MITIGATION OF FAULTS IN GRID-CONNECTED SINGLE MACHINE BRUSHLESS DOUBLE-FED INDUCTION GENERATOR

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ABSTRACT

The effect of three-phase grid fault on the performance of a wind-driven single machine-brushless double fed induction generator (SM-BDFIG) is investigated. The fault-ride-through (FRT) of the grid-connected SM-BDFIG is then studied when installing a Static Synchronous Compensator (STATCOM) between the grid and the generator. Recovery from the grid fault before installing the STATCOM is studied and compared to the generation system recovery with installed STATCOM. The performances of the stator and rotor currents, stator and rotor voltages, electric torque, active power, reactive power, and battery pack voltage and current are presented for both cases. The total harmonic distortion (THD) of stator and rotor voltages and currents are also presented and compared. Results proved the faster recovery from grid faults, the continuity of currents and voltages, and the continuity of active power supplied to the grid when installing the STATCOM. However, slightly higher THD took place in the stator and rotor voltages and currents due to the switching pattern of the STATCOM.

INTRODUCTION

Wind energy conversion system "WECS" are expected to supply11.7%-12.6% of global electricity by 2022. The main trend is to use doubly fed induction generator (DFIG) in recently manufactured WECS, due to the significant reduction in the rating of the associated converter, which was proved to be not more than 10% of the DFIG rating [1]. The benefits of DFIG are undeniable; however, the presence of copper slip rings and carbon brushes to transfer electrical energy to/from the rotating winding of the generator from/to the stationary electronic converter creates the need for frequent inspection and maintenance. The need for frequent maintenance due to the presence of brushes increases sharply the operating costs of WECS especially in remote areas and offshore installations, [2, 3].

In a previous paper by the authors, a new design for a brushless double fed induction generator BDFIM was proposed and published in [4]. Its dynamic response was investigated in another paper [5]. As shown in Fig.(1), the single machine brushless doubly fed induction generator (SM-BDFIG) is composed of three main components; a regular three phase wound rotor induction machine, a power electronic converter, and a pack of rechargeable Lithium-ion batteries. The converter is mounted on the outer surface of a web reinforced hollow metallic (aluminum) or fiber glass cylinder. The battery packs are embedded in the inner part of the cylinder between the webs. The hollow cylinder is mechanically coupled with the induction machine on the same shaft. The battery pack's two output terminals are electrically connected to dc terminals of back to back converter. The ac terminals of the converter are connected to the rotor winding of the induction machine. Since all the three main components of the SM-BDFIG are mounted on the same shaft, i.e. all rotate with the same angular speed, then the connections between them are rigid electrical connections without any sliding contacts, slip rings, or brushes.

When the SM-BDFIG operates in the super-synchronous speed range, the excess rotor slip power is converted to dc power which is used to charge the batteries.

One of the most important problems related to integration of wind generators to grid is the disconnection of the generators in the case of a decrease of network voltage under a certain value, i.e. voltage dip. Many researchers dealt with grid faults ride through (FRT) in generation systems involving DFIG using different techniques [6-7]. However, FRT in SM-BDFIG was not investigated. The behavior of this newly proposed machine during grid fault is expected to differ from the response of DFIG because its rotor is not connected to the grid, but to the battery pack as described above. Hence it is important to investigate the performance of the SM-BDFIG during grid faults and methods to mitigate the fault effect.

In this paper mitigating the effect of ground faults on a grid-connected SM-BDFIG operating in the super-synchronous speed range is proposed by connecting a STATCOM between its stator terminals and the grid. Recovery from the grid fault before installing the STATCOM is studied and compared to the generation system recovery with installed STATCOM. The performances of the stator and rotor currents, stator and rotor voltages, electric torque, active power, reactive power, and battery pack voltage and current are presented for both cases. The THD of stator and rotor voltages and currents are also presented and compared. Results proved the faster recovery from grid faults, the continuity of currents and voltages, and the lower voltage and current transient peaks when installing the STATCOM. However, slightly higher THD took place in the stator and rotor voltages and currents due to the switching pattern of the STATCOM.

