01 Jan 2006

Real-Time Implementation of a STATCOM on a Wind Farm Equipped with Doubly Fed Induction Generators

Wei Qiao

Ganesh K. Venayagamoorthy
Missouri University of Science and Technology

Ronald G. Harley

Recommended Citation

W. Qiao et al., "Real-Time Implementation of a STATCOM on a Wind Farm Equipped with Doubly Fed Induction Generators," *Conference Record of the 41st IAS Annual Meeting of the Industry Applications Conference, 2006*, Institute of Electrical and Electronics Engineers (IEEE), Jan 2006.
The definitive version is available at https://doi.org/10.1109/IAS.2006.256657

Real-Time Implementation of a STATCOM on a Wind Farm Equipped with Doubly Fed Induction Generators

Wei Qiao[1], Ganesh K. Venayagamoorthy[2], and Ronald G. Harley[1]

[1]Intelligent Power Infrastructure Consortium
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0250 USA
E-mail: {weiqiao, rharley}@ece.gatech.edu

[2]Real-Time Power and Intelligent Systems Laboratory
Department of Electrical and Computer Engineering
University of Missouri-Rolla
Rolla, MO 65409-0249 USA
E-mail: gkumar@ieee.org

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. A Static Synchronous Compensator (STATCOM) is applied to a power network which includes a DFIG driven by a wind turbine, for steady state voltage regulation and transient voltage stability support. The control schemes of the DFIG rotor-side converter, grid-side converter and the STATCOM are suitably designed and coordinated. The system is implemented in real-time on a Real-Time Digital Simulator (RTDS®). 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.**

Keywords-doubly fed induction generator; real-time implementation; STATCOM; wind turbine

I. INTRODUCTION

The worldwide concern about the environmental pollution and a possible energy shortage has led to increasing interest in technologies for generation of renewable electrical energy. Among various renewable energy sources, wind generation has been the leading source 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 due to its advantages over other wind turbine concepts [1]-[4]. In the DFIG concept, the induction generator is grid-connected at the stator terminals as well as at the rotor mains via a partially rated variable frequency AC/DC/AC converter (VFC), which only needs to handle a fraction (25-30%) of the total 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 in order to protect it from over-current in the rotor circuit [1], [3]-[4]. The wind turbine trips shortly after the converter has blocked and automatically re-connects to the power network a few seconds after the fault has cleared. In [1], the author proposed an uninterrupted operation feature of a DFIG wind turbine during grid faults. In this feature, the rotor circuit is short-circuited through a crow-bar circuit (an external resistor); the generator 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. The pitch angle controller might be activated to prevent the wind turbine from fatal over-speeding. When the fault has cleared and when the voltage and the frequency in the power network have been re-established, the RSC will re-start 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, the RSC will not re-start and the wind turbine will be disconnected from the network. 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 that incorporation of wind farms into the East Danish power system could cause severe voltage recovery problem following a three-phase fault on the network [5]. This problem of voltage instability can be solved by using dynamic reactive power compensation.

Shunt Flexible AC Transmission System (FACTS) devices, such as the Static Var Compensator (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 applications of a SVC or a STATCOM to fixed-speed wind turbines equipped with induction generators have been reported in [7] for steady state voltage regulation, and in [1] for short-term transient voltage stability.

This paper investigates the application of a STATCOM to help with the uninterrupted operation of a VSWT equipped with

This work was supported in part by the National Science Foundation, Washington, DC, USA, under grant ECS 0524183 and the Duke Power Company, Charlotte, North Carolina, USA

a DFIG during grid faults. The STATCOM is shunt connected at the bus where the wind turbine is connected to the power network in order to provide steady state voltage regulation and improve the short-term transient voltage stability. The system is implemented on a Real-Time Digital Simulator (RTDS®). The power network model, the DFIG model with its control scheme, the wind turbine model, and the STATCOM model with its control scheme are presented in the next four sections, respectively. The real-time implementation results show that with suitably designed STATCOM and DFIG control schemes, the DFIG can ride through grid faults to remain in service. On the other hand, without the STATCOM to provide local dynamic reactive power support, the voltage cannot recover and therefore the wind turbine has to be tripped from the power network.

II. POWER NETWORK MODEL

In a real power system, a large wind farm generally consists of hundreds of individual wind turbines. A STATCOM can be placed at the PCC between the wind farm and the power network. 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.

Figure 1 shows the single-line diagram of the power system used for this study. A 3.6 MW DFIG driven by a wind turbine [8] is connected to a power network 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.

