APPLICATION OF SMES UNIT TO IMPROVE THE VOLTAGE PROFILE OF THE SYSTEM WITH DFIG DURING GRID DIP AND SWELL

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ABSTRACT

One of the most important parameters of the system where wind turbine generators (WTGs) are connected is voltage profile at the point of common coupling (PCC). In the earlier stage, WTGs were possible to be disconnected from the system to avoid the damage of WTGs. Following the rapid injection of WTGs to the existing network during last decades, the transmission line operators (TSOs) require WTGs to stay connected in certain level of fault to continue support the grid. This new requirements have been compiled in new international grid codes. In this paper, superconducting magnetic energy storage (SMES) is applied to improve the voltage profile of PCC bus where WTGs equipped with doubly fed induction generator (DFIG) is connected to meet the used gird codes of Spain and German during grid dip and swell. The voltage dip at the grid side is examined to comply with the low voltage ride through (LVRT) while the voltage swell at the grid side is examined to comply with the high voltage ride through (HVRT) of both Spain and German voltage ride through (VRT).

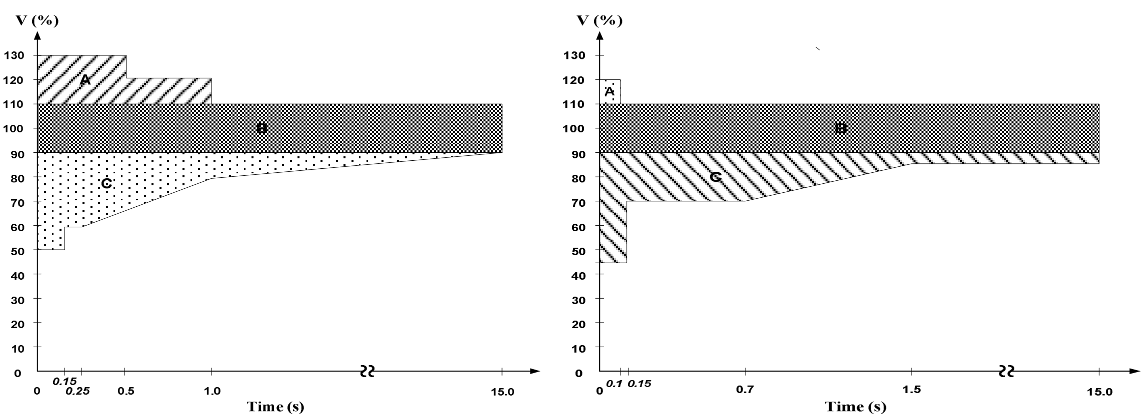
KEYWORDS: *Voltage Ride through (VRT), SMES, DFIG, Voltage Dip & Voltage Swell.*

I. INTRODUCTION

The effect of pollution from conventional energy to the environment and the implementation of carbon tax have become a trigger of the increase of renewable energy utilization in the world. In addition, conventional energy is very limited and would soon be finished if exploited on a large scale because of oil, gas or coal is a material created in the process of millions of years. The limited amount and high demand for energy resources will affect the rise in oil prices from time to time. Therefore, attention is directed now onto the renewable energies which are clean and abundantly available in the nature [1]. The first wind turbines for electricity generation had already been developed at the beginning of the twentieth century. The technology was improved step by step from the early 1970s. By the end of the 1990s, wind energy has re-emerged as one of the most important sustainable energy resources. During the last decade of the twentieth century, worldwide wind capacity doubled approximately every three years [2]. The global installed capacity worldwide increased from just less than 2000 MW at the end of 1990 to 94000 MW by the end of 2007. In 2008, wind power already provides a little over 1% of global electricity generation and by about 2020, it is expected that wind power to be providing about 10% of global electricity [3]. Moreover, the total 121 GW installed capacity of wind turbine in 2008 has produced 260 TWh of electricity and has saved about 158 million tons of CO_2. In addition, the predication of total installed capacity of wind turbines will be 573 GW in 2030 [4]. Power quality issue is the common consideration for new construction or connection of power generation system including WTGs installation and their connection to the existing power system. In this paper, voltage dip (sag) and swell will be considered as the conditions of the fault ride through capability of WTG equipped with DFIG. Voltage dip (sag) and swell are two common types of power quality issue. Voltage dip is a decrease to between 0.1 and 0.9 pu in rms voltage or current at the power frequency for durations of 0.5 cycles to 1 minute. Voltage dips are usually associated with system faults but can also be caused by switching of heavy loads or starting of large motors. A swell is defined as an increase in rms voltage or current at the power frequency for durations from 0.5 cycles to 1 minute. Typical magnitudes are between 1.1 and 1.8 pu. As with dips, swells are usually associated with system fault conditions, but they are much less common than voltage dips. A swell can occur due to a single line-to-ground fault on the system resulting in a temporary voltage rise on the unfaulted phases. Swells can also be caused by switching off a large load or switching on a large capacitor bank [5, 6]. Since voltage dip is a common power quality problem in power systems, most of studies are focused on the performance of WTGs during voltage dip [7-14]. Although it is a less power quality problem, voltage swell may also lead to the disconnection of WTGs from the grid. In this paper, voltage dip and swell will applied on the grid side to investigate their effects on PCC which could affect the continuation of WTGs connection if complying with the used grid codes in this paper as explained below with and without SMES connected.