BEHAVIOR OF SM-BDFIG DURING GRID FAULTS

The abrupt drop of the grid voltage causes a dc component on the stator flux resulting in high rotor-induced voltages**.** This gives rise to high rotor currents, and which damages the rotor converter. Conventionally, a resistive network called crowbar is connected to the rotor circuit, and the rotor side converter (RSC) is disabled. But the machine draws a high short circuit current when the crowbar is activated [8], resulting in a large amount of reactive power drawn from the power network.
Other proposed solutions for fault ride-through of a DFIG utilized a series dynamic resistance in the rotor in or in the stator or Dynamic voltage restorer (DVR) [9]. Since injecting reactive power is essential for quick voltage restoration at low voltages, a STATCOM is an effective solution for voltage dips and ground faults for injecting reactive current into the grid to assist the grid voltage recovery [10].

MODELING THE GRID-CONNECTED WECS WITH SM-BDFIG

The proposed system is a grid-connected SM-BDFIG operated by a horizontal axis wind turbine. A STATCOM is connected between the grid and the stator to mitigate the effects of grid faults.

SM-BDFIG MODEL

The SM_BDFIG voltage equations in the d-q synchronously rotating axes are given by:

$$\begin{aligned} v_{sd} &= R_s i_{sd} + \frac{d\lambda_{sd}}{dt} - \omega_s \lambda_{sq} \\ v_{sq} &= R_s i_{sq} + \frac{d\lambda_{sq}}{dt} + \omega_s \lambda_{sd} \\ v_{rd} &= R_r i_{rd} + \frac{d\lambda_{rd}}{dt} - \omega_r \lambda_{rq} \\ v_{rq} &= R_r i_{rq} + \frac{d\lambda_{rq}}{dt} + \omega_r \lambda_{rd} \end{aligned} \quad (1)$$

Where, the stator and rotor magnetic fluxes λ are given by:

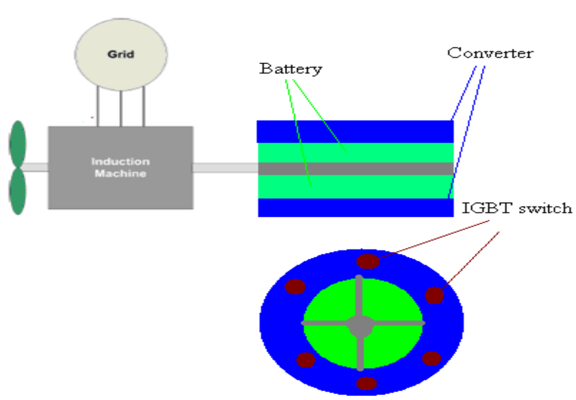

Fig. 1, Schematic of SM-BDFIG

$$\begin{aligned} \lambda_{sd} &= (L_{ls} + L_m) i_{sd} + L_m i_{rd} \\ \lambda_{sq} &= (L_{ls} + L_m) i_{sq} + L_m i_{rq} \\ \lambda_{rd} &= (L_{lr} + L_m) i_{rd} + L_m i_{sd} \\ \lambda_{rq} &= (L_{lr} + L_m) i_{rq} + L_m i_{sq} \end{aligned} \quad (2)$$

LI-ION BATTERY MODEL

The charging equation for a Lithium-ion battery is modeled in Matlab software package as:

a- Discharge Model ($i^* > 0$)

$$f_1(it, i^*, i) = E_o + K\frac{Q}{Q-it}i^* - K\frac{Q}{Q-it}it + Ae^{-B^*it} \quad (3)$$

b- Charge Model ($i^* < 0$)

$$f_2(it, i^*, i) = E_o + K\frac{Q}{it-0.1Q}i^* - K\frac{Q}{Q-it}it + Ae^{-B^*it} \quad (4)$$

