Fault Current Contribution from VSC-based Wind Turbines to the Grid

Iov, Florin; Valentini, Massimo; Akhmatov, V.; Thisted, Jens

Published in:
Proceedings of The Second International Symposium on Electrical and Electronics Engineering, ISEEE08

Publication date:
2008

Document Version
Publisher's PDF, also known as Version of record

Fault Current Contribution from VSC-based WindTurbines to the Grid

Massimo Valentini, Vladislav Akhmatov, Florin Iov and Jan Thisted

Abstract—**When performing short-circuit investigations in power systems including wind power, valuable and accurate results can only be obtained by considering the real behavior of wind turbines which is specified in national grid codes. This requires the consideration of the exact active and reactive current injections during the fault. In this paper an equivalent VSC-based wind turbine model for short-circuit calculations at steady-state conditions is developed and presented. The model is implemented in DigSILENT PowerFactory using the DPL-Programming Language. The developed wind turbine model is successfully evaluated proving that the DPL routine accurately implements the injection of the desired active and reactive current components according to the German grid code; the model is also compared with the validated 3.6MW variable-speed wind turbine dynamic model developed and provided by Siemens Wind Power. The wind turbine model is finally rescaled to obtain an aggregate wind farm model and used to perform short-circuit calculations in a realistic scenario; the Danish transmission system is considered and a large offshore wind farm with VSC-based wind turbines is included in the investigation.**

***Index Terms*— Wind Power, Grid Integration, Power Converters, Short-circuit current contribution, Grid support**

I. Introduction

IN the recent years an increasing attention has been paid to alternative methods of electricity generation as a consequence of increasing environmental concern and growing global energy demand. The very low environmental impact of the renewable energies makes them a very attractive solution. The progress of wind technology experienced in the last years has exceeded all expectations, leading to cost reduction to levels comparable, in many cases, with conventional methods of electricity generation [1]. As a result wind turbines participate actively in the power production of several countries around the world. This development raises a number of challenges regarding grid stability, power quality and behavior during fault situations.

Power electronics is nowadays used to efficiently interface renewable energy systems to the grid [2] [3]. It plays a very important role in modern wind energy conversion systems (WECSs), especially for multi-MW wind turbines in large wind farms. The control of WECSs, performed by means of power electronics, contributes to the fulfilment of grid requirements, a better use of the turbine capacity by means of variable-speed operation and the allevation of aerodynamic and mechanical loads improving the lifetime of the installation [4]. The active control of the wind energy leads to higher performance that is essential to enhance the competitiveness of the wind technology.

A. Problem definition

Short-circuit studies form an important part of the power system analysis. The problem consists of determining bus voltages and line currents during various types of faults. They are frequently requested and performed by power system companies as they provide the maximum fault current used for the design of electrical components (i.e. cables, transformers, circuit breakers) and the minimum fault current for proper relays' setting and coordination. They are normally performed using commercially available power system simulation tools. For network planning purposes, short-circuit studies only consider steady-state SC currents, mostly use calculation methods that require less detailed network modelling and might apply worst-case estimations. These calculation methods apply the IEC/VDE and the ANSI standardized methods, which are normally implemented in commercially available power system simulation tools; they take into account the SC current contribution of conventional grid components such as synchronous generators and induction motors; however they do not consider the fault contribution of VSC-based components [5]. Accordingly, the fault current contribution from VSC-based WTs can not be taken into consideration when performing SC studies with such simulation tools. In the past, wind turbines were allowed to disconnect from the power system during a grid fault, meaning that they had no contribution to the fault. As wind turbines begin to displace conventional power plants, an increasing support of the grid during faults is required; for this reason, in specific conditions, they are expected to remain connected to the power system during faults; this requirement is identified as fault ride-through (FRT) capability. At the beginning of this project, there was no standardized method to perform steady-state short-circuit studies including the fault current contribution from VSC-based wind turbines. The reason of this lack is that there is not enough experience;

M. Valentini is with Institute of Energy Technology, Aalborg University, Denmark (e-mail: masvalentini@gmail.com)

F. Iov is with Institute of Energy Technology, Aalborg University, Denmark (phone: +45 9940 9266; fax: +45 9815 1411; e-mail: fi@ iet.aau.dk).

