EVALUATING THE PERFORMANCE OF EXTERNAL FAULT RIDE-THROUGH SOLUTIONS USED IN WIND FARMS WITH FIXED SPEED INDUCTION GENERATORS WHEN FACING UNBALANCED FAULTS

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Resumo: Na sequência da integração da energia eólica em larga escala foram estabelecidos códigos de rede pelos vários operadores de sistema, exigindo que os parques eólicos permaneçam em serviço durante e após a ocorrência de defeitos na rede a montante. Nos parques eólicos equipados com sistemas de velocidade constante este requisito pode ser assegurado pela instalação, no ponto de interligação à rede, de equipamento de compensação dinâmica de potência reactiva, controlado como fonte de tensão, sendo as funções de controlo baseadas em medidas efectuadas no ponto de interligação relativamente às componentes directas da tensão e da corrente. Como a adopção deste tipo de soluções externas é adequada ao funcionamento do sistema em regime equilibrado, este artigo foca a avaliação do desempenho da solução no caso da ocorrência de defeitos assimétricos. Os resultados obtidos através das simulações dinâmicas evidenciam o aparecimento de sobre tensões nas fases não afectadas pelo defeito que poderão colocar o parque eólico fora de serviço.

Abstract: The continuous growth of wind energy integration on electrical networks has led many utilities to impose fault ride-through capability to wind farms. This means that wind turbines must remain connected to the system during severe fault occurrence. Regarding the existing wind farms equipped with fixed speed induction generators directly connected to the grid, fault ride-through capability is commonly assisted with dynamic compensation devices, such as DSTATCOM units. These power electronic devices are controlled for voltage regulation purposes and behave like a balanced three-phase voltage source converter since commonly used control techniques are based only on the positive sequence of both voltage and current measured at its connection point. These control techniques are suitable only when compensation devices are operated under balanced conditions and therefore its performance when facing unbalanced faults needs to be evaluated. This paper tackles with this subject and the results obtained through numerical simulations demonstrate that over voltages can arise on non faulty phases leading to the wind farm disconnection.

Palavras-chave: Cavas de tensão, DSTATCOM, geradores de velocidade constante, defeito assimétrico, sobre tensões
Keywords: Fault ride through, DSTATCOM, fixed speed generators, unbalanced faults, over voltages

1. Introduction

The continuous increase of installed wind power generation and its penetration into the electrical grids has lead the Transmission System Operators (TSO) to make the utility interconnection requirements for wind farms, also known as Grid Codes, more restrictive in order to limit the propagation of problems into the grid as a result of the presence of wind generation. Two of the main requirements are reactive power control during normal operating conditions and Fault Ride-Through (FRT) capability during fault conditions (Gaztañaga, 2007).

Concerning FRT requirements, wind farms are aimed at avoiding as much as possible the loss of generation capacity in case of an external fault occurrence. Thus, in order to comply with these requirements, wind generator manufacturers have developed systems with ability to provide some voltage support, trying to attenuate voltage dips during short-circuits.

In spite of the current use of variable speed wind turbine generators, many Fixed Speed Induction Generators (FSIG) directly connected to the grid are still in operation. However, they do not have the capacity to control their reactive power exchange because they always need to absorb a certain amount of reactive power. Although shunt capacitors are typically used to fully compensate for reactive power consumption during steady state operation, these devices exhibit rather poor performance especially during fault conditions due to the decrease of their reactive power injection capability following voltage drops. Therefore additional external power electronic compensation devices are necessary to fulfil the FRT requirements (Qi, 2008), (Marques, 2006).

Two existent devices usually employed for dynamic reactive power compensation are the Static Var Compensator (SVC) and the STATic synchronous COMpensator (STATCOM). Although these two devices can improve the stability performance of FSIG directly connected to the grid, simulation results show that the utilization of a STATCOM with the same power capability of a SVC may lead to a better dynamic performance of the FSIG. When compared to SVCs, STATCOMs are faster, smaller and have better performances at reduced voltages (Salles, 2004).

Recently a new family of Distribution STATCOMs (DSTATCOM) especially adapted for distribution applications was proposed in (Grunbaum, 2005), which is based on the series connection of Insulate Gate Bipolar Transistors (IGBT) and operated with Pulse Width Modulation (PWM) techniques. The DSTATCOM solution connected to the wind farm substation and serving a single wind farm is considered in (Gaztañaga, 2007), (El-Helw, 2007), (Sudrià, 2005) as one of the most interesting solutions to improve FRT capability of wind farms based on FSIG directly connected to the grid. For this purpose, the DSTATCOM is controlled to regulate the wind farm terminal bus voltage through the reactive power exchange with the network. When system voltage drops, the DSTATCOM injects immediately reactive power on the connection point in an attempt to limit the voltage dip.

Control techniques commonly used are based on ac-positive sequence voltage and current measured at the DSTATCOM connection point. Therefore, depending on the voltage dip, the DSTATCOM injects the same amount of reactive power in all of the three phases. This control technique is suitable when the DSTATCOM is operated under balanced conditions, such as following three-phase short-circuits when all the three grid voltages register the same drop amplitude and the system remains balanced. Although balanced faults are the most severe ones, its occurrence is extremely rare. In contrast, unbalanced faults, which occur when one or two phases are shorted to ground or to each other, happen most often, leading with the appearance of the negative-sequence component in the grid voltages. Thus, the performance of the DSTATCOM when facing unbalanced faults and the impacts inside the wind farm in these situations needs to be evaluated.

