International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

March 2015 | Issue 22 | Volume 7 | Number 1 | Pages 100-106

# VOLTAGE SAG REDUCTION IN DFIG BASED WIND TURBINE DURING UNBALANCED FAULTS USING SMES AND SVC WITH FUZZY LOGIC AND PID CONTROLLERS

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**Abstract-** Unbalanced faults are the most common type of faults occurring in the power system and effects of this kind of faults on wind turbine is so important. This paper presents enhanced control algorithms for doubly fed induction generator (DFIG) based wind power generation systems during unbalanced fault conditions. A superconducting magnetic energy storage (SMES) unit and static var compensator (SVC) are employed to improve the dynamic behavior of a wind energy conversion system equipped with DFIG during these situations. The simulation is done by considering the detailed design and using MATLAB/SIMULINK software and real time digital simulation results during contingencies, such as unbalanced faults are analyzed and the performance of the system in response to various unbalanced faults is investigated.

**Keywords:** SMES, SVC, Unbalanced Fault, Contingency.

## I. INTRODUCTION

The unbalanced voltage results in improper effects on the power quality. Use the unbalanced power in system and electrical equipment are causing problem to them [1], [2]. Structure and requirements of the power system is one of the important factors in the absorption or release the real power of superconducting magnetic coils. Supply and receive the quantity of energy in SMES unit is depend on controlling the firing angle of the SMES unit converter.

SMES units are capable of storing energy to several MWh. To improve system performance, their response is too fast. Due to these items, they are suitable for energy management. The enhancement of transient stability for a balanced 3 phase fault due to the application of SMES is demonstrated.

Because of various applications of SMES in solving problems associated with voltage stability and power quality for large customers and industrial electrical installations and military, their use is considered [3-5]. Due to the multiple applications of fuzzy logic in various fields, especially in control and data processing, it can be used as powerful and useful tool.

The Fuzzy logic controllers using fuzzy logic implementation and has been programmed into membership functions, fuzzy rules and rule interpretation. So far, several methods have been used to control SMES. To get the best performance, the control system for SMES system depending on hysteresis current control together with fuzzy logic control is employed [6].

SVC using power electronic components is effective in improving network stability. Its main task is to control the reactive power that can be done by adjusting the firing angle of the thyristor [7, 8]. A SVC is controlled externally by a Proportional Integral Differential (PID) controller to improve the voltage performance [9].

In this paper the response of doubly fed induction generator (DFIG)-based wind power generation systems during unbalanced faults when applying SVC and SMES is investigated and simulation results are compared. Reactive power compensation using the SVC at the point of common coupling (PCC) is presented to enhance the reactive power capability and voltage controllability of the DFIG wind turbine system for improving dynamic and steady state stability of the wind turbine system.

A 9 MW wind farm with six units of 1.5 MW DFIG wind turbines is modeled during occurrence of unbalanced faults. Voltage at PCC, voltage across DC link capacitor, active and reactive power are shown and discussed in these scenarios.

## II. SYSTEM CONFIGURATION

In this study, to investigate DFIG wind power plants behavior during unbalanced faults, SVC and SMES are used. Figure 1 illustrates the power network. The network has six 1.5-MW DFIGs. The DFIG consists of an induction generator or asynchronous generator. Wind turbines are connected to the network via step-up transformer (575 V to 25 kV) and a transmission line of 30 km. In this analysis, according to the wind speed of 15 m/s, the turbine output power is 1.0 pu, and the generator speed is 1.2 pu. A SMES and a SVC are connected to the PCC to improve the dynamic behavior of DFIG during unbalanced faults analysis.

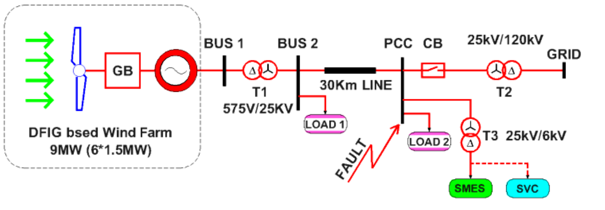



Figure 1. Single line diagram of the wind farm and the power network

The SMES/SVC unit are connected to the 25 KV Bus. Wind turbine model characteristics are given in Table 1.