V. Akhmatov is Centre of Energy Technology, Danish Technical University (e-mail: vladislav_akhmatov@hotmail.com).

J. Thisted is with Siemens Wind Power A/S (email: jat@siemens.com)

however the interest in this topic will increase as the wind power penetration grows. Nowadays, the SC contribution from VSC-based grid connected components can only be evaluated by performing full dynamic simulations based on a dynamic network model for electromagnetical and electromechanical transients. This is a time consuming analysis and therefore it is not preferred to the SC calculation according to international standards. As the level of penetration of the wind energy increases, detailed analysis about the impact of the wind power on the power system operation have to be performed [6]. Therefore increased demand for experience, knowledge and simulation models for the fault current contribution from VSC-based WTs to the grid is required.

B. Limitations

In this paper the investigation on the fault current contribution from wind turbines to the grid is limited to wind turbines with full-rating power converter, such as VSC-based wind turbines. In fact, for other wind turbine concepts, stator windings of the generator are directly connected to the grid by means of transformers and power electronics is not involved in the grid connection in normal operation. As a consequence, in case of a grid fault, those types of wind turbine basically behave as the electric generator involved, whose behavior is well known for of induction and synchrounous generators [7]. The investigation is carried out with balanced three-phase short-circuit faults; although it is not the most frequent grid fault, it is the only one considered in this work because (i) it is often the most severe fault condition and (ii) is often assumed that not cleared faults may develop into a three-phase shortcircuit [8].

The investigation is carried out with the support of a power system simulation tool. Among several possible tools, the simulation tool DIgSILENT PowerFactory is chosen for this work as it is among the tools used by Siemens Wind Power which has collaborated on the present project work.

II. Requirements for Fault Ride-Through Capability for Wind Turbines

Significant incorporation of wind power into a power system might affect the system operation especially in case of weak grids. In the past, requirements for wind turbines were primarily focused on their protection in case of grid faults (e.g. rules for disconnection); they did not consider the impact that WTs might have on the power system if the WTs stayed grid-connected [9]. However, with the increasing wind power penetration level, the loss of a considerable part of the wind generators in case of grid fault has become unacceptable as the stability of the power system can be negatively affected. To ensure the electrical system stability, transmission system operators in many countries are setting grid connection requirements for wind generators also known as grid codes. For MW-size WECSs and depending on the country, they provide several technical requirements; in this paper only requirements for fault ride-through capability are of concern. FRT is the ability of WTs to remain connected to the grid during a voltage dip. In most national grid codes, this capability is specified by a voltage profile that wind turbines shall withstand remaining connected to the grid. Only in few GCs (i.e. Germany and Spain), WTs are not only supposed to remain connected during a grid fault but also to support the grid voltage due to well formulated requirements.

Requirements for fault ride-through capability for wind turbines play an important role in this work as the study of the short-circuit current contributions from wind turbines to the grid makes sense only if WTs are required to remain connected in case of grid fault. In the past, wind turbines were subject to very simple requirements concerning their expected behavior in case of grid fault; they where expected to disconnect in a time dependent on the voltage amplitude and frequency variations. Nowadays, requirements for FRT require WTs to remain connected and, in some countries, to support the grid to ensure the stability of the power system. In order to highlight the importance of fault ride-through capability when interested on the short-circuit current contribution from wind turbines to the grid, a SC calculation performed in the network owned by the German transmission system operator Vattenfall Europe Transmission (VE-T) is presented in [9] and reshow in Fig.1; it considers a balanced three phase SC in the north-east part of Germany, where there is a high wind power penetration.

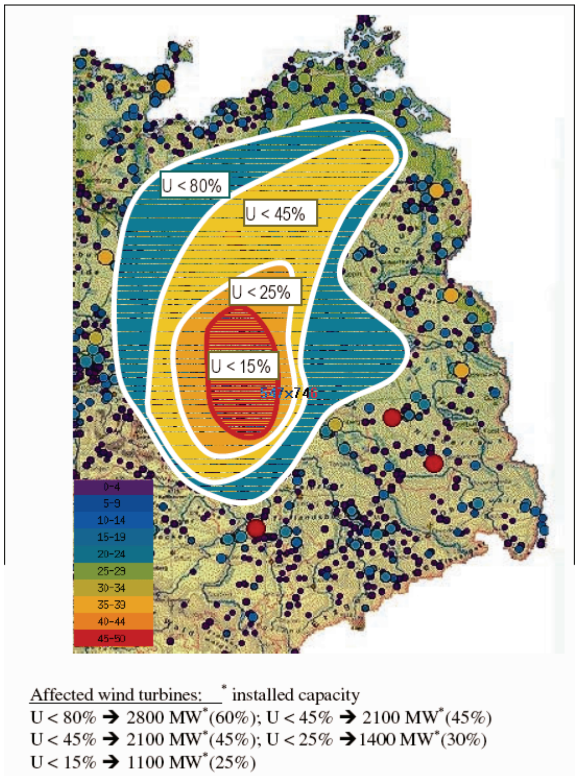

Fig. 1. Voltage collapse during a three-phase short circuit in the north-east part of Germany [9].

