Enhancing LVRT Capability of DFIG-Based Wind Turbine Systems with SMES and STATCOM

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الملخص:

في الوقت الحاضر، شهدت تقنيات الطاقة المتجددة مثل توربينات الرياح نموًا سريعًا في العالم. تُستخدم المولدات الحثية ذات التغذية المزدوجة (DFIG) حاليًا على نطاق واسع في محطات طاقة الرياح متغيرة السرعة نظرًا لمزاياها الفائقة التي تشمل تقليل مقننات المغير، تقليل المفاقيد وتحسين الكفاءة، التنفيذ السهل لعملية تصحيح عامل القدرة، التشغيل متغير السرعة والقدرة على التحكم في الطاقة الفعالة والتفاعلية. من ناحية أخرى، تمثل حساسية المولدات الحثية ذات التغذية المزدوجة لاضطرابات الشبكة، خاصة بالنسبة لانخفاض الجهد، العيب الرئيسي لهذا النوع من المولدات. في هذا البحث، تم تطبيق وحدة تخزين الطاقة في المجال المغناطيسي لموصل فائقة التوصيل (SMES) والمعوض المتزامن الثابت (STATCOM)لتحسين (LVRT) لتوربينات الرياح متغيرة السرعة تعمل بمولد ذو التغذية المزدوجة (DFIG). تم استخدام كود الشبكة الالمانية لاختبار الفاعلية من الطرقتين المقترحتين لتحسين (LVRT) وإبقاء التوربينات موصلة على الشبكة خلال فترة العطل. تم بناء ومحاكاة النظام المدروس باستخدام Matlab software.

Abstract:

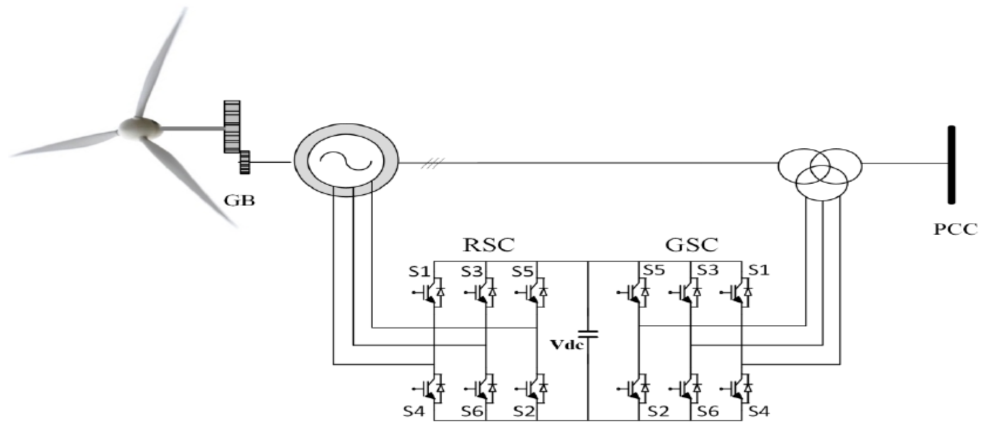
Nowadays, renewable energy technologies such as a wind turbine have experienced a rapid growth in the world. Doubly Fed Induction Generators (DFIGs) are extensively used in variable speed wind power plants due to their advantages that include reduced converter rating, reduced losses with an improved efficiency, easy implementation of power factor correction schemes, variable speed operation and four quadrants active and reactive power control capabilities. On the other hand, DFIG sensitivity to grid disturbances, especially for the voltage dip represents the main disadvantage of the equipment. In this paper, an application of superconducting magnetic energy storage (SMES) unit and Static Synchronous Compensator (STATCOM) are implemented to enhance the low voltage ride-through (LVRT) of DFIG-based wind energy conversion systems (WECS). German grid code is used to examine the capability of the two technologies for improving the low voltage ride through (LVRT) of the DFIG to maintain the wind turbine connection to the grid through fault durations. Simulation is carried out using Simulink / Matlab softwareز

Keywords: DFIG, SMES, STATCOM, voltage sag, grid code.