Where: E_o = Constant voltage (V)
Exp(s) = Exponential zone dynamics (V)
K = Polarization constant $(Ah)^{-1}$ or Polarization resistance (Ohms)
i^* = Low frequency current dynamics (A)
i = Battery current (A)
it = Extracted capacity (Ah)
Q = Maximum battery capacity (Ah)
A= exponential voltage (V)
B= exponential capacity $(Ah)^{-1}$

STATCOM

STATCOM consists of a shunt connected VSC, a DC energy source, and a coupling transformer. If the system voltage is less than the voltage at the STATCOM terminals, the STATCOM acts as a capacitor and reactive power is injected from the STATCOM to the system. On the other hand, if the system voltage is higher than the voltage at the STATCOM terminal, the STATCOM behaves as an inductor and the reactive power transfers from the system to the STATCOM.

CONTROL STRATEGY

The control scheme aims to supply the stator with constant voltage magnitude during grid faults to keep generator connected and to return to normal operation conditions after the fault.

SIMULATION RESULTS

The performance of the SM-BDFIG during grid fault is investigated without the STATCOM and when connecting the STATCOM. A speed of 1.04 of synchronous speed is assumed for simulation. Figure 2 shows the grid voltage with a 100 msec. three phase ground fault. Figures 3a and 3b display the single phase stator voltage during grid fault with and without the STATCOM respectively. It is clear that the STATCOM supplies stator voltage during the ground fault but with smaller magnitude. The presence of stator voltage during the fault prevents the generator speed from increasing dramatically due to the continuous input mechanical power from the wind turbine.

The THD of stator voltage during normal operation is shown in Fig. 4, while Fig. 5 illustrates a slight increase in the THD of the stator voltage during grid fault than its value during normal operation (from 10.88% to 10.98%) when installing the STATCOM, which is due to switching pattern of the VSC.

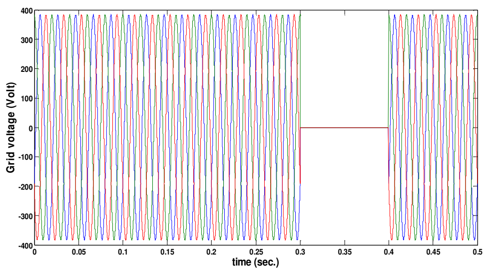

Fig. 2, Grid voltage with ground fault

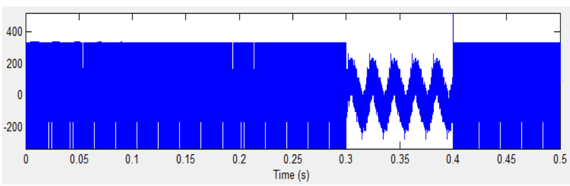

Fig. 3 (a) Stator voltage with STATCOM

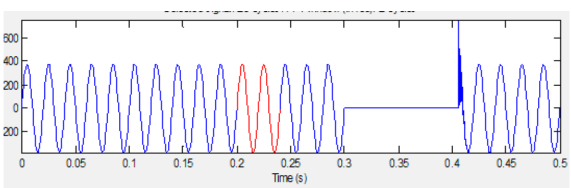

Fig. 3 (b) Stator voltage without STATCOM

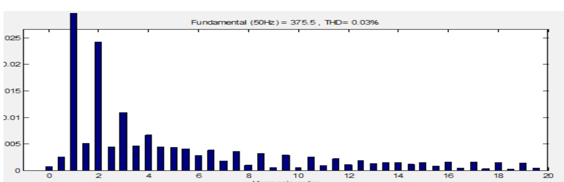

Fig. 4, THD of stator voltage during normal operation

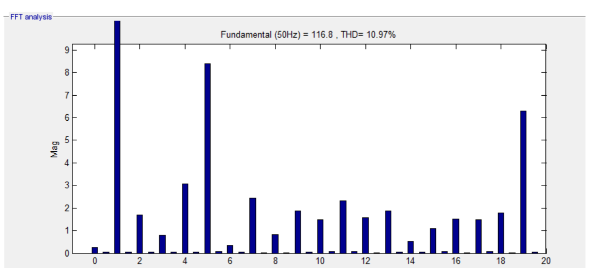

Fig. 5, THD of stator voltage with STATCOM during grid fault

Figures 6a and 6b display the single phase stator current during grid fault with and without the STATCOM respectively. It is clear that the STATCOM allows the continuity of the stator current during the ground fault but with smaller magnitude. The THD of stator current during normal operation is shown in Fig. 7, while Fig. 8 illustrates the THD of the stator current during grid fault. A slight increase in the THD of the stator current during grid fault than its value during normal operation (from 1.55% to 1.98%) takes place. This is due to the switching of the VSC- IGBTs. However, this increase is substituted by the continuity of the stator current during the ground faults, avoiding the disconnection of the generator.

