Reactive Power Generation by DFIG Based Wind Farms with AC Grid Connection

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Abstract: **Reactive power generation by wind farms, which must operate similar to other conventional power plants, is a major concern during both steady state and fault conditions. This paper addresses the reactive power generation of offshore wind parks using doubly-fed induction generators (DFIGs) connected to the main grid with long cables along with reactive power compensating devices. During steady-state operation, reactive power can be generated with minimum power loss of wind energy system while meeting the grid code requirement. This is an optimization problem which, in this paper, is solved using a new adaptive particle swarm optimization (APSO) embedded in the Newton-Raphson load flow program. During grid disturbance, the wind power generators have to provide voltage support by increasing reactive current supply. The paper also discusses control measures which enable DFIG based wind turbines to provide effective voltage support and is demonstrated on a real offshore wind farm, which is currently in planning stage, in Germany.**

Index Term: **Wind Energy, Reactive Power Scheduling, Particle swarm optimization, Wind power interconnection, Grid code, Wind generator reactive power control**

I. INTRODUCTION

WIND energy is the fastest growing power generation technology in the world. According to [1], the worldwide installed capacity reached 47,616 MW in 2004. In Germany, the installed capacity of wind energy converters added up to 20,622MW with 18,685 wind turbines at the end of 2006 [1]. According to a study of the German Energy Agency [2], the expected increase in installed capacity of onshore wind power will be supplied by retrofitting, which means the exchange of old turbines by new ones with taller towers and thus higher rated power. However, the main part of the forthcoming increase will take place offshore where large wind farms are already under construction. Most of these wind farms will be connected to the 400-kV-grid via 150-kV-AC submarine cables. According to the German grid code wind farms have to supply not only active power but also reactive power into the grid. The requirements are defined with respect to the power factor as a function of the voltage at the point of common coupling (PCC) with the grid.

During the steady-state operation, reactive power sources such as wind power reactive generation, switchable capacitors or reactors, flexible AC transmission systems (FACTS) etc, as well as devices impacting the reactive power demand indirectly like on-line tap changer (OLTC) should be operated to provide minimum real power loss on wind energy system while meeting the grid code requirement. As wind power output depends totally on the availability of wind, the output varies from time to time. If more than one wind farm cable is available, cables can be switched off during low power periods to control the reactive power of the cable system. Reactive power management in wind farms is a non-linear optimization problem having both continuous and discrete variables. In this paper, this task is solved using adaptive particle swarm optimization (APSO) approach [3]. The effectiveness of the proposed algorithm is demonstrated on a real offshore wind farm, which is currently in planning stage, in Germany.

Particle swarm optimization (PSO) method as introduced by Kennedy and Eberhart [4,5] is a self-educating stochastic optimization algorithm that can be applied to any linear, nonlinear, mixed-integer optimization problem having continuous and/or discontinuous objective and constraint functions. PSO has many prominent merits over the other evolutionary algorithms. It has a high probability of finding a global minimum. Adaptive particle swarm optimization (APSO) [3,6] is a parameter free technique. The significant feature of this algorithm is that the optimization algorithm can be used as a black box where only the search space, the objective function to be minimized, and a stopping criterion for the algorithm are to be given. The algorithm is totally free from parameter tuning and also from the burden of selecting the most appropriate swarm (population) size.

According to the grid codes, the wind turbines have to provide voltage support during grid faults by increasing reactive current supply. This requires also, that wind turbines stay connected to the grid during the low voltage period. DFIG based wind turbines are able to supply the reactive current required by the grid codes using rotor and line side converters (RSC and LSC respectively) control. However, severe grid faults may lead to separation of the converter from the DFIG and on-switching of the crowbar resistances in the rotor circuit. During this time the controllability of the DFIG is lost. Nevertheless, the LSC continues to supply reactive power by utilizing temporary overload capability. This paper also discusses the control measures which enable DFIG based wind turbines to provide effective voltage support during fault condition.

