Protection System Behavior of DFIG Based Wind Farms for Grid-Faults with Practical Considerations

Tamer Kawady, *MIEEE, Christian Feltes, MIEEE, Istvan Erlich, SMIEEE, and A.I. Taalab, SMIEEE*

Abstract—**Doubly-Fed Induction Generators (DFIGs) are commonly utilized in wind farms nowadays due to their advantages as compared with single fed ones. Control complexities and their unique dynamic characteristics may, however, raise different problems during abnormal or faulty operating conditions. Accordingly, the behavior of the associated protective elements at the Point of Common Coupling Point (PCC) may be affected during grid faults remarkably. These situations are investigated thoroughly in this paper. Detailed dynamic modeling of a 60 MW off-shore wind farm is utilized including the rotor protection circuitry with either crowbar or DC chopper. Also, the own protective functions of the rotor converters are considered. Different simulation examples are illustrated to clarify the related impacts of the DFIGs on utilized protective elements with large integrated wind farms.**

Index Terms—**DFIG, Wind farm Protection, Modeling, Crowbar, DC chopper, MATLAB.**

I. Introduction

RECENT changes in energy markets, rapid growth in global consumption of non-renewable fossil fuels and the consequent dramatic increases in energy prices have combined to spur increased interest in harnessing renewable energy resources. Among these resources, wind energy power plants has emerged as the leader at the present time. According to the new energy policies regarding the share of renewable energy by 2020, European Union raises his target to 20%. Similar targets were aimed in different countries as well. In Germany, nearly 55 GW is expected to be installed by 2020 which is more than 50% of the German peak load [1]. As the penetration of wind energy resources increases, as the expected impacts of wind energy conversion systems on power systems exaggerate as well. This has consequently spawned active research activities for different issues such as reliability, security, stability, power quality and protection.

Owing to the economic factor, wind farms still utilize surprisingly simple and none-integrated protection methodologies. As reported by Bauschke et al. in [2], different levels of damage were recorded resulting occasionally from the drawbacks of the associated protection systems. These faulty cases and their statistics in Germany, Finland and Sweden were well documented in [3]-[5].

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Wind farm protection system is usually divided into different protection zones including the wind farm area, wind farm collection system, wind farm interconnection system and the utility area. First, the protection of induction generators is typically accomplished via the generator controller. For short circuits, the generator is protected with its circuit breaker which is practically dimensioned to 2-3 times the generator rated current. Electric fuses are utilized for protecting the local step-up transformer against short circuits. The protection of the collector feeder is simplified considering it as a radial distribution feeder using overcurrent protection. On the other hand, protecting the main collector bus, grid power transformer and the integration transmission system is well equipped with multi-function numerical relays. For off-shore farms, in particular, utilized submarine cables are protected with either current differential or distance relays. Also, overcurrent relays serve as a backup protection. Further details are available in [6]-[8].

Wind power is usually extracted by wind turbines using either fixed speed or variable speed regimes. The latter is distinctive with getting more energy for a specific wind speed, better aerodynamic efficiency, less mechanical stresses and reduced noise levels. The variable speed operation of wind turbines can be realized by driving DFIGs, Wound Rotor Synchronous Generator (WRSG) or Permanent Magnet Synchronous Generator (PMSG). Among of these types, DFIG represents the most popular one due to its overall lower cost. DFIGs are, therefore, emerging nowadays as the most preferred topology for recent wind farms. These machines basically consist of a slip-ring induction generator whose rotor is connected to the grid through a back-to-back converter. The major advantage of this design is the fact that the converter does not have to be rated for the machine's full power, but only for about a third of it.

Owing to the new policies of recent grid codes, wind farms are required to remain grid- connected during grid faults for a certain time so that they can directly contribute with active and reactive power to the grid. This leads to support the overall system stability [9], [10]. Different problems arise, however, for the associated generator/converter protection and control issues. During these voltage dips, the delivered active power to the grid by the farm is remarkably reduced. Consequently, the mechanical power exceeds the delivered active power resulting in increasing the rotor speed. Then, the control scheme of the DFIG variable-speed wind turbines embraces the wind turbine control for preventing over-speeding of the wind turbine and the control and protection of the power converter during and after the grid faults [11]-[13]. As a result, relay miss-coordination or miss-operation may occur due to the changes in fault current profile.

