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Improving the quality of power supply parameters During voltage sag and swell based on Super Conducting Magnetic EnergyStorage (SMES)

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Abstract. The emersion of critical loads in industrial, commercial, and domestic applications including power electronic equipments, computers, microprocessors, florescent lamps, and non-linear loads such as induction furnaces in distribution networks has made the subject of power quality one of the distribution system's main concerns. Any disturbance in the distribution system's power quality can lead to the disturbance in the operation of these loads and consequently leading to time loss and financial cost. Any deviation or unwanted change in the voltage, current, or frequency of the electricity which causes failure or dysfunction of the electrical equipments is called power quality or better to say weakness in the power quality. A unit of SMES will be introduced in this paper to improve the quality of power during voltage sag and swell. The convertor and the chopper of the SMES unit are respectively controlled via a PID controller and a Fuzzy logic controller.

Keywords: Fuzzy controller, Super Conducting Magnetic Energy Storage (SMES), Voltage Sag, Voltage Swell

1. INTRODUCTION

Variety of applications was introduced for Superconducting technology with its emersion. We can refer to SMES, out of all these applications, as one of the most famous ones. In SMES, energy is stored in a coil using a big inductance which is built out of a superconductor. SMES has rapid dynamic response since in this technique energy is converted from electric state to magnetic or vice versa. Hence, it can also be used to improve dynamic functionality. Therefore in summary, the most important capability of SMES is its ability to separate the production from consumption and gives it independency which has many benefits such as economical utilization, improvement in dynamic function, and reduction in pollution [1-4]. An ideal power network is a kind of network in which electrical energy is transferred in the form of voltage and sinusoidal current in fixed frequency and in specified voltage levels from the power plants to the stations.

In the generation and transmission section, the rotating coils not being ideal, the transformers' magnetizing current and non-linear characteristics of the used power electronics devices causes the appearance of the harmonic distortions in the form of current sinusoidal waves and delivered voltage. Also occurrence of different defects in the transmission and

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distribution section cause some undesired changes in the range of the voltage. Connecting distributed generation sources to the network, due to their dependency on the atmospheric conditions, can also cause distortion in the voltage and the power network current, and they are one of the most important parameters in creating reactive current. Besides, these loads are also very sensitive to distortions in the voltage and current and any sort of change in the voltage and current wave form causes undesired impact on the performance [5].

The aim of this project is to control voltage sag and voltage swell and to improve the quality of electricity during voltage sag and swell. Generation source is the synchronous generator whose rotation is done with wind power.

This paper, is investigating a new application of SMES unit to improve the performance of a wind turbine equipped with synchronous generator during voltage sag and swell, a new control system for the SMES unit based on fuzzy logic controller is suggested. We have used the "SIMULINK/MATLAB" software to simulate the wind turbine, SMES unit, and the model under the study. To show the improvement of the dynamic performance, WECSs integrated into SMES unit were also analyzed.

2. SMES

An SMES unit consists of a superconducting electromagnetic coil, a power correction system, a cryogenic cooling mechanism, and a vacuum tank/cryostat to keep the electromagnetic coil in the needed low temperature to create the superconducting state. This configuration makes the SMES to store electricity with the efficiency range of 95%-98%. Other benefits of an SMES unit are very fast response and the usability in high power applications. A sample structure of SMES is shown in figure 1 [6].

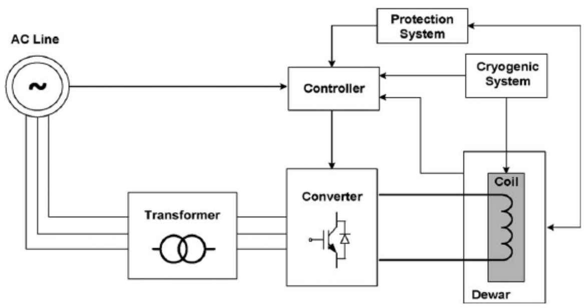


Figure 1. Sample Schematic diagram of an SMES unit.