Table 1. Design Parameters

| Device | Parameters | Value |
|---|---|---|
| DFIG | Rating power | 9 MW |
| | Rating voltage | 575 V |
| | Stator leakage reactance | 4 mH |
| | Rotor leakage reactance | 2 mH |
| | mutual inductance | 69.31 mH |
| Rotor-side converter | switching frequency | 5kHz |
| Grid-side converter | rating power | 120 kVA |
| | Filter inductor (*L*) | 0.3 p.u |
| | switching frequency | 5 kHz |
| DC chopper | rating power | 80 kVA |
| | switching frequency | 10 kHz |
| | DC Link capacitor | 10000 μF |
| | DC rating voltage | 1150 V |

The most common types of faults are single line-ground (SLG) and line-line (LL). Other types are double line-ground (DLG), open circuit, and symmetrical three phase faults [10, 11]. The DFIG with a dynamic source (induction machine) has a different behavior during faults than conventional synchronous sources. In other words, their impact on fault current magnitudes is expected to be different than conventional synchronous machines of similar power rating.

Moreover, the presence of power electronic interface between the distributed generators and the grid causes the behavior to be even more complex. The unbalance in distribution systems has been shown to have effects on the magnitude of fault currents in the system. Therefore, the presented results illustrate the impact of unbalance in distribution systems and the fault currents supplied by the DFIG. All types of asymmetrical faults have been studied and the fault currents supplied by wind generators have been presented.

## III. MODELING OF DFIG SYSTEM WITH SVC

The most important characteristic of SVC is reactive power compensation that is able to generate or receive reactive power. The SVC using power electronic components to control the power flow and enhance network stability [12]. When system voltage is less than the voltage at SVC terminals, the SVC generates reactive power (SVC acts as capacitive). When system voltage is higher than voltage at the SVC terminals, it absorbs reactive power (SVC acts as inductive). SVC shall apply with respect to the best location and the level of compensation, which can increase the system var margin [13].

Under normal operating situations, system and SVC terminal are the same voltage and power transfer doesn't take place between the SVC and the grids. Figure 2 shows the SVC coupled with DFIG generation system.

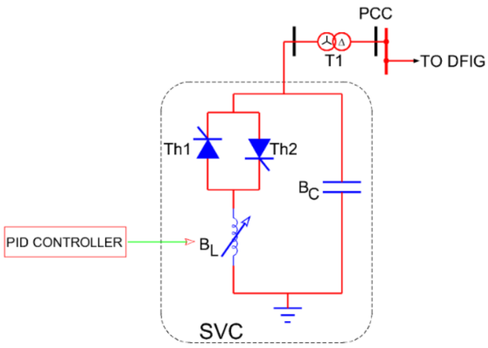



Figure 2. SVC coupled with DFIG

In the studied SVC, the equivalent susceptance ($B_L$) is controlled according to the control block diagram as shown in Figure 3. For voltages below the reference value, the value of $B_L$ would be positive and the reactive power would flow toward the system; on the other hand, for voltages higher than the reference value, the value of $B_L$ would be negative and the reactive power is absorbed from the power system. Detailed design method proposed in [14, 15] is used to design a PID damping controller for the introduced SVC in this paper.

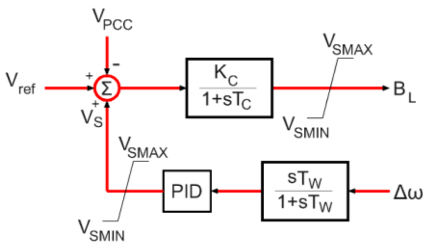



Figure 3. SVC control block

## IV. MODELING OF DFIG SYSTEM WITH SMES

During the operation and use of the superconducting magnet and when energy is charged or discharged, the current and magnetic field of SMES change. Then the eddy current and magnetization loss result in the SMES system.

The SMES unit in this study contains a two winding transformer with Yd vector group and 25/6 kV voltage level, a thyristor controlled bridge ac to dc converter, and a 0.5 H superconducting coil. The convertor implies the supplied voltage across the superconducting coil. The charge and discharge controls can easily be acquired by altering the delay angle ($\alpha$) controlling the thyristor's sequent firing. As it is shown in Figure 4, in case of α below 90°, the converter acts in the rectifier status (charging) and when α is above 90°, the converter acts in the inverter status (discharging).So, based on the system prerequisites, the direction of power injection to the power system can be specified i.e. absorption from or injection to the system [16].