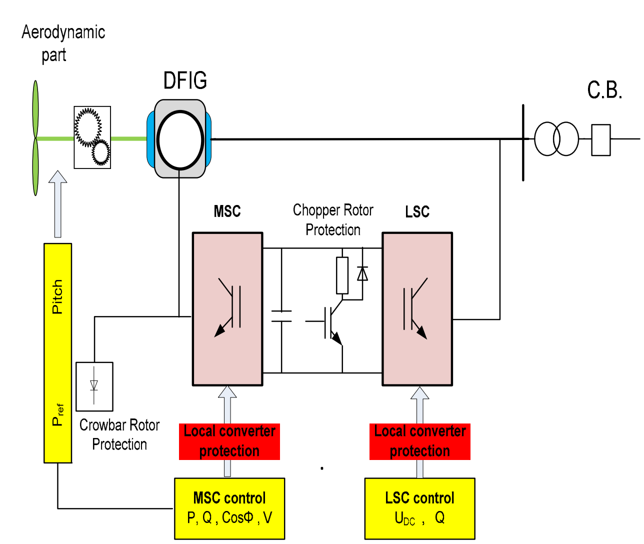

Fig. 1 Schematic of the DFIG wind conversion system

The aim of this paper is to investigate the impacts of the DFIG behavior on the utilized protective elements against grid faults. For this target, a detailed dynamic modeling of a 60 MW off-shore was developed using MATLAB. The farm, consisting of twelve 5MW DFIGs, was integrated in the 110 kV via a 70 km submarine cable. Details of the back-to-back converter, rotor protection circuitry and dedicated converter protective system are fully described in the developed model. This facilitates understanding the essence of the contribution of the overall DFIG system in grid fault conditions and the associated behavior of the common utilized protective elements.

II. Modeling Issues of the Developed Simulation

A. DFIG modeling

Fig. 1 demonstrated a schematic of a grid-integrated DFIG unit. The theoretical background for modeling induction machines is widely developed and is exhaustively dealt with numerous papers and textbooks. The construction of a DFIG is similar to a wound rotor induction machine comprising a three-phase stator winding and a three-phase rotor winding fed via slip rings. The rotor terminals are fed with a symmetrical three-phase voltage of variable frequency and amplitude. This voltage is supplied by a voltage source converter usually equipped with Insulated Gate Bipolar Transistors (IGBTs). As compared with SFIG machines, connecting the rotor via a four-quadrant ac-to-ac converter enables decoupled control of active and reactive power of the generator. The variable frequency rotor voltage permits the adjustment of the rotor speed to match the optimum operating point at any practical wind speed. The electrical part of the machine model was described with a fourth-order state space model, whereas its mechanical part was described with a first-order representation. Its associated dynamic model is derived in the synchronous reference frame using orthogonal direct (d) and quadrature (q) axis components. Further details are available in the relevant literatures [14], [15].

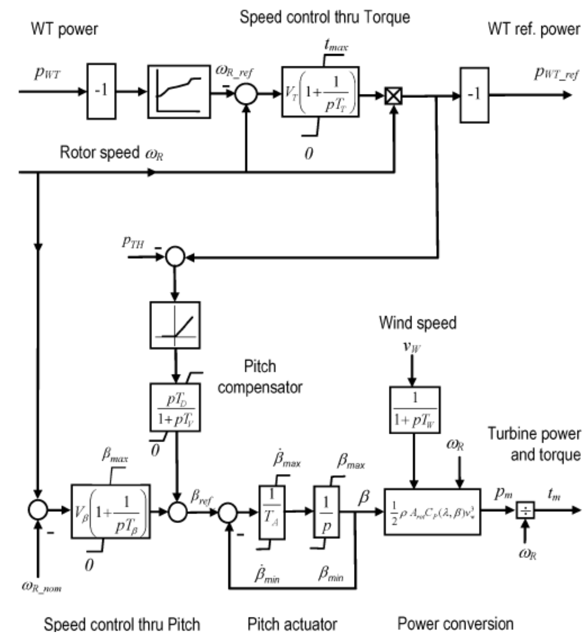

Fig. 2 Rotor speed and pitch angle control loops

B. Speed and pitch control loops for DFIGs

The available mechanical power (P_m) is computed as a function of the air density (ρ), the swept area (A), the wind speed (v_w), the power coefficient factor (c_p) and the pitch angle (β)as,