II. SPAIN AND GERMAN GRID CODE

In the earlier stage, WTGs are possible to be disconnected from the system to avoid the damage of WTGs. Following the rapid injection of WTGs to the existing network during last decades, the transmission line operators (TSOs) require WTGs to stay connected in certain level of fault to continue support the grid. This new requirements have been compiled in new grid codes. However, most of grid codes are only providing low voltage ride through (LVRT) in their codes without any restriction information regarding the high voltage ride through (HVRT) which might be can lead instability in the PCC. The following figures are the international grid codes of Spain and German which used in this study. Figure 1a and 1b show the voltage ride through (VRT) of Spain and German respectively. The selection of these grid codes is based on their strictness in low voltage ride through (LVRT), meanwhile providing complete voltage ride through (VRT) with their HVRT.



(a) (b)

Figure 1. (a) FRT of Spain grid code and (b) FRT of German grid code [15]

In Figure 1 (a), the FRT of Spain is divided by 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 PCC is 130% lasts for 0.5 s. After that the maximum high voltage is reduced to 120% until next 0.5 s. All high voltage profiles above “A” block will lead 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 are classified as a normal condition (90% to 110%). The low voltage ride through

(LVRT) is limited in "C" block. The minimum voltage drop allows in this grid code is 50% lasts for 0.15 s and increased to 60% until 0.25s. The low voltage restriction then ramp to 80% at 1 s and reaching the normal condition in 15 s since the fault occurs. The HVRT of German grid code (shown in Figure 1(b)) is much strict then Spain. The maximum allowable HVRT is 120% for 0.1 s (shown in "A" block). The normal condition that is shown in "B" block is the same with Spain grid code. However, the LVRT is allowed to reach 45% lasts for 0.15 s and should be at least 70% until 0.7 s. After that the voltage margin ramps to 85% at 1.5 s.

III. SYSTEM UNDER STUDY

There are two major classifications of wind turbine generator, fixed-speed turbine and variable-speed turbines. One of the most popular variable speed wind turbine is doubly fed induction generator (DFIG). About 46.8 % of this type has been installed in 2002 [2]. A doubly fed induction generator (DFIG) using a medium scale power converter. Slip rings are making the electrical connection to the rotor. If the generator is running super-synchronously, electrical power is delivered to the grid through both the rotor and the stator. If the generator is running sub- synchronously, electrical power is delivered into the rotor from the grid. A speed variation of $\pm$ 30% around synchronous speed can be obtained by the use of a power converter of 30% of nominal power. The stator winding of the generator is coupled to the grid, and the rotor winding to a power electronic converter, nowadays usually a back-to-back voltage source converter with current control loops. In this way, the electrical and mechanical rotor frequencies are decoupled, because the power electronic converter compensates the different between mechanical and electrical frequency by injecting a rotor current with variable frequency. Variable speed operation thus became possible. The typical of generic model of DFIG is shown in Figure 1.

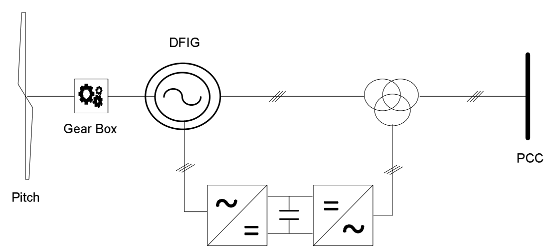


Figure 2. Typical configuration of WTG equipped with DFIG

The system under study shown in Figure 3 consists of six-1.5 MW DFIG connected to the AC grid at PCC via Y/Δ step up transformer. The grid is represented by an ideal 3-phase voltage source of constant frequency and is connected to the wind turbines via 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 (PCC) bus and is assumed to be fully charged at its maximum capacity of 2 MJ.

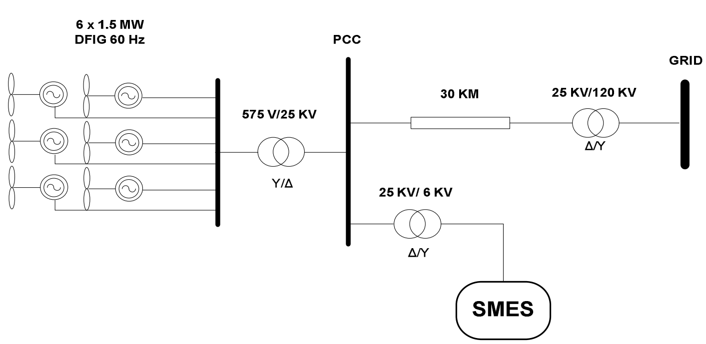


Figure 3. System under study

IV. SMES Configuration and Control System

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 90-99% [16-18]. The high efficiency of the SMES unit is achieved by its lower power loss because electric currents in the coil encounter 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 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 may become economically viable [1]. The stored energy in the SMES coil can be 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 inductor coil.