I. INTRODUCTION

Conventional energy sources such as natural gas, oil, and coal are considered among the main sources of global warming. This was coincided with increasing the penetration of renewable energy sources in order to decrease global warming and encourage carbon free technologies. Among different renewable energy sources, wind energy has the major portion due to their relatively low cost. Furthermore, they have low maintenance requirements and clean operation. Therefore, wind energy can be built on a large scale with future economic benefits (Khamaira, Abu-Siada et al. 2014). The global installed wind power capacity worldwide has significantly increased from 539 GW at the end of the year 2017 to 650.8 GW by the end of the year 2019, and it is expected to be nearly 1000 GW by the year 2024 (GWEC 2017). Currently, doubly fed induction generator (DFIG) is the most commonly used machine for wind turbines over 1 MW (Khamaira, Abu-Siada et al. 2014). DFIG based wind energy conversion system (WECS) is gaining popularity because of its superior advantages over other wind turbine generator concepts. DFIG application in large WECS reaching 55% of the worldwide total wind capacity during the year 2012 (Morren and De Haan 2005, Mohseni, Islam et al. 2010). A generic model of a DFIG is shown in figure 1. Rotor side converter (RSC) and grid side converter (GSC) interface the DFIG with the grid. Both converters use forced commutated power electronic switches such as insulated gate bipolar transistors (IGBT) to convert from AC to DC and vice versa. A capacitor connected to the DC side of the converter acts as a DC voltage source (Li and Haskew 2007, Qin, Li et al. 2020).

Figure 1: Generic model of a DFIG



At early stages of a DFIG application, it was permissible to disconnect the wind turbines during several grid faults to protect it from being damaged. Nowadays, and due to the substantial portion of load that wind farms contribute, transmission line operators want the wind turbine to continue connected to support the grid during grid disturbance events. This has run to the creation of strict grid codes that wind turbine generator must meet to keep its linking to the grid. While many papers can be found in the literature investigating various approaches to compensate WECS reactive power during fault events by mainly connecting a flexible AC transmission system (FACTS) device such as static synchronous compensator (STATCOM) to the PCC (Qiao, Venayagamoorthy et al. 2009, Yong, Jian et al. 2009, Alharbi, Yunus et al. 2011, Ezzat, Benbouzid et al. 2013, Bharti, Dewangan et al. 2016), a few publications considered the compensation of active power as well (Ferdosian, Abdi et al. 2013, Alharbi and Abu-Siada 2015). Superconducting magnetic energy storage (SMES) unit is a FACTS device that can compensate both active and reactive power smoothly, independently and rapidly in four quadrant operation. Applications of SMES unit for enhancing the dynamic performance of DFIG-based WECS have been investigated in the literature (Ali, Park et al. 2009, Shi, Tang et al. 2011, Elshiekh, Mansour et al. 2012, Guo, Xiao et al. 2012, Khamaira, Yunus et al. 2013, Khamaira, Abu-Siada et al. 2014, Handayani, Abu-Siada et al. 2020, Yunus, Abu-Siada et al. 2020).

The main contribution of this paper is the presentation of an application for SMES unit and STATCOM for enhancing the low voltage ride-through (LVRT) of DFIG-based wind energy conversion systems (WECS) during voltage sag at the grid side.

II. SYSTEM UNDER STUDY

Figure 2: System under study

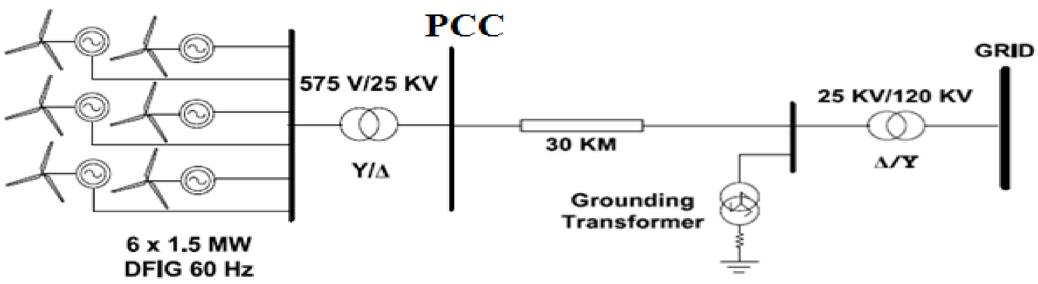
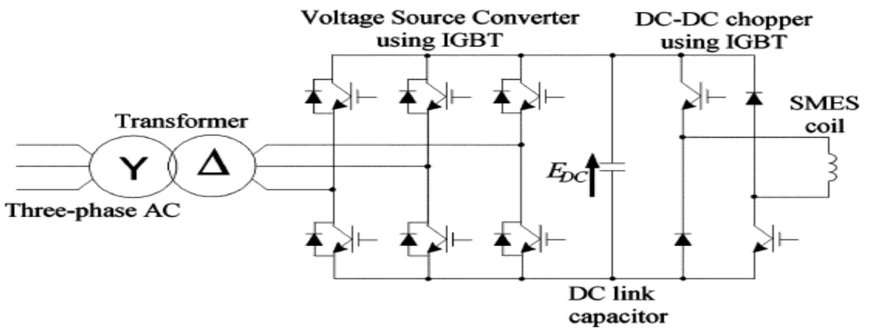