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II. STEADY-STATE OPERATION

A. Grid Requirements

When a wind farm is connected to the high voltage or even ultra-high voltage grid, it has to fulfill the same requirements as every conventional power plant does. The Transmission System Operators (TSOs) define such requirements in their grid codes for the respective voltage level. These grid codes can differ from company to company even in one country because they depend on the structure of the TSO's grid.

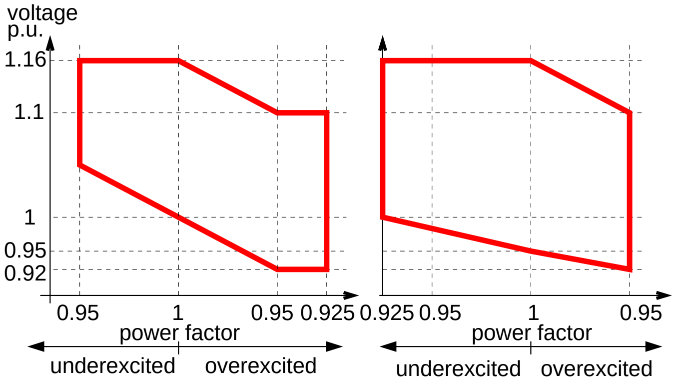

Fig. 1. Power-factor requirements of two different TSOs for generating units connected to the high voltage grid

In Fig. 1, the requirements of two different utilities for steady state operation are illustrated. Operation points are given to the generators by means of schedules or in the form of online set-point preset. As the PCC voltage may vary in a wide range as shown in Fig.1, wind farm transformer should be equipped with on-load tap changer to operate the wind farms, most of the time, on its optimum voltage.

B. Reactive Power Sources

Due to the layout of large offshore wind farms, several ways for fulfilling the requirements are offered. For this, Fig.2 gives a short overview. Each option is discussed below in detail.

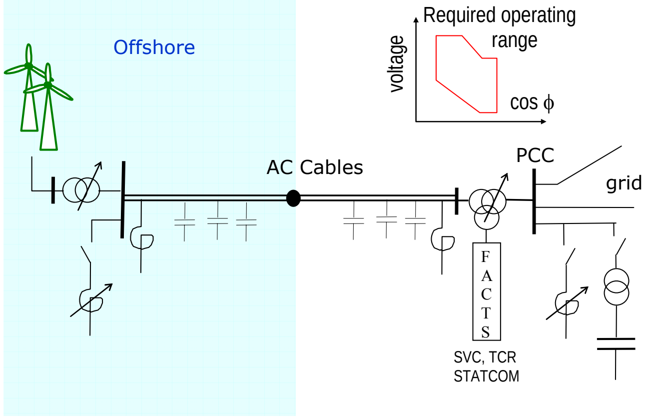

Fig. 2. Alternatives for reactive power generation

1) Cables

The cable itself represents a VAr source that should be used to supply reactive power into the grid. With slightly under-compensated cables it is possible to provide a considerable contribution to VAr generation. However, to increase the transmission capacity and reduce the losses, long AC cables always need compensation by shunt reactors on both sides. Besides, the capacitive switching capability of circuit breakers is limited and should therefore not be exceeded. To avoid phases without compensation, fixed connection of the reactors to both ends of the cable is recommended so that the cable and reactors will always be switched together. The degree of under-compensation and thus the utilizable cable VAr source is determined by the required transmission capacity, additional transmission losses and the circuit breaker switching capability to interrupt capacitive currents.

2) Transformers equipped with on-load tap changers

By using tap changers the voltage on the wind farm side can be controlled in a definite range. In consequence the charging power of the cable including that of the shunt reactors will also be controlled. Furthermore, it is possible to reduce the reactive power demand by operating the system at higher voltage levels.

