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Application of DSTATCOM coupled with FESS for Power Quality Enhancement and Fault Mitigation

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***Abstract* -** In power systems, the use of renewable energy, especially Wind power generation is steadily increasing around the world. However, this incorporation and the lack of controllability over the wind, and the type of generation used cause problems in the power quality and in the dynamics of the system. In this work, the use of a Distribution Static Synchronous Compensator (DSTATCOM) coupled with a Flywheel Energy Storage System (FESS) is proposed to mitigate problems introduced by the intermittency of wind power generation. A dynamic model of the DSTATCOM/FESS device is briefly presented and a multi-level control technique is proposed. The proposed control technique has one control mode for active power, and two control modes to choose between, for reactive power and voltage control. The above technique has been used here to enhance not only the steady state operation but also to mitigate sudden load changes. The control system under consideration, with the DSTATCOM/FESS, and its controls are analyzed also, under the conditions of different faults which may happen in the system. Simulation tests of the device are analyzed when it is combined with wind generation in the electric system. The results demonstrate satisfactory performance of the proposed control techniques, as well as a high effectiveness of the control system to mitigate problems introduced by wind power generation.

***Keywords* -** Distribution Static Synchronous Compensator (DSTATCOM), Flywheel Energy Storage System (FESS), power quality, Wind Power, fault.

I. INTRODUCTION

Due to the increase in population and industrialization, demand of electricity is increased too. So, integration of renewable energy in power networks becomes very important in the generation of power now a day [1].

The generated power from the wind energy is considered to be the most economical alternative within the renewable energy resources; due to its main advantages such as the large number of potential sites for planting installation and a rapidly evolving technology, with many suppliers offering from individual turbine sets to turnkey projects. However, due to the lack of controllability over the wind and the type of generation system used, problems arise in the electrical systems. One of the major problems of wind conversion systems is the variations of the output power produced by short-term wind fluctuations, which affect the power quality and may lead to system instability [2]. In order to mitigate the variation in power quality, and enhance the during-fault performance of the system, which may occur due to wind variations, load step changes, which can last for seconds or minutes or even longer, a scheme of Distributed Static Synchronous Compensator (DSTATCOM) connected at a point of common coupling with flywheel (FESS) is suggested [3].

A DSTATCOM is one of the main shunt controllers to be used in distribution systems. It is suitable for its fast-response. Its solid-state power controller provides flexible voltage control at the point of common coupling with the utility grid, a matter which leads to power quality improvements. This device can exchange active and reactive powers with the wind energy resource, if an energy storage system, in this case a flywheel system, is included with it into the DC bus [4].

A FESS stores kinetic energy in its rotating mass. In this paper, the flywheel system has been used as a short-term energy storage device. Flywheel systems can be classified as low-speed flywheel (LS-FESS) and high-speed flywheel (HS-FESS) devices. However, HS-FESS represents a newer technology than LS-FESS. In fact, HS-FESS provides better speeds of response, cycling characteristics and electric efficiencies. As the HS-FESS will be the only type used here, it will be referred to as FESS from now. It works as a motor while charging, and as a generator while discharging. It has several advantages over other energy storage systems due to its simple structure with the very high efficiency, higher power, energy density with high dynamics and fast response, and longer lifetime with low maintenance requirements. FESS merely consists of a flywheel, electric machine, power conversion system and bearings [5].

From the foregoing discussion, it is obvious that a DSTATCOM/FESS supporting system is able to correct the active and reactive power fluctuations of a wind power system.

In this paper, a detailed model and a multi-level control of a DSTATCOM controller coupled with FESS, meant to improve the integration of wind generators (WGs) into a power system, and to mitigate wind power fluctuations are presented in details. It can be also, helpful, and efficient in the mitigation of the effects of some different types of faults. A validation of a DSTATCOM/FESS device and control schemes are carried out through MATLAB/Simulink. Results are obtained, and presented in the paper. Moreover, the complete control design for DSTATCOM/FESS is presented which includes three modes of operation, namely, voltage control, power factor correction, and active power control. This control scheme implements a new approach depending on multi-level control technique.