Fig.1 reveals that a large amount of the wind power (60% of the installed capacity in the considered area) is subject to a voltage drop below 80%. According to the old rules for WTs in that area, they must disconnect when the voltage is below 80% [9]. This means that most of the wind power would be lost when previous rules are applied; such a big loss of generation (i.e. 2800MW) would definitely affect the stability of the power system. The important consideration that follows is that, when old rules are applied, most wind turbines are disconnected in case of grid fault due to undervoltage protection settings; this means that their fault current contribution is not relevant as only few WTs would remain connected. On the contrary, when present FRT requirements are fulfilled, almost all wind turbines are expected to remain connected and support the grid in case of fault, leading to a strong fault current contribution which should be taken into consideration.

III. Model OF VSC-Based Wind Turbines for Short-Circuit Calculations

In this section an equivalent model of a VSC-based wind turbine for steady-state short-circuit studies is developed and presented. The wind turbine is assumed to be compliant with the German grid code from E.On Netz regarding the grid voltage support [10]. Although [10] refers to WTs connected to the transmission level, it is assumed to be the reference grid code for the considered WT which is connected to the distribution level (i.e. 30kV).

The equivalent model of the WT allows the consideration of the fault current injected into the grid by the WT during a grid fault and therefore the evaluation of the grid support performed by reactive current injection. The presented model is suitable for all electrical components connected to the grid by means of a full-rating power converter. The steady-state behavior of any similar component is characterized by the active and reactive current injected into the connection point (i.e. WT generator terminals for a wind turbine); for wind turbines complying with the German or Spanish grid codes, the reactive current component is specified depending on the WT terminal voltage, whereas the active current component is chosen to avoid excessive overload of the wind turbine and its transformer.

A. Model structure

The structure of a suitable model for the wind turbine during short-circuits is the first issue and strictly connected to the selected simulation tool where the model will be implemented. While performing short-circuit calculation in DigSILENT PowerFactory, the current contribution from components connected to the grid by means of power converters is neglected; this means that alternative components must be used in the model in order to take into consideration the current injection during a grid fault. The Thevenin equivalent is used to model the wind turbine connected at the LV-side of the WT transformer; this is shown in Fig.2.

It has been noticed that the value of the reactance X has a strong effect on the injected reactive current component at steady-state. Also, the phase angle of the a.c. voltage source ' and the series resistance R have a strong effect on the injected active current component at steady-state; the voltage magnitude, on the contrary, has a similar effect on both current components and therefore is kept fixed.

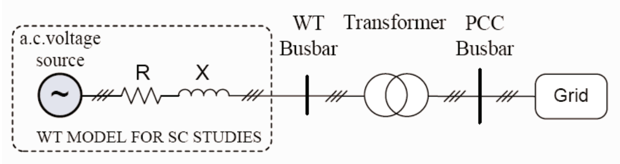

Fig. 2. Thevenin equivalent-based model of the WT for short-circuit studies at steady-state conditions.

Knowing the reference active and reactive current components that the wind turbine shall inject at the WT terminal during a grid fault, the equivalent model can be adjusted by changing the parameters X, R and φ to fit with the expected WT behavior. The grid in Fig.2 represents the power system at which the wind turbine is connected; it is characterized by the ratio Rg/Xg and the symmetrical short-circuit power Skg at the Point of Common Coupling (PCC).

B. Algorithm for short-circuit calculations

When a grid fault occurs, it reflects into a voltage dip at the PCC bus-bar and the WT bus-bar; knowing the measured WT voltage u_{WT} (i.e. at the LV-side of the WT transformer), the reactive current to be injected by the wind turbine into the WT bus-bar to support the grid is defined by the German grid code.

According to [10], the reactive current injection shall be performed within 20ms after a voltage dip on u_{WT} above 10% has occurred; it shall act according to Fig.3.