Figure 2 shows the studied system, which consists of six 1.5 MW DFIGs connected to the ac grid at the PCC. The grid that is represented by an ideal three-phase voltage source of constant frequency is connected to the wind turbines via 30km transmission line and step-up transformer. The proposed SMES unit and STATCOM are connected to the PCC via a coupling transformer.

III. SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES)

Figure 3 shows the typical configuration of the SMES unit, which consists of a Wye-Delta transformer, a six-pulse width modulation (PWM) rectifier/inverter using insulated gate bipolar transistor (IGBT), a two-quadrant dc-dc chopper using IGBT, and a superconducting coil. The PWM converter and the dc-dc chopper are linked by a dc link capacitor. This configuration makes SMES highly efficient in storing electricity with typical efficiency in the range of 95%–98%. Other advantages of the SMES unit include very quick response and possibilities for high-power application.

Figure 3: Typical configuration of SMES unit



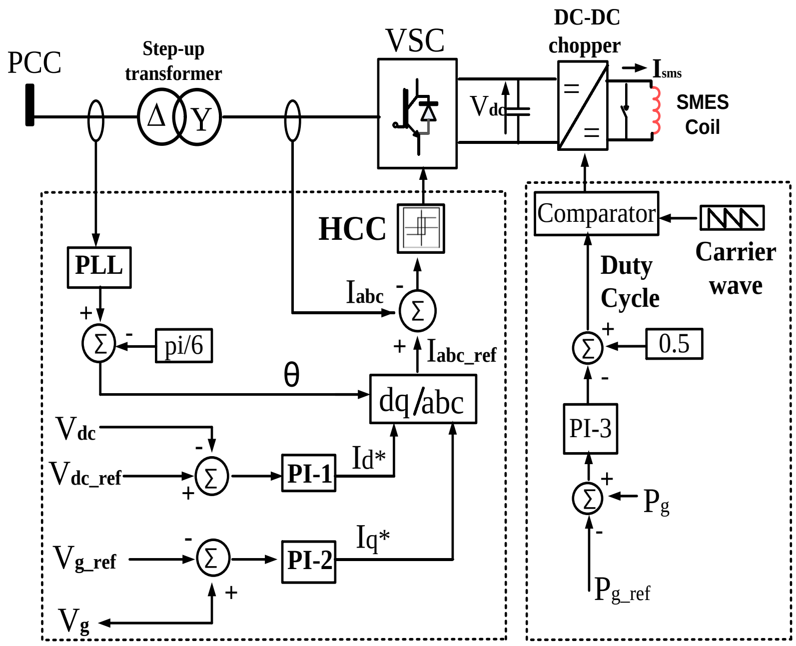
The stored energy in the SMES coil can be calculated as

$$E_{sms} = 0.5\ (I^2_{sms}\ L_{sms}) \qquad (1)$$

Where E_{sms}, L_{sms} and I_{sms} are the stored energy, superconductor inductance, and the dc current through the SMES coil respectively.