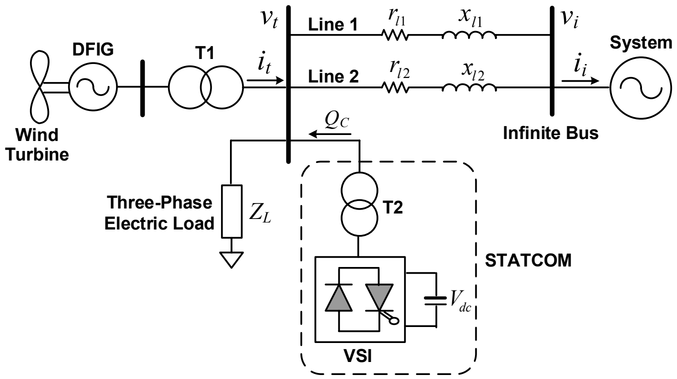

Fig. 1. Single-line diagram of the power network.

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-speed shaft 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 side. The stator is directly connected to the grid while the rotor is fed 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 IGBT PWM converters connected back-to-back by a dc-link capacitor [9]. The crow-bar is used to short-circuit the RSC in order to protect the RSC from over-current in the rotor circuit during transient disturbances.

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		

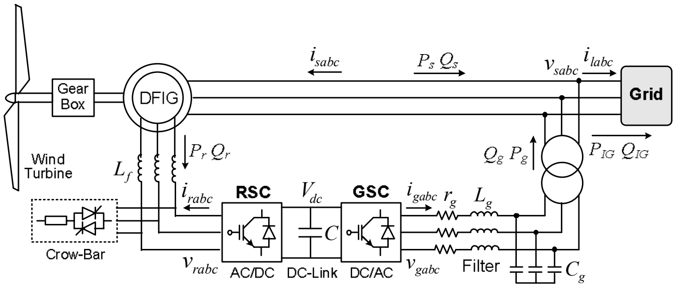

Fig. 2. Configuration of a DFIG driven by a wind turbine.

Control of the DFIG is achieved by control of the VFC, which includes control of the RSC [4], [9]-[11] and control of the GSC [9]. The objective of the RSC is to regulate both the stator active and reactive powers, P_s and Q_s, independently. 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. Figure 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 dq components i_{dr} and i_{qr} in the stator-flux oriented reference frame. The reference values for 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 v_{dr1} and v_{qr1}. The two voltage signals (v_{dr1} and v_{qr1}) are compensated by the corresponding cross coupling terms (v_{dr2} and v_{qr2}) to form the d-q voltage signals v_{dr} and v_{qr}. These are then used by the PWM module to generate the IGBT gate control signals to drive the rotor-side IGBT converter.

The objective of the GSC is to keep the dc-link voltage constant regardless of the magnitude and direction of the rotor power [9]. 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 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 re-establishment, after a grid fault has been cleared and the RSC has been blocked. Figure 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-axis and q-axis current components (i_{dg}^* and i_{qg}^*), respectively. 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 (v_{dg1} and v_{qg1}) are compensated by the corresponding cross coupling terms to form the d-q voltage signals v_{dg} and v_{qg}. They are then used by the PWM module to generate the IGBT gate control signals to drive the grid-side IGBT converter.

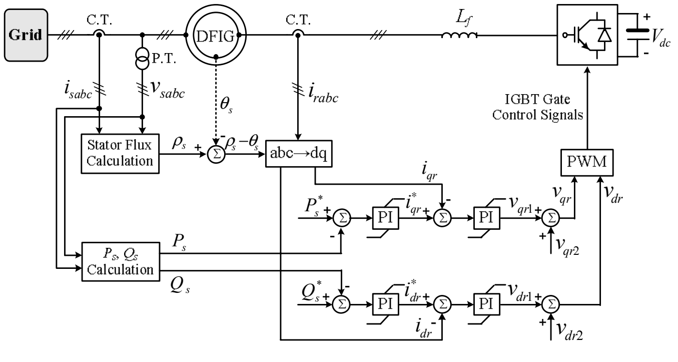

Fig. 3. Overall control scheme of the RSC: $v_{dr2} = -s\omega_s\sigma L_r i_{qr}$, $v_{qr2} = s\omega_s(\sigma L_r i_{dr} + L_m^2 i_{ms}/L_s)$.

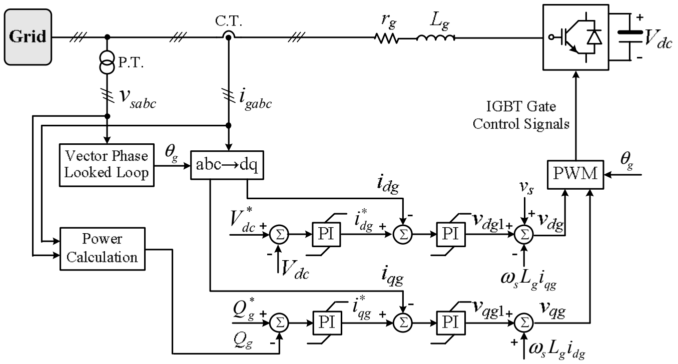

Fig. 4. Overall control scheme of the GSC.