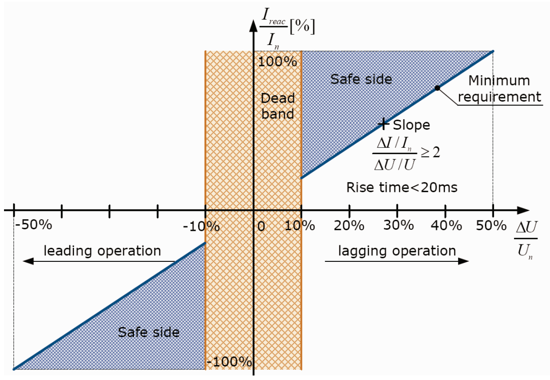

Fig. 3. Reactive current injection for grid voltage support according to the German code.

It has to be noticed that the bold line in Fig.3 represents the minimum requirement for FRT capability; however WT manufacturers can decide to support the grid voltage more than required by injecting more reactive current. In this work, the minimum requirement of the E.On grid code is used to calculate the reference reactive current i^*_{react}. Knowing i^*_{react}, the reference active current component i^*_{act} can be calculated; however it is necessary to use one more constraint: the wind turbine is assumed to work at the rated current, such as at *1pu*. This constraint is reasonable as it corresponds to the maximum fault current contribution from the wind turbine to the grid and, thus, it is assumed as the worst case. The steady-state reference active current is calculated as $i_{act}^{*} = \sqrt{1 - i_{react}^{*}{}^{2}}$

The wind turbine model shall inject into the WT busbar the reference active and reactive currents at steady-state conditions; to do this, an algorithm has been developed. The algorithm is based on an iterative process that changes the reactance X, the resistance R and the phase angle of the a.c. voltage source, φ, until the measured errors ε_{act} and ε_{react} are both below the selected maximum error $\varepsilon_{max} = 0.005pu$. The algorithm for the short-circuit calculation including the fault current contribution from VSC-based wind turbines is graphically represented in Fig.4; the flow-chart provides a simple explanation of the code used for the implementation.

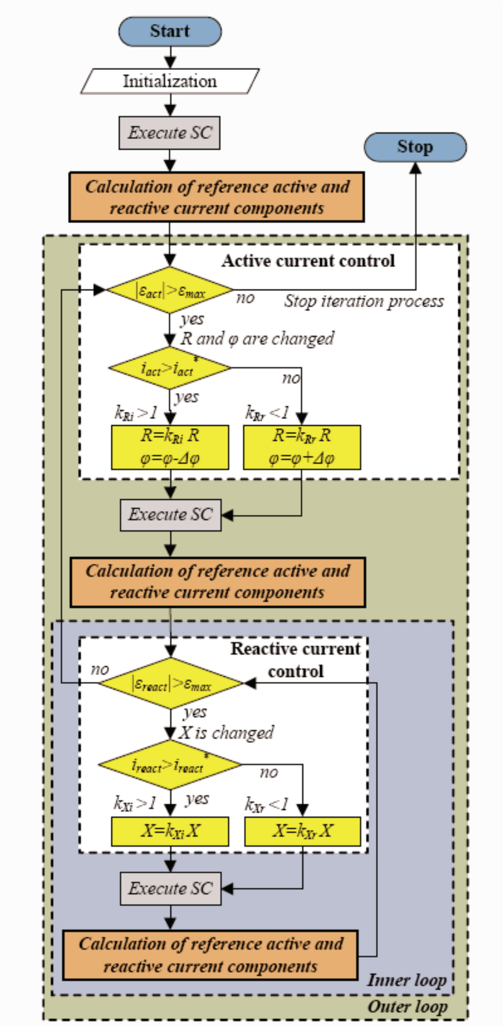

Fig. 4. Flow-chart of the algorithm for short-circuit calculation.

The following blocks in Fig.4 need to be explained:

Execute SC: the short-circuit calculation based on the complete method is launched; it is not possible to use approximated methods, such as the IEC and ANSI methods as they do not consider the a.c. voltage source whose phase angle is used to control the active current component (i.e. φ would not have any effect on the WT active power);

Inner loop: in the inner loop X is chanded by an iterative loop until the reactive current error $|\varepsilon_{react}| < \varepsilon_{\max}$;

Outer loop: in the outer loop R and ' are changed by an iterative loop until the active current error $|\varepsilon_{act}| < \varepsilon_{\max}$.

The algorithm shown in Fig.4 has been implemented in DIgSILENT PowerFactory using the DIgSILENT Programming Language DPL. The developed DPL routine only implements one WT model at a time; however the same algorithm can be modified to model more WTs in a later implementation.

IV. Wind Turbine Model Verification

In this section, the developed DPL-based wind turbine model for short-circuit calculations is evaluated and verified.