To control the power exchange between SMES unit and the grid, Hysteresis Current Control (HCC) is chosen based on its advantages such as simplicity, fast dynamic response, and insensitivity to load parameter variations. As can be seen in the figure 4, the basic implementation of the HCC is based on deriving the converter switching signals from the comparison of the actual phase currents with a fixed tolerance band around the reference current associated with that phase. The HCC is comparing the three-phase line currents (I_{abc}) with the reference currents (I_{abc_ref}), which is dictated by the I_d^* and I_q^* references. The values of I_d^* and I_q^* are generated through conventional proportional integral (PI) controllers based on the error values of V_{dc} and V_g. The value of I_d^* and I_q^* is converted through Park transformation ($d_{q0\text{-}abc}$) to produce the reference current (I_{abc_ref}).

Figure 4: Control system of SMES unit



The superconducting coil is charged or discharged by adjusting the average voltage, V_{sms_av}, across the coil which is determined by the duty cycle (D) of the two quadrant DC-DC chopper. To determine the value of the duty cycle of the DC-DC chopper, the power generation is used as input to a proportional integral (PI) controller. Based on this concept, the control system of a DC-DC chopper is constructed as shown in figure 4. Under normal operating condition, duty cycle is equal to 0.5 and there is no power exchange between the SMES unit and the grid. During grid disturbance events that call for power support such as voltage dips, the PI controller acts to adapt the duty cycle to be in the range of 0 to 0.5 and the stored energy in the coil will be transferred to the grid (Discharging mode). The charging mode of the SMES coil takes place when duty cycleis within the range of 0.5 to 1. The relation between V_{sms} and V_{dc_sms} can be written as

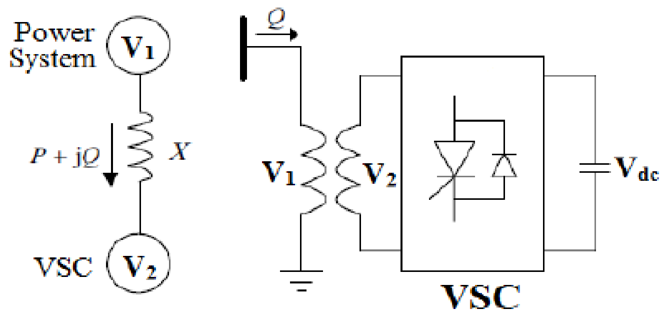
$$V_{sms\_av} = (1\text{-}2D)\ V_{dc\_av} \qquad (2)$$

Where V_{sms_av} is the average voltage across the SMES coil, D is duty cycle, and V_{dc_av} is the average voltage across the dc- link capacitor of the SMES configuration

IV. STATIC SYNCHRONOUS COMPENSATOR (STATCOM)

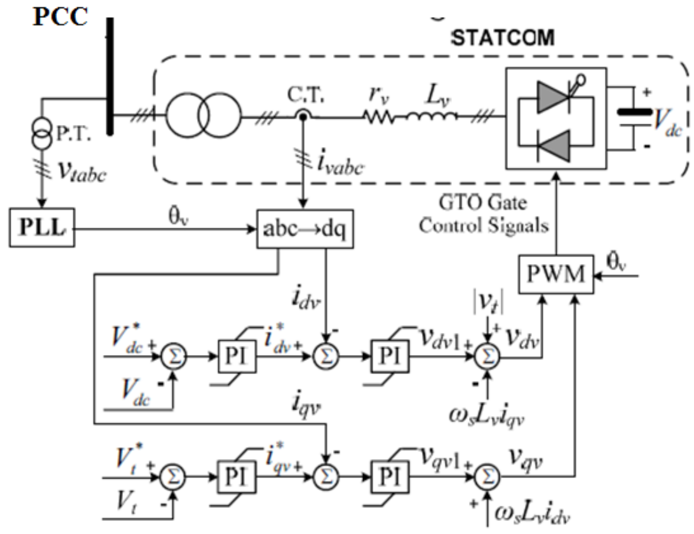
A STATCOM is a voltage-source converter (VSC) that changes the DC voltage input to an output alternating voltage for compensating the active and reactive power needed by the system. The STATCOM is a shunt-connected device of FACTS family using power electronics to control power flow and improve transient stability on power grid. The STATCOM regulates voltage at its terminal by controlling the amount of reactive power injected into or absorbed from the power system. When the system voltage is low, the STATCOM generates reactive power (STATCOM capacitive) and when the system voltage is high, it absorbs reactive power (STATCOM inductive) Mohamed, S. A., et al. 2018. A STATCOM circuit diagram is shown in Fig. 5 (a), which is seen as an adjustable voltage source behind a reactance. It means that the capacitor banks and shunt reactors are not needed for reactive-power generation and absorption; thereby it gives the STATCOM a compact design. The coupling transformer plays two different roles. First, it connects the converter to the high voltage power system. Secondly, the transformer inductance ensures that DC capacitor is not short-circuited and discharged rapidly. The overall control scheme of the STATCOM figure 5 (b) is presented in Sharath and Burthi 2019.