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

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

where R is the blade length in m, ω_t is the wind turbine rotor speed in rad/s, and v_w is the wind speed in m/s. 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], [8]

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

where ρ is the air density in kg/m^3; $A_r = \pi R^2$ is the area in m^2 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 at 0°. 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 this situation, the pitch control is activated to increase the wind turbine pitch angle to reduce the mechanical power extracted from wind. Figure 5 shows the structure of the pitch angle controller [1], [8]. P_t (= $P_s + P_r$) is the total output active power from the induction generator.

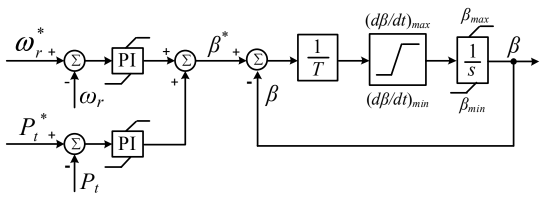

Fig. 5. Wind turbine pitch angle controller

V. STATCOM MODEL

A STATCOM [6], [12], also known as an advanced static VAR compensator, 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 GTO PWM converter with a dc-link capacitor. The objective of the STATCOM is to regulate the voltage at the PCC rapidly in the desired range and keep its dc-link voltage constant. 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 feature is that the wind turbine does not trip when the RSC has blocked during the grid fault.

During the RSC blocking, the rotor circuit is short-circuited by a crow-bar, which is simply implemented by connecting an external resistor to each phase of the rotor circuit. The value of the external resistance is chosen as $R_{ext} = 20 \cdot r_r$, as recommended in [13]. The wind turbine continues its operation with the induction generator with a short-circuited rotor circuit. During such an operation condition, the controllability of the RSC is naturally lost and there is no longer any independent control of active and reactive power in the DFIG. The generator 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 over-speeding, the pitch angle controller can be activated to keep the speed around the pre-defined value.

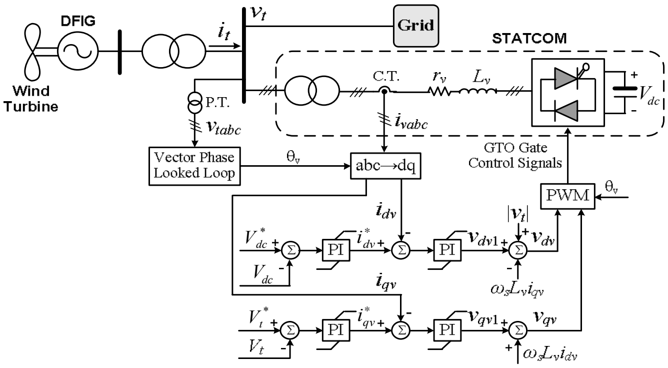

Fig. 6. Overall control scheme of the STATCOM.

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 back to their pre-defined 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 $v_{dr} = i_{dr} \cdot R_{ext}$ and $v_{qr} = i_{qr} \cdot R_{ext}$, 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 re-starts. When the RSC has re-started, the DFIG again has independent active and reactive power control and the wind turbine returns to normal operation.

The advantages of this uninterrupted operation feature include: (1) the wind turbine continues supplying the active power to the power network and therefore the demand for immediate power reserves does not exist or it is reduced; (2) the wind turbine can contribute to maintaining the frequency in the power network during a transient state.

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 RSC, however, is limited due to the small capacity of the converter. In the case of a weak power network, there can be a risk of voltage instability initiated by the grid fault. As a result, the RSC will not re-start and the wind turbine will be disconnected from the network. One solution to this problem is to use the dynamic reactive compensator – the STATCOM, to provide transient voltage support to help the RSC ride through grid faults. In addition, the STATCOM can also be used for steady state voltage regulation and power factor control of the DFIG.

VII. REAL-TIME IMPLEMENTATION SETUP

The RTDS® is a fully digital electromagnetic transient power system simulator capable of continuous, sustained real-time operation [14]. That is, 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. Because the solution is real-time, it can be connected directly to 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.

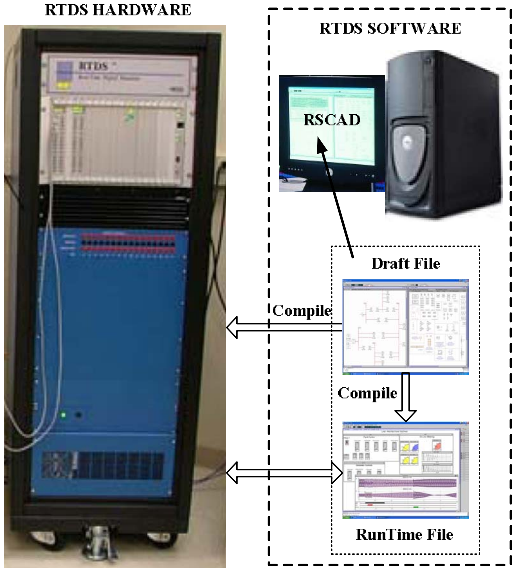

Fig. 7. Real-time implementation setup using RTDS®.