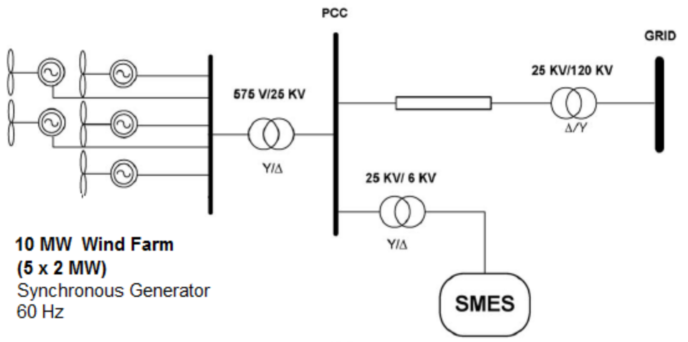


Figure 2. Understudy system.

3. THE SYSTEM UNDER STUDY

The understudy system in the figure 2 consists of a synchronous generator with the power of 5×2 MW with the wind turbine propulsion and voltage of 575 V and frequency of 60 HZ which is connected to a 25 KV bus via an increasing transformer 25/0.575 KV Y/Δ and in the end is connected to a grid 120 KV bus via a 25/120 KV Δ/Y transformer.

For the average wind speed of 15 m/s which is considered in this paper, the output power of the turbine and the generator speed will be respectively 0.98 pu and 1.0 pu. The SMES unit is connected to the 25 KV bus.

4. SMES CONTROL METHODS

Generally, there are two major configurations for SMES meaning the current source converter (csc) and (vsc). Normally csc is connected via a 12-puls-converter configuration to omit the fifth and the seventh harmonic currents from the ac side and the sixth harmonic voltage form the dc side and thus significant saving happens in the harmonic filters. The cost is relatively high as the configuration uses a pair of 6-puls csc which is connected in parallel. In other words, vsc have to be connected via a dc link to a dc-dc chopper in which case the energy exchange between the SMES electromagnetic coil and the ac network is facilitated [6].

The [7] reference estimates that the overall cost of csc switching parts is 173% needed switching parts and power diodes for the vsc equal capability and chopper. In addition, a vsc with self-commutating capability (converting ac current to dc) is better and enters smaller harmonic currents to the ac network than a comparable csc. Using IGBTs in a configuration is more profitable than GTO since the switching frequency of a IGBT is about 2-20 KHZ while the switching frequency of GTO cannot be more than 1 KHZ. The suggested SMES configuration in this project consists of a VSC and a dc-dc chopper as you can see in figure 3 [6].

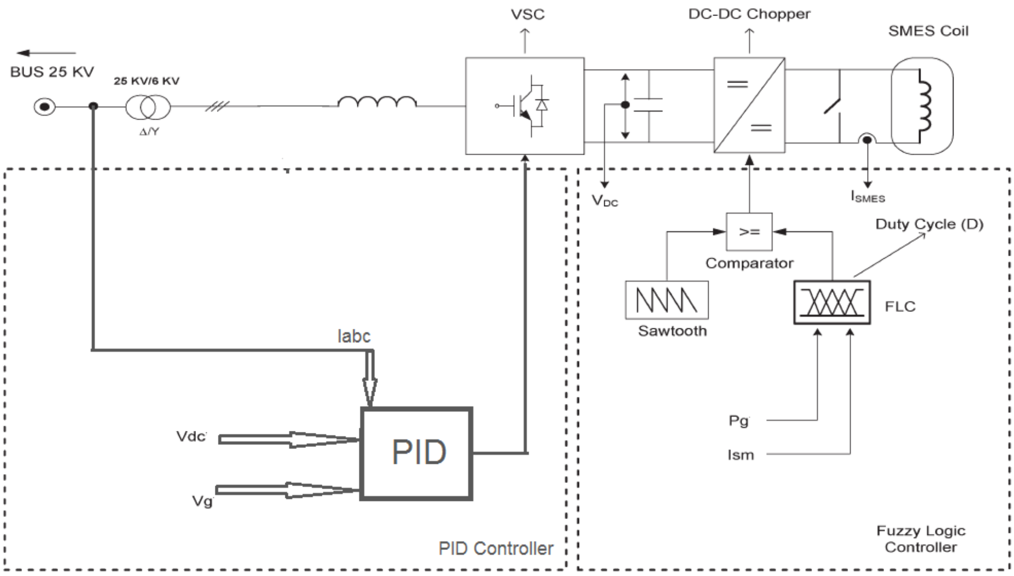


Figure 3. SMES unit configuration and PID-FLC control design.