Figure 5: (a) STATCOM circuit diagram



V_1 is the bus terminal voltage, V_2 is the output voltage of STATCOM, V_{dc} is the DC capacitor side voltage, X_L is the inductive reactance, and δ is the phase angle of V_1 with respect to V_2.

Figure 5 (b): Overall control scheme of the STATCOM



General mathematical equation of STATCOM for active or real power, reactive power and STATCOM output voltage can be expressed as follows:

$$P = \frac{(V_1 . V_2)\sin\delta}{X_l} \qquad (3)$$

$$Q = \frac{V_1 . (V_1 - V_2 \cos \delta)}{X_l} \qquad (4)$$

The following operation modes of STATCOM are given:

1- Normal excited mode of operation ($V_2 = V_1$):

If the output voltage is equal to the AC system voltage, then the reactive power exchange is zero.

2- Over exited mode of operation ($V_2 \geq V_1$):

If the amplitude of the output voltage is increased above that of the AC system voltage, then the current flows through the reactance from the STATCOM to the AC system and the STATCOM generates reactive (capacitive) power for the AC system.

3- Under exited mode of operation ($V_2 \leq V_1$):

If the amplitude of the output voltage is decreased below that of the AC system, then the reactive current flows from the AC system to STATCOM, and the STATCOM absorbs the reactive (inductive) power for the AC system (Fazli, Shafighi et al. 2010).

V.SIMULATION RESULTS

In order to evaluate the system performance under the two proposed techniques, the system under study is simulated. In this simulation, there are three cases. First is without the connection of the two proposed techniques, and second is with the connection of the SMES unit and in the third case, with the connection of the STATCOM, both are placed at the PCC. The system performance in the three cases are observed when a voltage sag is applied at the PCC at t = 5s and is assumed to last for 50 ms. Figures 6 through 11 show the performance of the studied system. The voltage profile at the PCC is shown in figure 6, where without the connection of the two offered techniques, voltage experiences voltage sag of 70 % that violates the LVRT of the Garman grid code; this will call for the disconnection of the wind turbines from the grid. By connecting the SMES unit, voltage drop at the PCC will be raised to 0.45 pu due to reactive power supplies by the SMES unit, while by connecting the

STATCOM voltage drop will be raised to about 0.6 pu which means that the reactive power supplied by the STATCOM more than that is supplied by the SEMES unit. Compared with the fault ride through of Germany, the voltage at the PCC violates the low voltage ride through (LVRT) of the mentioned grid code when the SMES or the STATCOM is not connected as shown in figure 8 which calls for the disconnection of the wind turbine from the grid. By connecting one of the proposed methods to the PCC bus, the amount of voltage drop decreases and reaches a safe level of the grids requirement (figure 8) and therefore the wind turbine connection to the grid is maintained.

