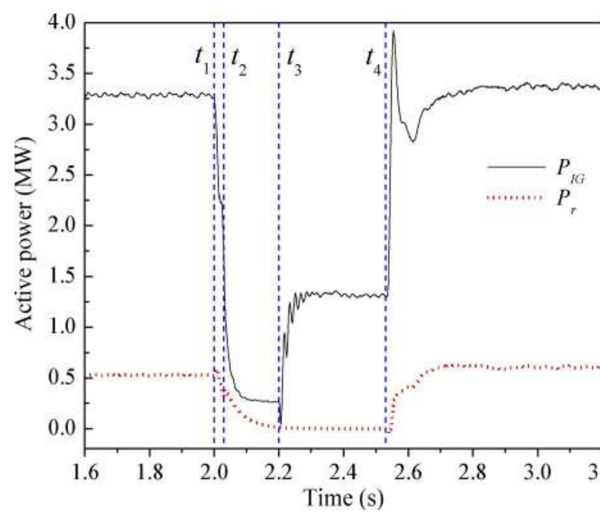

Fig. 15. Uninterrupted operation of the wind turbine with a STATCOM during a grid fault: P_{IG} and P_r.

Fig. 16 shows the total reactive power Q_{IG} exchanged between the induction generator and the grid, as well as the rotor reactive power Q_r. During the time period t_3–t_4 (the fault has cleared but the RSC is still blocking), the induction generator absorbs a large amount of reactive power from the power grid, and therefore, the use of dynamic reactive power compensation is required.

During the time period t_3–t_4 in Fig. 17, the RSC is blocked, and the STATCOM is providing 2.3-MVar reactive power. This could not have been provided by the GSC, which has a rating of 0.9 MVA, and underlines the need for a STATCOM or some other form of reactive compensation.

Another requirement for the successful uninterrupted operation of the wind turbine is the dc-link voltage stability of the VFC. As shown in Fig. 18, after the grid fault, the GSC controller successfully controls the dc-link voltage back to the nominal value of 4.0 kV. The overshoot of the dc-link voltage after t_4 when the RCS restarts, is less than 10% of the nominal value, which is a necessary condition for the RSC to restart.

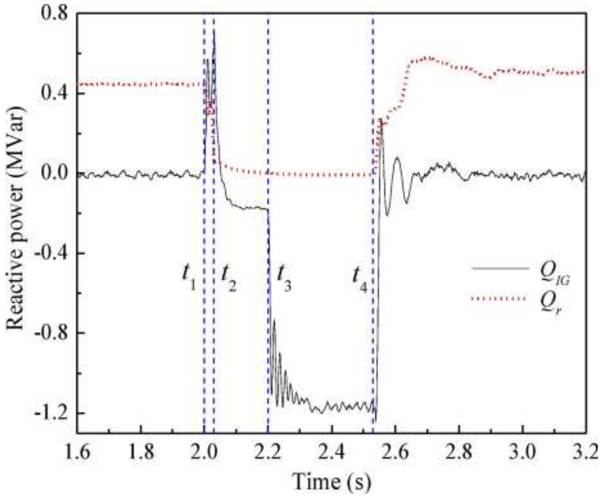

Fig. 16. Uninterrupted operation of the wind turbine with a STATCOM during a grid fault: Q_{IG} and Q_r.

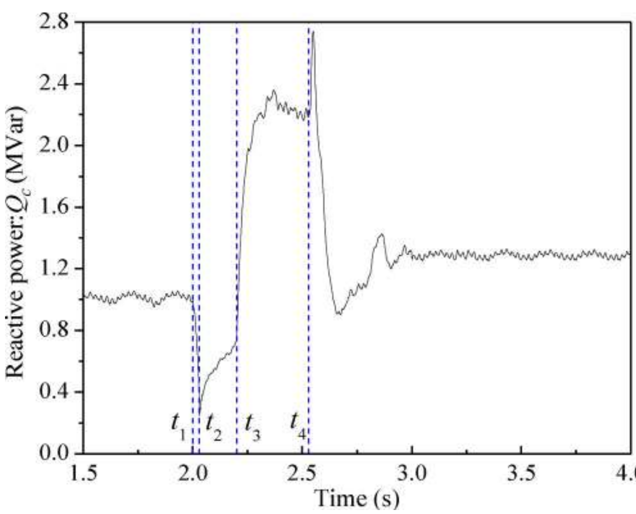

Fig. 17. Uninterrupted operation of the wind turbine with a STATCOM during a grid fault: Q_c in Fig. 1.

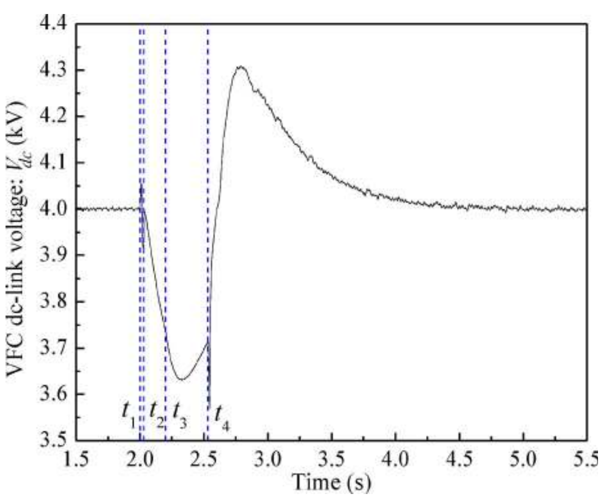

Fig. 18. Uninterrupted operation of the wind turbine with a STATCOM during a grid fault: V_{dc}.

IX. Conclusion

The successful integration of wind farms to power systems might need dynamic reactive compensation to assist with voltage support, particularly during grid disturbances. This paper has investigated the application of a STATCOM to achieve the uninterrupted operation of a DFIG wind turbine during grid faults. The STATCOM is placed at the bus (PCC) where the DFIG is connected to the power grid, for steady-state voltage regulation and transient voltage support. The control schemes of the DFIG RSC, GSC, and the STATCOM have been suitably designed and coordinated.

The system has been implemented on an RTDS and subjected to short-circuit grid faults. During grid faults, the RSC is blocked and restarts when the fault is cleared and the PCC voltage is reestablished. Real-time implementation results show that with the STATCOM providing dynamic voltage support, the PCC voltage can be reestablished shortly after grid faults, and therefore, the wind turbine remains in service. However, without the STATCOM for voltage support, the PCC voltage cannot be reestablished after grid faults so that the wind turbine has to be tripped from the power network. The STATCOM improves the transient voltage stability and therefore enhances the grid fault ride-through capability of the wind-turbine generator system.

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