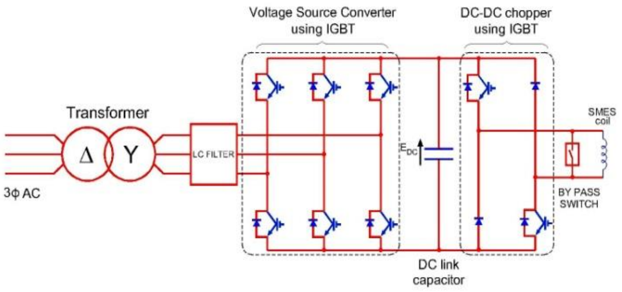



Figure 4. Typical configuration of VSC-based SMES system

By setting the average voltage across the coil, superconducting coil is charged or discharged that this is due to the positive or negative value of the duty cycle (D) of dc-dc chopper which is controlled by the fuzzy logic controller. When the duty cycle is greater than 0.5, the coil is in charging mode and for the duty cycle is less than 0.5, the coil is in discharging case.

The VSC and the DC-DC chopper are linked by a DC link capacitor of 50 mF. The rated DC link voltage is 1150 V, which is considered to be constant [17]. For a SMES system, the amount of energy stored in the coil and the rated power which are characterized by (W in Joule) and (P in Watt) respectively and their relationships will be as follows:

$$W = 1/2 I_{SMES}^{2} L_{SMES} \quad (1)$$

$$P = \frac{dW}{dt} = L_{SMES} I_{SMES} dI_{SMES} / dt = V_{SMES} I_{SMES} \quad (2)$$

where $L_{SMES}$, $I_{SMES}$ and $V_{SMES}$ are expressed for the inductance of the coil, the dc current flowing through the coil and the voltage across the coil respectively. It should be noted that the average of SMES coil's current is too close to the peak of line current and this value can be an important factor in the design of the SMES coil [18].

## V. CONTROL STRATEGY

The SMES used in this paper is composed of a VSC and dc–dc chopper, as shown in Figure 5. Hysteresis current controller (HCC) controls the voltage source converter and the dc-dc chopper is controlled by a fuzzy logic controller (FLC).

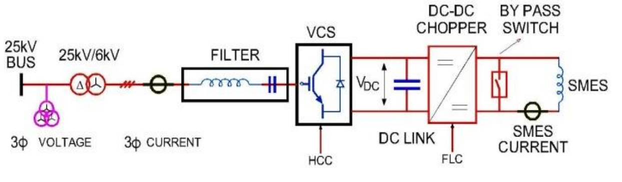



Figure 5. SMES configuration

### A. Hysteresis Current Controller

A hysteresis current controller is used to control the current of converter. The reasons for employing of this controller are: easy to use, rapid dynamic response and not sensitive to the parameters of the load. Being error in the current are produced the switching signals. By comparing between the reference current and actual current, the error generates. The main function of this approach of control is that in each phase, the input current follows the reference current. In this method, the deviation of the current is limited between the upper and lower range in the hysteresis band [19].

Phase dependency can be reached to the minimum value by implementing the phase-locked loop (PLL) technique while converter switching being preset at a fixed frequency. PLL block with its input and output is shown in Figure 6. In HCC block, three phase currents $(I_{abc})$ are compared with the reference currents $(I_{abc}^{*})$, which is displayed by d and q axis of coordinate instead of a vector and its related angle.

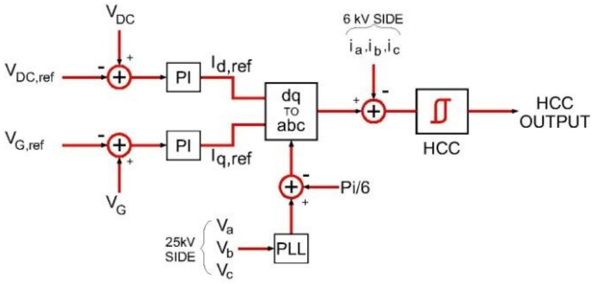



Figure 6. HCC control scheme

### B. FLC

A very successful and feasible method for designing a controller is Fuzzy logic which utilizes the system characteristics and principals and solves the problems with ambiguity or uncertainty. This controller (Fuzzy logic) has three categories: a process that converts conventional expressions to fuzzy terms, list of rules or rule base and a process that converts fuzzy terms to conventional expressions [16]. A dc–dc chopper control the power transfer between the SMES coil and the ac system, on the other hand, to control the duty cycle (*D*), fuzzy logic is selected. For good operation of the IGBT's of the chopper, they need signals for their gates; these signals are generated from the comparison between the reference signal of PWM and the saw tooth carrier signal as demonstrated in Figure 7. The desired frequency of the saw tooth carrier signal for the chopper is 100 Hz.

