Fault Ride through Capability Improvement of DFIG Using SMES Unit during Short Circuit

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***Abstract*—Catastrophic impacts of conventional based power plants on the environment has forced many nations to concern more on exploring renewable energy (RE) source for power plants. One of the most popular RE sources is wind, where the wind has been installed about 430 GW in 2015. Among wind turbines generator that available in the market niche, Doubly Fed Induction Generator (DFIG) is the most popular type. DFIG type dominates the total wind turbine installed capacity by about 17.5% in 2015 according to the report of JRC (Joint Research Center). Although DFIG is capable in extracting 5% more energy if compared to the fixed speed type, it is however, very sensitive to the fault that may violate the Fault Ride Through (FRT) which leads to the disconnecting of the DFIG from the grid. In this paper, a Superconducting Magnetic Energy Storage (SMES) unit is applied to improve the FRT capability of the system with DFIG during a short circuit event in the distribution lines. A Fuzzy Logic Type-2 is employed on the SMES to obtain the most optimum response of the DFIG during the fault.**

***Index Terms*—DFIG, Fault Ride Through, Fuzzy Type 2, Wind**

I. INTRODUCTION

Catastrophic impacts of conventional power plants on environment enforced many of countries worldwide to invest more on renewable energy based power plant. Currently, wind turbine generators (WTGs) are placed to be the most popular renewable energy based power plant which reaches about 430 GW installed capacity worldwide in 2015 [1]. Additionally, among other types of WTGs that available in the market niche, Doubly Fed Induction Generator (DFIG) type dominates the wind turbine installation by about 17.5% of the total wind generator installed capacity in 2015 according to the report of JRC (Joint Research Center). The popularity of DFIG is laid on the capability of DFIG in extracting 5% more energy compare to Fixed Speed Wind Turbine Generator [2].

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Moreover, with its one-third capacity of power electronics that equipped with the generator, a DFIG could reduce the overall cost significantly compared to its close rival, Full Converter Wind Turbine Generator (FCWTG) or so-called Type-D WTG.

The market share profile of DFIG can be seen in Fig. 1.

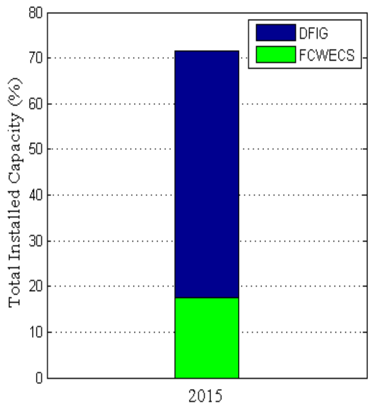

Figure 1. Market share profile of DFIG and FCWECS [1]

Along with its advantages, a DFIG apparently, is very sensitive with a fault that might reduce the voltage at the point of common coupling (PCC) [3]. When voltage profile at PCC is violated (according to the selected grid code), DFIGs must be disconnected from the grid to avoid any damages on the WTGs.

One of Fault Ride-Through (FRT) of grid codes is FRT of Spain. As can be seen in Fig. 2, FRT of Spain [4] is divided into three main categories that must be complied by the connected WTGs.

Area "I" is classified as high voltage tolerance for the voltage at the PCC. The maximum high voltage allowed during fault even is 130% and last for 0.25s. After that, it can be tolerated for 120% and last until 1.0s. The normal condition is placed among 90-110% that is shown in area"II". Area "III" indicates the minimum allowable low voltage during faults. The minimum voltage is allowed to drop up to 50% but last only for 0.15%, after that voltage restoration must follow the minimum determined voltage limit as shown in Fig. 2. When voltage drop hit beyond

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the limit, WTG must be disconnected from the grid to avoid any damages.