The RTDS® hardware has a number of different types of processor cards available including the Triple Processor Cards (3PC), the RISC Processor Card (RPC) and the Giga Processor Card (GPC). The 3PC contains three Analog Devices 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 microseconds. 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 microseconds) simulations of Voltage Source Converters (VSC) 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 study, 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. The control systems are simulated on the 3PC cards. Figure 8 shows the RTDS modules and the processor assignments for real-time implementation of the system in Fig. 1. In RTDS®, an interface transformer is used to connect the small timestep power system module (< 2 microseconds) to large timestep (50 microseconds) power system module.

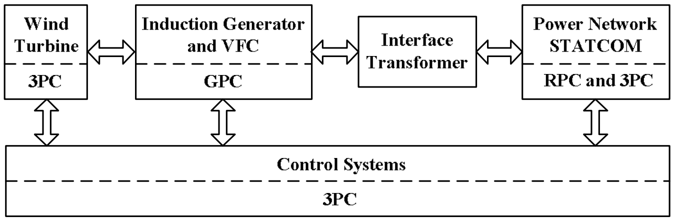

Fig. 8. RTDS modules and processor assignments for real-time implementation.

VIII. REAL-TIME IMPLEMENTATION RESULTS

This section presents the real-time implementation results of the system in Fig. 1 at the following operating condition: (1) the wind speed is constant during the simulation (this assumption is reasonable for investigating the short-term voltage stability [1]); (2) the DFIG is running at a supersynchronous speed with the generator rotor speed at about 1.2 pu; (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 (Fig. 6), V_t^*, is step changed from 0.92 pu to 1.02 pu at $t = 2$ s and back to 0.92 pu at $t = 5$ s. Figure 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 pu which is below the lower limit value of 0.95 pu. With the STATCOM inserted for reactive compensation, the PCC voltage is kept at the desired value of 1.02 pu. The response of the STATCOM to the step change of the voltage command is fast and smooth.

B. A Three-Phase Short Circuit Test: RSC not Blocking

Grid faults, even 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 current transients, the GSC current transient, the dc-link voltage fluctuations and a change in speed. The over-current in the rotor circuit (as shown in the previous subsection) leads to the blocking of the RSC.

A temporary three-phase short circuit is applied for 200 ms to the infinite bus at $t = 2$ s. The protective system of the wind turbine and the DFIG is disabled in this test. Figure 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 pu in order to regulate the PCC voltage at 1.02 pu. These results show that during the fault and post-fault transient state, the rotor current exceeds its limit value in both cases. Therefore, the RSC must be blocked to avoid being destroyed by the over-current in the rotor circuit.

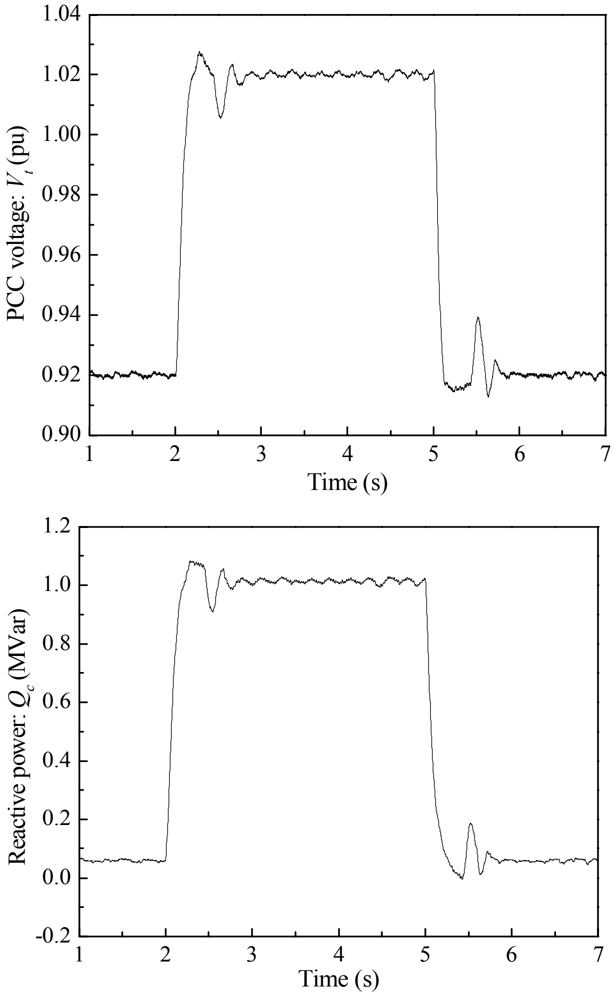

Fig. 9. Steady state voltage regulation result of STATCOM at PCC: V_t and Q_c, when the reference V_t^* has a step-change.