The SMES unit configuration used in this paper consists of voltage source converter (VSC) and DC-DC chopper which are connected through a DC shunt capacitor. The VSC is controlled by a hysteresis current controller (HCC) while the DC-DC chopper is controlled by fuzzy logic controller (FLC) as shown in Figure 4.

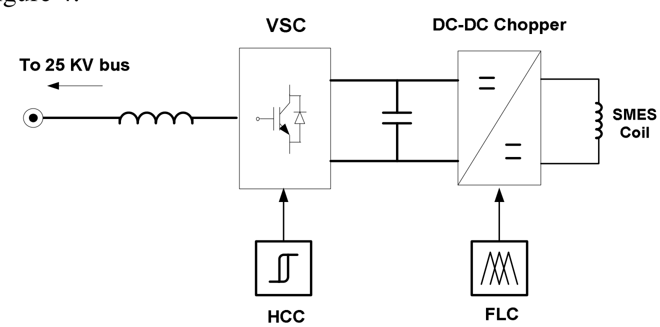


Figure 4. SMES configuration

DC-DC Chopper along with FLC is used to control charging and discharging process of the SMES coil energy. The generator active power and the current in the superconductor coil are used as inputs to the fuzzy logic controller to determine the value of the DC chopper duty cycle, active power of DFIG and SMES coil current are used as inputs of the fuzzy logic controller. The duty cycle (D) is compared with 1000 Hz saw-tooth signal to produce signal for the DC-DC chopper as can be seen in Figure 5.

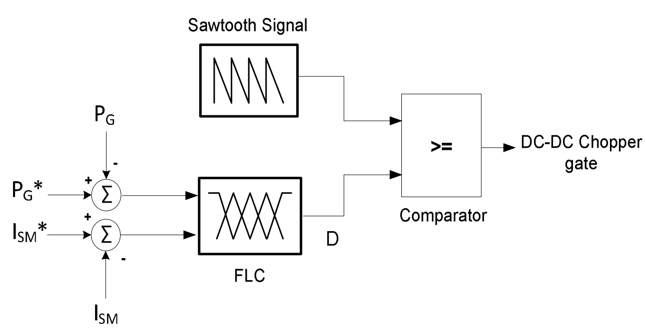


Figure 5. Control algorithm of DC-DC chopper

Compared with pulse width modulation (PWM) technique, the hysteresis band current control has the advantages of ease implementation, fast response, and it is not dependent on load parameters [19].

Hysteresis current control (HCC) is used to control the power flow exchange between the grid and the SMES unit. HCC is comparing the 3-phase line currents with the reference currents (I_d* and I_q*). The value of I_d* and I_q* are generated through the conventional PIs controller both from the deviation of the capacitor voltage V_{dc} and system voltage V_s. To minimize the effect of phases interference while maintaining the advantages of the hysteresis methods, phase-locked loop (PLL) technique is applied to limit the converter switching at a fixed predetermined frequency [20]. The proposed control algorithm in this paper is much simpler and closer to realistic application compared with the controller used in [21], where four PIs controller were used which complicate the process of finding the optimal parameters of the PIs, moreover, only P_g was used as the control parameter of the DC-DC chopper and it ignored the energy capacity of the SMES coil. The detailed VSC control scheme used in this paper is shown in Figure 6. The rules of duty cycles D and the corresponding SMES action are shown in Table I. 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 system. 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 inputs and power will be transferred from SMES coil to the system. 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.

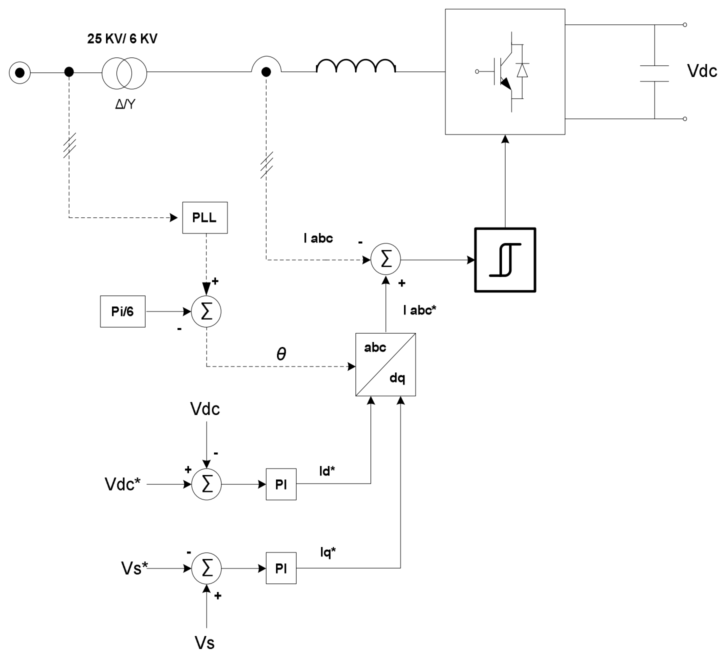


Figure 6. Control algorithm of VSC

Table 1. Rules of duty cycle

Duty cycle (D)	SMES coil action
D = 0.5	standby condition
0 ≤ D < 0.5	discharging condition
0.5 < D ≤ 1	charging condition