The converter and the chopper are controlled respectively via a PID controller and a fuzzy logic controller (FLC). Stored energy in the SMES coil is calculated as below:

$$E=1/2\ L_{SMES}.I_{SMES}^2 \qquad (1)$$

In which E, ISMES, and LSMES are respectively the stored energy, current, and SMES unit coil inductance. Although dc-dc chopper control system is shown in [8],but the control method for VSC as a part of SMES configuration is not shown. In comparison with [8], dc-dc chopper control system in [9] is not shown. SMES configuration in [10] is new, however its application for WTG is low and limited and since SMES coil is connected to separate DFIG converters, this topology is only suitable for new WECS installations. The application of SMES system in small networks is explained in [11] while SMES system is used for stabilizing the whole small network system. The control design introduced in this paper is very complicated since it is used for three different controlling levels and this increases the cost of installation and maintenance. In addition it needs a very strong calculation system as well. The suggested controlling algorithm in this paper is much simpler and closer to real applications in comparison with the suggested similar controller in [12] and [13]. In the noted articles, four (PI) controllers are considered which need more calculation time to set their parameters optimally to keep the whole system stable and to get a desirable dynamic response during transient events. In addition, the controlling system for dc-dc chopper in these articles has only considered the generated active power (PG) by DFIG as a controlling parameter, and energy capacity of SMES unit is ignored

[6]. In [14], improving power systems transient stability by SMES is investigated. In this article the transient stability for a single machine system connected to an infinite bus where SMES is used to control stability is studied. The systems variable is $\Delta\omega$. The selected controlling signal for the study is the deciding factor in the several amounts of $\Delta\omega$. To understand the impact of SMES on the improvement of the power system's transient stability, its performance is compared with a normal dynamic brake. The results show that a system with SMES performs better than a system with a optimal dynamic brake in the similar operational conditions. SMES performance under different operational conditions is very desirable (for conditions with light loads conditions as good as heavy loads conditions). This article proves the superiority of SMES with PI controller for VSC by presenting the acquired results. In [15] a new design for SMES module as a DC power source for a DVR based distribution system is presented.

The results of the simulation shows that SMES is more suitable as a DC source for DVR, however the controlling system for SMES unit is not shown and only PI controlling system related to VSC converter is shown, and only line's voltage is referred to as the input related to the controller.

In [16] to improve stability of the wind turbine with inductive generator (IG) and PI controller for VSC, a comparison is made between using SMES with fuzzy controller and using pitch angle fuzzy controller whose results show that SMES with fuzzy controller is more effective for the related chopper than pitch angle controller for the stability in inductive generator based wind turbine. In this article, only the generator's power is referred to as the input of the SMES fuzzy controller and VDC related to SMES is ignored and also the THD amount is not mentioned.

In [17], compensation for voltage sag and swell via dynamic voltage restorer using a PI controller and fuzzy controller is explained. Superiority of the fuzzy controller is shown in this article, but harmonic content production is high and this DVR's controller does the control only via sampling of the line voltage while in our paper for the control operation the sampling is done on the line current, the generation power of the generator, and DC voltage related to SMES as well. Subsequently the harmonic production decreases and helps improving the dynamical condition of the generator during error.

Controlling design in our paper only consists of two PI controllers and the current of the SMES electromagnetic coil is considered to calculate the amount of energy stored in SMES, and also to define direction and the level of power exchange between SMES coil and ac system, the produced power by the generator and the current of the SMES coil are considered as control parameters. This control system is efficient, simple with easy installation.

5. FLC [6]

A chopper is used to control power transmission between SMES electromagnetic coil and ac system, and also fuzzy logic is selected to control duty cycle (Figure 3). According to the fuzzy logic flow chart shown in figure 4, a process of formulating a map from a given input to output is created. The input variables for the model are the real produced power by the generator and SMES coil current.

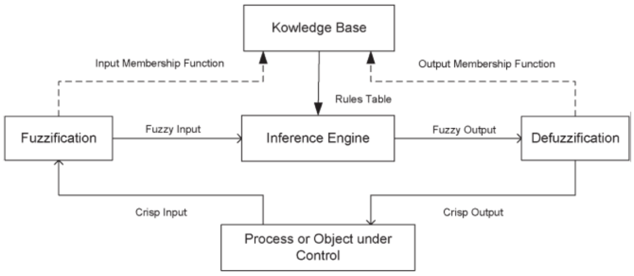


Figure 4. Structure of the suggested fuzzy controller.