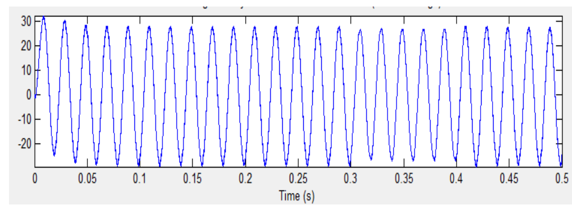

Fig. 6 (a) stator current with STATCOM

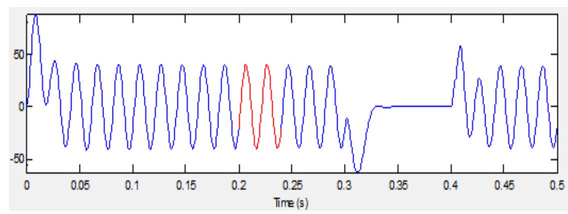

Fig. 6 (b) stator current without STATCOM

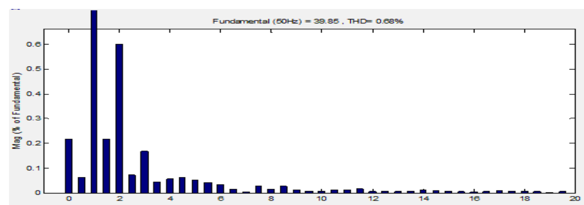

Fig. 7, THDs of stator current during normal operation

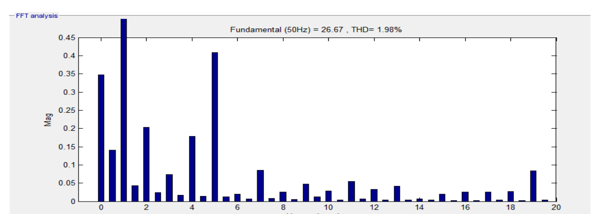

Fig. 8, THD of stator current with STATCOM during grid fault

Figures 9a and 9b display the single phase rotor voltage during grid fault with and without the STATCOM respectively. It is clear that the STATCOM leads to lower magnitude of the rotor voltage with lower transient peaks, hence protecting the rotor converter. The THDs of rotor voltage during normal operation is shown in Fig. 10, while Fig.11 demonstrates the THD of the rotor voltage during grid fault. These THDs are nearly the same, demonstrating the decreased effect of the STATCOM switching pattern on the rotor circuit due to air gap. This proves the effect of the device in mitigating the consequences of ground fault on the rotor voltage.