The variation range in SMES current and DFIG output power and the corresponding duty cycle are used to develop a set of fuzzy logic rules in the form of (IF-AND-THEN) statements to relate the input variables to the output. The duty cycle for any set of input date (P_g and I_{SM}) can be evaluated from the surface graph shown in Figure 7.

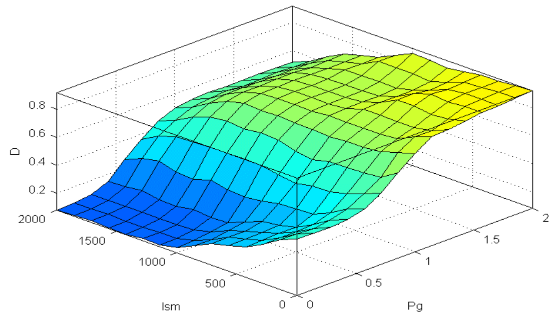


Figure 7. Surface graph- Duty cycle

V. SIMULATION RESULTS

In this paper, two grid disturbances will be applied. The first disturbance would be a voltage dip of 20% and the second is a voltage swell of 135%. Both of disturbances are applied at 0.5 s and last for 5 cycles.

5.1. Voltage Dip

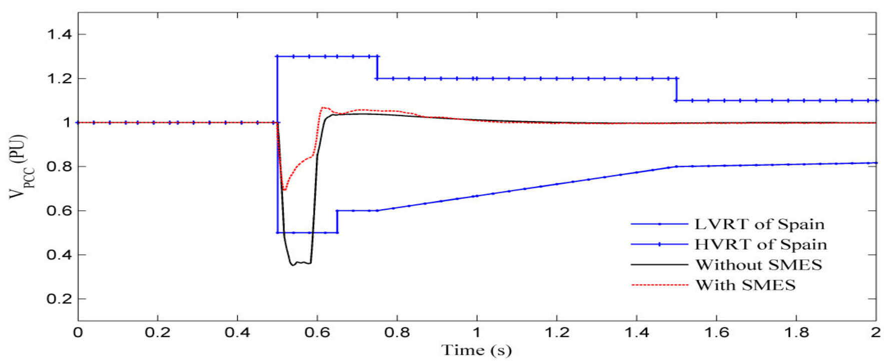


Figure 8. Complying voltage profile at PCC with Spain VRT during grid dip

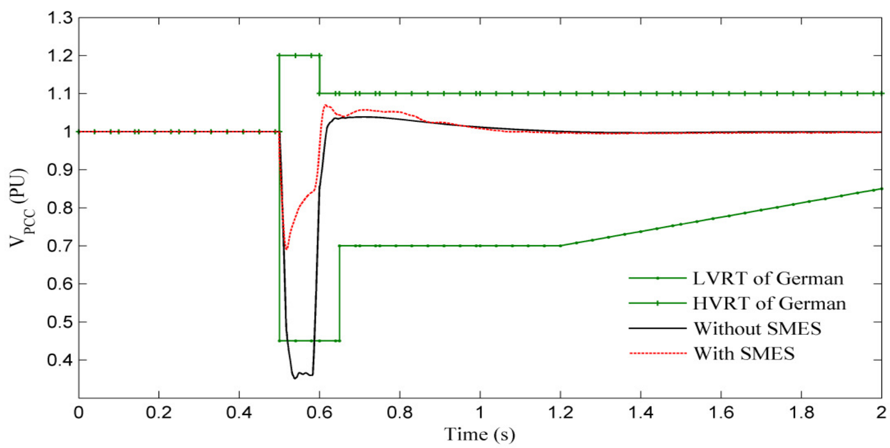


Figure 9. Complying voltage profile at PCC with German VRT during grid dip

As can be seen in Figures 8 and 9, during voltage dip at the grid side, voltage profile at the PCC will be dropped about 0.35 pu without SMES connected. This value is beyond the LVRT of both Spain and German, therefore in this case, the DFIGs have to be disconnected from the system. However, when SMES is connected voltage drop at the PCC can be significantly corrected to about 0.8 pu far from the lowest limit of LVRT of both Spain and German. When fault is cleared, it is naturally that there is a spark which forces the overshoot voltage, however, the overshoot is still under the safety margin of both Spain and German HVRT.

