Improvement of LVRT Capability of Variable Speed Wind Turbine Generators Using SMES Unit

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***Abstract*—The ability of variable speed wind turbines technology to optimally tracking the power from wind energy has become the main reason of their popularity compared with the fixed speed wind turbines. In the earlier stage of connecting wind turbines (WTs) to the existing electricity grids, WTs were allowed to be disconnected from the grid in case of grid faults which might lead to the damage of the turbines. However, recently, the transmission system operators (TSOs) require to maintaining the connection of WTs with the grid to support the grid during fault and to assure the continuity of power supply. This requirement has been compiled in new grid codes in several countries. In this paper, super conducting magnetic energy storage (SMES) unit is used with two different types of variable speed wind turbine generators to comply with Spain grid codes. Results show that the low-voltage-ride-through (LVRT) of Type-3 and Type-4 wind turbine generators are significantly improved when SMES unit is connected to the system.**

***Index Terms*-- LVRT, SMES, Type-3 WT and Type-4 WT**

I. Introduction

WIND energy is one of the most promising renewable energy resources in the world. The global wind energy installed capacity has been increased from 2 GW at the end of year 1990 to 94 GW by the end of year 2007. In 2008, electricity generation using wind power has reached to 1% of the global electricity generation and by year 2020, it is expected that wind power to supply about 10% of the global electricity [1]. There are two major classifications of wind turbine generator, fixed-speed and variable speed turbines. Variable speed turbines are the most popular when compared to the fixed-speed because variable speed turbines are able to track 5% more power and can reduce the impact of transient wind gusts and subsequent fatigue which cannot be done by fixed speed turbines [2]-[3]. The common variable speed wind turbines are classified into Type-3 which is also known as doubly fed induction generator (DFIG) and Type-4. The Type-3 stator winding is directly connected to a transformer low voltage side while its rotor winding is connected to a bidirectional back to back IGBT voltage source converter as shown in Fig. 1. The converter helps in decoupling mechanical and electrical frequencies and making variable speed operation possible. Because of the fact that Type-3 WTG is equipped with partial scale converter, the turbine cannot operate in full range from zero to the rated speed, however the speed range is quite sufficient [2]. About 46.8% of the global installed WTs in 2002 were of this type [4].

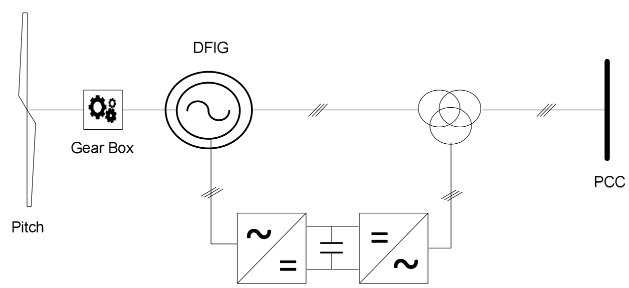

Fig. 1. Typical configuration Type-3 WT

The second popular type of variable-speed wind turbines is the direct-drive variable speed wind turbine with multi-poles synchronous generator or so called type-4 wind turbine. A low-speed synchronous generator that is coupled with wind turbine converts the mechanical energy into electricity. In this type, a synchronous generator is connected to a three phase diode rectifier and a chopper as shown in Fig. 2. When the speed of the synchronous generator alters, the voltage value on the DC side of the diode rectifier will change. A step-up chopper is used to adapt the rectifier voltage to the dc-link voltage of the inverter [2]. The trend shows that Type-4 WT has been increased in the market share by about 20.3 % in 2002 [4].

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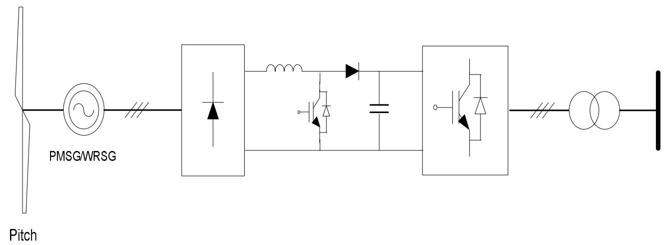


Fig. 2. Typical configuration of Type-4 WT

In this paper, the two types of variable speed wind turbine generators mentioned above are used with and without the connection of super conducting magnetic energy storage (SMES) unit to the system under study to investigate their comply with Spain grid codes shown in Fig. 3 during voltage dip at the grid side [5-8].