II. DSTATCOM/FESS GENERAL MODEL

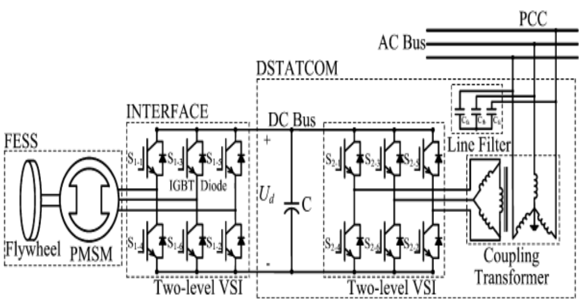

Fig.1. DSTATCOM/FESS controller

For studying the dynamic performance of the DSTATCOM/FESS controller, a detailed model of the combined system is presented. It mainly consists of the DSTATCOM controller, the Interface converter and the FESS, as shown in Fig.1.

The DSTATCOM and the interface use a voltage-source inverter (VSI), in which the valves used are: Insulated Gate Bipolar Transistors (IGBT) with anti-parallel diodes. The VSI is modeled by detailed blocks, and is presented into the simulation program. Other components are the coupling transformer, the line filter and the DC bus capacitor. They are all represented in the model

The stored energy of the FESS device is computed by:

$$\Delta E = \frac{J(\omega_{max}^2 - \omega_{min}^2)}{2} \qquad (1)$$

Where ΔE is the available stored energy by the flywheel, J is the flywheel moment of inertia, ω_{max}, ω_{min} are the maximum and minimum flywheel operational speed, respectively.

A permanent magnet synchronous machine (PMSM) is used to allow the exchange of power between the flywheel and the Interface. The PMSM is worked at high speeds as its type of rotor is brushless, and there is no rotor winding. It is also modeled in the simulation program with a detailed block. The flywheel itself is modeled as an additional mass connected to the rotor shaft of the PMSM [6].

III. DSTATCOM/FESS CONTROL

The control system presented here for the DSTATCOM/FESS device is divided into two parts, the DSTATCOM control, and the FESS control. To avoid system complexity, each one of the two parts is divided into multi-level control schemes. Similarly, each scheme has its own control objectives. In this way the system control will be simpler in design [7].

For each part, i.e., the DSTATCOM and the FESS, three distinct control levels are done: external, middle and internal level, as shown in Fig. 2

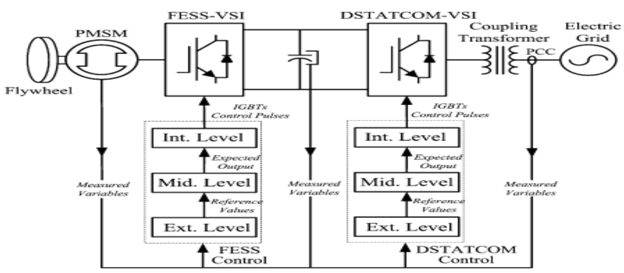

Fig.2. DSTATCOM/FESS multi-level contro

A. DSTATCOM CONTROL

Each control level of the DSTATCOM has functions to be fulfilled. By the external level, active and reactive power exchange between the DSTATCOM and the utility system can be