$$P_m = \frac{1}{2}\rho A_{rot} c_p(\lambda, \beta) v_w^3 \tag{1}$$

where the tip speed ratio (λ) is expressed as a function of the blade length (R) and the blade angular velocity (ω_b) as,

$$\lambda = \frac{\omega_b R}{v_w} \tag{2}$$

The control scheme shown in Fig. 2 has two outputs: the WT reference power to be passed on to the converter control and the pitch reference value. Both control channels have speed deviations as input. The torque controller tries to keep the speed at the optimum level corresponding to the actual WT power. The optimum speed is stored in a look-up table. When the speed exceeds the nominal speed, the pitch controller initiates pitching of the blades. Thus, the mechanical power generated by the wind will be reduced and subsequently also the shaft speed [14].

C. Rotor protection system

Rotor protection can be achieved via different scenarios. Deep voltage sags may trigger the crowbar (when utilized) to short-circuit the rotor terminals. Then, the machine behaves as an asynchronous single fed machine, whereas the DFIG is not controlled by the machine-side converter. The crowbar firing is triggered by the DC-voltage which rises due to the first rotor current peak. The IGBT's are usually stopped by its protection. The current and the energy continue to flow into the DC-link through the freewheeling diodes leading to a very fast voltage increase. When the crowbar is switched on, the converter is separated from the rotor circuits.

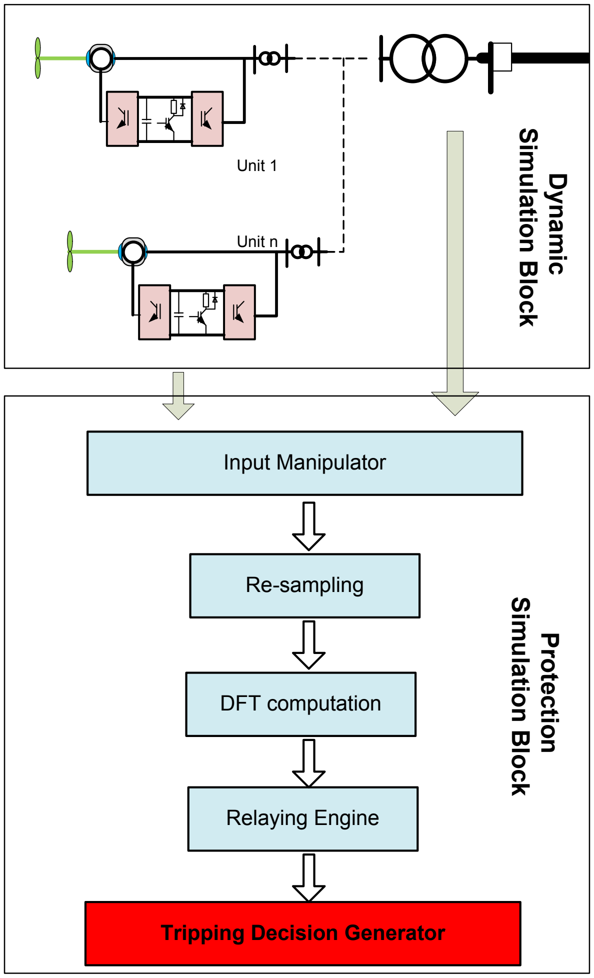

Fig. 3 Schematic of the testing procedure

Practically, crowbar mechanisms raise some problems. The crowbar ignition leads to the loss of the generator controllability through the machine side converter (MSC), since the machine rotor is short-circuited through the crowbar resistors and the MSC is blocked. During this time slot, the generator acts as a common single fed induction generator consuming reactive power which is not desirable. Another protection scenario is recently employed by utilizing a DC chopper to keep the dc-voltage within acceptable limits by short-circuiting the DC circuit through the chopper resistors. This consequently reduces the number of crowbar actions or even under circumstances prevents crowbar action at all.