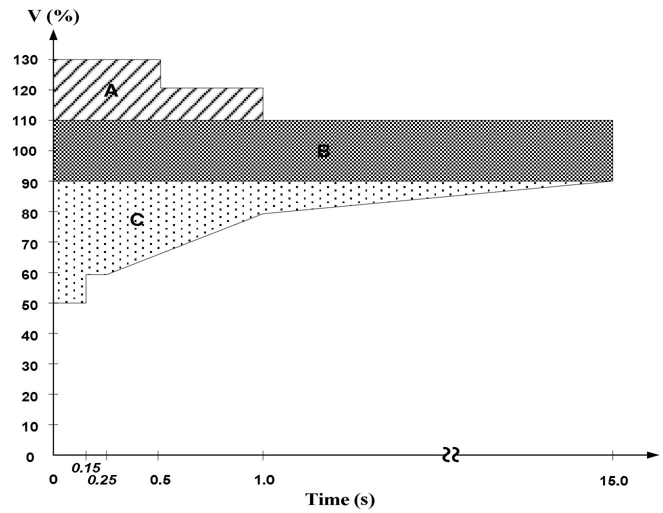


Fig. 3. Fault-Ride-Through of Spain grid code [5]

In Fig. 3, the Fault-Ride-Through of Spain grid code is divided into three main blocks. “A” block is representing the high voltage ride through (HVRT) of Spain grid code. The maximum allowable high voltage in the vicinity of the point of common coupling (PCC) is 130% that lasts for duration of 0.5 s from the instant of fault occurrence. After that the maximum voltage is reduced to 120% for the next 0.5 s. All high voltage profiles above “A” block will lead to the disconnection of WTGs from the system. The normal condition of this grid code is laid on “B” block. All voltage profiles within this block range (90% to 110%) are classified as a normal condition. The low voltage ride through (LVRT) is limited in “C” block. The minimum voltage drop allowed in this grid code is 50% which lasts for 0.15 s from the instant of fault occurrence and then increased to 60% for 0.1 s. The low voltage restriction then ramps up to 80% at 1 s and reaches the normal condition in 15 s from the instant of fault occurrence. Similar to the HVRT, any voltage level at the PCC below the levels constrained by “C” block will lead to the disconnection of WTGs from the system.

II. System Under Study

The system under study shown in Fig. 4 consists of five-2 MW of Type-3 or Type-4 WT connected to the AC grid at a PCC through Y/Δ step up transformer.

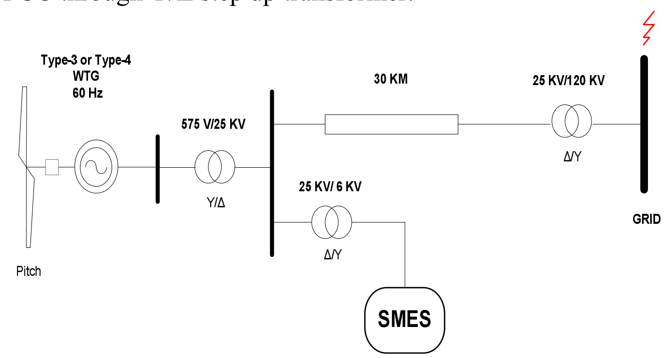


Fig. 4. System under study

The grid is represented by an ideal 3-phase voltage source of constant frequency and is connected to the wind turbines through 30 km transmission line. The reactive power produced by the wind turbine is regulated at 0 Mvar at normal operating conditions. For an average wind speed of 15 m/s which is used in this study, the turbine output power is 1 pu and the generator speed is 1 pu. SMES Unit is connected to the 25 KV bus and is assumed to be fully charged at its maximum capacity of 1 MJ.