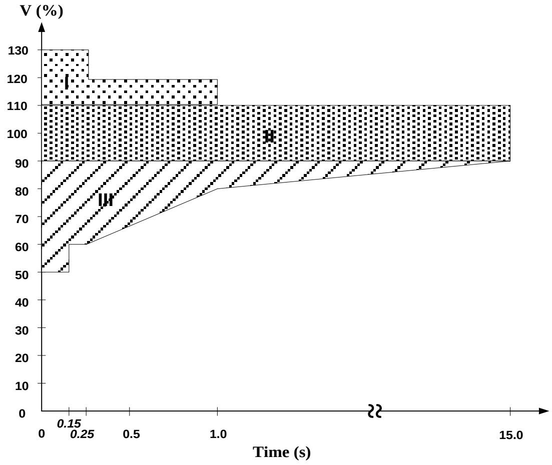


Figure 2. Fault Ride-Through (FRT) of Spain [4].

II. SYSTEM UNDER STUDY

A. System under Study

The overall system under study is shown in Fig. 2. It consisted of 6 x 1.5 MW DFIG that connected to the grid via 30 km distribution line. A SMES Unit is connected to the PCC bus to compensate for the DFIG performance during faults. All the parameters of the system under study including distribution lines are provided in Table I.

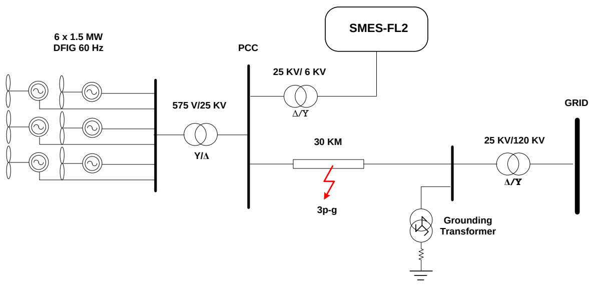


Figure 3. System under study

B. Typical Model of A DFIG

As can be seen in Fig. 3, A DFIG consists of two converters. Converter that connected with the stator of the induction generator is called Rotor Side Converter (RSC) while the converter that connected to the grid is called Grid Side Converter (GSC). A capacitor is placed as a DC link to allow transfers some amount of energy from/to the grid. The used parameters of DFIG in this study are provided in Table II and the equivalent circuit of A DFIG is shown in Fig. 4.

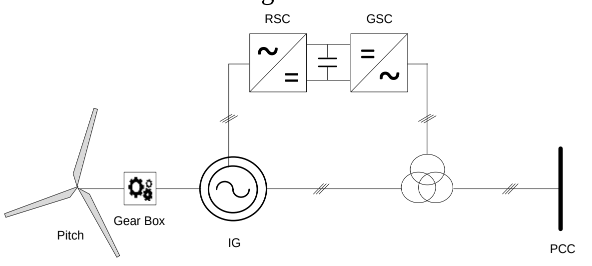


Figure 4. A typical model of A DFIG

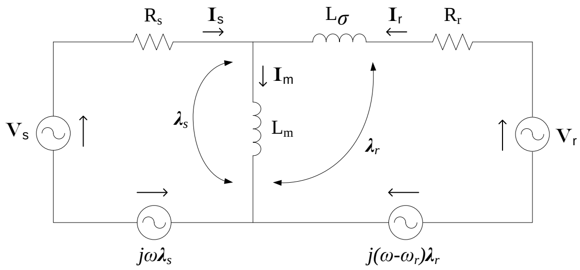


Figure 5. An equivalent circuit of A DFIG in Γ- form [5]

For convenient analysis, some references adopted the transient model of DFIG using an equivalent circuit of the DFIG machine in Γ-form as shown in Fig. 5 [5]

Key equations for quick review are provided in equations (1) to (3). Voltage vectors in the arbitrary references frame for the stator and rotor are given in the following equations:

$$V_s = R_s I_s + \frac{d\lambda_s}{dt} + j\omega\lambda_s \quad (1)$$

$$V_r = R_r I_r + \frac{d\lambda_r}{dt} + j(\omega - \omega_r)\lambda_s \quad (2)$$