3) Shunt reactors and capacitors

Reactors are essential to make long cables, as they are projected for offshore sites, feasible. However, additional reactive VAr sources can also be installed to generate the reactive power required by the grid. For this purpose the best location for connecting is the PCC bus bar. However, switching of large static reactors may be undesirable from power system operation point of view. On the other hand shunt reactors can be equipped by tap changers so they can be controllable in smaller steps. Switched shunt capacitor banks may also be an option to generate capacitive power, but it presupposes a proper medium or low voltage level where the capacitors can be connected.

4) FACTS

Flexible AC transmission systems (FACTS) are widely discussed in the literature but usually utilities hesitate to include FACTS into their systems basically due to high costs. However, when smooth reactive power control is needed, FACTS may be the right option. Different FACTS can be used to generate/absorb the reactive power required at the PCC. Static VAr compensators (SVC) and static synchronous compensators (STATCOM) are two basic shunt devices used to maintain the voltage in the system by controlling the reactive powers. When reactive current supply is required following the grid faults, STATCOM is the preferable option due to its better performance compared to the SVC at low voltage levels.

C. Wind Turbines

Variable speed wind turbines are equipped with voltage source converters. Focusing on the converter, two types of turbines have to be distinguished: fully converted machines and doubly-fed induction machines. For the first one, the converter must be designed for the full rated power of the machine. For the latter one, the converter has to provide only one third of the rated power. In this paper, the focus is set to the doubly-fed induction machine (DFIM). A typical layout is shown in Fig. 3. The stator of DFIM is directly connected to the grid whereas the rotor winding is connected with a VSC. By supplying a voltage with variable frequency and variable amplitude to the rotor circuit, the voltage at the stator terminal can be kept constant. This mechanism brings the advantage of utilizing the turns ratio of the machine, so the converter does not need to be rated for the machine's maximum power. Furthermore, when using vector-current control for the converter, it is possible to realize decoupled active and reactive power control of the machine. Then, the rotor side converter (RSC) usually provides active and reactive power of the machine while the line-side converter (LSC) keeps the voltage of the DC-circuit constant.

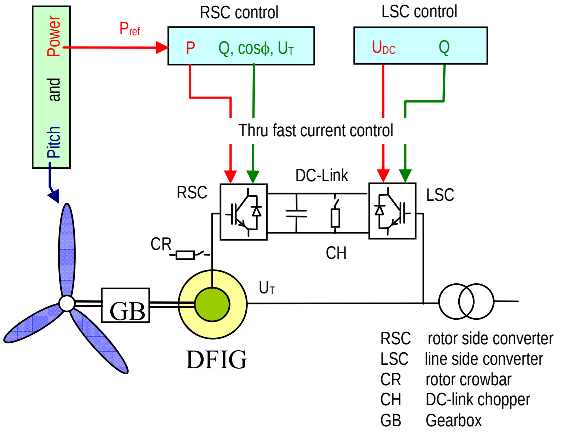

Fig. 3. Typical layout of a DFIG

The LSC can also supply reactive power, which is utilized, however, following grid faults only. Thus, the DFIG is able to operate in all four quadrants of the complex plane. This makes it suitable as another VAr source for fulfilling the grid requirements. Additionally, the DFIG can also provide reactive current in transient situations as will be discussed in section V.

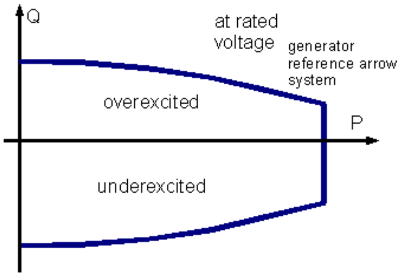

Fig. 4. P-Q characteristics of DFIG

Fig. 4 shows a typical steady state characteristics of doubly-fed induction generators used in wind farms. Two features may catch attention: The machines can feed more reactive power in under-excited mode than when over-excited and the turbines are able to feed reactive power even if no active power is generated. The maximum reactive and active power of the converter is limited by the maximum absolute current.