III. SMES Configuration and Control Scheme

The selection of SMES Unit in this paper is based on its advantages over other energy storage technologies. Compared to other energy storage options, the SMES unit is ranked first in terms of highest efficiency which is in a typical range of 90-99% [9-13]. The high efficiency of the SMES unit is achieved by its lower power loss because electric current in the coil encounters almost no resistance and there are no moving parts, which means no friction losses. SMES stores energy within a magnetic field created by the flow of direct current in a coil of superconducting material. Typically, the coil is maintained in its superconducting state through its immersion in liquid helium at 4.2 K within a vacuum - insulated cryostat. A power electronic converter interfaces the SMES to the grid and controls the energy flow bidirectionally. With the recent development of materials that exhibit superconductivity closer to room temperatures this technology will become economically viable in the near future [14]. The stored energy in the SMES coil is calculated as:

$$E = \frac{1}{2} I_{SM}{}^{2} L_{SM} \qquad (1)$$

Where E is the SMES energy; I_{SM} is the SMES Current and L_{SM} is the SMES coil inductunce.

To control the direction of power flow from the Voltage Source Converter (VSC), Hysteresis Current control (HCC) is preferred based on its advantages, which include ease of implementation, fast dynamic response, maximum current limit and its insensitivity to load parameter variations [15]. The solid state switching component of VSC consists of six-

IGBT to support the optimal application of SMES unit since it simplifies the converter design and enables considerably higher switching frequency compared to bipolar junction transistor [16]. The SMES coil is connected to the VSC by a DC link. The charging and discharging process of SMES energy is determined by fuzzy logic control (FLC) of a DC-DC chopper as shown in Fig. 5. The capacitor is used to store a constant DC voltage that is maintained by VSC controller. The active power from the generator and the current in the superconductor coil are used as inputs to the fuzzy logic controller. Hysteresis current control is used to control the power flow exchange between the grid and the SMES unit which is performed by comparing the 3-phase line currents with the reference current that is indicated by I_d* and I_q*. The value of I_d* and I_q* are generated through the conventional proportional-integral (PI) controllers both from the error values of V_{dc} and V_s as shown in Fig. 6. The proposed control algorithm in this paper is much simpler and closer to realistic application compared with the controller used in Ref [17], where four PI controllers were used and only P_g was used as a feedback signal to the DC-DC chopper while the energy capacity of the SMES unit was ignored.