Where ω is the angular speed and notations, s and r indicate stator and rotor quantities, respectively. From Fig. 5, it can be written that the flux space vectors of both stator and rotor are:

$$\lambda_s = L_m I_m \quad (3)$$

$$\lambda_r = L_\sigma I_r + L_m I_m \quad (4)$$

where L_m is the magnetizing inductance and L_σ is the leakage inductance. As $I_m = I_s + I_r$, it could be expressed that the stator current as:

$$I_s = \frac{\lambda_s}{L_m} - I_r \quad (5)$$

III. SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES)

Superconducting state of the coil is capable of storing energy based on the nature of inductor as formulated in equation (1):

$$E = \frac{1}{2} \times i^2 \times L \quad (6)$$

Where:
E = Stored Energy (Joule)
i = Current Flow in the Coil (A)
L = Inductor (H)

When a coil is placed on the very extremely low temperature that is so-called cryogenic temperature, a coil will obtain its superconducting state which the current flow almost encounter zero resistance.

Superconducting coil stores energy in form of a magnetic field that is generated by the flow of DC current in the coil which must maintain the superconducting state during immersion in liquid Helium at 4.2 K and placed in vacuum condition.

SMES is the only storage energy system that is recognized as a storage technology that stores electrical energy directly into electric current [6].

The energy substance in an electromagnetic field is formed by the flow of current on the N turns of the magnet coil. The product of turns number and flowed current, NI, is called magnetomotive force. The electromotive force in the coil can be assumed as written in equation 7 and the energy produced is given by equation 8. By integrating the magnetic field strength H over the entire volumes in which the induction B is significant, the stored energy is obtained. With a direct relationship between H and B, the volume of energy density can be acquired from those equations as written in equation 9. The energy density obtained in a magnetic field can be expressed by equations 8 and 9.

$$e = -N\frac{d\emptyset}{dt} \quad (7)$$

$$E = \int_0^{\emptyset} Ni(t)\, d\emptyset = \int_0^{B} lHA\, dB = \int_{Volume}\int_0^{B} H\, dB \quad (8)$$

$$E_{Volume} = \frac{B^2}{2\mu} \quad (9)$$

For instance, typical ferromagnetic materials at $B = 2T$ are about 2 x 106 J/m^3, which is an order of magnitude greater than the electrostatic field but tranquil small compared to electrochemical batteries. Inductor stores energy is proportional to the inductance value and to the square of the current as designated by equation 6. Consequently, it is reasonable to mention that large values of energy density can only be achievable by using such medium as a vacuum with very high current values, but electrical resistance of the coil is a limiting factor [7].

Electrical resistance drops significantly almost to zero at the point of the critical temperature. All superconductors' state can be achieved close to 4 K using liquid Helium. Niobium-Titane (NbTi) filaments normally used as the main material of superconducting coil which could operate in very extremely low temperature [8]. After the 1980s, a new superconductor made by chopper oxide ceramic was introduced. Employing liquid Nitrogen, this material can be frozen up to 100 K. This chopper oxide ceramic with liquid Nitrogen mechanism is known as high-temperature superconductor (HTS) [7].

A power electronic converter is interfaced the SMES coil and the grid to control the energy exchange between the SMES coil and the system. With fast innovation and research development regarding materials that demonstrate the superconductivity closer to room temperature, SMES will become cost-effectively viable in the near future [9]. Depends on the coil material and the configuration used, the overall efficiency of SMES exhibits in a typical range of 90-98% [10]. This high efficiency is achieved due to the fact that power loss is very low because the electric current that flows in the coil towards almost no resistance, moreover, no rotating parts are included in the SMES unit system.

The other advantages of SMES are that the time for charging and discharging process is very fast [11], power available immediately and very high power output can be provided for a short period of time. Thus, for immediate load characteristic, a SMES unit can be the better option. Moreover, compared with a MW size pumped hydro, the proposed MJ capacity of SMES can be claimed to be the only energy storage device that can supply the large bulk power load leveling applications with high efficiency [12] and even though its costs are high compared to other storage technologies with respect to the cost per unit of energy stored, SMES has cost competitive with other flexible AC transmission systems (FACTS) device or transmission upgrade solutions. This SMES currently is used generally to provide power-grid stability in a distribution system and maintain the power quality of supplied manufacture facilities with critical loads [13].