This paper tackles with such problems. The dynamic performance of DSTATCOM to improve FRT capability of wind farms equipped with FSIG following unbalanced faults is evaluated through numerical simulations. The results obtained demonstrate the potential benefits of the DSTATCOM concerning the FRT capability improvement. However, the over voltages that arise on non-faulty phases would lead the operation of over voltage protections and therefore to the wind farm disconnection.

2. Grid code requirements for wind farm connection

Following the large expansion of wind power generation, a matter of great concern for most European TSO is the capability of wind farms to stay connected to the grid in the event of faults which give rise to voltage dips in order to increase the stability margin of the power system. For this purpose, wind turbines connected to the grid should be equipped with FRT capability (Marques, 2006), (Sudrià, 2005), (Arulampalam, 2007). According to the Portuguese grid code proposal, the new wind power plants must fulfil the following minimum technical requirements (Estanqueiro, 2007):

• To remain in operation during voltage dips, if the value of the effective terminal bus voltage remains above the curve depicted in figure 1 during the fault and after its clearance for the time limits also defined by figure 1.

• To deliver reactive power during voltage dips providing thus voltage support for the network. The requested reactive power is indexed to the reactive current flowing through the Point of Common Coupling (PCC) before the fault occurrence, being the wind farm obliged to stay in the white region of the curve depicted in figure 2.

• To adjust, by request of the TSO, the reactive power injected in the network for $tg(\varphi)$ in the range between 0 and 0.2, corresponding to a power factor between 1 and 0.98 inductive.

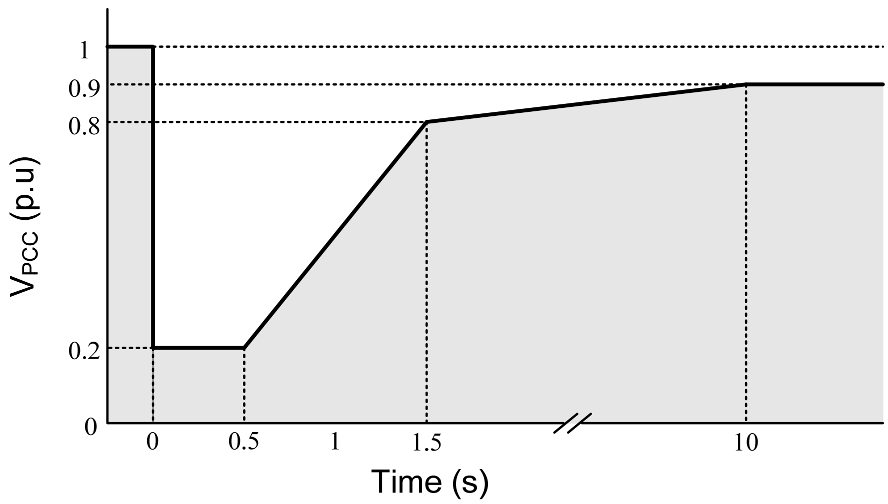

Fig. 1: Time voltage characteristic proposed to Portuguese wind systems

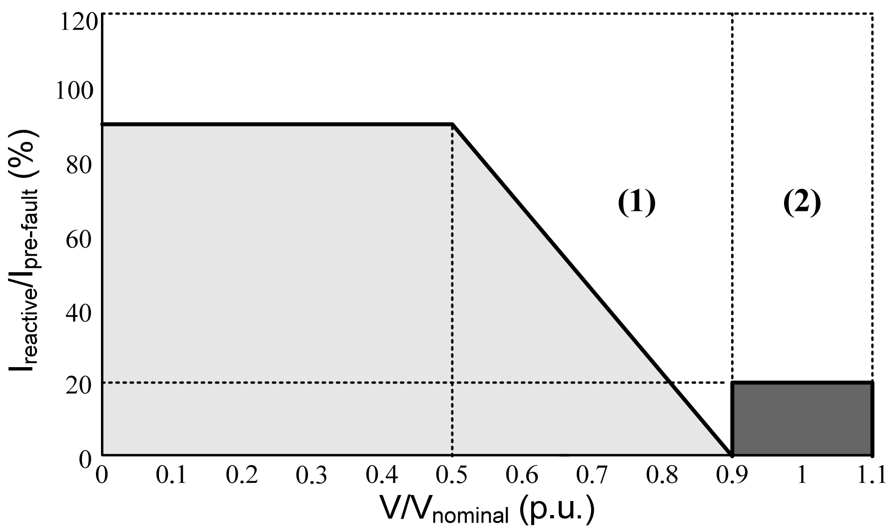

Fig. 2: Characteristic curve of the reactive current delivery by wind power plants during/after voltage dips. (1) Fault and recovery region. (2) Normal operating region.

Assuming that the existing wind farms equipped with FSIG directly connected to the grid should fulfil these FRT requirements, the DSTATCOM to be installed on the wind farm terminals should provide sufficient dynamic reactive power compensation. The reactive power injected during steady state conditions is assured by a capacitor bank installed at the wind farm substation.

3. Behaviour of fixed speed induction generators under power system disturbances

Following a fault occurrence in a power system, two effects can be observed on wind turbines equipped with FSIG directly connected to the grid: The stator is demagnetized and the rotor speed increases (Gaztañaga, 2007), (Chen, 2007).

The voltage drop provokes the demagnetization of the stator flux. Since the rotor flux cannot decrease immediately the machine delivers reactive power to the grid during a transient period. At the same time, the active power delivered to the system is significantly reduced as well and the electromagnetic torque, whereas the mechanical torque may remain almost constant. Due to the torque unbalance the rotor will accelerate.