C. A Three-Phase Short Circuit Test without the STATCOM: RSC blocking

The same three-phase short circuit test as in Fig. 10, is applied without using the STATCOM, but now the RSC is blocked from $t = 2.2$ s due to the protection from over-current in the rotor circuit. Figure 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 0.25 pu instead of 0) from 2 s; and the curve NC indicates the result without any reactive compensation from 2 s. In both cases GSC and NC, the reactive power command of the RSC is set to 0.28 pu instead of 0 before applying the fault in order to regulate the PCC voltage at 1.02 pu. The PCC voltage can not be re-established without any reactive compensation or only using the GSC. Therefore, the RSC cannot re-start and the wind turbine has to be tripped from the system.

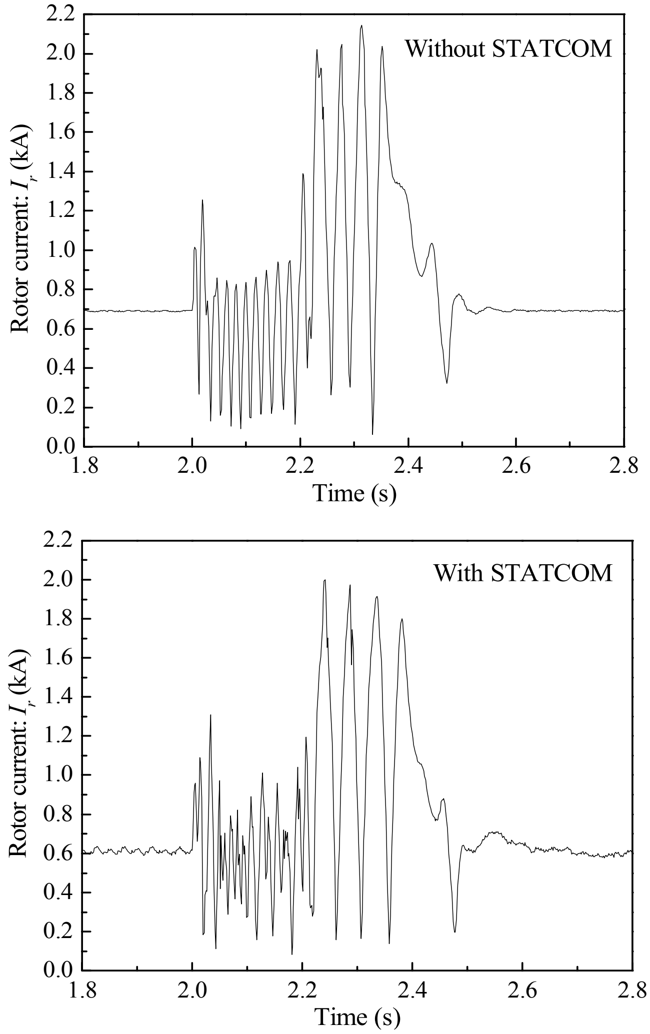

Fig. 10. RMS rotor current I_r during a 200 ms three-phase short circuit at the infinite bus, RSC not blocking.

Figure 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 been cleared (at $t = 2.2$ s) but the RSC is still blocking, the induction generator absorbs some reactive power from the network. However, with the GSC providing reactive compensation, the induction generator generates more active power to the power network, and the reactive power absorbed by the induction generator is reduced.

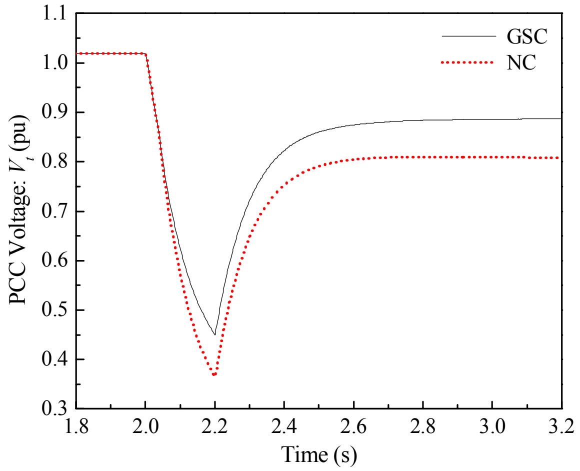

Fig. 11. A 200 ms three-phase short circuit at the infinite bus, RSC blocking without STATCOM: PCC voltage V_t.