III. OPTIMAL REACTIVE POWER GENERATION

The optimal management of VAr sources in a wind farm is an optimization task which can be divided into two stages: before installation of the wind farm (planning stage) and continuously during service (operation). The optimization algorithm can be used to calculate several scenarios in the planning stage. Feasible objectives in this stage are for example the installation of minimum VAr sources at the PCC or if and how it is possible to provide a specific power factor at the PCC continuously. Since some solutions cause additional losses, economic feasibility studies should be accomplished to assure optimum layout of the wind farm.

During operation of the wind farm, a modified version of the optimization algorithm should be implemented in the control center of the wind farm. It will optimize load flow with regard to losses and will give set points of the equipment which the operator needs to control. Some of the VAr sources can be varied continuously while others allow variation only in steps so that the task, which has to be solved, represents a mixed-integer optimization problem. The objective function is to have minimum loss subject to the operating constraints and can be defined as

$$\min \ \boldsymbol{P_{loss}}\left(\boldsymbol{t_{Tr,k}}, \boldsymbol{Q_{QS}}, \boldsymbol{n_{cable}}, \boldsymbol{Q_{WF}}\right) \tag{1}$$

subject to the equality and inequality constraints as defined below:

Equality constraints: Power flow equations corresponding to both real and reactive power balance equations are the equality constraints. The voltage at PCC (U_{PCC}) should also match the set point value given by the utility and can be mathematically written as

$$U_{PCC} = const. \tag{2}$$

Inequality constraints:

(i) Reactive power generator limit (continuous)**:** Let $Q_{WF}{}^{max}$ and $Q_{WF}{}^{min}$ be the maximum and minimum reactive power generation limits of wind generator-*i* respectively. Mathematically it can be written as

$$\boldsymbol{Q_{WF}^{\min}} \le \boldsymbol{Q_{WF}} \le \boldsymbol{Q_{WF}^{\max}} \tag{3}$$

(ii) Voltage limit (continuous): This includes the upper (U^{max}) and lower (U^{min}) limits on the bus voltage magnitude.

$$U_{\min} \le U \ \le U_{\max} \tag{4}$$

(iii) OLTC limits (discrete): The transformer tap ratio should be well between lower ($\boldsymbol{t_{Tr,k}^{\min}}$) and upper ($\boldsymbol{t_{Tr,k}^{\max}}$) limits.

$$\boldsymbol{t_{Tr,k}^{\min}} \ \le \ \boldsymbol{t_{Tr,k}} \le \boldsymbol{t_{Tr,k}^{\max}} \tag{5}$$

(iv) Line flow limit: This constraint represents the maximum current flow in a cable and is usually based on thermal and dynamic stability considerations. The line flow limit can be written as

$$I_n < I_{n,\max} \tag{6}$$

where I_n is the current through the n-th cable (discrete).

(v) Other reactive power sources: Reactive power generation

(Q_{QS}) of other sources such as capacitor, reactors and FACTS should be with in limit.

$$Q_{QS}^{min} \le Q \le Q_{QS}^{max} \tag{7}$$

Usually, wind park providers are interested in reducing the losses in the wind farm system, since these losses are quoted using the full feed-in tariff. To minimize losses while fulfilling the requirements of the grid code, grid operators must be interested in reactive power compensation at the PCC. If compensation devices are installed on the wind farm side of the line, they will cause additional losses. However, extra devices at the PCC must be installed, whereas wind turbines with their ability of reactive power compensation are in place. This is a classical engineering problem, where the costs of the installation of devices at the PCC must be compared to the costs caused by higher losses over the whole operation time. The adaptive PSO algorithm is used to minimize losses in several different scenarios.