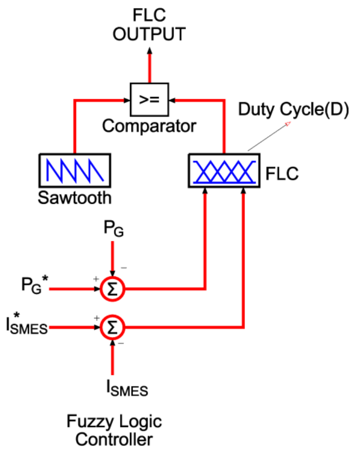



Figure 7. FLC control scheme

Power generated by DFIG and SMES unit current act as the inputs of FLC model. The duty cycle determines the direction and the magnitude of the power transfer between the SMES coil and the ac system. If the duty cycle ($D$) is equal to 0.5, the coil does not take any action, and then the system will operate normally. In this situation where the system is in normal operating conditions, a bypass switch that is placed across the SMES coil (as shown in Figure 5 will be closed to prevent the discharge of SMES energy. In other words, the bypass switch is controlled just like that it will be closed if the value of $D$ is 0.5; otherwise, it will be opened.

The model is built up using the graphical user interface tool provided by MATLAB. Each input was fuzzified into five sets of Gaussmf-type membership function (MF). The variation range in the SMES current and DFIG output power, as well as the corresponding duty cycle, is used to develop a set of fuzzy logic rules in the terms of (IF–AND–THEN) statements to link the inputs to the output. The corresponding MFs for the input variables $P_G$ and $I_{SMES}$ are shown in Figures 8 and 9, respectively. The MFs for the duty cycle as output variable are considered with the scale of 0 to 1, as shown in Figure 10. The duty cycle for any set of mentioned input variable i.e. $P_G$ and $I_{SMES}$ can also be assessed based on the surface graph shown in Figure 11.

With a single-input single-output variable, the fuzzy controller has a simple control strategy [20]. Practical application and system performance according to the test, trial and error specifies the control rules of the controller.

Logical conclusion based on the basic inference engine performance is achieved. Exactly, the inference engine comprises the rule base and the controller input data to gain the perfect result. The outcome of the inference engine is the fuzzy output of the controller that provides the input to the defuzzification interface. For this purpose, Mamdani's method has been applied [16].

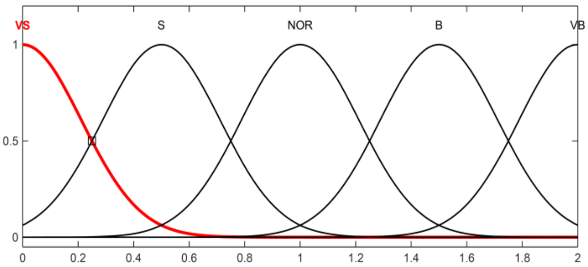



Figure 8. MF for the input $P_G$ (pu)

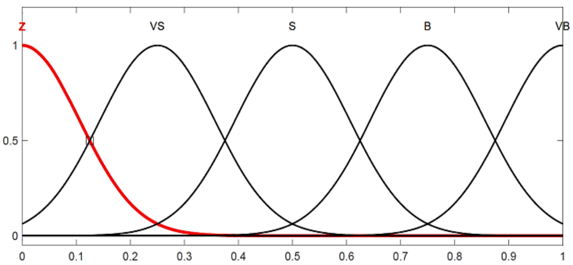



Figure 9. MF for the input $I_{SMES}$ (pu)

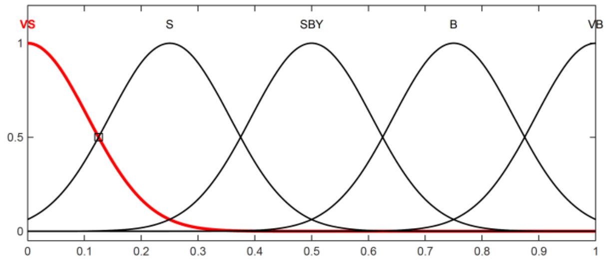



Figure 10. MF for the output D (duty cycle)