After the fault is cleared the voltage tends to recover and FSIG directly connected to the grid require a large amount of reactive power to recover the air-gap flux and due to the increased speed during the fault. This could cause an inrush current to be drawn by FSIG from the power system, resulting in a voltage drop, which, in turn, could prevent the machine terminal voltage to return quickly to its nominal value. If the voltage could be recovered and the generator speed is not too high, the electromagnetic torque could be restored, so that the rotor speed can be slowed down and the FSIG may restore its normal operation. In contrast, if the voltage is not able to be recovered back to around its nominal value or the generator speed is too high, the electromagnetic torque may be not sufficient to balance the mechanical torque and the machine continues to accelerate, increasing then the reactive power consumption. Therefore the voltage may decrease further and the generator will not return to its nominal speed being then tripped out by over speed protection devices.

4. The DSTATCOM operation and control

Concerning FSIG with stall regulated wind turbines, it is not possible to control the input mechanical power and therefore the effective approach is based on dynamic reactive power compensation with a fast reactive power control in order to help the voltage recovery and to re-establish the machine magnetic field and torque (Chen, 2007). In this context, the DSTATCOM is used for enhancing the reactive power supply in order to restore system voltage. As a consequence, the wind farm dynamic response concerning the fulfilment of FRT requirements presented in section II will be improved. However, the rating of the DSTATCOM should be approximately of 100% of the wind farm nominal power in order to guarantee a successful voltage recovery (Gaztañaga, 2007), (Aten, 2005), (Molinas, 2007).

A DSTATCOM consists of a three-phase Voltage Source Converter (VSC) shunt connected to the wind farm terminal bus through a coupling transformer (Salles, 2004), (Hingorani, 2000), as depicted in figure 3(a). The STATCOM principle of operation is based on the injection or absorption of reactive power in the network connection point. Thus suitable control and measurement systems are required, as described in figure 3(a).

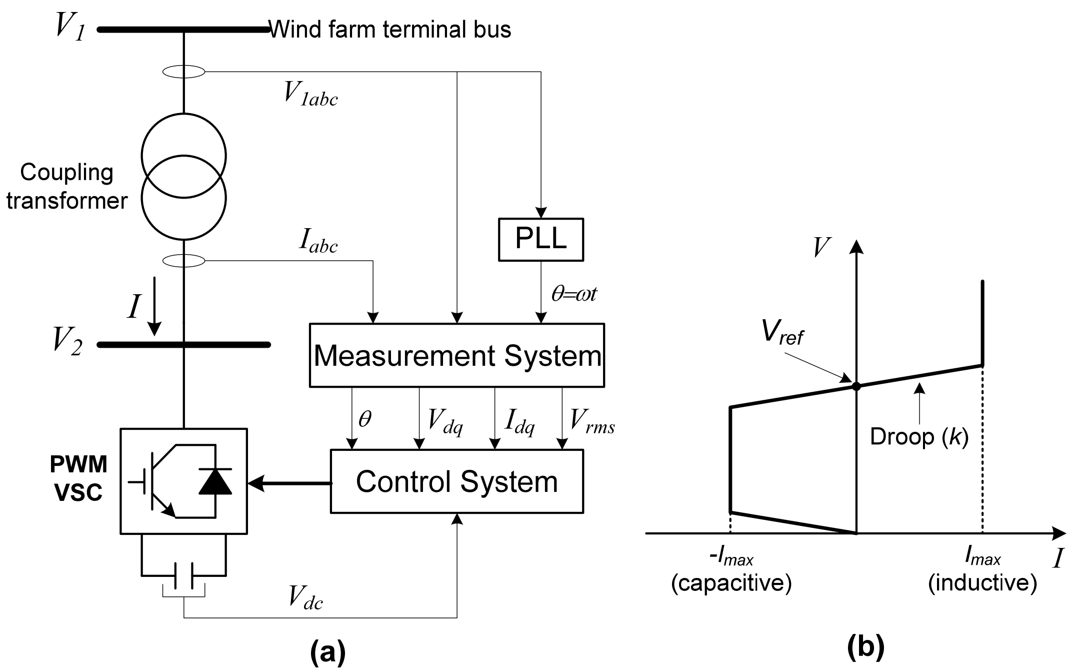

Fig. 3: The DSTATCOM: (a) structure; (b) V-I characteristic

The VSC using IGBT based PWM inverters uses a PWM technique to synthesize a sinusoidal waveform from a DC voltage source. Power electronic components should be switched on and off at a high frequency (several kHz) and high frequency harmonics and ripples will be limited by connecting filters at the AC side of the VSC (Chen, 2007). As a consequence of the high switching frequency, a small time step is required for dynamic simulations. However in this research the inverter behaviour is not a matter of concern. In this way, a simplified modelling was adopted such that the VSC ideally reproduces the reference voltage from the control system.

According to the figure 3(a), the active and reactive power transfer, (P and Q, respectively), between the VSC and the grid can be expressed as follows:

$$P = \frac{V_1 V_2 \sin\delta}{X}$$
$$Q = \frac{V_1 (V_1 - V_2 \cos\delta)}{X} \tag{1}$$

where X is the reactance of both the interconnection transformer and the DSTATCOM filter and δ is the angle of V_1 with respect to V_2.

In steady state operation, $\delta = 0$ and only reactive power is flowing. The DSTATCOM absorbs reactive power if V_2 is lower than V_1. Otherwise it generates reactive power.