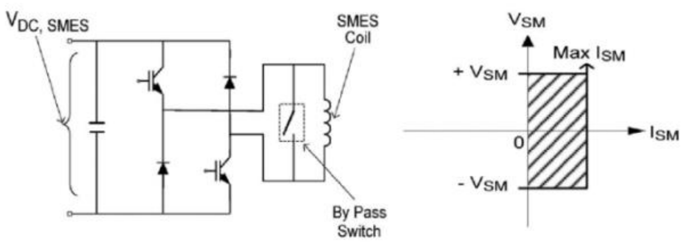


Figure 5. a: class D dc-dc chopper topology with a SMES coil b: SMES coil operational range.

FLC output is duty cycle (D) for the class D dc-dc chopper (Figure 5.a) and also in figure 5.b, V-I operational range for the SMES coil is shown.

If duty cycle (D) is 0.5, then nothing is done by the coil and the system is working under normal conditions. A bypass switch which is installed within the SMES coil (Figure 5.a) is closed to prevent SMES energy discharge during normal conditions. The bypass switch is controlled in a way to be closed if D is equal to 0.5, otherwise it will be open. This technique is introduced in some articles such as [18] and [19].

When the network power is decreased, D also decreases between the range of 0-0.5 on that basis and the stored energy in SMES coil is transmitted to ac system. The process of charging the SMES coil happens when D is in the range of 0.5-1. The relationship between VSEMS, and VDC, SMES can be written as below:

[18] $V_{SMES} = (1\_ 2D) V_{DC, SMES}$ (2)

In which V_{SMES} is the average SMES voltage, D is Duty Cycle, and $V_{DC, SMES}$ is the average voltage within SMES structure dc link capacitor. The model is created via graphic tool by MATLAB. Each input is phased with five sets of MF Gaussmf-type membership functions. Gaussian curve is a function of the vector X and is dependent on parameters σ and C.

$$F(x; \sigma, c) = e^{-(x-c)^2/2\sigma^2} \quad (3)$$

In which σ and C are variables which respectively define the center of the peak and width of the bell curve. MFs related to input variables of P_G, I_{SMES} are respectively shown in figure 7 and 8.

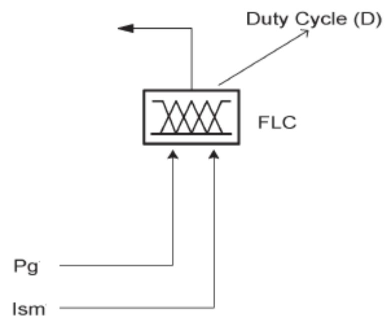


Figure 6. FLC inputs and outputs.

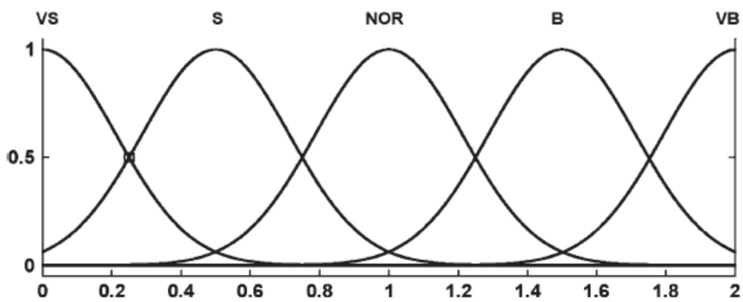


Figure 7. MF for the input variable PG(pu).

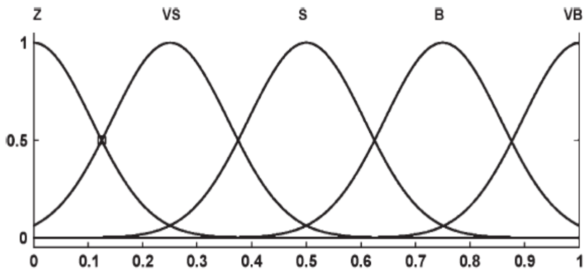


Figure 8. MF for the input variable (pu)ISMES.