There are some references inform the capability of SMES in storing high energy capacity, for instance, Ref [7], states that SMES is capable of storing energy by about 10 MW. However, with a shorter time span, the size can be higher because a coil of around 150 to 500 m radius would be able to accommodate a load of 5000 MWh. Ref [14], mentions that SMES is able to store energy at the level of 1000 to 10,000 MWh. For real installation, there might be as much as 100 MW capacity already installed in the world [6].

Micro-SMES Unit is defined as a storage system in the range of 1 to 10 MW. This micro-SMES are currently available in the market and have been installed about 30 micro-SMES with capacity more than 50 MW. These micro-SMES are installed in different places of the United State for UPS and power quality improvement purpose [15]. The Engineering Test Model is a large SMES with a capacity of about 20 MWh, capable of supplying 400 MW of power for 100 seconds.

Design of 2 MJ SMES has been introduced by ACCEL instruments GmbH team in Germany. The SMES system is to ensure the power quality of a laboratory plant of Dortmunder Elektrizitats und Wasserwerke is maintained within the permissible standard. On the other hand, a D-SMES has been commercialized by American Superconductor, which is a FACTS device that is shunt-connected, to improve the power transfer, improve grid stability and enhance reliability [7].

The main disadvantage of SMES is based on the high cost of construction and installation and environment issue associated with a strong magnetic field. However, with the use of HTC's materials, the drawbacks might be reduced and market niece of SMES will be available soon in the next few years [16].

Other drawbacks are discussed in [17], where the coil is sensitive to temperature. A small change of temperature could make the coil become unstable and lead to high loss of energy. In addition, refrigeration can suffer the overall system with parasitic losses. The aforementioned drawbacks above are mostly related to possible technical problems. But, with accurate design, all those technical problems will be able to mitigate.

IV. Control Algorithm of SMES Unit

Superconducting Magnetic Energy Storage (SMES) is one of the promising compensators that might be applied to the power system. There are many papers proposed the wide application of SMES as discussed in [18]-[23]. Due to its enormous benefits including fast response, high storage capacity, capable in injecting both P and Q, etc, a SMES Unit is suitable to be employed in the wind farm as a compensator to enhance the WTGs performance. The proposed SMES Unit in this study is similar to the prior study in [24].

The SMES Unit consists of Voltage Source Converter (VSC) and DC-DC Chopper, where the focus in this study is on the use of Fuzzy Type-2 to control the transferability of required energy to/from the DFIG. The proposed control algorithm is described in Fig. 6.

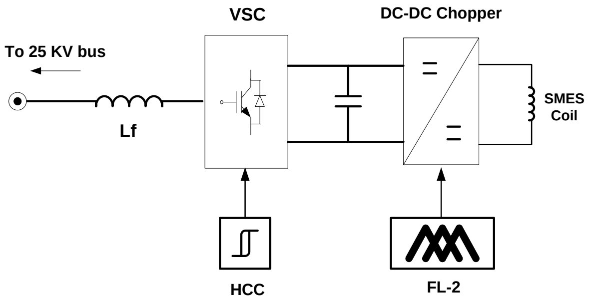
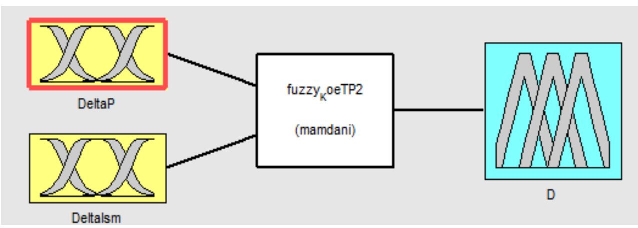