As the DSTATCOM is controlled to regulate V_1, it implements the $V - I$ characteristic presented on figure 3(b). Thus, the DSTATCOM can operate with its rated current even at reduced voltages and, in addition, as long as the reactive current stays within its minimum and maximum values imposed by the converter rating ($-I_{max}$ and I_{max}), the voltage is regulated according to its reference value, V_{ref}. However, a voltage droop (usually between 1% and 5% at maximum reactive power output) is normally used, being the $V - I$ characteristic described by

$$V = V_{ref} + k \times I \tag{2}$$

where V is the positive sequence voltage (p.u.), I is the reactive current (p.u./P_{nom}) and P_{nom} is the three-phase nominal power of the DSTATCOM.

The control system of the DSTATCOM can be designed according to the several known control techniques. However, concerning FRT capability improvement of wind farms equipped with FSIG, it is essential to inject the appropriate amount of reactive power within the minimum time delay, since this fact influences notably the recovery process, as already mentioned previously. Therefore, the vector control technique is commonly used to deal with fast dynamics and to provide decoupled control ability (Gaztañaga, 2007), (Qi, 2008), (Chen, 2007), (Molinas, 2007), (Rao, 2000).

Thus, the DSTATCOM control system implemented in this work, which is presented on figure 4, is based on the vector control technique, with the reference frame oriented along the wind farm terminal bus voltage vector position. With the abc-to-dq transformation the active and reactive power flows can be represented with voltages and currents in a dq-reference frame rotating at the grid frequency. Aligning the d-axis of the reference frame along the position of the wind farm terminal bus voltage, the active and reactive power will be proportional to I_d and I_q, respectively, so that the reactive power flow can be controlled via I_q and the dc-link voltage can be controlled through I_d (Chen, 2007).

Since the DSTATCOM control scheme is based on the dq rotating reference frame, a Phase Locked Loop (PLL) is employed, as it can be observed from figure 3(a), to synchronize on the positive sequence component of the three-phase voltage V_1 and to provide the angle $\theta = wt$ to the transformation abc-to-dq and its inverse. A measurement system is also included to measure the d and q components of the ac positive sequence voltage and current to be controlled (I_d, I_q, V_d and V_q) and the dc voltage, V_{dc}.

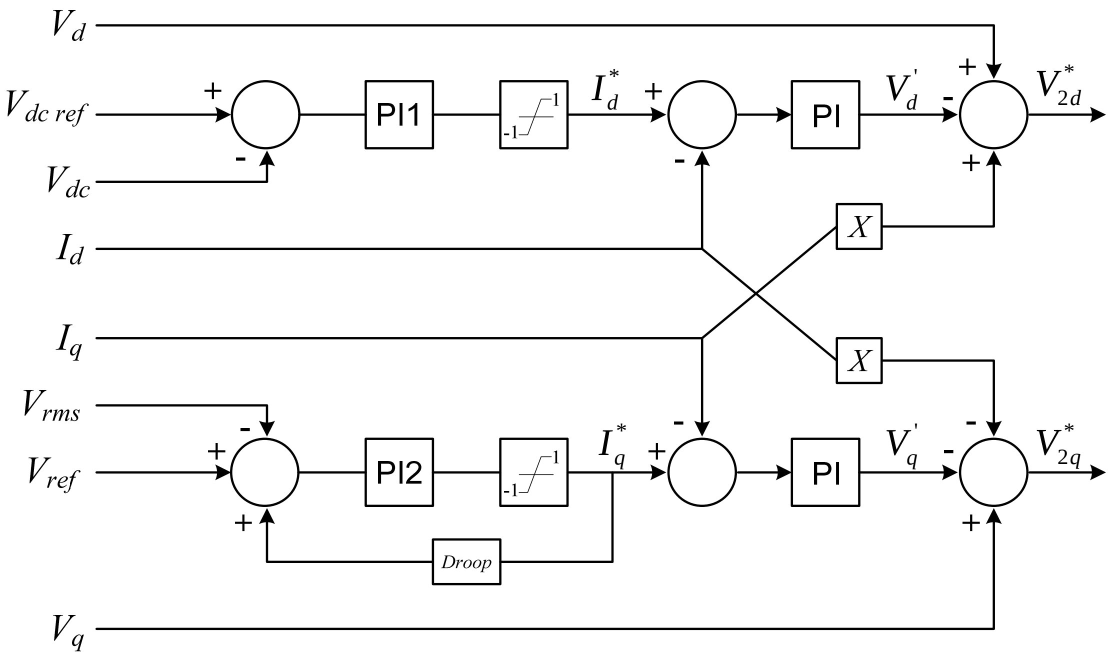

Fig. 4: The DSTATCOM control system

As it can be observed from figure 4, there are also four PI regulators. The PI1 is responsible for keeping constant the dc voltage through a small active power exchange with the ac network, compensating the active power losses in the transformer and inverter. This PI regulator provides the active current reference, I_d^*. The PI2 regulator is responsible for controlling the terminal voltage through the reactive power exchange with the ac network. This PI regulator provides the reactive current reference, I_q^*, which is limited between 1 p.u.

capacitive and -1 p.u. inductive. This regulator has one droop characteristic, which allows small variations around the terminal voltage. The other two regulators, denoted as PI in figure 4, determine voltage references, V_{2d}^{*} and V_{2q}^{*}, which are sent to the PWM signal generator of the converter, after a dq-to-abc transformation. Finally, V_{2abc}^{*} are the three-phase voltages desired at the converter output.

5. The test system and models

The test system presented in figure 5 is used to evaluate the dynamic performance of a DSTATCOM concerning FRT capability improvement of a wind farm equipped with FSIG directly connected to the grid when facing external faults.