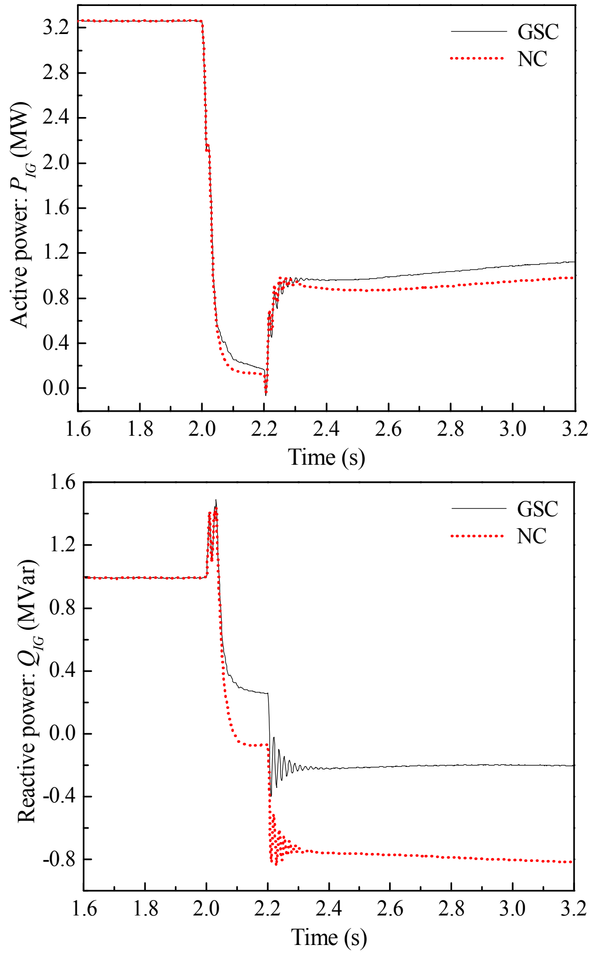

Fig. 12. A 200 ms three-phase short circuit at the infinite bus, RSC blocking without STATCOM: P_{IG} and Q_{IG}.

D. Uninterrupted Operation of the Wind Turbine with the STATCOM

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 $Q_g^* = 0$.

A three-phase short circuit is now applied to the receiving end of line 1 at $t_1 = 2$ s. Figure 13 shows the voltage profiles at the PCC. Before $t = t_1$, the power system is at normal operation. 30 ms after applying the short circuit (at $t_2 = 2.03$ s), the RSC is blocked due to the protection from over-current in the rotor circuit. 200 ms 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 re-established shortly after the fault has cleared. When the PCC voltage returns back to a pre-defined value, the RSC starts switching. Finally, 500 ms after blocking the RSC (at $t_4 = 2.53$ s), the RSC re-starts successfully and the uninterrupted operation of wind turbine is achieved.

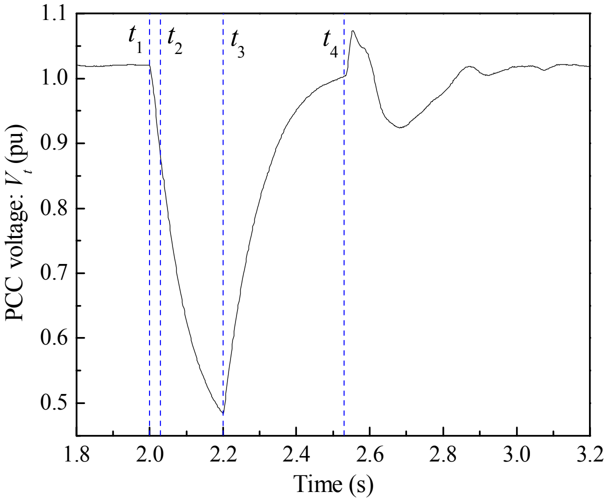

Fig. 13. Uninterrupted operation of the wind turbine with a STATCOM during a grid fault: V_t.

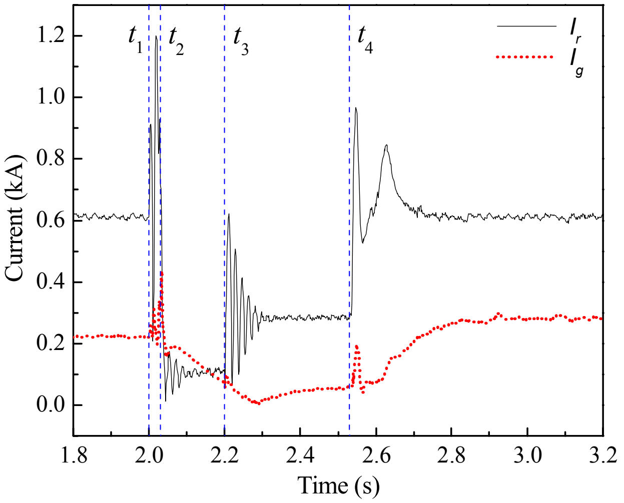

Fig. 14. Uninterrupted operation of the wind turbine with a STATCOM during a grid fault: I_r and I_g.

Figure 14 shows the magnitudes of the rotor current, I_r, and the GSC current, I_g. Compared to Fig. 10, the rotor current transient is significantly reduced. During the RSC blocking, the rotor current magnitude is limited within its normal operating range by connecting a suitably selected external resistance to the rotor circuit. In addition, with a proper re-starting procedure and a suitably designed control system, the RSC successfully re-starts with only a small transient in the rotor current.