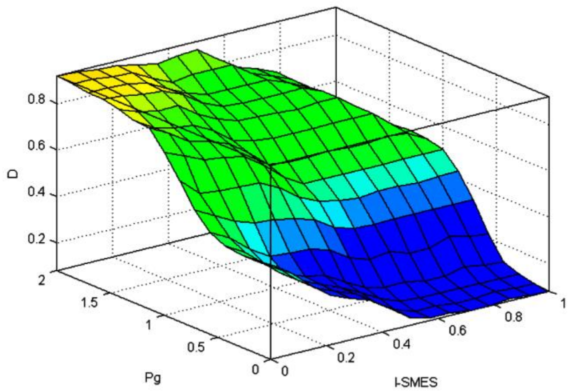



Figure 11. Surface graph: duty cycle

## VI. SIMULATION RESULTS

Simulations according to the following three types of unbalanced faults are done: single line to ground fault, line to line fault and double line to ground fault. The fault occurred at time equals to 1.3 s, and is cleared 0.1 s later.

### A. Single Line to Ground Fault

For this case it is assumed that a single phase fault has appeared on phase (a). In this situation, the faulted phase lost its excitation but the other two are still at the same level of excitation as shown in Figure 12. This situation caused high currents in all the three phases. Influence of SMES and SVC in two healthy phases is negligible.

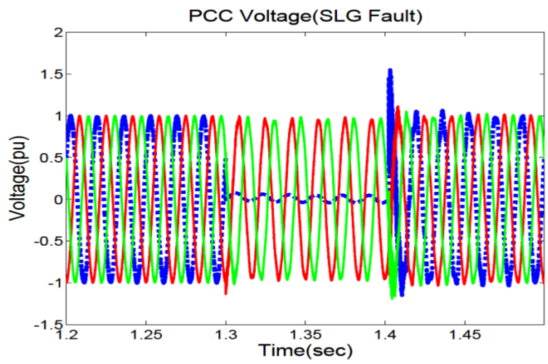
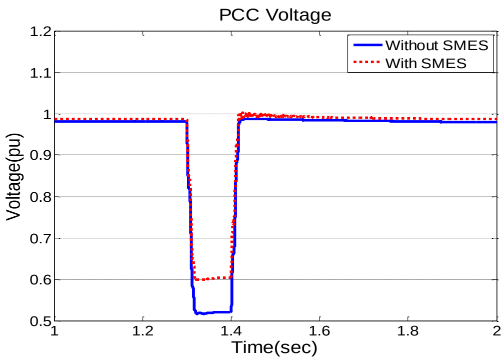


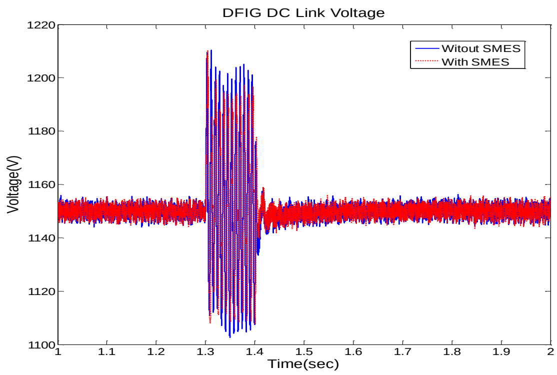

Figure 12. Single Line to ground Fault

### B. Single Line to Ground Fault

For this case, the fault is applied on phases (a) and (b). Results for this scenario are given in Figure 13 and Figure 14. Figure 13 gives the influence of SMES and Figure 14 gives the influence of SVC.

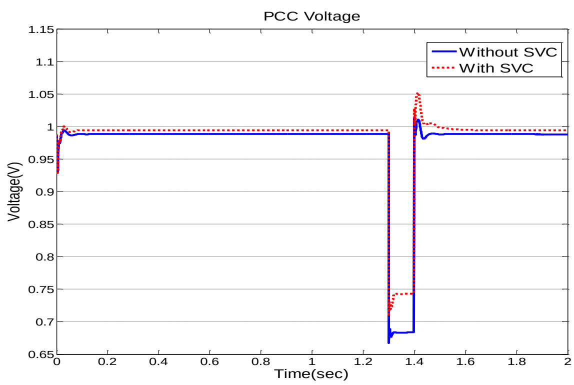



(a)