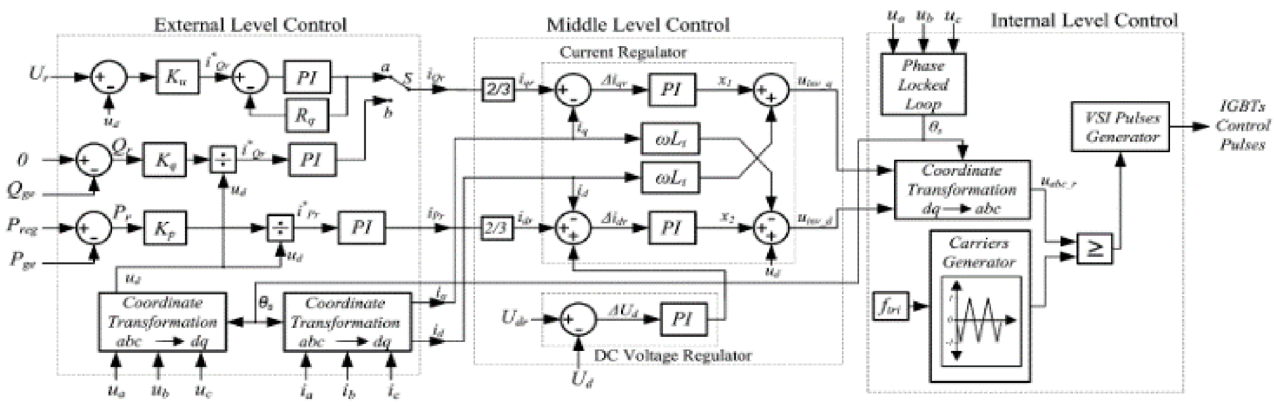

Fig.3. three-level control of DSTATCOM

determined. The external control level is designed for performing active power control mode (APCM), power factor control mode (PFCM) and voltage control mode (VCM). By the middle level, the expected output is dynamically tracked to the reference values set by the external level. This block has two main parts, the current regulator and the DC voltage regulator. By the internal level, firing signals are generated for the switching valves of the VSI of the DSTATCOM. The internal level is mainly composed of a line synchronization module and a three-phase pulse-width modulation firing pulses generator [8]. The three control levels of the DSTATCOM with all parts given in details are shown in Fig. 3.

B. FESS CONTROL

The control of the FESS is done through the control of the Interface -VSI. For a three-phase voltage of controllable amplitude and phase with the VSI, the PMSM can work as a motor storing energy or as generator delivering energy. Like the DSTATCOM control, by the external level, power exchange between the DC bus of the DSTATCOM and the FESS can be determined so as to fulfill the required power imposed by the DSTATCOM as shown in Fig. 4. The maximum efficiency of the PMSM is obtained by computing the reference current i_{qmr} from the torque of the PMSM by using Eq. (2), and the reference current i_{dmr} is set to zero [9].

$$T_{e\_r} = \frac{3}{2} p\, \psi_m i_{qmr} \qquad (2)$$

Where, T_{e_r} is the electromagnetic reference torque of the machine, p is the number of pairs of poles, and ψ_m is the magnetic flux.

The reference torque is calculated through a speed regulator which adjusts the actual speed of the machine (ω_m) to the reference speed of the machine (ω_{mr}) .The reference speed is computed from the reference power of the

machine, $P_{mac\ r}$, which is the power, to be stored or delivered by the flywheel, which can be expressed using Eq. (3).

$$P_{mac\_r} = d/dt\,\left(\frac{1}{2} J\, \omega^2_{mr}\right) \qquad (3)$$

The reference power of the machine is calculated by summing up the reference power of the DSTATCOM/FESS (P_r) and the power losses of the machine (P_{loss}), which denotes the sum of the copper losses (P_{Cu}), the iron losses (P_{Fe}), and the mechanical losses (P_{mec}) [10].

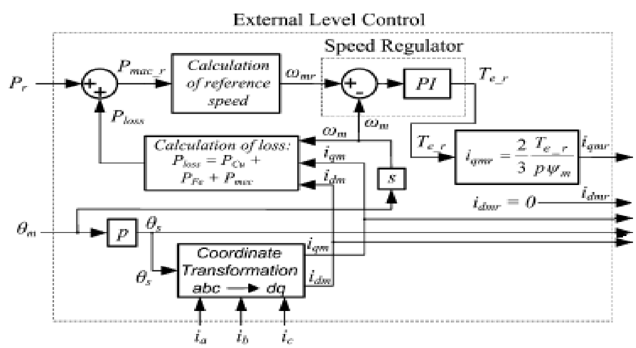

Fig.4. the external -level control of FESS

The middle level has the same functions as the middle level of the DSTATCOM, except that the angle of synchronism for making the coordinate transformation, θ_s, is computed in a different way. Here, the angle is obtained by measuring the position angle of the machine (θ_m) and multiplying this angle by the number of pair poles.