Figure 15 shows the total active power generated by the induction generator, P_{IG}, and rotor active power, P_r. During the RSC blocking, the total active power generated by the induction generator is reduced and no active power flowing through the rotor circuit ($P_r \approx 0$). However, compared to 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 time t_3 and t_4).

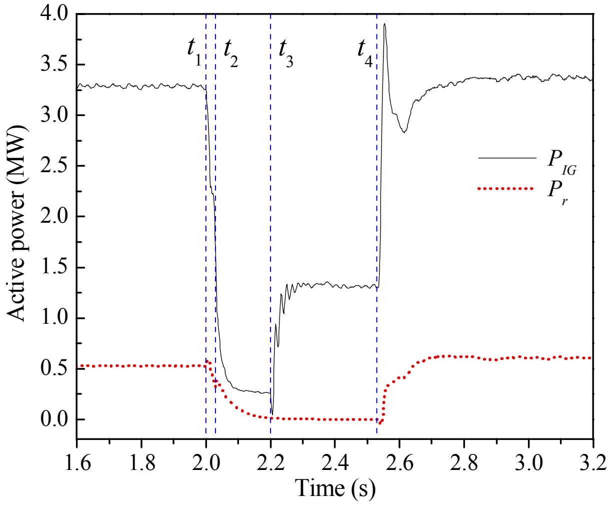

Fig. 15. Uninterrupted operation of the wind turbine with a STATCOM during a grid fault: P_{IG} and P_r.

Figure 16 shows the total reactive power, Q_{IG}, exchanged between the induction generator and the grid, and rotor reactive power, Q_r. During the RSC blocking, the induction generator absorbs a large amount of reactive power from the power network and therefore the use of dynamic reactive power compensation is required.

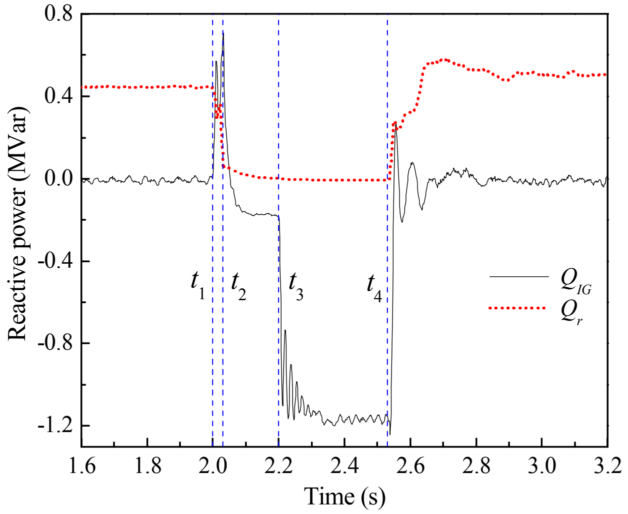

Fig. 16. Uninterrupted operation of the wind turbine with a STATCOM during a grid fault: Q_{IG} and Q_r.

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.

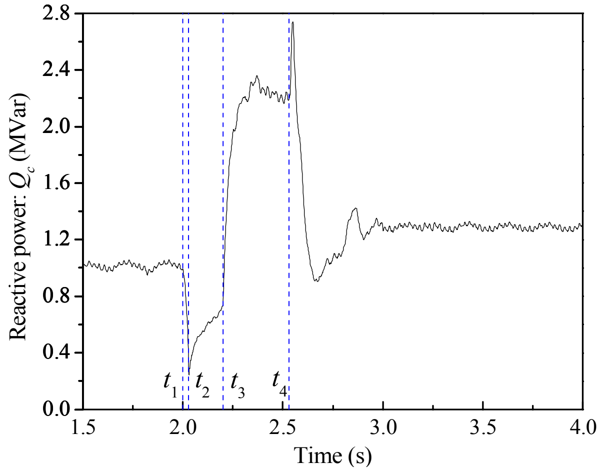

Fig. 17. Uninterrupted operation of the wind turbine with a STATCOM during a grid fault: Q_c in Fig. 1.

Another issue to successfully achieve the uninterrupted operation of the wind turbine is the dc-link voltage stability of the VFC. As shown in Fig. 18, during the RSC blocking, the GSC controller successfully controls the dc-link voltage within the desired range, which is a necessary condition before the RSC can be re-started.

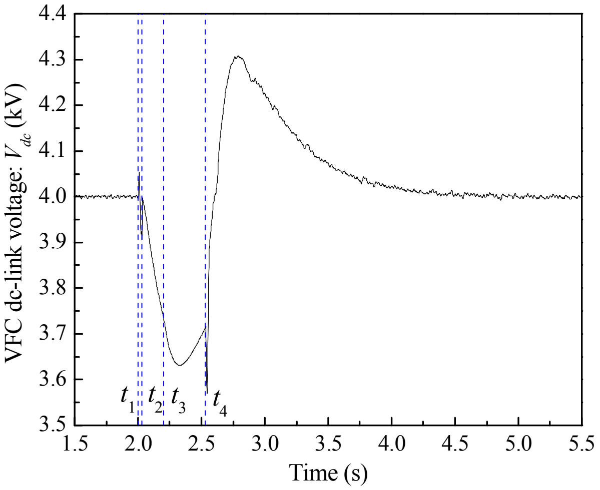

Fig. 18. Uninterrupted operation of the wind turbine with a STATCOM during a grid fault: V_{dc}.