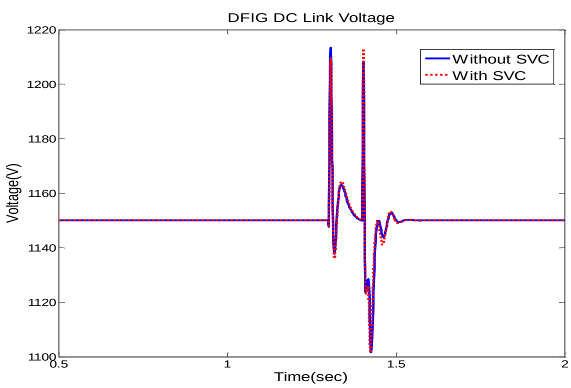



(b)

Figure 13. The influence of SMES in case of line to line fault, (a) PCC voltage, (b) DC Link Voltage




(a)

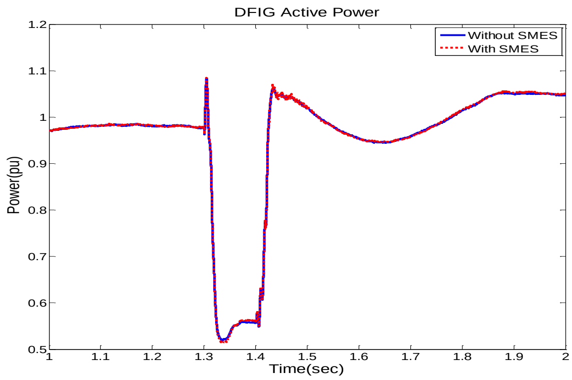



(b)

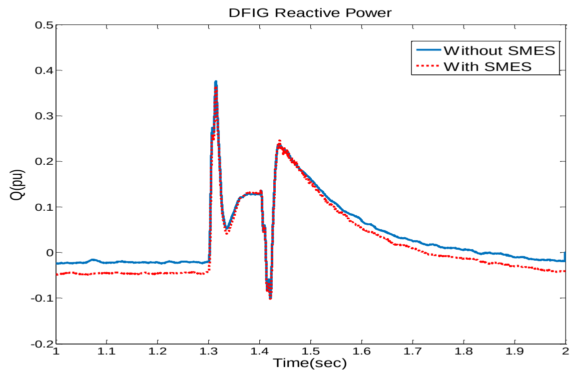
Figure 14. The influence of SVC in case of line to line fault, (a) PCC voltage, (b) DC link voltage

In this scenario, because of fast reply of SMES, the response of SMES is a little better than SVC. It also can be seen that the connection of the SMES and SVC units to the studied system at the fault clearing time, the voltage overshoot across the dc-link capacitor is slightly decreased.

Figure 15 shows the results for active and reactive power with and without SMES and Figure 16 illustrates active and reactive power in case with and without SVC. Once the fault is cleared at 1.4 sec, the voltage at the DFIG terminal starts to rise. The active power increases while the reactive power decreases. The effect of SMES and SVC on reactive power is shown.

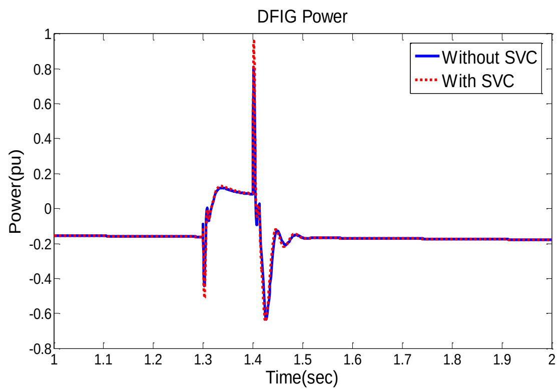



(a)

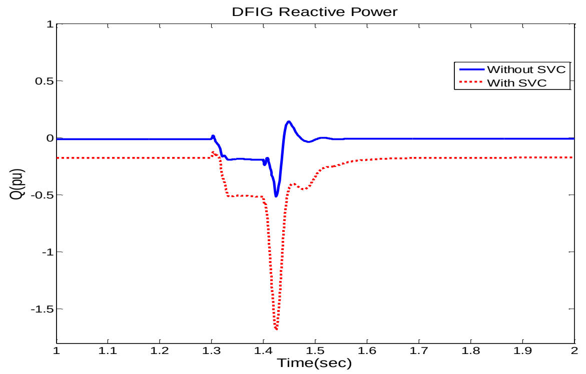



(b)