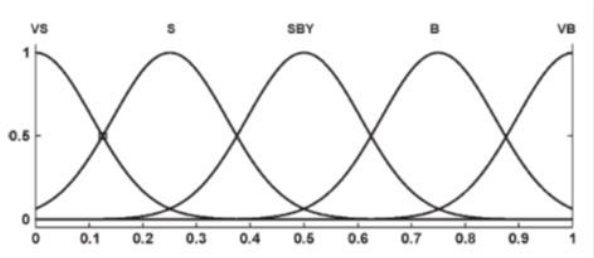


Figure 9. MF for the output variable D (Duty Cycle).

The center of gravity which is used in fuzzy models is also used for the reverse fuzzy process (defuzzification). The desired output Z_O is also calculated as below:

$$Z_O = \frac{\int z.\mu c(z) dz}{\int \mu c(z) dz} \quad (4)$$

Where, μc (z) is the MF of the output. The variation range in SMES current and generator's output power as well as the corresponding Duty Cycle, are used to produce a set of fuzzy logic rules in the form of (IF-AND-THEN) statements and to relate input variables to output. Duty Cycle for each set of input variable (I_{SMES}, PG) can be calculated using surface graph shown in figure 10.

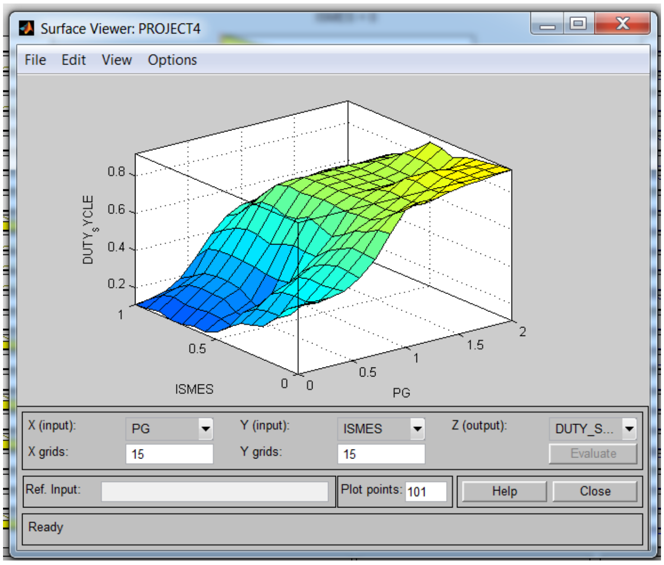


Figure 10. Surface graph: Duty Cycle.

Table 1. SMES unit parameters.

Rated Energy	1.0 MJ
L_{SMES}	0.5 H
I_{SMES}	2000 A

6. SMES CAPACİTY

SMES unit capacity depends on the type of application and the duration of charge. The very high energy rate has a deep impact on balancing the fluctuations; however SMES unit cost due to the existence of large current in the coil will be very high. Also, if the energy rate is very low, then the SMES unit's output during disturbances will be limited and the system won't be sufficiently functional in rapid controlling of the fluctuations. The first SMES unit with energy of 30MJ and coil current of 5KA was installed in Tacoma (power management center of Bonneville) in 1982. Electromagnetic energy of SMES with lower amount of generator's rated power of 0.15 will be enough to protect the system against momentary power cutoff. Synchronous generator's rated power and the rated energy of the SMES electromagnetic coil are respectively 10MW and 1Mj in the understudy system. Since the amount of 0.5H is chosen as the inductance of the SMES coil, the rated self current is 2KA (Table 1).

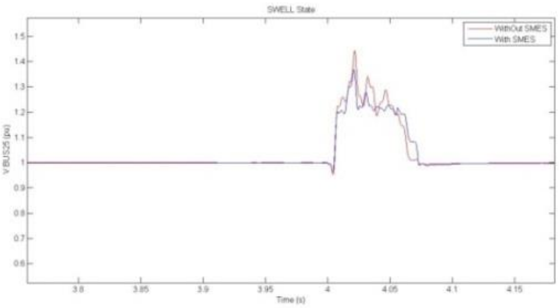
According to the relation (1)