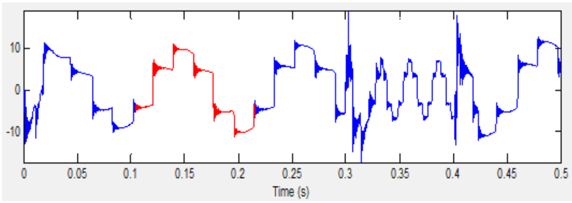

Fig. 9 (a) Rotor voltage with STATCOM

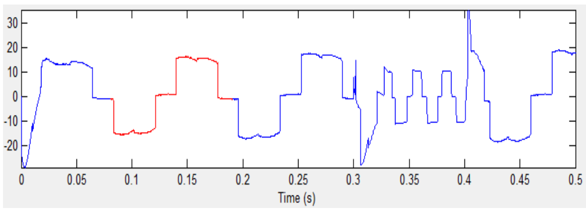

Fig. 9 (b) Rotor voltage without STATCOM

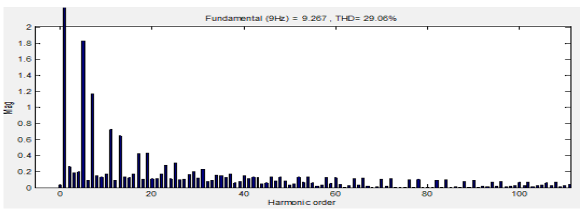

Fig. 10, THD of rotor voltage during normal operation

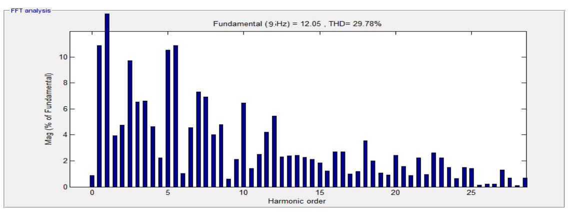

Fig. 11, THD of rotor voltage with STATCOM during grid fault

Figures 12a and 12b show the single phase rotor current during grid fault with and without the STATCOM. The decrease in the rotor current with installed STATCOM prevents damaging of the rotor converter. However a change from sinusoidal to a nearly trapezoidal current shape took place. Figure 13 demonstrates the rotor current THD during normal operation, while Fig. 14 demonstrates the rotor current THD during fault with the STATCOM. An increase in the THD of the rotor current during grid fault than its value during normal operation (from 12.83% to 14.94%) occurs. This increase is due to the change from sinusoidal to trapezoidal current waveform. However the increase in the current THD is compromised by the decrease in the rotor current magnitude, thus protecting the rotor converter from damage due to the ground fault.

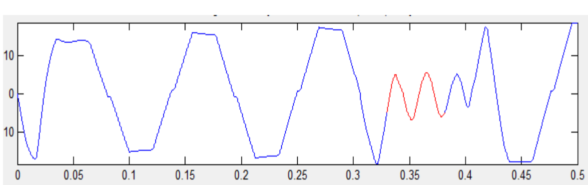

Fig. 12 (a) rotor current with STATCOM

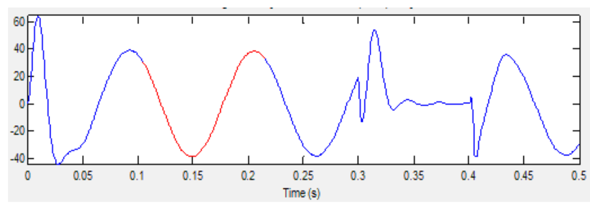

Fig. 12 (b) rotor current without STATCOM

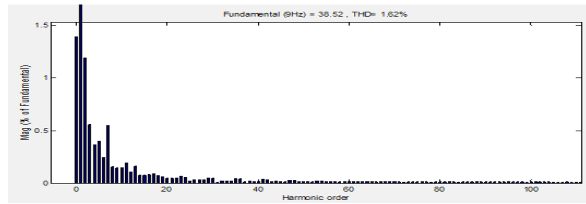

Fig. 13, The THD of rotor current during normal operation

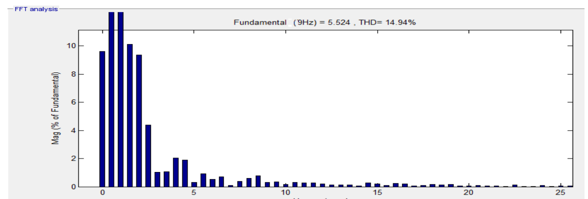

Fig. 14, THD of rotor current during grid fault

Figures 15a and 15b demonstrate the stator active and reactive power and the rotor active and reactive power with and without the STATCOM installation respectively. The continuous active power flow can be used to charge the battery supplying the VSC of the STATCOM during the grid fault.