This case study is a 10 MW wind farm connected to the utility system. The wind farm comprises 20 squirrel cage induction generators with a rating of 500 kW. Each wind turbine is connected to the wind farm internal network of 15 kV through a 630 kW, 0.55/15 kV transformer. Capacitor batteries for individual reactive power compensation are connected to the Low Voltage (LV) terminals of each wind generator, assuring its reactive power consumption on unload conditions. The additional reactive power required to FSIG when operated under load conditions as well as the reactive power injected in the network provide from another capacitor bank, which is connected to the Medium Voltage (MV) side of the wind farm substation. The wind farm is connected to the High Voltage (HV) network by means of a 10 MVA, 15/63 kV transformer. The short-circuit power at PCC is 200 MVA.

The wind farm is also equipped with a DSTATCOM with 10 MVA of rating power for voltage regulation of the MV wind farm terminal bus following short-circuits occurrence.

The model of this whole test system is implemented under the *EMTP-RV*® environment (version 1.0.2). The DSTATCOM model described previously in section III was built under *EMTP-RV*® environment, since it is not available in this version library. The induction machine model is based on a fourth-order state space model (Rogers, 1987) built in the library in *EMTP-RV*®. The wind speed is reproduced through the mechanical torque which is applied to the induction generator model. The utility system is represented by a constant voltage source connected in series with its Thevenin's equivalent impedance and the remaining components are represented through the models available on *EMTP-RV*® library.

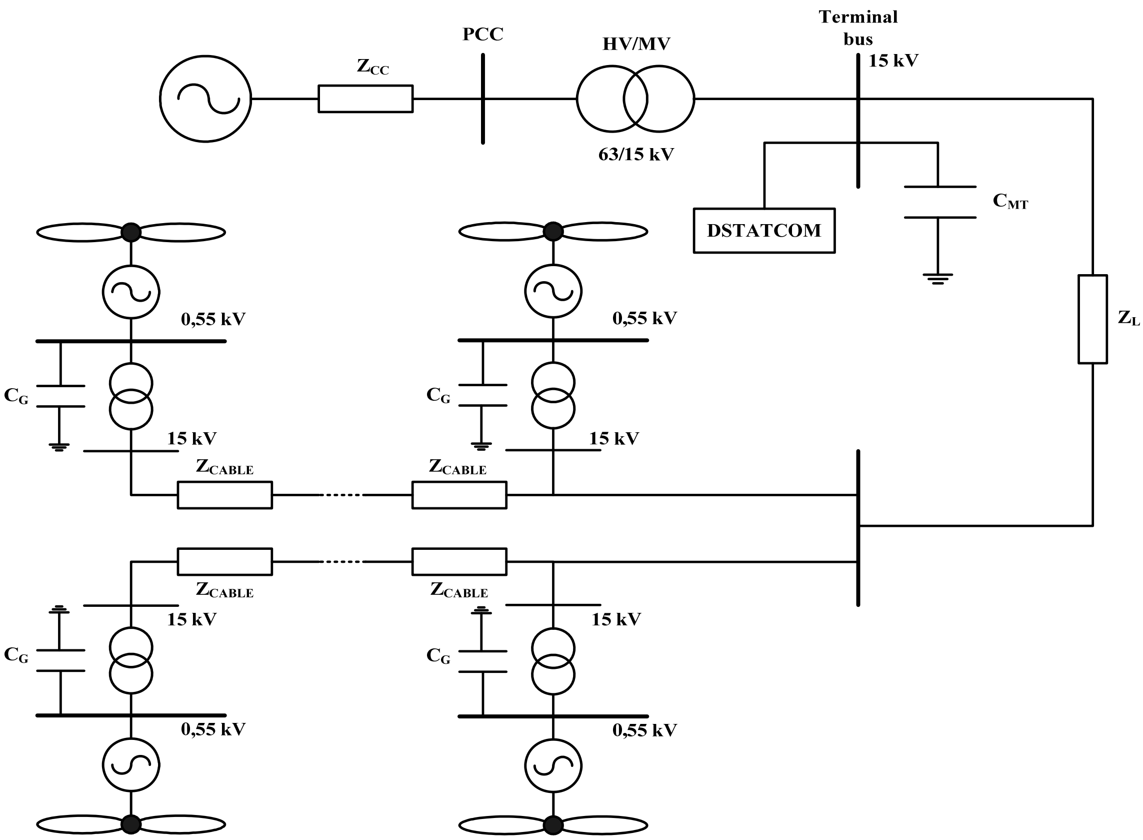

Fig. 5: Fixed speed wind farm equipped with a DSTATCOM.

6. Simulation results and discussion

In order to demonstrate the DSTATCOM contribution to the FRT capability improvement of wind farms equipped with FSIG directly connected to the grid and to evaluate its performance following external unbalanced faults, several simulation studies have been carried out using the *EMTP-RV*® simulation tool. Some of them are presented below.

7. DSTATCOM contribution for FRT capability

This study aims to demonstrate the DSTATCOM contribution for FRT capability improvement considering the most severe conditions for fault recovery. Thus, it was assumed that the wind farm is operating near to its rated power, corresponding to the maximum amount of reactive power required by the FSIG, and a three-phase short-circuit is simulated on the HV network, far from the wind farm, with a clearance time of 500 ms. The results are presented on the next figures (6 to 9).