$E = \frac{1}{2} L_{SMES}\text{-}I_{SMES}^2$

7. VOLTAGE SWELL PHENOMENON

It happens due to a large load's cut off or connecting a large capacitor's bank. During this simulation, voltage swell about 1.5pu for 0.05 second in the time t=4s is exerted to the circuit using 50MVAR capacitance. In this state the produced power by the synchronous generator increases after voltage swell and decreases with the removal of this state (Figure 11.b). Maximum overshoot of the power decreases with the connection of a SMES unit to the system. Primary power loss is due to switching and the entry of capacitive fault to the circuit. In the results (Figure 11) we can see the compensation of voltage swell. It can be seen in these figures that voltage swell is compensated when SMES is present in the circuit rather than when it is not present in the circuit. Due to swell error, in figure 11, a jump in the DC-Link capacitor charge is seen during error time (second 4).

RED LINES: results without SMES **BLUE LINES: results with SMES**



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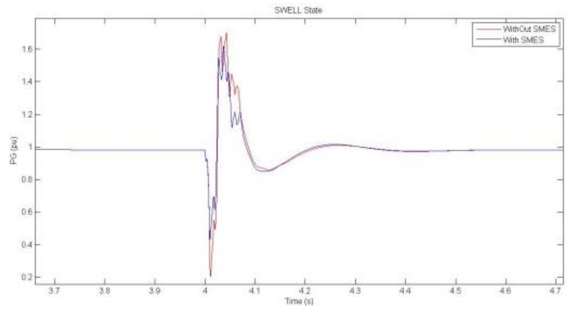

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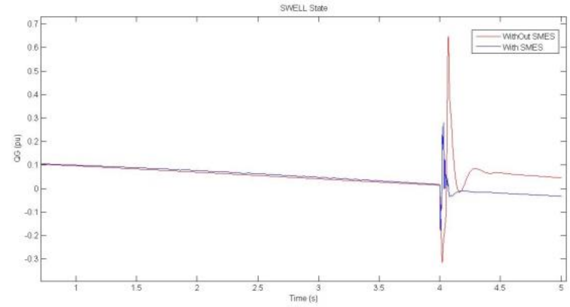

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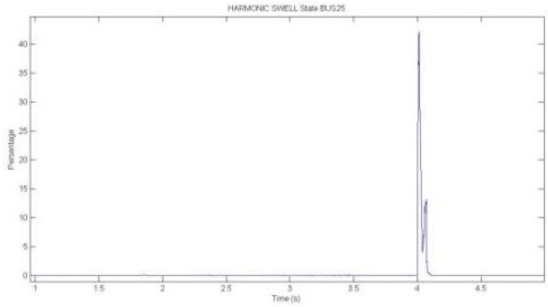

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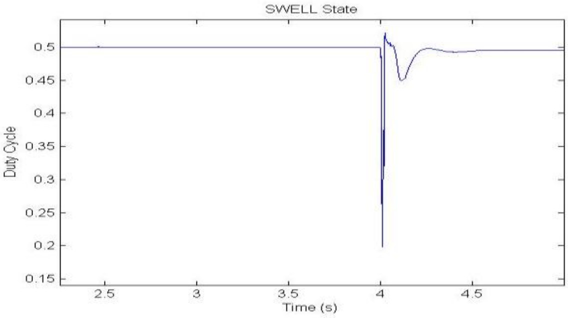

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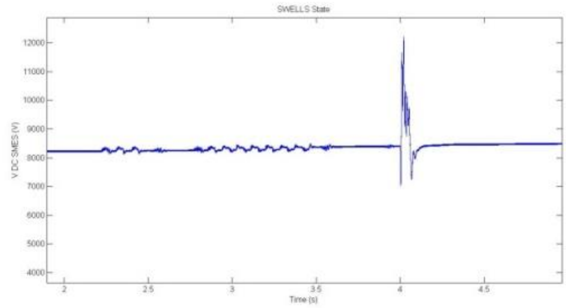

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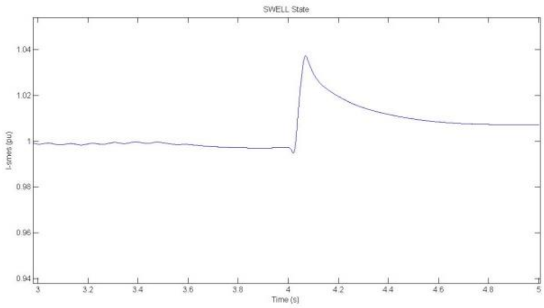