Figure 6. The control algorithm of the proposed SMES Unit

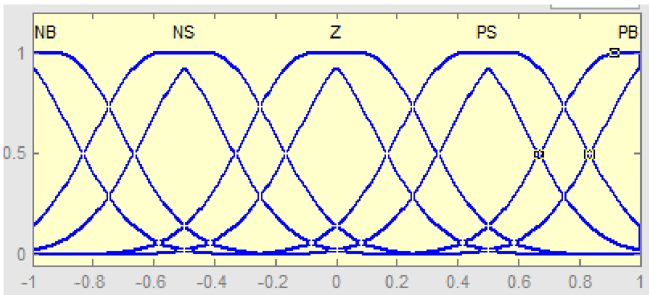
V. Fuzzy Type-2

Fuzzy type-2 is introduced first by A. Lotfi Zadeh [25] where it is capable to handle rule uncertainties which are not be able to handle by a conventional fuzzy. Currently, there are many papers pay more attention to the application of this fuzzy type-2. For example in [26], authors present a very comprehend discussion on theory and design of fuzzy type-2 including a simplified and efficient method in computing input and antecedent operations. The simplicity design of fuzzy type-2 is presented in [27].

In this study, two inputs for the fuzzy system are applied to obtain the optimal response of the SMES coil which is ΔP and ΔI_{SMES}. The fuzzy rules are set-up to dictate the duty cycle (D) for DC-DC chopper. The fuzzy input and output are exhibited in Fig. 7. SMES-FL2 parameters are available in Table III.



(a)



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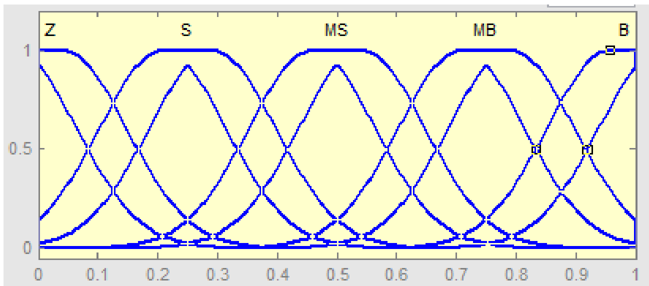

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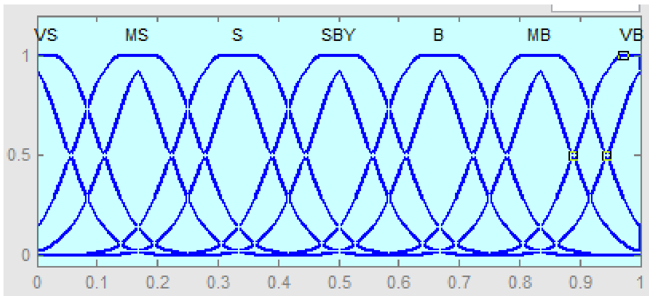
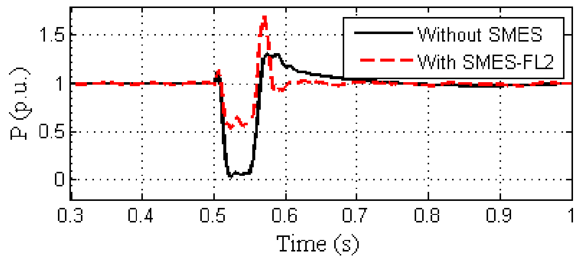


(d)

Figure 7. Fuzzy setting of the studied system: (a) layout system of FL with two inputs; (b) Fuzzy rules for ΔP input; (c) Fuzzy rules for ΔI_{SMES} input; and (d) Fuzzy rules for D output

VI. Results and Discussions

In this study, a 3p-g fault is applied in the distribution line as this kind of short circuit fault is the most severe and commonly occurred. The 3g-p fault lasts for 0.05s or about 3 cycles. All the models in this study are carried out using Matlab/Simulink. DFIG's responses can be seen in Fig. 8.