Blocking the IGBTs during abnormal conditions is usually initiated as a result of either severe voltage sags or overcurrent conditions. For, voltage sags, IGBTs are blocked and are kept blocked as long as the positive sequence voltage at the generator terminals is lower than a pre-determined value (typically 15 % of the nominal voltage). For overcurrent conditions, the IGBTs are temporarily blocked for a pre-determined short period (typically 5 ms.), meanwhile the rotor current commutates to the free-wheeling diodes. These scenarios may affect the reaction of the related protective elements. These circumstances are investigated extensively as described in the following sections.

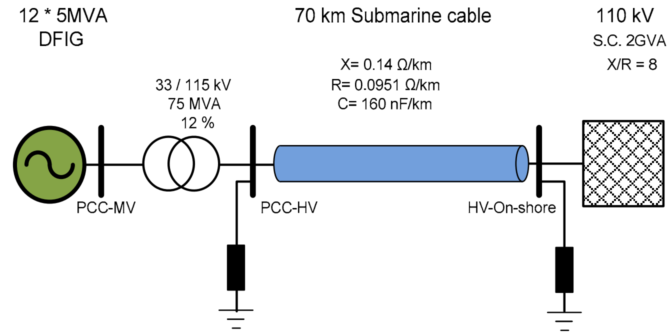

Fig. 4 Schematic of the selected wind farm

III. Description of the Testing Procedure

Fig. 3 illustrates a schematic of the employed testing procedure using MATLAB package. MATLAB was selected as the most common simulation platform with it huge library for dynamic simulation, user-friendly graphical interface and efficient programming environment. First, simulated test cases were prepared employing the dedicated Dynamic Simulation Block (DSB) developed in the MATLAB-Simulink environment. For each case, the associated voltage and current quantities were recorded at both cable ends for various locations in the simulated systems at both off-shore and on-shore sides respectively. For each DFIG unit, the related voltage and currents of the back-to-back converter in addition to the DC voltage and current were captured as well. These stored data are then fed to the dedicated Protection Simulation Block (PSB). The extracted signals were re-sampled to a sampling frequency of 1600 Hz to cope with the common profiles of real digital relay configuration. These data were then fed to the "Relay Engine" block via a "Discrete Fourier Transform" (DFT) digital filtering stage. The DFT filtering has been nominated amongst different digital filter routines, as the most dependable filter for practical relaying implementation. This filter is characterized with a maximum gain at the frequency of the fundamental and zero gain for the dc and integer higher order harmonics. The "Relaying Engine" block is adopted to compute the associated reaction of each selected protective function. Finally, the "Tripping Decision Generator" produced the resulted tripping indices.

IV. Simulation Test Examples

A. Selected wind farm example

Fig. 4 shows the structure of the simulated off-shore wind farm selected for this study. 12 DFIG generating units (with 5 MW for each one) are collected together at the 33 kV collection point. Collected power at the common coupling point is raised to 110 kV with a 75 MW, 33/115 kV step-up transformer. The off-shore wind farm is connected to the on-shore coupling point with a 70 km, 110 kV submarine cable with the seen parameters. Shunt reactors are connected at both cable ends for compensation purposes. Finally, the transferred power is integrated to the 110 kV grid.