IV. APSO RESULTS

The effectiveness of the developed adaptive particle swarm optimization is tested on a German offshore wind park as shown in Fig.1 having 80 wind turbines each rated at 5 MW, 0.95 kV, connected to the main grid (380 kV) with two, 144 km long cables (94 km AC submarine cable and 50 km onshore cable) each rated at 150 kV. Two step-up transformer of rating 36 kV/150 kV and 150kV/380kV with on-load tap changing facility are used as shown in Fig. 1.

To fulfill the grid code, the amount of reactive power interchanged with the transmission grid is set to a fixed value, in this case zero. Any other amount of reactive power is also possible, if it is within the limits of the grid code. Three different cases are studied:

Case-I: Reactive power generated by wind farm only

In this case, all necessary reactive power is supplied by the wind farm. There are no FACTS or other compensation devices at the PCC. For this scenario, the compensation of the cable is optimized. Its value is then kept constant for the other scenarios to ensure comparability.

Case-II: No VAr generation by wind farm

This scenario uses exclusively the supply of reactive power at the PCC. The reactive power output of the wind turbines is set to zero. At the PCC, the reactive power could be maintained by STATCOM, SVC or thyristor controlled reactors (TCR).

Case-III: Both PCC and WT VAr sources are used to run the system with minimum wind farm losses

This case represents a combination of the previous two cases, since now reactive power is supplied by both the wind farm and devices installed at the PCC. In practice, this may be a compromise to reduce losses without installing large compensation at the connection point. The optimization algorithm is free to change both the reactive power of the wind farm and of the FACTS at the PCC.

The real power losses obtained in these cases are shown in Fig. 5. It can be seen from Fig. 5 that with installed reactive power sources at the PCC, losses are reduced by 1% at low power generation level however, the reduction at more than 80% loading is not significant. It should be noted that the reduction of losses are at the expense of installing new reactive power sources at the PCC. A complete economic analysis is required for making a proper decision of installation. Reactive power generation at the PCC is shown in Fig. 6 and the WT VAr generation in presented in Fig. 7. From these figures, it can be seen that inductive current is required during low loading conditions and vice versa. The curves in Figs. 5, 6 and 7 are not smooth due to optimally changing transformer taps for each loading conditions obtained from the APSO. Below the 30% loading only one cable is optimally required; however, both the cables are switched on at loading 30 % and more.