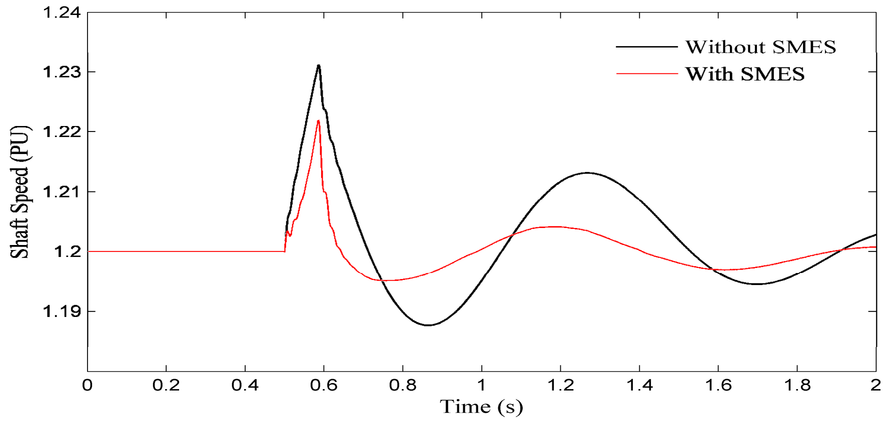


Figure 10. Shaft speed during grid dip

During voltage dip, the speed of shaft will increase at the time when the grip dip occurs to compensate the power drop due to the voltage drop at the PCC as shown in Figure 10. In some severe grid dip cases the extreme oscillation on shaft speed will lead to instability of the system. With SMES connected to the PCC, the oscillation, settling time and the overshoot of the shaft speed are significantly reduced if compared with the system without SMES.