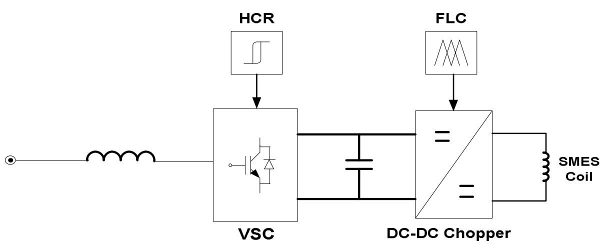


Fig. 5. SMES configuration

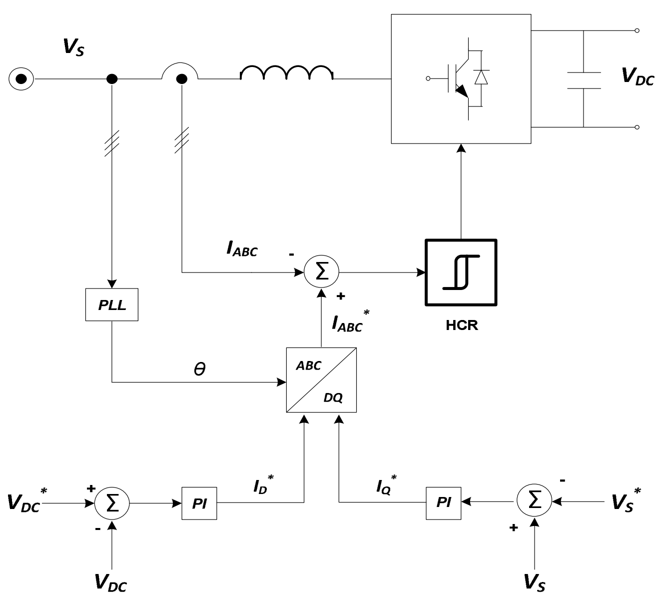


Fig. 6. Control algorithm of VSC

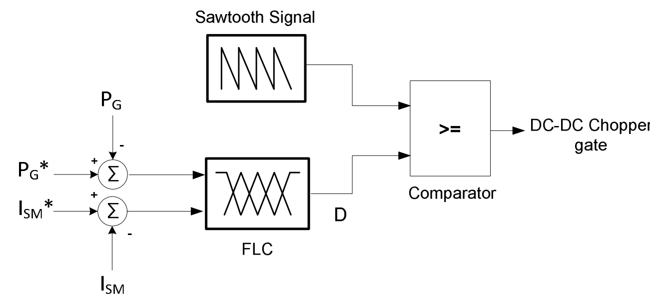


Fig. 7. Control algorithm of DC-DC chopper

To determine the value of the duty cycle of the DC chopper, real power of variable speed-WT and SMES coil current are used as inputs of the fuzzy logic controller. The duty cycle is compared with 1000 Hz saw tooth signal to produce signal for the DC-DC chopper as shown in Fig. 7. The controller is developed in accordance to fuzzy inference flow chart shown in Fig. 8 which is a process of formulating the mapping from a given input to the designated output.

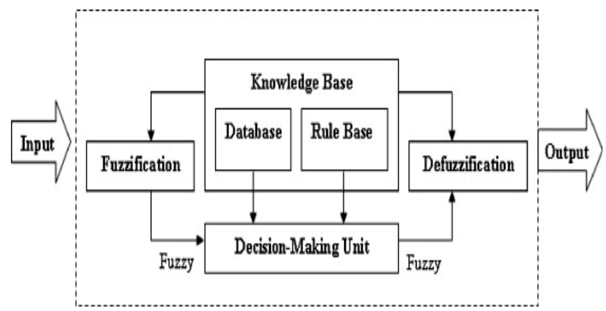


Fig. 8 Fuzzy logic model flow chart

The rules of duty cycles (D) and the corresponding SMES action are shown in Table I. As initial condition, it is assuming that SMES is fully charged when connected to the system. When D is equal to 0.5, SMES unit is in idle condition and there is no power exchange between the SMES unit and the grid. When there is any voltage drop because of fault, the controller generates a duty cycle in the range of 0 to 0.5 according to the value of the two input signals. The charging action (corresponding to the duty cycle higher than 0.5) will take place when SMES coil capacity is dropped and power will be transferred from the grid to the SMES unit.

TABLE I
RULES OF DUTY CYCLE

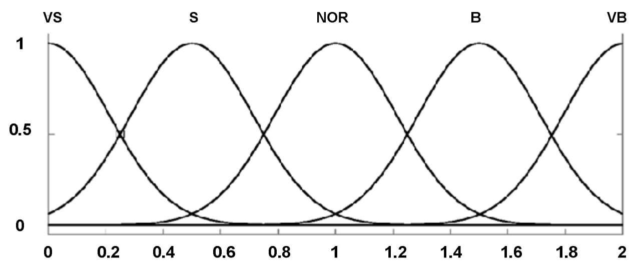
Duty Cycle (D)	SMES Coil Action
D = 0.5	standby condition
$0 \le D < 0.5$	discharging condition
$0.5 < D \le 1$	charging condition

The model is built using the graphical user interface tool provided by MATLAB. Each input was fuzzified into five sets of gaussmf type of membership function (MF). The gaussian curve is a function of a vector, x, and depends on parameters σ and c as given by:

$$f(x;\sigma,c) = e^{\frac{-(x-c)^2}{2\sigma^2}} \quad (2)$$

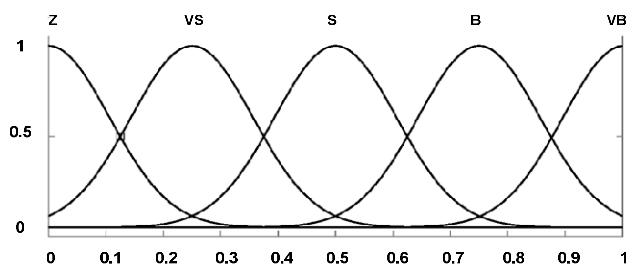
Where σ is a variable that determines the position of the centre of the peak and c is a variable that determines the width of the bell curve.

The membership functions for each input variable are shown in Fig. 9 and Fig. 10. Result of fuzzification from each input was then applied with fuzzy operator in the antecedent and related to the consequence, by application method. The membership functions for the output variable (Duty cycle) are considered on the scale 0 to 1 as shown in Fig. 11.