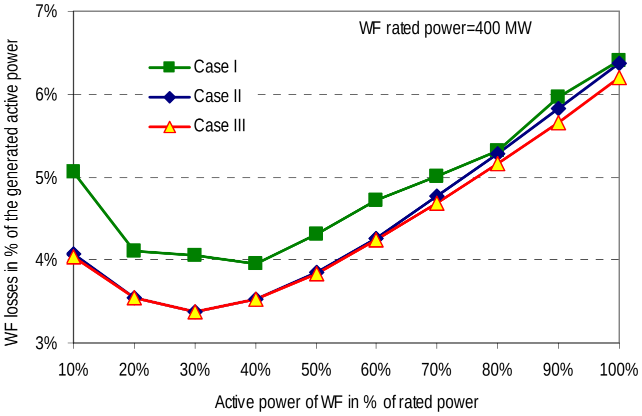

Fig. 5. Wind farm losses in relation to generated active power

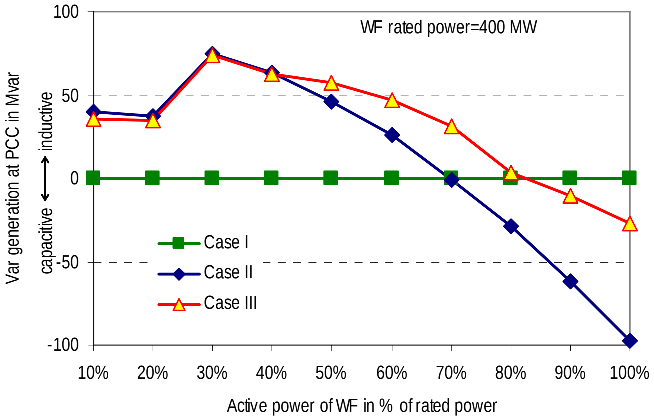

Fig. 6. Required VAr generation in PCC

V. REACTIVE POWER GENERATION DURING FAULTS

According to the German grid code, wind turbines have to provide a mandatory voltage support during voltage dips. The corresponding voltage control characteristics are summarized in Fig. 8 [7]. Accordingly wind turbines have to supply at least 1.0 p.u. reactive current whenever the voltage falls below 50%. A dead band of 10% is allowed to avoid undesirable control actions.

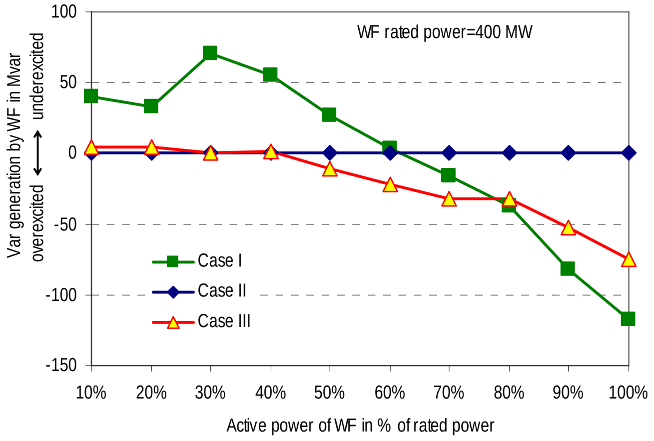

Fig. 7 Required VAr generation by WT

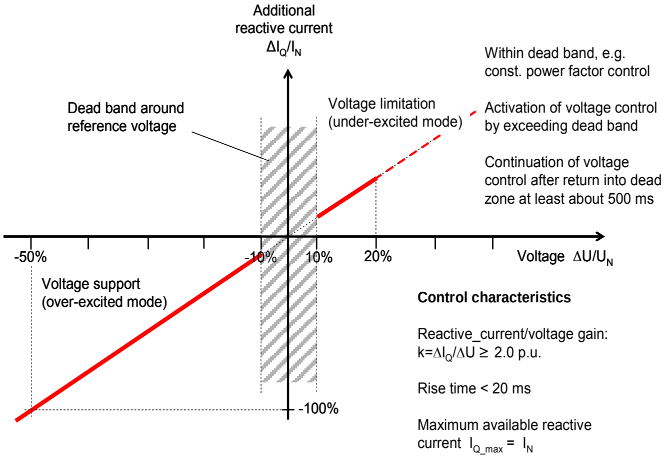

Fig. 8. Characteristic of wind turbine voltage control

However, large voltage dips may result in protection action temporarily restricting the controllability of the machine. Most of the DFIG based wind turbines use a so called *Crowbar* for protection against rotor overcurrents. When the current exceeds a certain limit, the rotor side converter (RSC) is disconnected and the crowbar resistance is switched in to the rotor circuits. In this phase, the DFIG is consuming reactive power needed for magnetizing the machine. Usually the crowbar is disconnected within 100 ms and subsequently, the DFIG continues to operate in normal mode even if the voltage remains low [8]. However, during the crowbar period the line side converter can be used for forced reactive power generation. Fig. 9 shows the behavior of the DFIG during the fault-ride through (FRT).

The different states marked in Fig. 9 are:

1. Normal operation

The turbines operate in normal mode following the set points of the TSO. Here, the reactive power is set to zero.

2. Fault with activation of crowbar

In fault situation, currents are flowing from the grid into the DC-circuit of the back-to-back converter. Even when the IGBTs are blocked, the current commutates to the reverse diodes. In the following, the DC-voltage rises which causes crowbar-switching. The first peak of reactive power is caused by demagnetization of the stator. Usually, the machine would become under-excited in this state. This is pointed out by the curve showing the reactive power of the stator. However, the LSC compensates for the stator and is even able to feed reactive power into the grid.