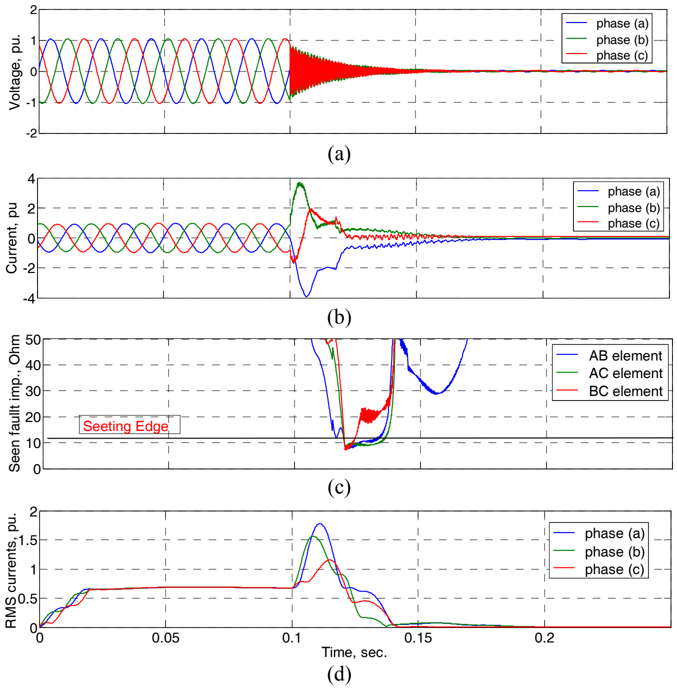

Fig. 5 Behavior of a three phase fault at the off-shore cable terminals.
(a) Three phase voltages (b) Three phase currents
(c) Response of phase distance relay at the off-shore side
(d) Three phase RMS currents at the off-shore side

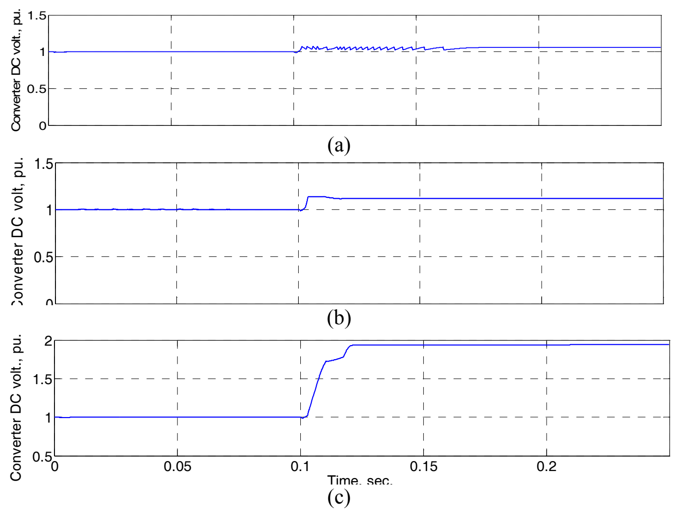

Fig. 6 Converter DC voltage for a three phase fault at the off-shore cable terminals.
(a) Rotor protection with chopper circuitry
(b) Rotor protection with crowbar circuitry
(c) Response without rotor protection

B. *Three phase fault conditions*

In spite of the scarce rates of three phase faults in transmission systems as compared with ground ones, they represent a special concern for wind farm networks. This may remarkably affect the performance of overcurrent and distance relaying functions, if they are utilized for protecting the interconnection transmission (cable) with wind farms. The instantaneous voltage and current quantities for a three phase fault occurring at the off-shore cable terminals were shown in Fig. 5(a) and (b). The fault was applied through small fault impedance (0.015 + j0.0792) to stabilize the numerical solution. The rapid drop of the fault current was due to switching off the converter IGBTs

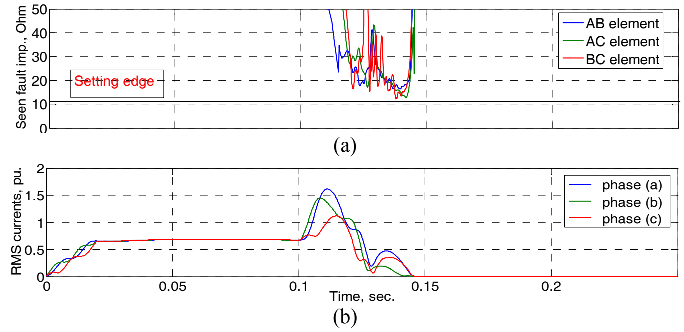

Fig. 7 Response to a three phase fault at the on-shore cable terminals.
(a) Response of phase distance relay at the off-shore side
(b) Three phase RMS currents at the off-shore side