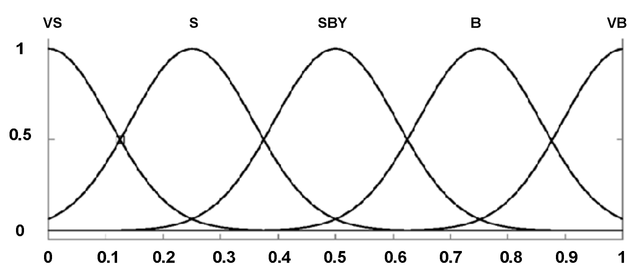
VS=Very Small, S=Small, NOR=Normal, B=Big, VB=Very Big

Fig. 9. Input variable MF – P_g (pu)



Z=Zero, VS=Very Small, S=Small, B=Big, VB=Very Big

Fig. 10. Input Variable MF – I_{SM} (pu)



VS=Very Small, S=Small, SBY=Stand-By, B=Big, VB=Very Big

Fig. 11. Output variable MF – Duty cycle

Centre-of-gravity which is widely used in fuzzy models was used for defuzzification method where the desired output z_0 is calculated as [18]:

$$z_0 = \frac{\int z.\mu_c(z)dz}{\int \mu_c(z)dz} \quad (3)$$

where $\mu_c(z)$ is the membership function of the output.

IV. Simulation Results

In this study, voltage sag of 0.25 % is applied at the grid side of the system under study shown in Fig. 4. The fault is assumed to start at 0.5 s and cleared at 0.58 s. Fig. 12 shows the rms voltage at the PCC bus without and with the connection of the SMES unit. As shown in Fig. 12 (a), without SMES unit connected to the PCC bus, both Type-3 and type-4 should be disconnected from the system as the voltage at the PCC will cross the lowest voltage level of the LVRT of Spain grid code.

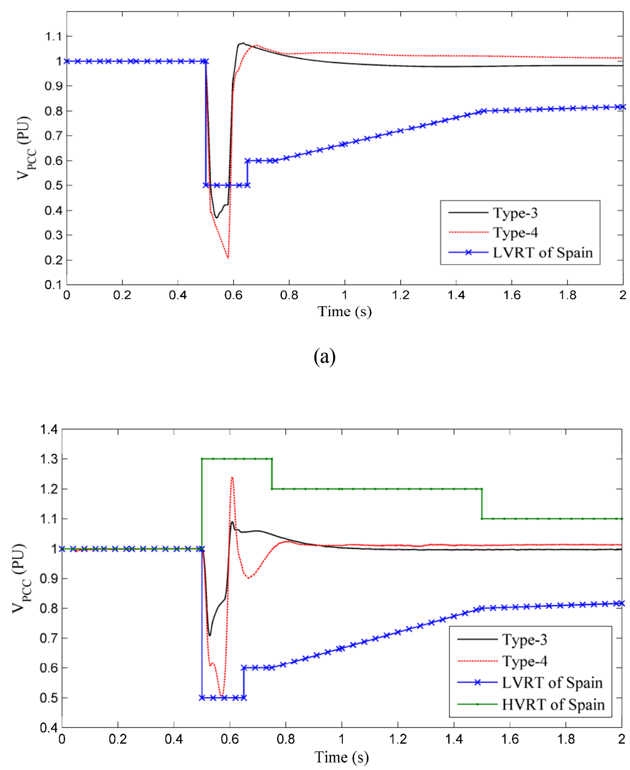
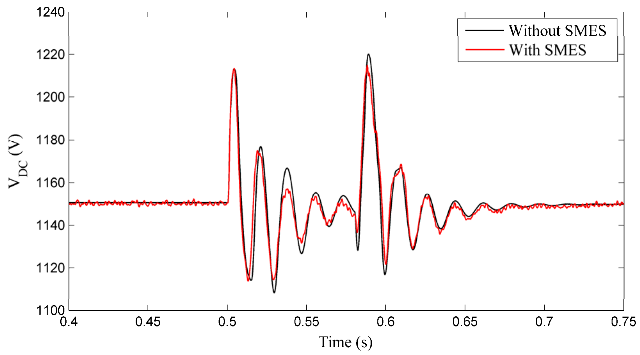
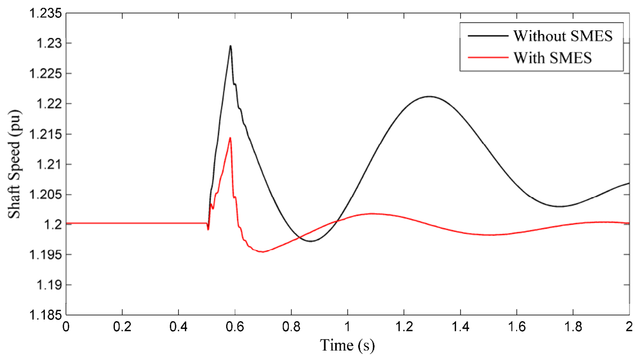