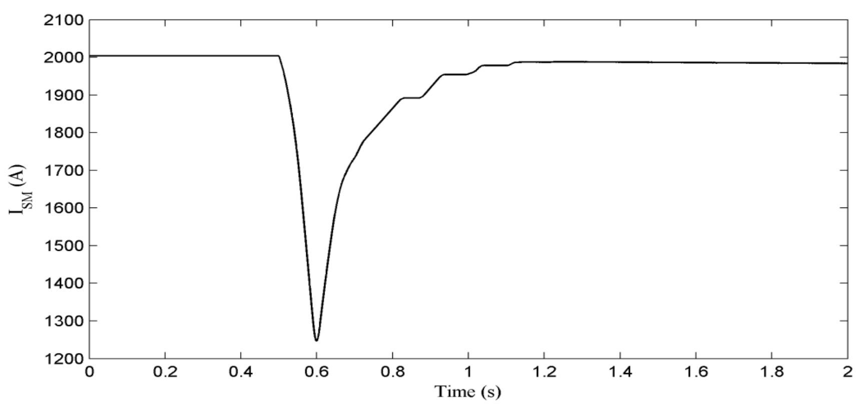


Figure 11. Current behaviour of SMES coil during grid dip

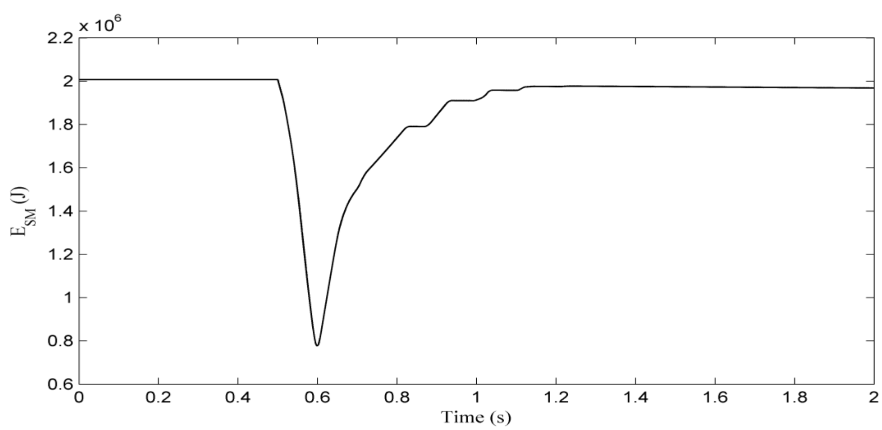


Figure 12. Stored energy behaviour of SMES coil during grid dip

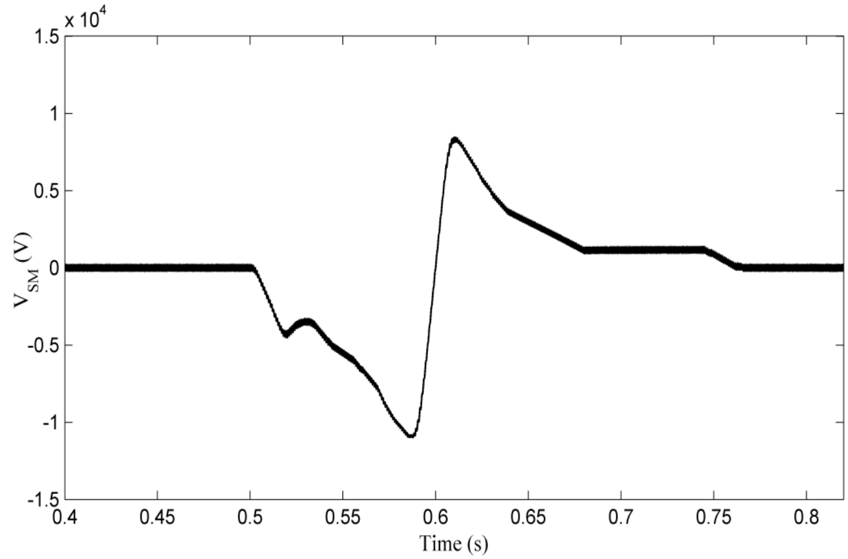


Figure 13. Voltage behaviour across the SMES coil during grid dip

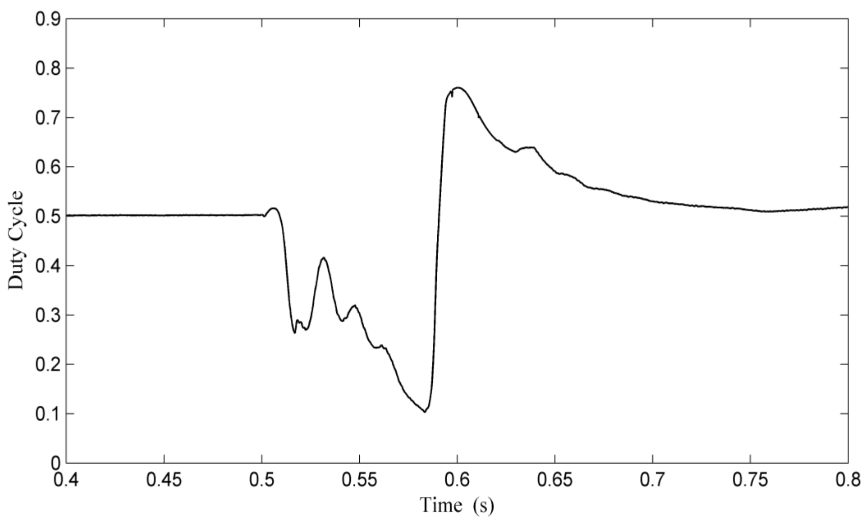


Figure 14. Duty cycle of DC-DC chopper during grid dip

The behavior of the SMES coil during the fault can be investigated through Fig 11 to Fig.13 which respectively show the SMES coil current, SMES stored energy and the voltage across the coil. The SMES coil energy is 2 MJ during normal operating conditions, when voltage dip occurs, SMES coil instantly discharges its energy into the grid as shown in Figure 11. The characteristic of SMES current shown in Figure 12 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 Figure 13. 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. As mentioned before, the duty cycle of DC-DC chopper play important role to determine the charging and discharging process of SMES coil energy. As shown in Figure 14, when voltage dip occur, power produced by DFIG will also reduced, hence the FLC will see this reduction and act according to the membership function rules shown in Figure 7, the duty cycle will in the range between 0 to 0.5 at this stage and once the fault is cleared, the control system will act to charging the SMES coil. In this stage, duty cycle will be in the range of 0.5 to 1 and will be back to its idle value of 0.5 once the SMES coil energy reach its rated capacity.

5.2. Voltage Swell

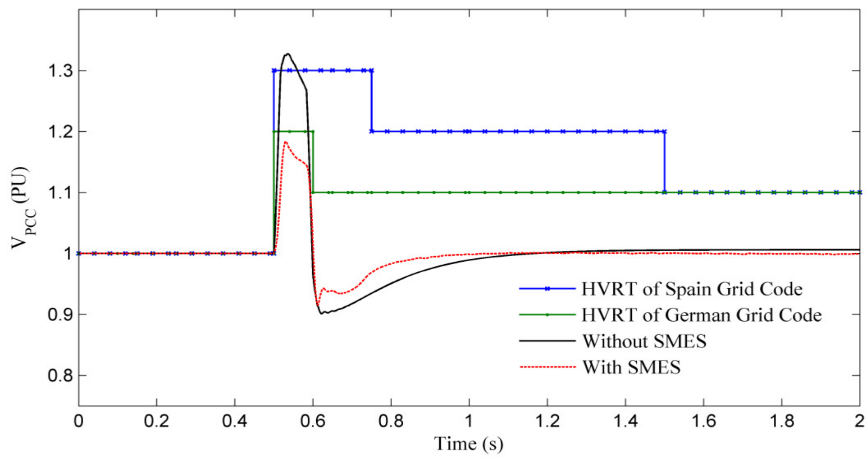


Figure 15. Complying voltage profile at PCC with Spain and German HVRT during grid swell

The grid swell is started at 0.5 s and lasts for 5 cycles. As can be observed in Figure 15, without SMES unit connected, during grid swell, voltage profile at the PCC will rise above 130 % and in this condition, DFIGs that connected at the PCC have to be disconnected from the grid if complying with both HVRT of Spain and German, however when fault is cleared out, the voltage profile can be soon recovered and remains in the safety margin of both LVRT of Spain and German. When SMES unit is connected, the voltage at the PCC is corrected to the safety margin of both HVRT of the grid codes of Spain and German, hence avoid the disconnection of DFIGs from the grid.