Figure 6: Three phase voltage profile at PCC

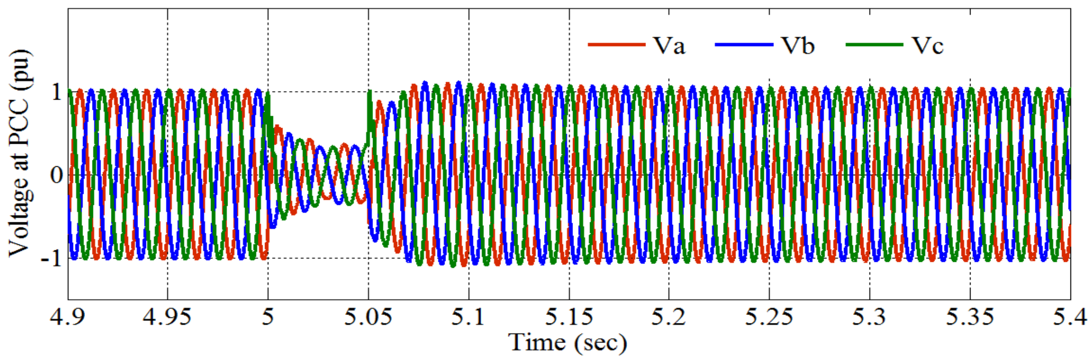


Figure 7: Voltage profile at PCC

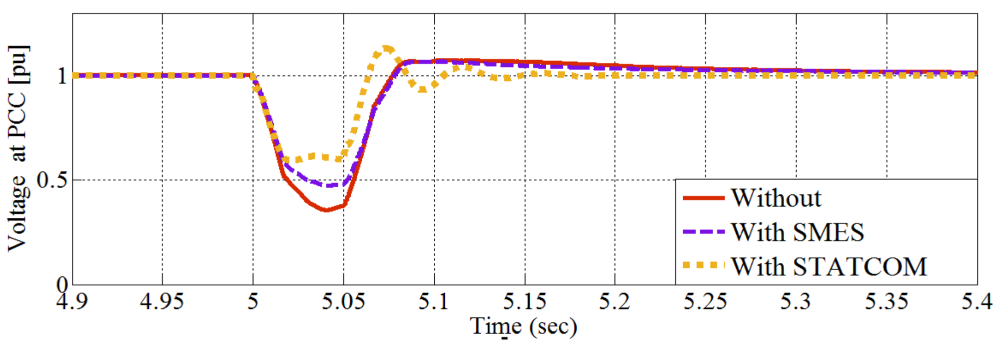
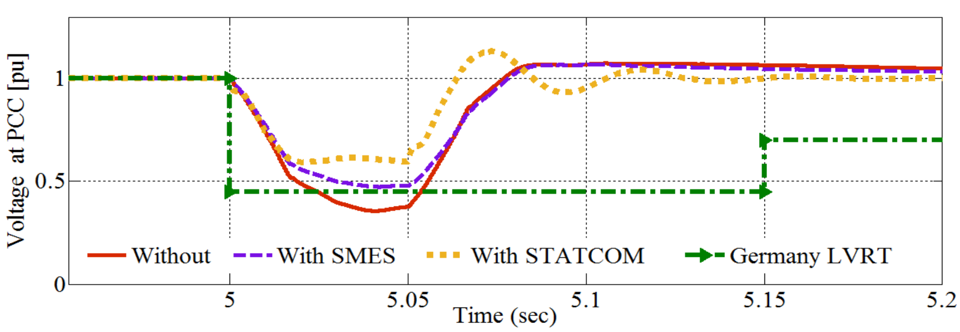


Figure 8: PCC voltage compliance with Garman grid code



Due to the voltage sag and without the connection of the SMES, the active power at the PCC will drop to 0.29 pu, indicating that the DFIG is absorbing active power from the grid and acting as a motor as shown in figure 9. When the SMES is connected, it can modulate the active power at the PCC to be 0.51 pu during the fault as shown in figure 9. Figure 10 shows the reactive power at the PCC without and with the integration of the SMES and STATCOM from which the amount of surplus reactive power compensated by the SMES and STATCOM clearly observable.

The energy stored in the coil of the SMES is shown in figure 11. It is being delivered to the grid (Discharging mode). When the fault is cleared at 5.05 sec the energy transfers from the grid to the coil (charging mode).