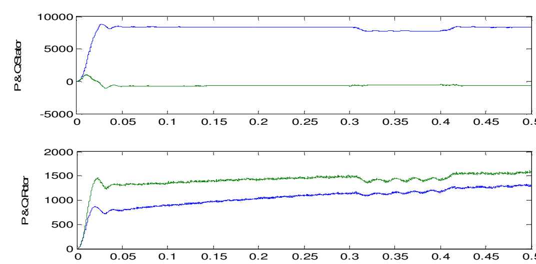

Fig. 15 (a) active & reactive power of stator*& rotor with STATCOM*

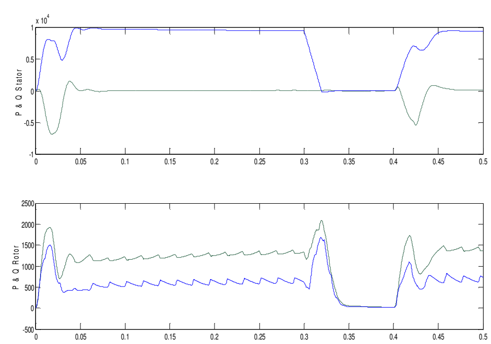

Fig. 15 (b) active & reactive power of stator & rotor without STATCOM.

The rotor over current, due to the ground fault, causes a sudden increase of the electric torque, typically reaching 2 to 3 times its rated value in the system without the STATCOM, as demonstrated in Figure 16 (b). While the electric torque during fault is within acceptable limits when installing the STATCOM as demonstrated in Fig. 16 (a). The battery voltage and current are shown in Figs. 17, while installing the STATCOM. The grid fault resulted in considerable ripples in battery voltage and current during its occurrence. However, the charging process continued.

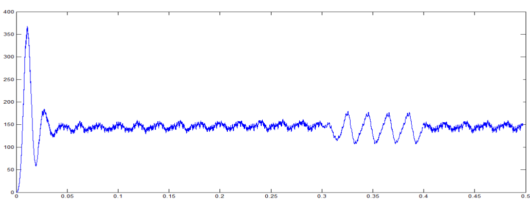

Fig. 16 (a) Electromagnetic Torque with STATCOM

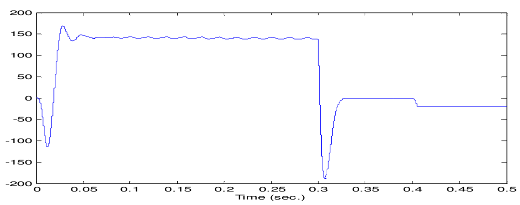

Fig. 18 (b) Electromagnetic Torque without STATCOM

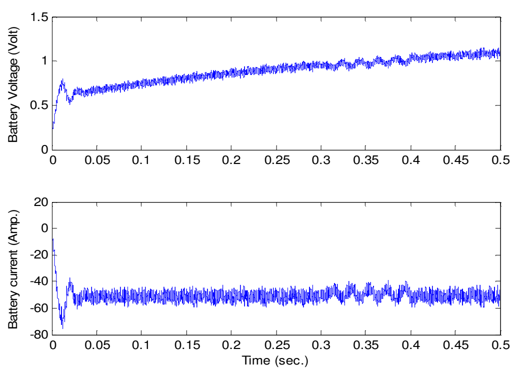

Fig. 19, Battery voltage and current

CONCLUSION

The three phase fault mitigation of a grid connected new design of a single machine brushless double-fed induction generator (SM-BDFIG) is investigated using STATCOM. A comparison between the performance of the SM-BDFIG with and without the STATCOM is presented, showing the importance of the device in improving the system performance during faults. The SM-BDFIG is driven by a wind turbine at super-synchronous speed, supplying the grid with active power and charging a battery pack via a rectifier connected to the rotor circuit. The PI-controlled STATCOM decreased the effect of the ground fault on the transients of the stator and rotor voltages and currents and maintained the battery charging process. The grid fault caused a tolerable increase in the THD of currents and voltages with the installed STATCOM due to the switching of the VSC. The torque increase due to the grid fault is tolerable when installing the STATCOM and is much lower than its magnitude without the STATCOM. The battery charging was continuous during the grid fault with low ripples.

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