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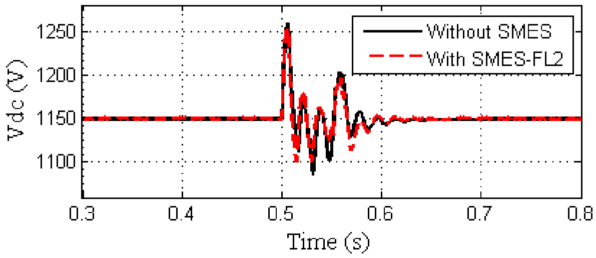

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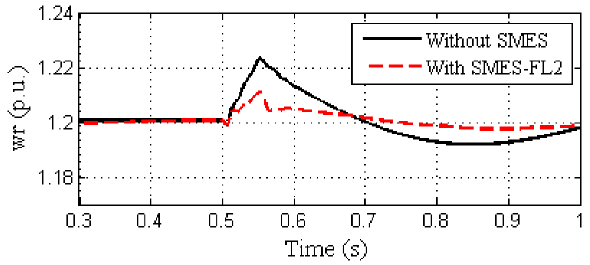

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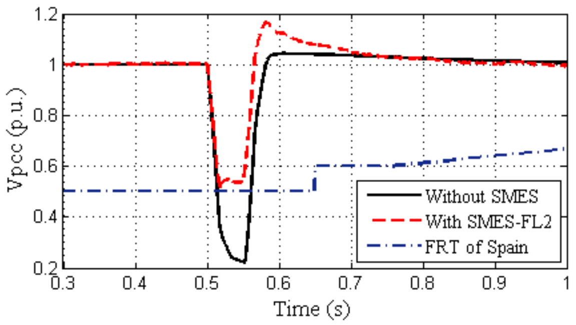

(d)

Figure 8. DFIG system response during 3p-g fault with and without SMES-FL2; (a) Generated Power: (b) Voltage at DC link; (c) Generator Speed (ω_r); and (d) Voltage at PCC.

As can be seen in Fig. 8(a), without SMES-FL2, generated power significantly drops during the fault, however, when SMES-FL2 is connected, the generated power drop is significantly reduced almost 50% compared to the system without SMES. The DC link response of DFIG is quite similar with and without SMES-FL2 as demonstrated in Fig. 8(b). Generator speed (ω_r) responses during fault are plotted in Fig. 8(c). It is clearly revealed from the figure that oscillation of generator speed with SMES-FL2 is smaller compared to the system without SMES.

When no SMES is connected, the voltage drop at the PCC reaches about 80% and hit beyond the limit of FRT of Spain and lead to the disconnecting of the WTG from the grid (as shown in Fig. 8(d)). However, when SMES-FL2 is connected to the PCC bus, voltage drop significantly reduced above the FRT of Spain and avoid the WTG from disconnection. If the WTGs are large MWs, disconnecting them from the grid means large of economic loss for WTGs' owner.

TABLE I. PARAMETERS OF DISTRIBUTION LINE

Parameters	Distribution line
R_1 (ohms/km)	0.1153
R_0 (ohms/km)	0.413
L_1 (H/km)	1.05e-3
L_0 (H/km)	3.32e-3
C_1 (F/km)	11.33e-9
C_0 (F/km)	5.01e-9

TABLE II. PARAMETERS OF DFIG

Parameters	DFIG
Rated Power (MW)	5 x 1.5 MW
R_s (p.u.)	0.023
H(s) (p.u.)	0.685
V_{dc} (V)	1150

TABLE III. PARAMETERS OF SMES-FL2

Parameters	SMES-FL2
Coil (H)	0.5
Capacity (MJ)	1.0
I_{SMES} (A)	2000

VII. CONCLUSION

The application of SMES-FL2 on power system with DFIG is investigated in this paper. The simulation results show that some responses of DFIG are significantly improved with SMES-FL2 during 3p-g fault compared to the system without SMES-FL2. Moreover, with SMES-FL2, the DFIG would not be disconnected during fault as the voltage drop at PCC could be reduced significantly above the allowable limit of FRT of Spain.

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