The aim is to prove that the DPL-based WT model correctly implements the fault current contribution from a wind turbine with full-rating power converter; an incorrect current contribution from a wind turbine to the grid during a fault may lead to a wrong voltage at the WT terminal and, thus, to a different requirement concerning the reactive current injection.

Since the DPL-based WT model is based on a general control routine, which does not necessarily represent the exact control applied by any WT manufacturer, the real behaviour is approximated by the expected behaviour which is based on the German grid code.

A. *Test scenario*

The test scenario is generically represented in Fig.2 as a single-line schematic. The considered wind turbine has a rated power S_{WTn} = 3.6MW. The schematic includes:

• the WT Thevenin equivalent that implements the WT fault current contribution to the grid; the series impedance has rated power $S_{IMPn} = S_{WTn}$ = 3.6MV A;

• the three-phase WT transformer with rated power S_{Tn}=S_{WTn}=3.6MV A, nominal frequency f_n=50Hz, rated voltages V_{LV}=0.69kV and V_{HV}=30kV and short-circuit voltage u_k=6%; since only balanced faults are considered, the vector group of the transformer is not relevant;

• external grid with symmetrical SC power S_{kg} and ratio R_g/X_g = 0.1.

B. *WT model evaluation*

In this section, it is proven that the fault contribution from a VSC-based WT with has been properly implemented in DIgSILENT Power Factory; this is proven by the full control of the WT active and reactive current components during a grid fault. The fault current contribution is considered in the following cases:

- **weak grid**: power grid with S_{kg} = 10MV A and ratio R_g/X_g = 0.1;
- **normal grid**: power grid with S_{kg}=10S_{WTn}=36MVA and a ratio Rg/Xg = 0.1, as specified by the Danish grid code [11];
- **stiff grid**: power grid with S_{kg} = 100MV A and a ratio Rg/Xg = 0.1.

In each study case, several measures are performed with WT terminal voltages obtained with different fault impedances.

Test results using this model are shown in Fig. 5 and Fig 6.

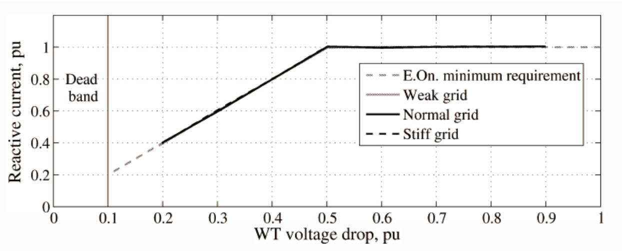

Fig. 5. Wind turbine reactive current according to E.On minimum requirement.

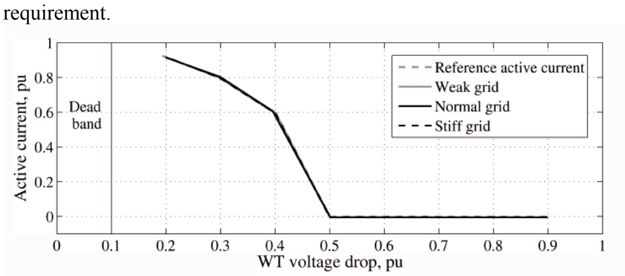

Fig. 6. Wind turbine active current according to E.On minimum requirement.

The grid voltage support/fault current contribution from the WT to the grid has been properly implemented in DIgSILENT PowerFactory, being the WT active and reactive current components very close to their references (i.e. within the selected accuracy) independently of the stiffness of the power grid; the reactive and active current errors, ε_{act} and ε_{react}, are shown in Fig. 7 and Fig. 8.

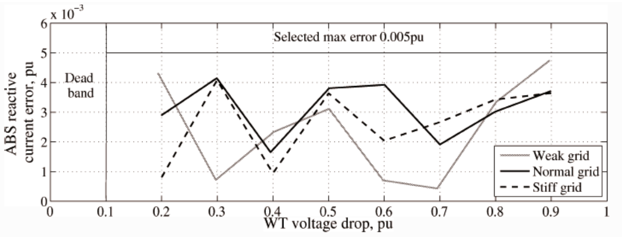

Fig. 7. Absolute reactive current error for the considered cases.

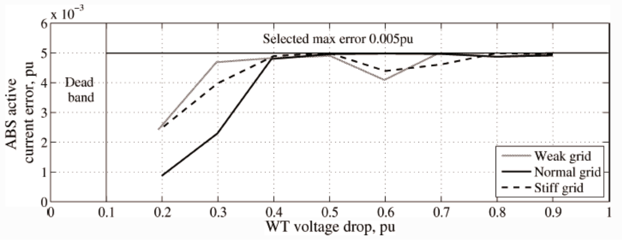

Fig. 8. Absolute active current error in pu.