Figure 15. Active and reactive power in case of DL and use of SMES, (a) Active power, (b) Reactive power




(a)




(b)

Figure 16. Active and reactive power in case of DL and use of SVC, (a) Active power, (b) Reactive power

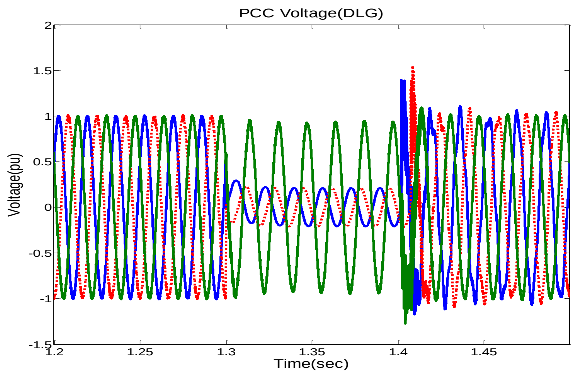
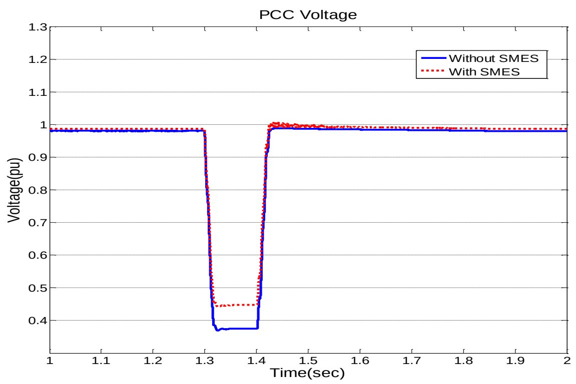
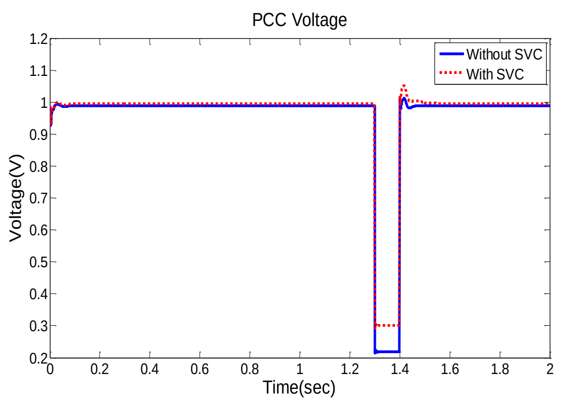



Figure 17. The PCC voltage waveforms in case of DLG fault




(a)




(b)

Figure 18. The PCC rms voltage in case of DLG fault, (a) use of SMES, (b) use of SVC

### C. Double Line to Ground Fault

For this case and contrary to the previous scenario, the faulted phases (a) and (b) completely lost excitation. Figure 17 is shown voltage waveforms. The loss of excitation of phases (a) and (b) caused a large current in healthy phase, which is larger than the currents flowing in the faulted phases. Figure 18 gives influence of using of SMES and SVC respectively. As shown in Figure 18, the influence of SMES and SVC in this situation approximately is equal.

## VII. CONCLUSIONS

In this paper, the transient behavior of DFIG-based wind power plant during unwanted contingencies was studied. A static var compensator (SVC) and also a SMES with PID and fuzzy logic controllers are introduced in the wind turbine doubly fed induction generation to mitigate the effect of unbalanced faults. The respective waveforms are verified for without and with SMES and SVC under unbalanced faults. Three scenarios were considered at the PCC terminal: line to ground fault, which in this case the effect of SMES and SVC is not noticeable in two healthy or normal phases; line to line fault that in this situation, performance of SMES is slightly better than the SVC and double line to ground fault which for this type of fault, there is no significant difference in the performance of SMES and SVC.

It is observed that, the effect of SMES and SVC to improve the dynamic performance of DFIG-based wind power plant despite of the quick response of SMES, approximately identical. In this regard, it is necessary that the cost and the complexity of controlling of SMES and SVC considered. For the future study, it could be applied SVC and SMES together and the results would be investigated.

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