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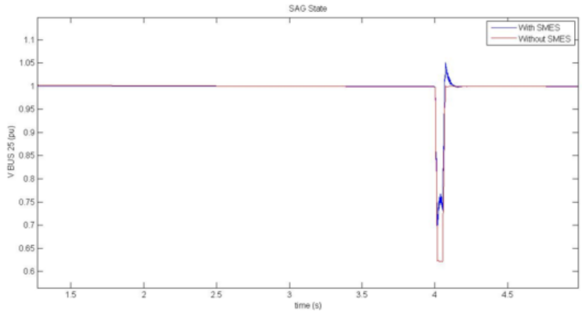
Figure 11. a) voltage swells compensation; b) synchronous generator's PG active production power compensation; c) synchronous generator's QG; d) THD with SMES; e) D ratio (duty cycle); f) DC link voltage related to SMES; g) SMES current.

8. VOLTAGE SAG PHENOMENON

A voltage sag of 0.45pu for 0.05 seconds at the time of t=4S is applied towards the understudy network system using 170 MVAR applying inductive load. In the results (Figure 12) we can see the compensation of voltage sag. We can see in these figures that voltage sag is compensated when the SMES in placed in the circuit rather than when it is not present in the circuit.

RED LINES: results without SMES **BLUE LINES: results with SMES**



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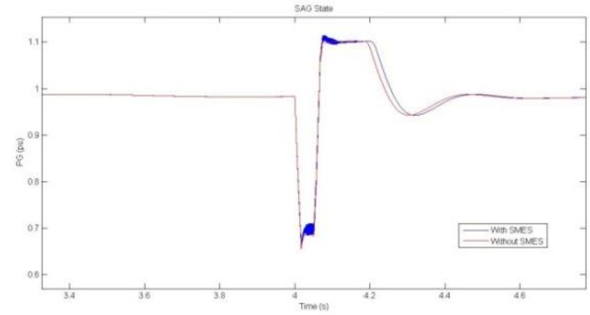

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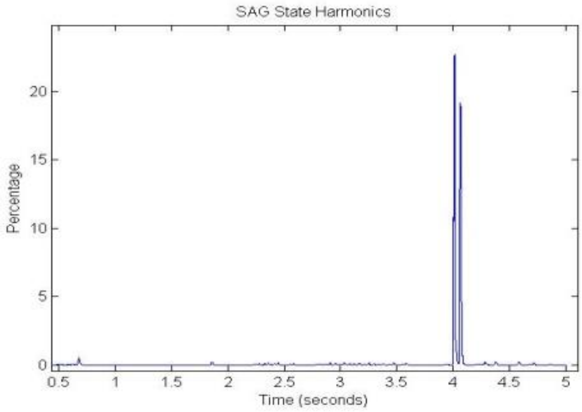

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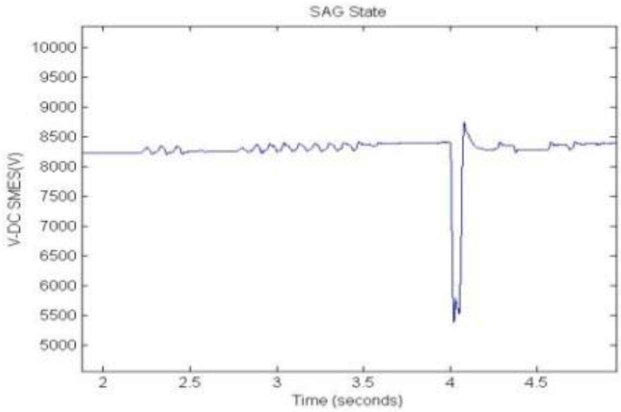

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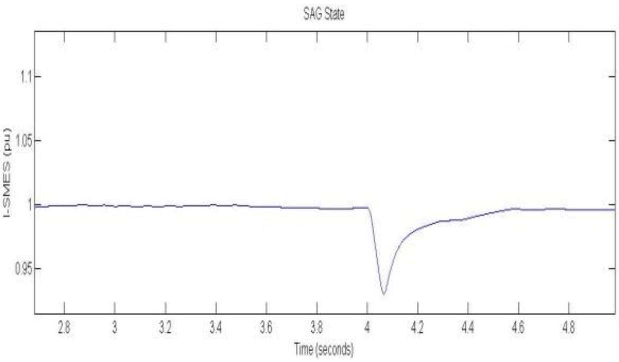