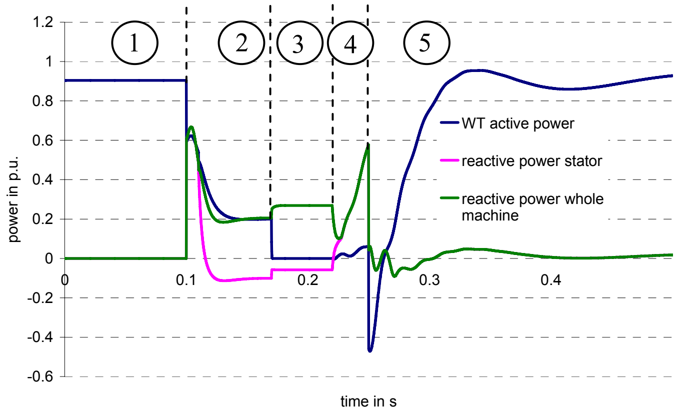

Fig. 9. DFIG response during fault ride-through

3. Crowbar switched off but rotor circuit still open

This is a no-load mode, where the RSC is switched off. In this state, the thyristor switches of the crowbar are turned off. The exact time of this state depends on the frequency of the rotor current, since thyristors can only interrupt at zero current. For simplification of the control, the controller waits a predefined time period before the RSC is started again.

4. Resynchronization on lower voltage

The machine is able to resynchronize on lower voltages. The active and reactive power fed by the machine in this state is only limited by the maximum magnitude of the machine's and converters' currents.

5. Voltage return

During the voltage return, the machine experiences a current in-rush similar to the one at the beginning of the fault but with opposite sign. However, when using another protection unit, called chopper, it is possible to handle this disturbance without activating the crowbar. A chopper is a shunt resistance in the DC-circuit (see Fig. 3), which can limit the DC voltage.

When wind turbines remain in normal operation mode (no crowbar action and no stator disconnection) and during grid faults additional reactive current can be supplied within the limitation of the RSC current. Because the limitation is due to the current magnitude, the available reactive current depends on the instantaneous active current. Taking into account that during low voltage periods the grid load decreases with the voltage, it is desirable to reduce also the active power in-feed of wind turbines during these times. With less active current, the reactive current available for voltage support will increase.

Concerning the voltage control characteristics, the German grid code defines minimum requirements. Merely the controller gain and the rise time are defined specifically. The grid code doesn't require a proportional type controller as could be easily concluded from Fig. 8. The dynamic characteristic of the controller should be chosen in such a way that corresponding transients are well damped. Besides, the controller should provide a positive contribution to the damping of power system oscillations. A PI type voltage controller can not only fulfill the grid code requirement but also enables the utilization of the total reactive current capacity of the wind turbine available at that particular moment. The simulations presented here considered a voltage dip at the PCC. However, since the cable and all other equipment of the grid connection represent considerable impedance, the voltage dip at the wind farm's terminal is clearly smaller. Fig. 10 shows the grid voltage recovery behavior when different control options are applied to the wind turbines. The voltage dip at the PCC is comparatively small, but shows clearly that the PI controller provides the best performance.

A more severe fault is shown in Fig. 11 requiring crowbar firing. The voltage dip at the PCC is around 0.4 p.u. but at the WT terminal voltage remains about 0.6 p.u. Most of the modern DFIG based wind turbines would ride through this fault without crowbar activation, but to demonstrate the effect of crowbar we have simulated this case with crowbar.

The voltage support of the wind turbines provided in the second case is not very large. The reasons are on the one hand, that the reactive current is smaller due to the crowbar activation, and on the other hand, that the grid modeled here is very strong.