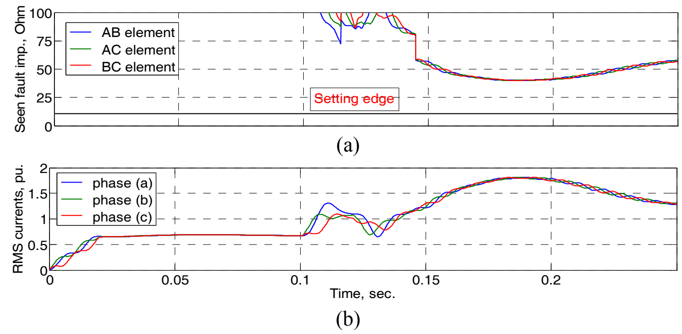

Fig. 8 Response to a three phase fault at the on-shore cable terminals measured at the HV-on-shore with 60% voltage sag.
(a) Response of phase distance relay at the off-shore side
(b) Three phase RMS currents at the off-shore side

as a result of the excessive voltage sag below its selected sitting. The response of the corresponding distance relaying elements was computed using the related fundamental components of seen voltages and currents at the off-shore cable terminals, where its zone-1 coverage was selected to cover the entire range of the interconnection cable. The response of the phase-fault distance elements was demonstrated in Fig. 5(c), where their operations were inhibited as a result of the fast switching-off of the converter IGBTs. On the other hand, the resulting fundamental RMS currents of the three phases were not sufficient to properly initiate the related overcurrent elements at the off-shore side as remarked from Fig. 5(d). For protecting the power electronic elements in the rotor circuitry, either crowbar or DC chopper elements can be utilized. The computed DC voltage for both aforementioned protection tools were demonstrated in Fig. 6 as compared with conventional DFIG operation (without rotor protection), where both crowbar and chopper elements reduced the resulting DC voltage effectively. On the other hand, the crowbar ignition leads to the loss of the generator controllability through the machine side converter (MSC). During this time slot the, generator acts as a common single fed induction generator and consumes reactive power, which is not desirable. Hence, DC chopper provides a better performance with reducing the DC-link voltage while keeping the DFIG operation during the fault period.

A similar response was obtained with the three phase faults at the on-shore cable terminals as shown in Fig. 7. The properness of the overcurrent and distance elements at the off-shore side can-not be realized. These problems were exaggerated for non-solid faults as demonstrated in Fig. 8 for a three phase fault with a 60% of voltage sag at the fault position.

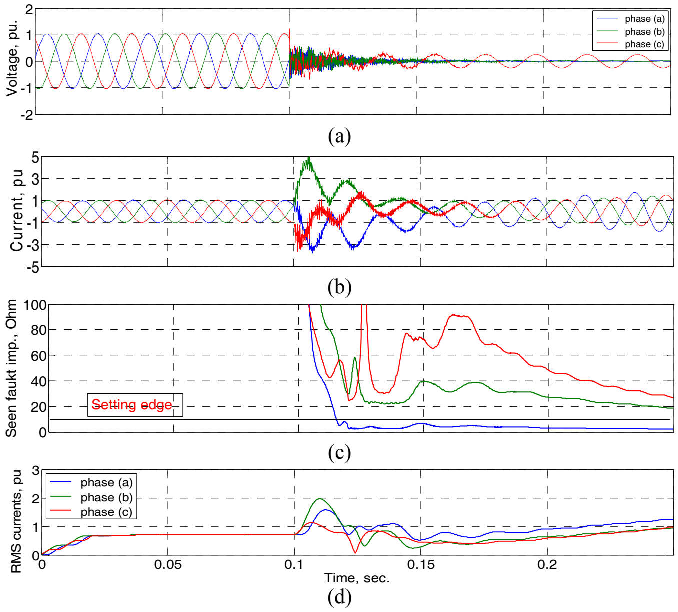

Fig. 9 Response to a phase-phase fault at the off-shore cable terminals.
(a) Three phase voltages (b) Three phase currents
(c) Response of phase distance relay at the off-shore side
(d) Three phase RMS currents at the off-shore side