The voltages at the PCC and at the wind farm terminal bus are depicted on figures 6 and 7, respectively, when the wind farm is operated with and without the DSTATCOM. Without the DSTATCOM, the voltage at the PCC drops below 0.2 p.u. during the fault occurrence, leading with the wind farm disconnection. The DSTATCOM based solution avoids this situation, since the voltage at the PCC remains above 0.2 p.u., as it can be observed from figure 6, contributing thus to FRT enhancement. In addition, after the fault is cleared, the voltage recovers faster and within the time limits required by the FRT characteristic depicted on figure 1. Moreover, a better improvement is achieved regarding the wind farm terminal bus voltage, as it can be observed from figure 7.

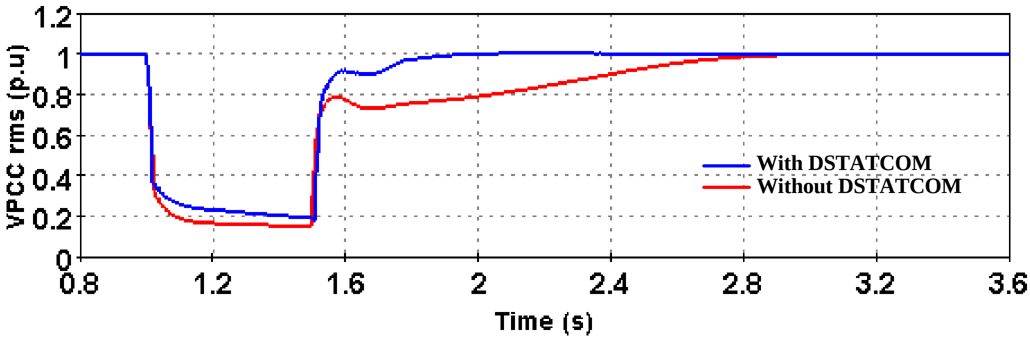

Fig. 6: Voltage at the PCC with and without DSTATCOM.

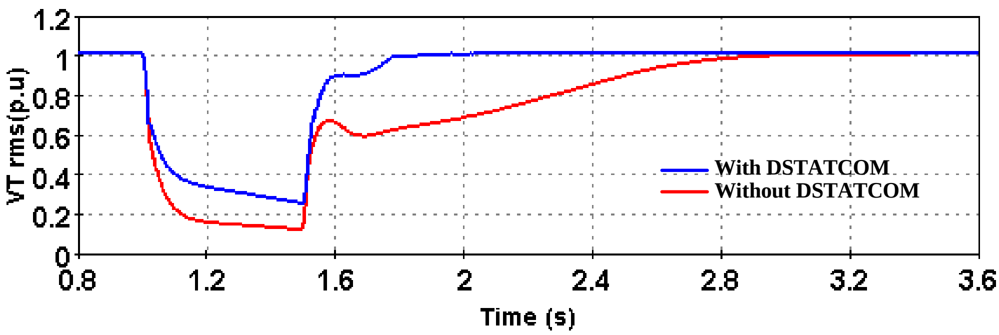

Fig. 7: Voltage at the wind farm terminal bus with and without DSTATCOM.

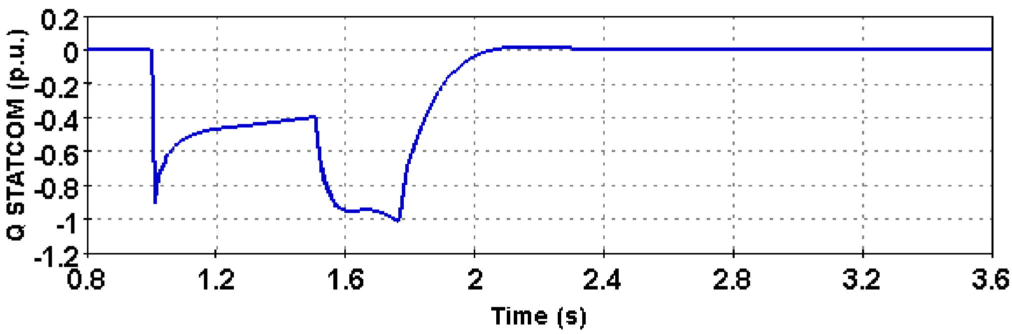

Fig. 8: Reactive power injected from the DSTATCOM.

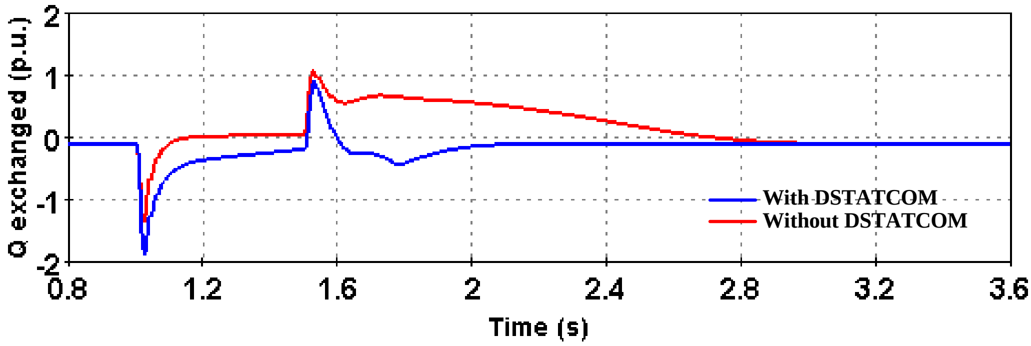

Fig. 9: Reactive power exchange with and without DSTATCOM.