It can be seen that the absolute values of these errors are always below *0.005 pu*, which is the selected maximum error.

The DPL routine has always converged for WT voltages between *0.1* and *0.8pu*; the convergence time is always below 10s; in most cases it is below 5s;

The DPL routine provides a general algorithm without specific details of the applied WT control strategy; this makes the routine generic and independent of WT type and manufacturer.

C. Comparison with the Siemens Wind Power WT dynamic model

In this section the developed DPL-based WT model is compared with the steady-state results obtained with the dynamic model of the 3.6MW variable-speed wind turbine developed and kindly provided by Siemens Wind Power. The latter model is implemented in DIgSILENT Power Factory and validated with certified fault-ride-through tests [12]; it complies with the German grid code and therefore is a suitable and accurate reference for the comparison.

Tests in case of weak, normal and stiff grids have been performed and very close results have been obtained. In this paper, only results in case of normal grid are shown in Fig. 9 and Fig.10; detailed results in case of normal and stiff grids can be found in [13].

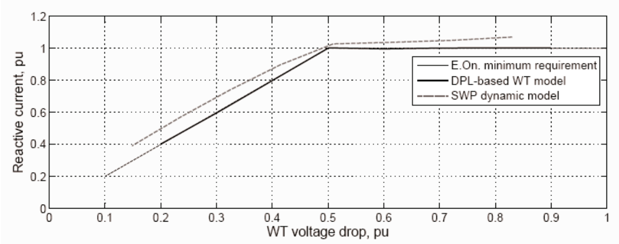

Fig. 9. WT reactive current. Comparison between the DPL-based WT model and the SWP dynamic model in normal grid operating conditions.

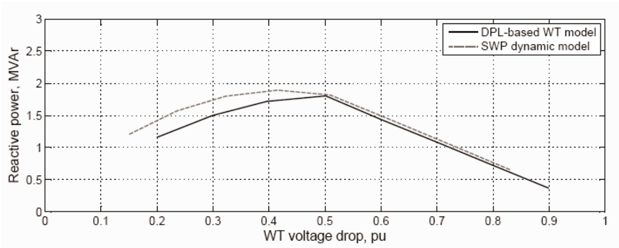

Fig. 10. WT active current. Comparison between the DPL-based WT model and the SWP dynamic model in normal grid operating conditions.

Some discrepancy has been obtained when comparing the results of the DPL-based general model and the manufacturer specific model provided by Siemens Wind Power. The discrepancy is present because the DPL-based general model is built up on a general algorithm regarding the grid-compliance rules of the German TSO E.On Netz and does not necessarily include specific control details used by Siemens Wind Power. The DPL-based model is developed as a general model to represent expected behaviour of wind turbines with full-rating power converters without direct relation to any specific manufacturer.

The results and discrepancy have been discussed with Siemens Wind Power which agreed that the DPL-based general model is implemented in a correct and sufficiently accurate way, but does not necessarily represents the specific control of Siemens Wind Power wind turbines. Indeed, the discrepancy might be expected since a general algorithm has been compared to the manufacturer specific control algorithm.

V. APPLICATION IN THE DANISH POWER SYSTEM

In this section, the developed DPL-based wind turbine model is used in a realistic scenario comprising a power system with large wind farms. The Danish transmission system is considered and the fault current contribution from a large offshore wind farm is included in the investigation. First, the DPL-based WT model is rescaled to the rated power of the large offshore wind farm; the obtained aggregate DPL-based wind farm model is then used to perform short-circuit calculations.

A. Fault current contribution from the Nysted-size offshore wind farm to the grid

The largest wind farm in Denmark is Nysted offshore wind farm at Rødsand built in 2003; it consists of 8 rows with 9 turbines each, yielding 72 wind turbines and a total installed capacity of 165.6MW [14].

The Nysted offshore wind farm is equipped with 2.3MW fixed-speed active-stall controlled wind turbines. This means that the actual wind farm configuration does not include VSC-based wind turbines. Furthermore, since the wind farm is installed in Denmark, it complies with the Danish grid code which does not require the grid voltage support in case of grid fault. It yields that it is not appropriate to represent the real Nysted offshore wind farm using the developed DPL VSC-based wind farm model that implements the German grid code.