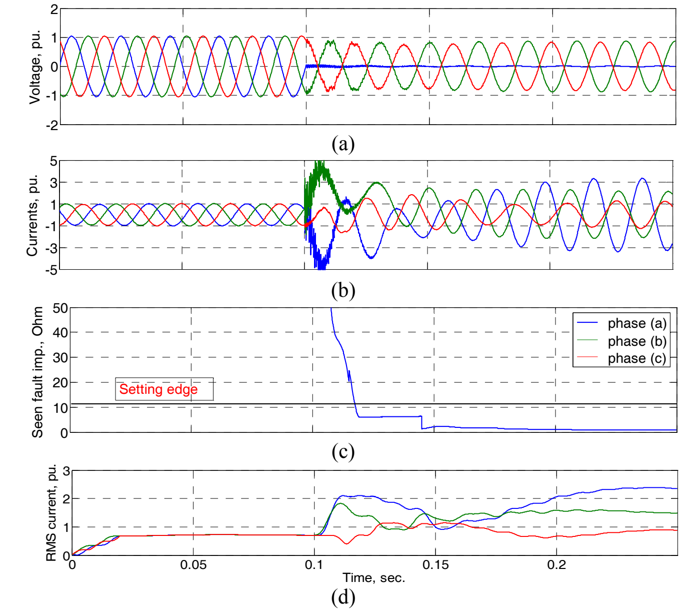

Fig. 11 Response to a phase-ground fault at the off-shore cable terminals.
(a) Three phase voltages (b) Three phase currents
(c) Response of phase distance relay at the off-shore side
(d) Three phase RMS currents at the off-shore side

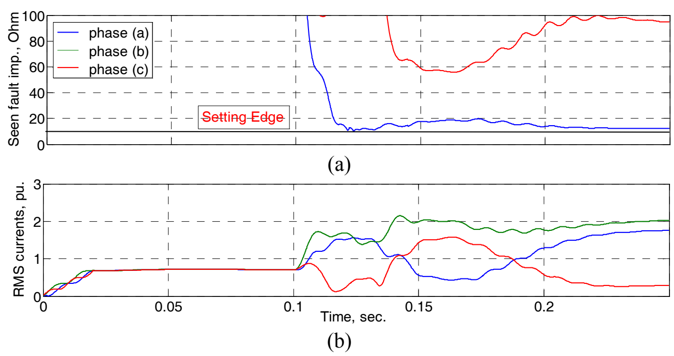

Fig. 10 Response to phase-phase fault at the on-shore cable terminals.
(a) Response of phase distance relay at the off-shore side
(b) Three phase RMS currents at the off-shore side

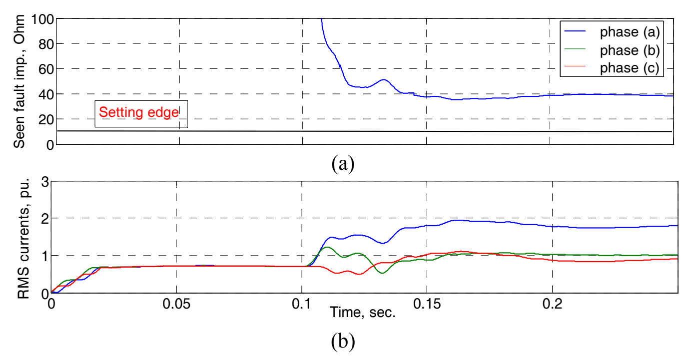

Fig. 12 Response to a phase-ground fault at the on-shore cable terminals.
(a) Response of phase distance relay at the off-shore side
(b) Three phase RMS currents at the off-shore side

C. Two phase fault conditions

Fig. 9 illustrates the system behavior for a solid phase-phase fault on the off-shore cable terminals. As remarked from the shown voltage and current quantities in Fig. 9(a) and (b), the resulting voltage reduction of the positive sequence voltage was not sufficient to block the IGBTs as experienced with three phase faults. On the other hand, the freewheeling diodes bypassed the fault currents during the temporarily overcurrent blocking of the IGBTs. Fortunately, one of the adopted phase fault distance elements at the off-shore side responded correctly to the fault as indicated in Fig. 9(c), whereas all related overcurrent elements surprisingly did not respond correctly to the fault condition as remarked n Fig. 9(d).