Fig. 12. Voltage profile of variable speed turbines at PCC: (a) without SMES (b) with SMES

However with SMES unit connected to the PCC bus, the voltage profile at the PCC bus is improved and the voltage sag for both types of WTs will be reduced to a level within the safe margin of the LVRT of Spain grid code as can be seen in Fig. 12 (b). The high-voltage- ride-through (HVRT) of the Spain grid code is included in Fig. 12 (b) to show that the maximum voltage overshoot at the moment when the fault is cleared for the system with Type-4 is remaining in a safety margin when complied with the Spain grid code, therefore both Type-3 and Type-4 connection can be maintained during fault when the SMES unit is connected to the system.

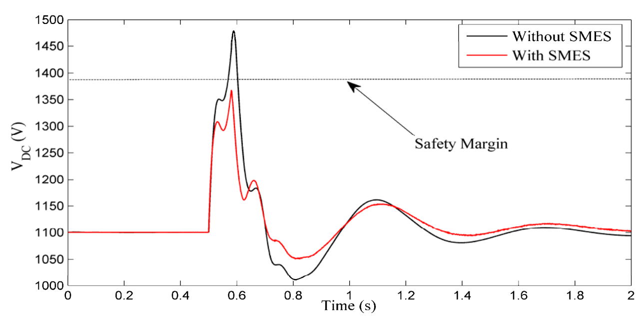


(a)

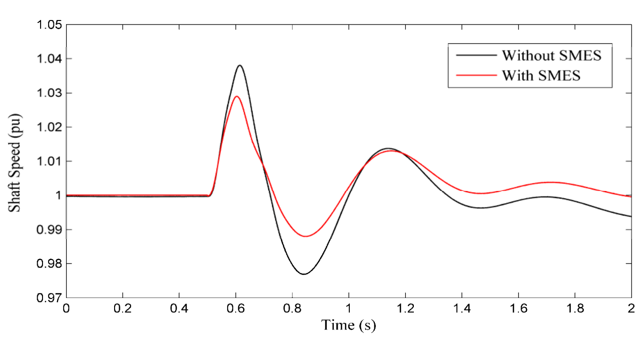


(b)

Fig. 13. Type-3 WTG response: (a) V_{DC} wave form (b) shaft speed response



(a)

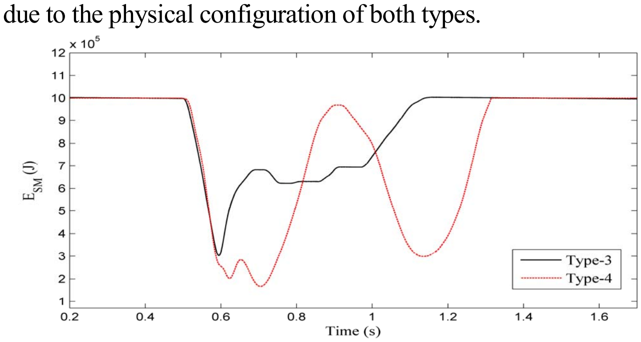


(b)

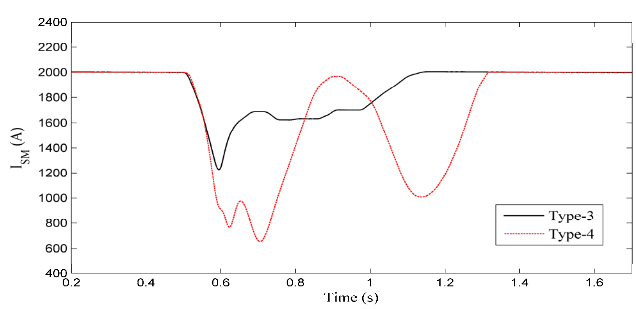
Fig. 14. Type-4 WTG response: (a) V_{DC} wave form (b) shaft speed response