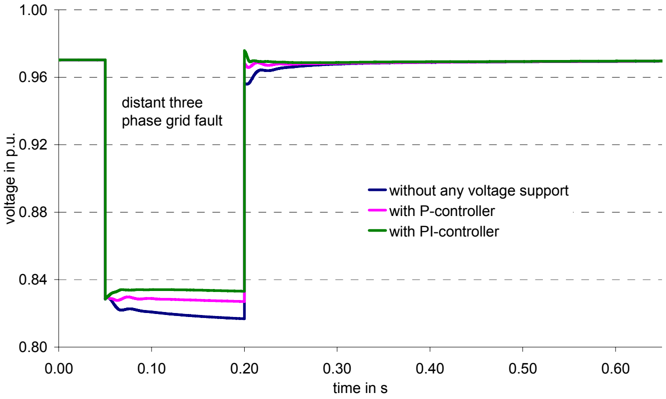

Fig. 10. PCC voltage by using different voltage control strategies (FRT without crowbar)

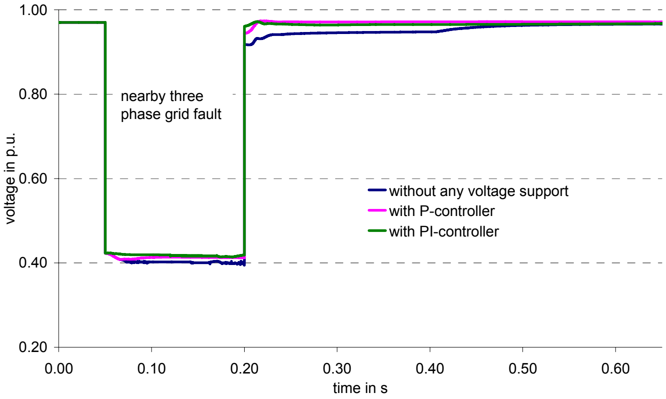

Fig. 11. PCC voltage by using different voltage control strategies (FRT with crowbar)

VI. CONCLUSION

Following the installation of large offshore wind farms, the influence of wind energy on the transmission grid will grow. This paper proposes an optimization algorithm to minimize the real power loss of wind energy system during normal operation while meeting the requirements of the TSO at the PCC. The optimal setting of reactive power sources including the cable switching are obtained for different cases. It is observed that with proper setting of reactive power sources, the real power loss is reduced significantly.

During transient situations, the behaviour of the wind farm has been shown. The difference between fault ride-through with activation of crowbar has been presented in contrast to a fault without crowbar action. When the crowbar is activated, the reactive current feed from the wind farm is limited. This is a disadvantage compared with fully converted wind turbines. It may be overcome to some extent in the future by increasing the utilization of DC-link choppers that can further reduce probability of crowbar firing.

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VIII. BIOGRAPHIES

Michael Wilch (1979) received his Dipl.-Ing. degree in electrical engineering with emphasis on Power Generation and Transmission from the University of Duisburg-Essen in 2006. He is currently a PhD student at the Institute of Electrical Power Systems of University Duisburg-Essen. His research interests include integration of large amounts of wind power into existing power systems.

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Istvan Erlich (1953) received his Dipl.-Ing. degree in electrical engineering from the University of Dresden/Germany in 1976. After his studies, he worked in Hungary in the field of electrical distribution networks. From 1979 to 1991, he joined the Department of Electrical Power Systems of the University of Dresden again, where he received his PhD degree in 1983. In the period of 1991 to 1998, he worked with the consulting company EAB in Berlin and the Fraunhofer Institute IITB Dresden respectively. During this time, he also had a teaching assignment at the University of Dresden. Since 1998, he is Professor and head of the Institute of Electrical Power Systems at the University of Duisburg-Essen/Germany. His major scientific interest is focused on power system stability and control, modelling and simulation of power system dynamics including intelligent system applications. He is a member of VDE and senior member of IEEE.