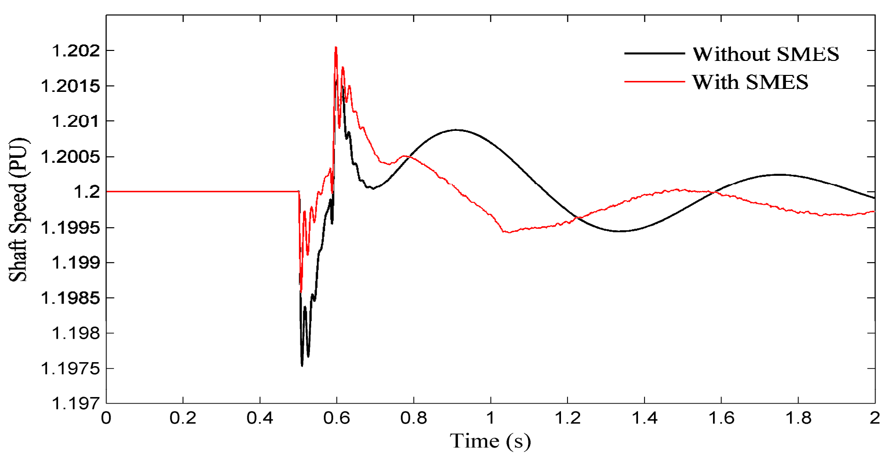


Figure 16. Shaft speed during grid swell

Voltage swell at the grid side will force the voltage at the PCC will increase accordingly depends on the percentage level of the swell. Hence, the power will be forced to level above the pre determined rated, the speed control in this condition will limit the speed to avoid over-speeding of the shaft, however in certain level of swell, the over speed protection may work and lead the generator to be shut down. As described in Figure 16, with SMES connected to the PCC, the settling time and oscillation of the shaft speed can be considerably reduced compared with the system without SMES.