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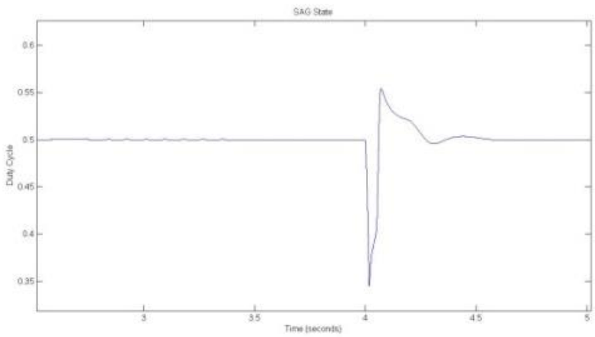

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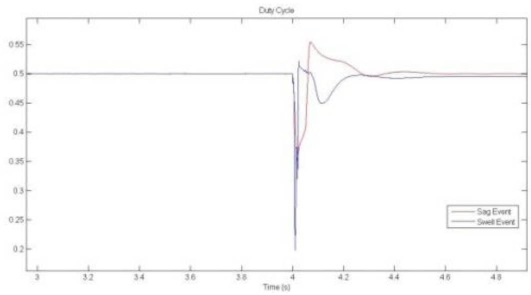
Figure 12. a) Voltage Sag compensation; b) Generator's PG electrical power compensation; c) THD with SMES; d) DC-link voltage related to SMES; e) SMES current; f) D ratio (duty cycle).

9. SİMULTANEOUS STUDY of VOLTAGE SAG and SWELL



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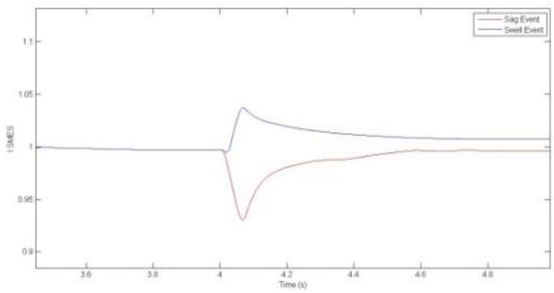

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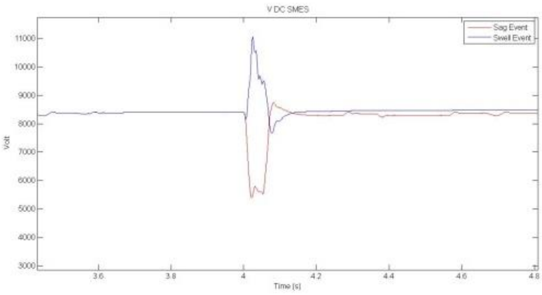

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Figure 13. a) D ratio (duty cycle); b) SMES current simultaneous in voltage sag and swell states swell states; c) DC-Link voltage, SMES simultaneous in voltage sag and swell states.

10. STUDY OF HARMONİC İMPACT

Considering the fact that in [17] harmonic amount (THD is 2.05%, which is decreased using an FLC controller to 0.44% at this paper. The amount of harmonic in the voltage sag and swell state is decreased to lower than 0.01% (Figure 11.d and 12.c).

11. CONCLUSİON

This project has studied the new application of SMES unit to improve the quality of power during voltage sag and swell towards the network with synchronous generator and a wind turbine. A new controlling system for SMES unit based on PID controllers combined with fuzzy logic controllers is presented. SIMULINK/MATLAB software is used for simulating SMES unit and the understudy model.

A new controlling algorithm along with a new application of SMES unit is introduced to improve the quality of power with synchronous generator during voltage sag and swell. Simulation results show that SMES unit is efficient and applicable to improve voltage in a power system with synchronous generator during voltage sag and swell towards network. The suggested controlling algorithm of SMES unit is simple and its operation is also done easily. It is also more efficient compared to previous controllers in decreasing the harmonic impact. In other words, SMES unit is still an expensive and costly part of the required equipments, however due to development of superconducting materials with high temperatures it is expected to have an increase and successful application in power systems in near future.

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