These improvements are done by means of reactive power injection from the DSTATCOM during the fault and after its clearance, as depicted on figure 8. The DSTATCOM control system reacts immediately to a sudden voltage dip, saturating the controller and injecting the maximum reactive current into the grid. However, it should be noted that the reactive power injection is limited by the large voltage drop and therefore the DSTATCOM provides a little contribution for voltage support during the fault. In contrast, after the fault is cleared, the reactive power injected from the DSTATCOM corresponds to its rated power contributing to a faster voltage recovery and a clear increase of the system stability margin. In addition, the magnetization process of FSIG is dynamically supported making it possible to decrease the rotor speed and to reduce the reactive power consumption from the grid, as it can be observed from figure 9.

DSTATCOM performance following unbalanced faults

In order to evaluate the DSTATCOM performance following unbalanced faults, a single-phase short-circuit (phase a) was simulated on the HV network at t=1s and with a clearing time of 500 ms. As the reactive power absorbed by FSIG depends on their operating conditions, two situations were considered in this study concerning the active power generation: The FSIG are operated near their nominal conditions and near one half of their ratings. Concerning the first situation, the results obtained are presented on figures 10 to 13.

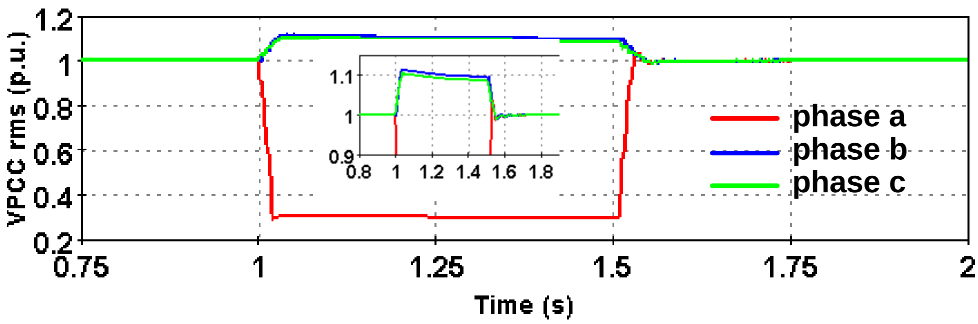

Fig. 10: Voltage at the point of common coupling.

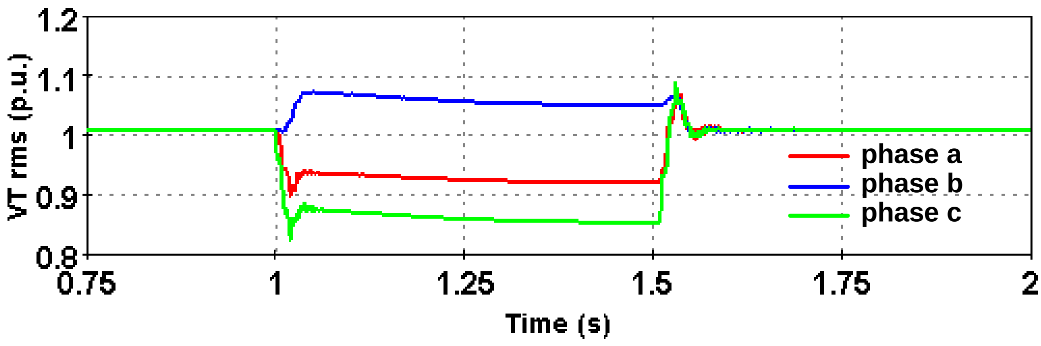

Fig. 11: Wind farm terminal bus voltage.

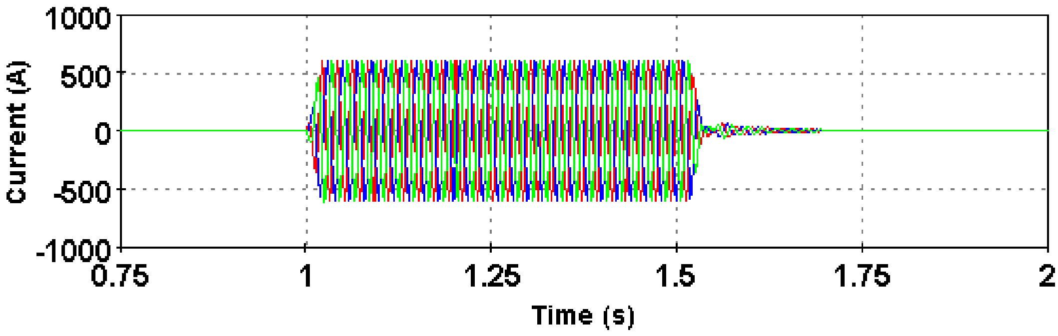

Fig. 12: Reactive current injected from the DSTATCOM.

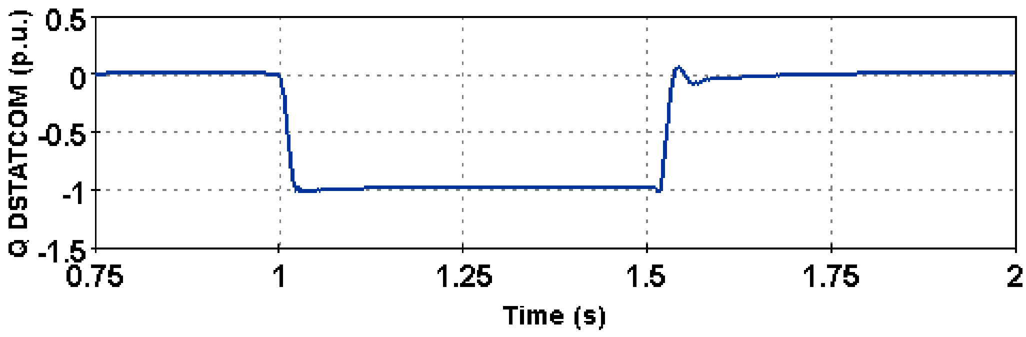

Fig. 13: Reactive power injected from the DSTATCOM.