Figure 9: Active power of SMES

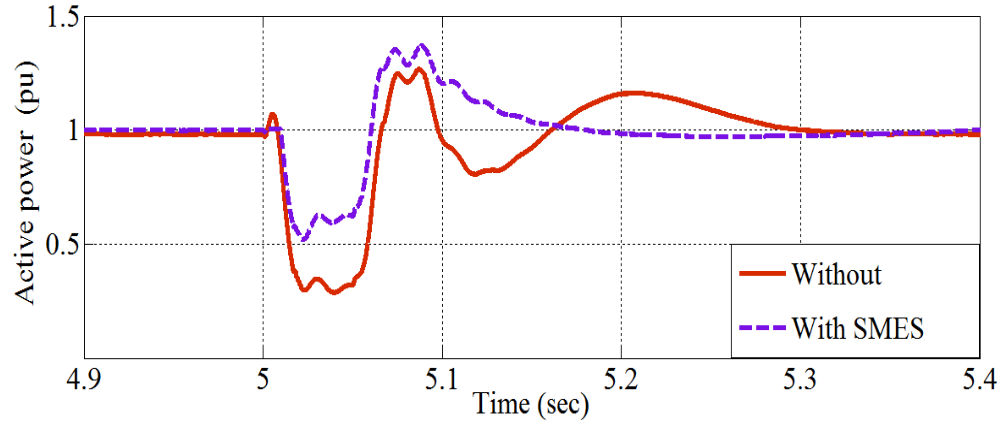


Figure 10: Reactive power of SMES and STATCOM

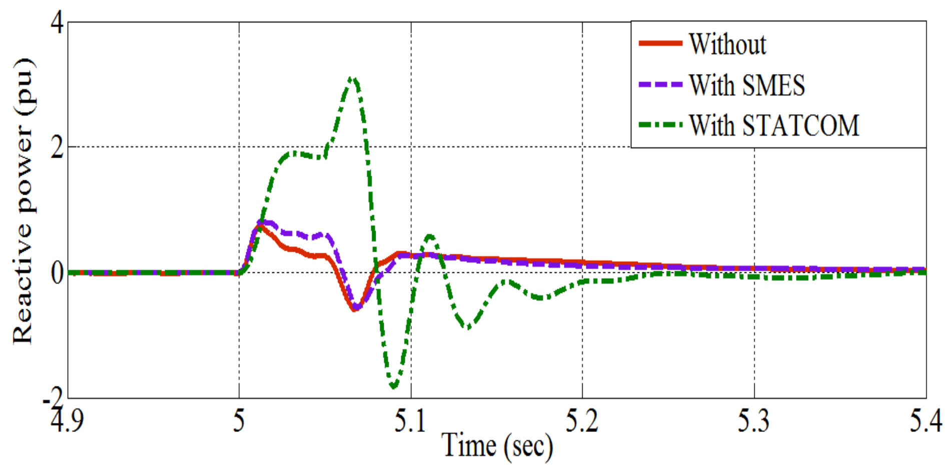
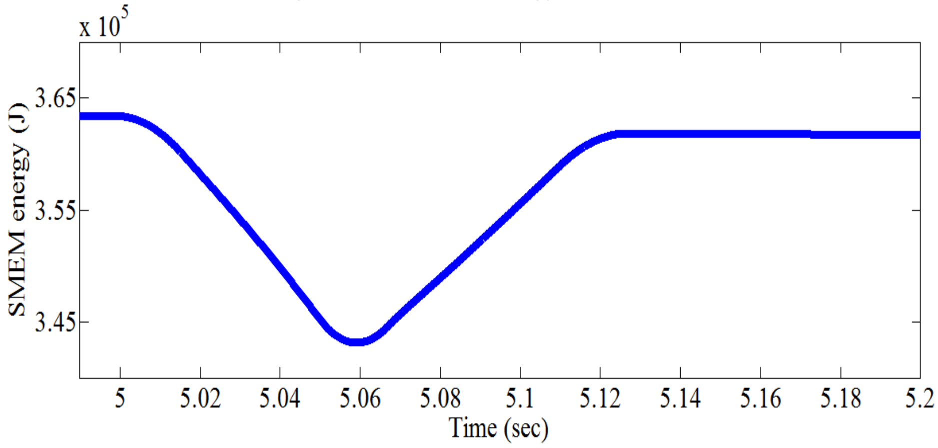


Figure 11: Stored energy of SMES



VI. CONCLUSION

In this paper, a SMES unit and a STATCOM are used for improving the LVRT of the DFIG-based WECS during voltage sag at the grid side. Each of the two presented techniques is individually placed at PCC of the system under study. Simulation is carried out using Simulink Matlab software. Results of each technique show that the two offered techniques can improve the LVRT of the DFIG-based WECS during fault events. It can also be observed that the reactive power supplies by STATCOM more than that supplies by SMES unit, which lead to better LVRT improvement. Moreover, it can be noted that the SMES unit has advantage over the STATCOM which is the capability to supplies active and reactive power.

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