IX. CONCLUSION

A doubly fed induction generator (DFIG) driven by a wind turbine has been modeled and implemented in real-time on a Real-Time Digital Simulator (RTDS®). A STATCOM is placed at the bus (PCC) where the DFIG connected to the power network for steady state voltage regulation and transient voltage support. The control schemes of the DFIG rotor-side converter (RSC), grid-side converter (GSC) and the STATCOM have been suitably designed and coordinated.

The wind turbine and the power network are subjected to short-circuit grid faults. During grid faults, the RSC is blocked and re-starts when the fault is cleared and the PCC voltage is re-established. Real-time implementation results show that with the STATCOM providing dynamic voltage support, the PCC voltage can be re-established shortly after grid faults and therefore the wind turbine remains in service. However, without the STATCOM for voltage support, the PCC voltage cannot be re-established 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 helps the wind turbine to ride through grid faults to achieve the uninterrupted operation.

REFERENCES

[1] V. Akhmatov, "Analysis of dynamic behavior of electric power systems with large amount of wind power," Ph.D. dissertation, Technical University of Denmark, Kgs. Lyngby, Denmark, Apr. 2003.

[2] R. Datta and V. T. Ranganathan, "Variable-speed wind power generation using doubly fed wound rotor induction – a comparison with alternative schemes,' *IEEE Trans. Energy Conversion*, vol. 17, no. 3, Sept. 2002, pp. 414-421.

[3] M. V. A. Nunes, J. A. Pecas Lopes, H. H. Zurn, U. H. Bezerra, and R. G. Almeida, "Influence of the variable-speed wind generators in transient stability margin of the conventional generators integrated in electrical grids," *IEEE Trans. Energy Conversion*, vol. 19, no. 4, Dec. 2004, pp. 692-701.

[4] J. Morren and S. W. H. de Haan, "Ridethrough of wind turbines with doubly-fed induction generator during voltage dip," *IEEE Trans. Energy Conversion*, vol. 20, no. 2, Jun. 2005, pp. 435-441.

[5] M. Bruntt, J. Havsager, and H. Knudsen, "Incorporation of wind power in the East Danish power system," in *Proc. IEEE Power Tech*, Budapest, Hungary, Aug. 29-Sept. 2, 1999, pp. 202-205.

[6] N. G. Hingorani and L. Gyugyi, Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems, IEEE Press, New York, 2000.

[7] Z. Saad-Saoud, M. L. Lisboa, J. B. Ekanayake, N. Jenkins, and G. Strbac, "Application of STATCOMs to wind farms," *IEE Proceedings – Generation, Transmission and Distribution*, vol. 145, no. 5, Sept. 1998, pp. 511-516.

[8] N. W. Miller, W. W. Price, and J. J. Sanchez-Gasca, "Dynamic modeling of GE 1.5 and 3.6 wind turbine-generators," GE-Power Systems Energy Consulting, General Electric International, Inc., Schenectady, NY, USA, Oct. 27, 2003.

[9] R. Pena, J. C. Clare, and G. M. Asher, "Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation," *IEE Proceedings – Electric Power Applications*, vol. 143, no. 3, May 1996, pp. 231-241.

[10] A. Tapia, G. Tapia, J. X. Ostolaza, and J. R. Saenz, "Modeling and control of a wind turbine driven doubly fed induction generator," *IEEE Trans. Energy Conversion*, vol. 18, no. 2, Jun. 2003, pp. 194-204.

[11] T. Tang and L. Xu, "A flexible active reactive power control strategy for a variable speed constant frequency generating system," *IEEE Trans. Power Electronics*, vol. 10, no. 4, Jul. 1995, pp. 472-477.

[12] C. Schauder and H. Mehta, "Vector analysis and control of advanced static VAR compensators," *IEE Proceedings – Generation, Transmission and Distribution*, vol. 140, no. 4, Jul. 1993, pp. 299-306.

[13] V. Akhmatov, "Variable-speed wind turbine with doubly-fed induction generators – part IV: Uninterrupted operation features at grid faults with converter control coordination," *Wind Engineering*, vol. 27, no. 6, 2003, pp. 519-529.

[14] P. Forsyth, T. Maguire, and R. Kuffel, "Real time digitial simulation for control and protection system testing," in *Proc. 35th Annual IEEE Power Electronics Specialists Conference*, Aachen, Germany, June 20-25, 2004, pp. 329-335.