As it can be observed from figures 10 and 11, the wind park transformer, usually of type ΔY, influences on how the grid fault appears on the wind farm terminal bus, being voltage dips verified on both phases a and c. However, as the DSTATCOM voltage regulation control system is based on the positive sequence of both voltage and current measured at the connection point, the DSTATCOM injects a balanced three-phase reactive current into the grid, as it can be observed from figure 12, corresponding to the reactive power output presented on figure 13. As a consequence, considerable over voltages arise on the non-faulted phases, as it can be observed from figures 10 and 11, being the voltage (phase a) at the PCC around 1.1. p.u.. After the fault elimination, over voltages take place, since the reactive power injection from the DSTATCOM is kept for some more time. These facts can lead to the operation of overvoltage protections and subsequent wind farm disconnection, missing the FRT capability improvement.

When the wind farm active power generation is reduced to a value near one half of its rated power, the amount of reactive power absorbed by FSIG is also reduced. Then, the reactive power injected from the MV capacitor battery was decreased in order to comply with power factor requirements. The results obtained are presented on figures 14, 15 and 16.

As it can be observed from figures 14 and 15, the over voltages that arise on the non faulted phases are larger than these ones observed from figures 10 and 11. This is due to the fact that more reactive power is injected into the grid since the reactive power absorbed by FSIG is decreased and the DSTATCOM is supplying its rated power. It should also be noted that these over voltages can become worse following less severe unbalanced faults.

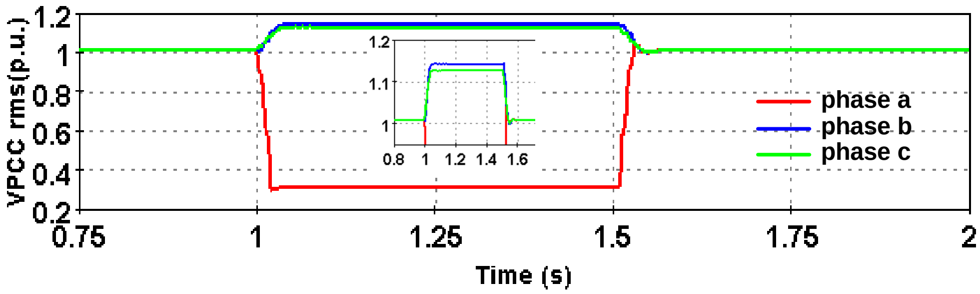

Fig. 14: Voltage at the PCC

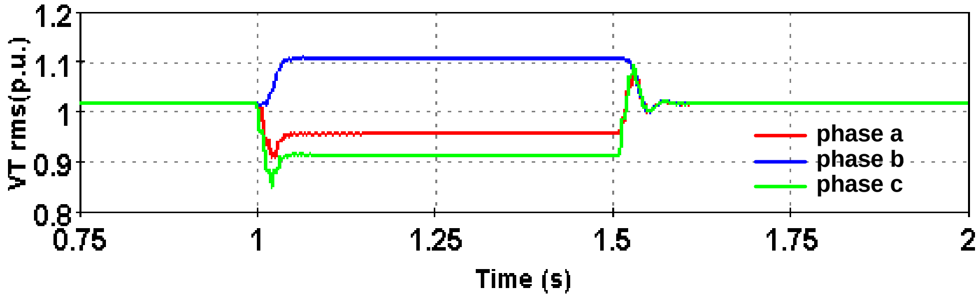

Fig. 15: Voltage at the wind farm terminal bus

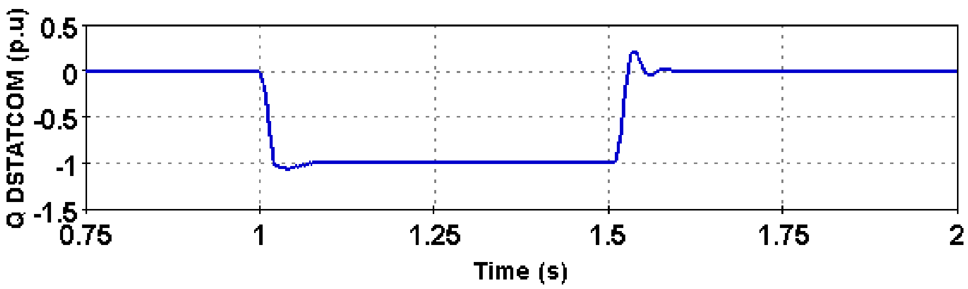

Fig. 16: Reactive power injected from the DSTATCOM.

8. Conclusions

In this paper the performance of the DSTATCOM based external FRT solutions used in wind farms equipped with FSIG is evaluated. The results obtained allow to conclude that the DSTATCOM provides voltage support following voltage dips that arise from external short-circuits occurrence, reducing voltage drops and increasing the stability margin of the power system. Therefore, the DSTATCOM can be considered as an effective mean to improve FRT capability of these existing wind farms. However, special care should be put regarding over voltages experimented by the non-faulted phases when single phase defaults arrive in the grid, due to current injection in the three phases, since over voltage protections can trip out the wind generators.

In order to avoid such situations, complementary control procedures to define the volume of reactive power injection from the DSTATCOM should be derived. For this purpose the negative sequence of the wind farm terminal bus voltage should be also taken into account. On the other hand, if possible, an adjustment of the over voltage protection settings can also be adopted. These issues will be the subject of further investigations.

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