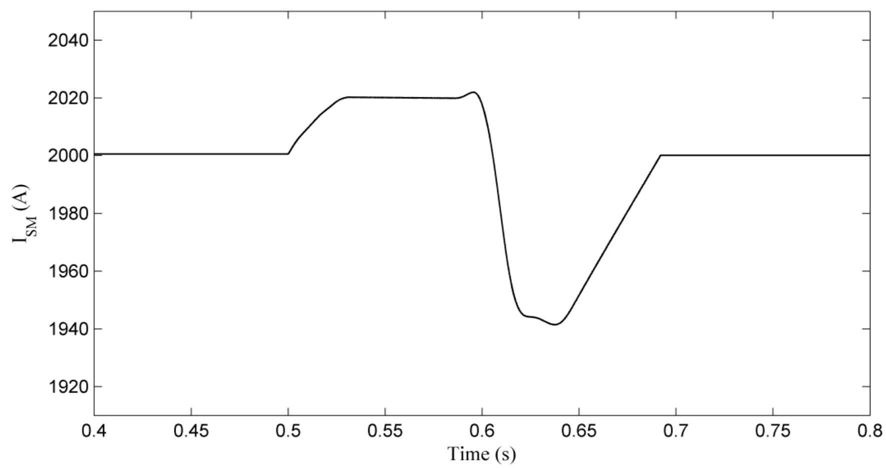


Figure 17. Current behaviour of SMES coil during grid swell

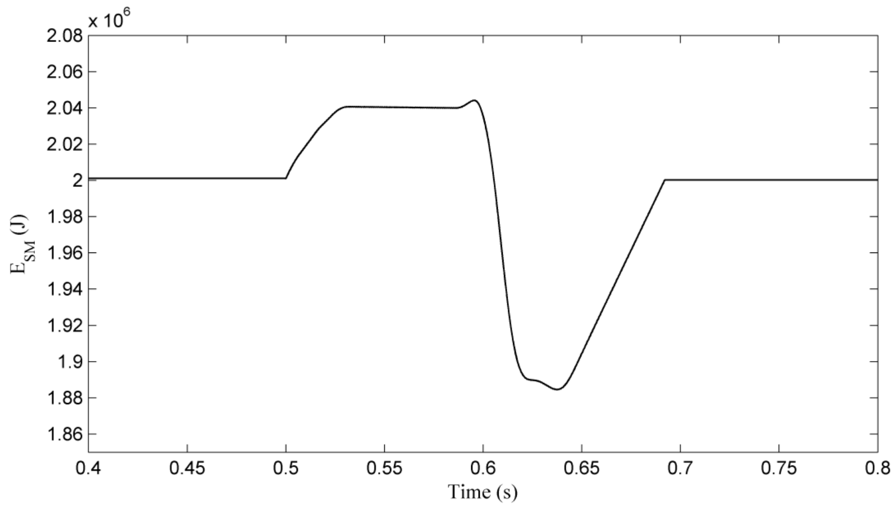


Figure 18. Stored energy behaviour of SMES coil during grid swell

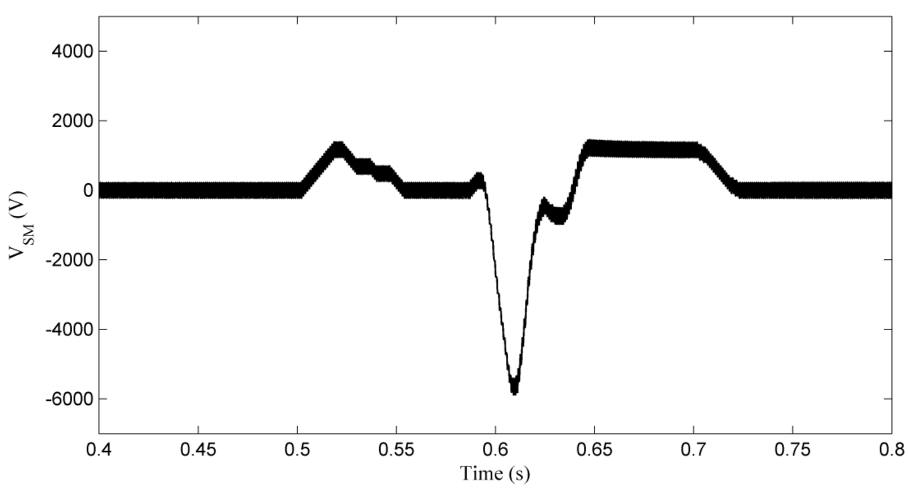


Figure 19. Voltage behaviour across the SMES coil during grid swell

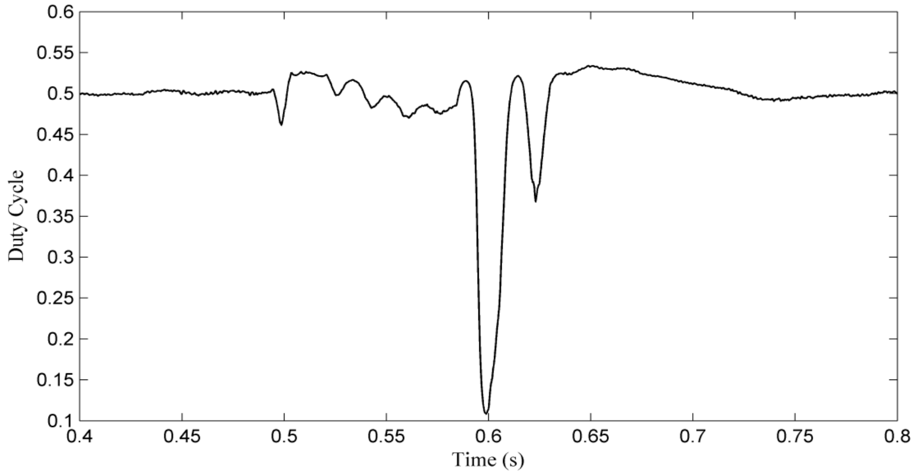


Figure 20. Duty cycle of DC-DC chopper during grid swell

Behaviours of SMES unit can be seen in Figures 17 to 20. Because the voltage swell at the grid side causing short overshoot of power produced by DFIGs, current in the SMES coil will rise slightly and likewise the energy in the SMES coil following the control regulation of FLC to damp the high voltage at the PCC. When voltage swell is cleared out, voltage at the PCC will slightly drop causing the power produced by DFIGs will drop either. This small amount of power drop is seen by the controller and taking action to discharging the small amount of energy and improve the voltage at the PCC, this can be justified in Figure 15, where voltage drop is lesser and voltage recovery is quicker with SMES unit connected if compare with the system without SMES.

VI. CONCLUSIONS

This paper investigates the use of SMES unit to enhance the VRT capability of doubly fed induction generator to comply with the grid codes of Spain and German grid codes. Results show that, without the use of SMES unit, DFIGs must be disconnected from the grid because the voltage drop during grid dip and voltage rise during grid swell at the PCC will cross beyond the safety margin of both the LVRT and HVRT of Spain and German, therefore in this condition wind turbines equipped with DFIG must be disconnected from the power system to avoid the turbines from being damaged. However, using the proposed converter and chopper of the SMES unit which are controlled using a hysteresis current controller (HCC) and a fuzzy logic controller (FLC), respectively, both the LVRT and HVRT capability of the DFIGs can significantly improve and their connection to the grid can be maintained to support the grid during faulty condition and to ensure the continuity of power supply.

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