The voltage across the WTG capacitor (V_{DC}) is an important parameter of FRT study. Fig. 13(a) and 14(a) show that during voltage sag at the grid side, the level of V_{DC} will not cross the V_{DC} safety margin without or with SMES unit connected to the Type-3 WTG, however without SMES unit connected, the level of V_{DC} of Type-4 WTG will cross the safety margin and lead to the stop of the converter operation. With the connection of SMES unit, the maximum overshooting of V_{DC} is reduced below the safety margin level which is considered to be 1.25 pu in this study [19], thus the WTG can be remains connected to the system. The shaft speed can also be used to examine the stability of WTG system. During voltage sag, the generated active power of Type-3 WTG will drop and causing the increase of shaft speed which in some cases will lead to system instability, however, with SMES unit connected, the overshoot and the time settling of the shaft speed can be reduced significantly as shown in Fig. 13(b). The effect of SMES unit on Type-4 shaft speed (Fig. 14(b)) is limited due to the configuration of the Type-4 that which uses a rectifier that connected directly to the generator terminal.

The behavior of the SMES coil during the fault can be investigated through Fig 15 (a) to (c) which respectively shows the SMES stored energy, SMES coil current and the voltage across the coil. The SMES coil energy is 1 MJ during normal operating conditions, when voltage sag occurs; SMES coil instantly discharges its energy into the grid as shown in Fig. 15 (a). The characteristic of SMES current shown in Fig. 15 (b) is similar to the energy stored in the coil. The charging and discharging process of SMES coil can also be examined from the voltage across SMES coil (V_{SM}) shown in Fig., 15 (c). During normal operating conditions, V_{SM} is equal to zero, it goes to negative value during discharging process and will return back to zero level after the fault is cleared. It can be noticed from Fig. 13 that the energy and voltage of SMES coil when connected to system with Type-3 WT have less fluctuation compared with the system with Type-4. This may be attributed to the fact that Type-3 is more flexible in terms of power exchange during voltage sag due to the physical configuration of both types.



(a)



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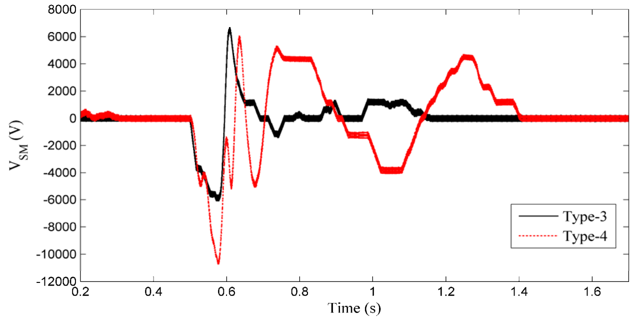

(c)

Fig. 15. SMES coil behavior during voltage sag: (a) Energy of SMES coil (b) Current of SMES coil and (c) Voltage across the SMES coil

V. CONCLUSION

This paper investigates the use of SMES unit to enhance the LVRT capability of two types of variable speed-WT namely, Type-3 and-4 to comply with the grid codes of Spain. Results show that, without the use of SMES unit, both Type-3 and Type-4 must be disconnected from the grid to avoid the turbines from being damaged. However, the proposed controller of the SMES unit can significantly improve the LVRT capability of Type-3 and Type-4 and their connection to the grid can be maintained to support the grid during faulty condition and to ensure the continuity of power supply. The proposed control algorithm using HCC and fuzzy logic control is simple and easy to be implemented.

VI. APPENDIX

PARAMETERS OF TYPE-3

Rated Power	10 MW (5 x @ 2 MW)
Stator Voltage	575 V
Frequency	60 Hz
R_S	0.023 pu
R_R	0.016 pu
V_{DC}	1150 V

PARAMETERS OF TYPE-4

Rated Power	10 MW (5 x @ 2 MW)
Stator Voltage	575 V
Frequency	60 Hz
R_S	0.006 pu
V_{DC}	1100 V

PARAMETERS OF SMES UNIT

Rated Energy	1 MJ
L_{SM}	0.5 H
Rated I_{SM}	2000 A

VII. ACKNOWLEDGMENT

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IX. BIOGRAPHIES

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