Repeating the fault at the on-shore cable terminals revealed the inability of the utilized distance elements at the off-shore side to detect such faults as shown in Fig. 10(a). On contrast, overcurrent elements raise a relatively better performance for this fault condition as compared with the latter one as described in Fig 10(b).

D. Phase-ground fault conditions

Similar responses were obtained for phase-ground faults with their related distance elements for fault locations at either off-shore or on-shore cable terminals. On the other hand, the related overcurrent elements at the off-shore side show a better performance for ground faults as compared with their corresponding ones for phase fault conditions. The results were summarized in Fig 11 and 12 respectively.

V. Conclusions

The DFIG represents nowadays the most common generator type for wind farms in either on-shore or off-shore turbines. Owing to the own dynamic behavior of the DFIG machines in addition to the embedded protective elements into their converter control system, the performance of their related protection schemes against grid faults may be perturbed. Moreover, utilizing submarine cables for integration purposes in off-shore farms in particular may raise other problems due to the different impedance characteristics and configuration possibilities of cable segments. These circumstances should be considered well for selecting and setting their protective elements. As remarked from the presented results in the paper, blocking the IGBTs of the rotor converter for severe voltage sags completely inhibit detecting the corresponding faults from the wind farm side using either distance or overcurrent elements. The response of both relaying elements was remarkably affected for other faulty conditions with lower voltage sag levels. On the other hands, pilot distance or current differential relays may represent solutions for eliminating the aforementioned problems. However, depending on the reliability of their communication systems is a drawback of such schemes. Also, cable capacitance and shunt reactors located into their protection zones may raise problems for both schemes as well. Careful selectivity including desensitizing the setting, restraining increasing or incorporating additional time delays may help to eliminate these effects. Further efforts need to be carried out for providing such farms with a proper and versatile protection schemes against these faults.

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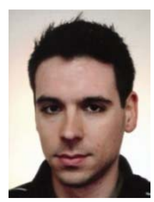
VII. Biography

Tamer A. Kawady (M'02) was born in Shebin El-kom, Egypt on Sept. 30, 1972. He received his B.Sc. (honors) and M.Sc. degrees in Electrical Engineering, Menoufiya University, Egypt, Ph.D. degree (excellent) from Technical University Darmstadt, Germany in 1995, 1999 and 2005 respectively. Dr. Kawady is currently an assistant professor at Menoufiya University, Egypt since April 2005. His interests are in digital protection, Power system simulation using the Electromagnetic Transient Program (EMTP) and Artificial Intelligence applications to power system protection.



Christian Feltes (1979) received his Dipl.-Ing. degree in electrical engineering from University of Duisburg-Essen/Germany in 2005. Since January 2006 he is doing his Ph.D. studies in the Department of Electrical Power Systems at the same University. His research interests are focused on wind energy generation, control, integration and dynamic interaction with electrical grid. He is student member of IEEE.

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Abdel-Maksoud I. Taalab (M'99–SM'03) received his B.Sc degrees in 1969, in Electrical–Engineering from Menoufiya University, Egypt, M.Sc. and Ph.D degrees from Manchester University (UMIST), U.K., in 1978, and 1982, respectively. In the same year of his graduation, he was appointed as an assistant professor at the Menoufiya University. He joined GEC Company in 1982. He is now a full Professor at the department of Electrical Engineering, Faculty of Engineering and vice dean of the Desert Environment Institute, Menoufiya University. His interests are in hvdc transmission systems, power system protection, and power electronics.