In the following, it is considered that a large offshore wind farm replaces the Nysted wind farm; it is assumed that: it has the same installed capacity of the Nysted wind farm (i.e. 165.6MW); it has the same location; it comprises VSC-based WTs; it complies with the German grid code regarding the grid voltage support in case of grid fault.

Since they have the same total installed capacity, the large offshore wind farm is identified as Nysted-size offshore wind farm.

B. Small test model of the Danish transmission system

A small test model of the Eastern Danish transmission system is presented in [14]; it has been developed by the Danish TSO Energinet.dk and submitted to the Centre of Energy Technology of the Danish Technical University, other universities and companies for education and research projects on wind power integration. It is implemented in DIgSILENT Power Factory and it is available to all interested parties. Details about the topology can be found in [14]; it can be summarized that the model contains 17 buses with voltages from 0.7kV to 400kV , four central power plants and their control, a static VAR compensator, several consumption centres, a lumped equivalent local onshore wind farm and an equivalent of a large offshore wind farm. The large offshore wind farm has the rating of 165MW and generically represents the Danish offshore wind farm commissioned at Nysted/Rødsand in the year 2003 [14]. In the following, the dynamic model of the large offshore wind farm (i.e. Nysted/Rødsand) is substituted by the aggregate DPL-based wind farm model for short-circuit calculations in order to perform short-circuit investigations.

C. Results of short-circuit calculations with the DPL-based wind farm model

The fault location can be any bus-bar or line in the entire transmission system. Although several study cases are analyzed in the main reference (i.e. [13]), in this paper only a three-phase short-circuit fault at the 135kV onshore connection point of the Nysted/Rødsand wind farm is considered.

The fault impedance is $Z_f = 0.5$, with $R_f = X_f /5$. The DPL routine for the SC calculation converges within 10s to the solution. The most important results are listed in Table I.

Table 1. Main Short-Circuit Calculation Results.

WF terminal voltage u_{WF}	[pu]	0.2802
PCC voltage u_{PCC}	[pu]	0.2266
WF symmetrical SC power S_k	[MVA]	166.37
WF symmetrical SC current I_k	[kA]	139.21
WF symmetrical SC current i_k	[pu]	0.9042
Reference active current i^*_{act}	[pu]	0.0000
Active current i_{act}	[pu]	-0.0049
Reference reactive current i^*_{react}	[pu]	1.0000
Reactive current i_{react}	[pu]	1.0046
WF active power P_{WF}	[MW]	-0.2290
WF reactive power Q_{WF}	[MVAr]	46.611

A more detailed presentation of test results is shown in [13], where all bus-bar voltages, line currents, loading factors, active and reactive powers are shown on the single-line schematic of the power system. The wind farm provides full reactive current injection (i.e. $i_{react}=1.0046pu$) in order to support the grid voltage as required by the German grid code for $u_{WF} < 0.5pu$.

The wind farm reactive current operating point is represented in Fig.11, where it can be seen that it corresponds to the minimum requirement of the E.On. grid code regarding the grid voltage support.

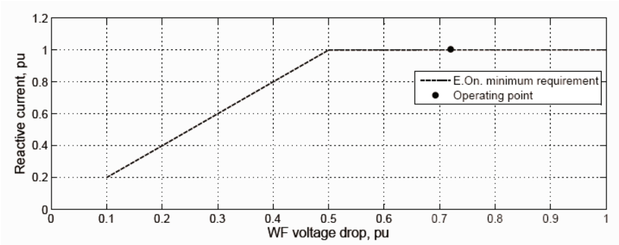

Fig. 11. Wind farm reactive current operating point. Comparison with the minimum German grid code requirement.

Fig.11 proves that the grid voltage support has been successfully implemented in the Nysted-size wind farm model for SC calculations and, thus, also its fault current contribution to the grid.

VI. CONCLUSIONS

In this paper a suitable model of wind turbines with full rating power converters for steady-state short-circuit calculations has been developed and presented. It is based on the Thevenin equivalent whose parameters are adjusted by a general routine in order to fit the model with the expected behavior which is specified in national grid codes (e.g. the German E.On Netz grid code). A general routine for short-circuit calculations including the fault current contribution from VSC-based WTs has been developed and implemented in DIgSILENT Power Factory using the DPL-Programming Language.

The DPL routine does not includes specific control details but, on the contrary, it is based on a general algorithm reflecting requirements for the grid voltage support, without any direct relations to a specific wind turbine manufacturer. The wind turbine model has been verified by evaluating the reactive and active current injection during grid faults; it is proven that they fit with the expected reactive and active current injection, meaning that the model correctly implements the behaviour of a WT complying with the German grid code concerning the grid voltage support. Test results in significant study cases have proven that the current contribution from the wind farm has been successfully implemented in a general way.

The DPL-based WT model has been compared with the steady-state results obtained with the dynamic model of the 3.6MW variable-speed wind turbine developed and kindly provided by Siemens Wind Power. Some discrepancy is obtained but it is present because the DPL-based general model is built up on a general algorithm regarding the grid-compliance rules of the German TSO E.On Netz and does not necessarily include specific control details. The developed DPL-based wind turbine model has been rescaled to represent a large wind farm. The obtained aggregate DPL-based wind farm model has been used in a realistic scenario; the Danish transmission system is considered and the fault current contribution from a large offshore wind farm to the grid is included in the investigation. Test results has proven that the fault current contribution from the large offshore wind farm have been successfully implemented in DIgSILENT Power Factory.

ACKNOWLEDGMENT

This paper is entirely based on the Master Thesis Fault Current Contribution from VSC-based Wind Turbines to the Grid, defended by Massimo Valentini on the 25th June 2008 at the Institute of Energy Technology at Aalborg University, Denmark [13]. The first author kindly acknowledges the support from Siemens Wind Power A/S.

REFERENCES

[1] "Worldwide wind energy capacity at 47616MW-8321MW added in 2004." World Wind Energy Association, Press Release March 2005. Available on line: www.wwindea.org

[2] F. Blaabjerg and F. Iov, "Wind power - A power source now enabled by power electronics," 30 September-4 October 2007, keynote paper in Proc of 9th Brazilian Power Electronics Conference COBEP 07, Blumenau Santa Catarina, Brazil, ISBN 978-85-99195-02-4.

[3] M. Valentini, T. Ofeigsson, and A. Raducu, "Control of a variable speed variable pitch wind turbine with full power converter," 17 December 2007, project report at the Institute of Energy Technology, Aalborg University, Pontoppidanstraede 101, DK-9220 Aalborg, Denmark.

[4] F. D. Bianchi, H. D. Battista, and R. J. Mantz, Wind Turbine Control System. Springer, 2007, ISBN 1-8462-8492-9.

[5] DIgSILENT Technical Documentation: PWM Converter, 30.03.2007, techRef ElmVsc V1.

[6] C. Eping, J. Stenzel, M. Poller, and H. Muller, "Impact of large scale wind power on power system stability," DIgSILENT publication available on line: http://www.digsilent.de/Consulting/Publications/PaperGlasgowDIgSILENT.pdf.

[7] T. Boutsika, S. Papathanassiou, and N. Drossos, "Calculation of the fault level contribution of distributed generation according to IEC standard 60909," Available on line: http://users.ntua.gr/stpapath/Paper 2.52.pdf.

[8] P. M. Anderson, Analysis of faulted power systems. IEEE Press Power Systems Engineering Series, 1995, ISBN: 0-7803-1145-0.

[9] I. Erlich and U. Bachmann, "Grid code requirements concerning connection and operation of wind turbines in Germany," June 12-16, 2005, pp. 2230-2234.

[10] "Grid code. high and extra high voltage." E.ON Netz BmbH, Bayreuth, 1 August 2006.

[11] EnergyNet.dk, "Grid connection of wind turbines to networks with voltages above 100kV," in Technical Regulations TF 3.2.5. EnergyNet.dk, December 2004.

[12] J. N. Nielsen, V. Akhmatov, J. Thisted, E. Grondahl, P. Egedal, M. N. Frydensbierg, and K. H. Jensen, "Modelling and fault-ride-through tests of Siemens Wind Power 3.6MW variable-speed wind turbine," Wind Engineering, vol. 31, No. 6, 2007.

[13] M. Valentini, "Fault current contribution from VSC-based wind turbines to the grid," Master's thesis, Institute of Energy Technology, Aalborg University, Pontoppidanstraede 101, DK-9220 Aalborg, Denmark, 25 June 2008, ISBN 978-87-89179-73-5.

[14] V. Akhmatov and A. Nielsen, "A small test model of the transmission grid with a large offshore wind farm for education and research at Technical University of Denmark," in Power Systems Conference and Exposition, 2006. PSCE '06. 2006 IEEE PES, Oct. 29 2006-Nov. 1 2006, pag.650-654, ISBN: 1-4244-0177-1. Digital Object Identifier 10.1109/PSCE.2006.296395.