The internal control level is also similar to that of the DSTATCOM except that it does not have the phase locked loop block (PLL) as the angle θ_s is obtained by the measurement as mentioned before.

IV. TEST MODEL

To study the dynamic performance of the DSTATCOM/FESS device, the test power system shown in Fig. 5, as a single line diagram, is used. This sub-transmission system works at 13.8 kV, and 50Hz, and implements a dynamically modeled wind generator linked to a bulk power system, represented by an infinite bus type.

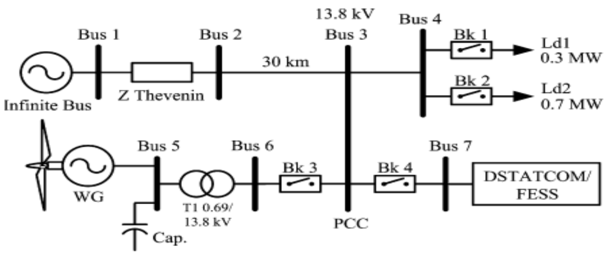

Fig.5. sub-transmission power system network

The WG used is an induction generator with a squirrel-cage rotor and of rated power 750 kW.

It is connected to the grid through a transformer of star-triangle winding. The demand of the reactive power for the WG is supplied by capacitors in order to reach approximately unity power factor. WG is modeled with blocks of a wind turbine of induction generator type which are available in the library of the simulation program and with parameters taken from [11]. The sub-transmission line is modeled by using lumped parameters. All loads are modeled by constant impedances and are connected at bus 4 in which Ld1 has a power 0.3 MW and Ld2 has power 0.7MW. The DSTATCOM/FESS proposed is connected to bus 3 (the main bus). The DSTATCOM has DC voltage of 750 V and the used capacitor is of 1000 μF. The DSTATCOM-VSI works with a frequency of 8 kHz, whereas the Interface-VSI works at 20 kHz. The parameters of the FESS (PMSM and flywheel) are obtained from [11].

The analysis and validation of the models and control algorithms, suggested for the DSTATCOM/FESS controller, are done through simple tests that impose high demands upon the dynamic response of the device. For this purpose, a variable profile of wind speed is applied to the WG, so that the DSTATCOM/FESS may work in both ways, by storing and delivering energy. In addition, external disturbances, such as sudden load change and different fault types are imposed, and the behavior of the device in the different modes of control is observed.

V. SIMULATION RESULTS

The test model shown in Fig. 5 is used to verify the suggested control scheme. A wind speed variation of the form shown in Fig. 6 is applied.

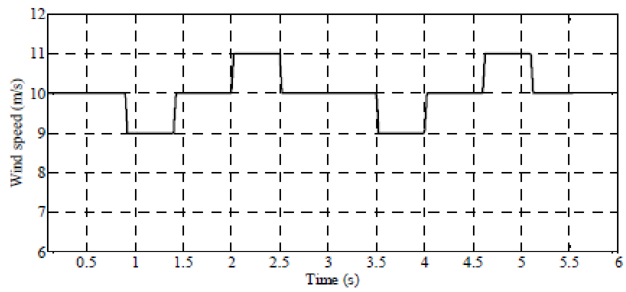

Fig.6. variation of the wind speed

The wind speed variations applied cause fluctuations in the active and reactive power injected by the WG. A capacitor bank is used to compensate the reactive power of the WG, when it operates at a mean wind speed of 10 m/s.

1. SUDDEN LOAD VARIATION

At bus 4 of Fig.5, a load Ld1= 0.3MW is first connected (t = 0 sec.) and then, load Ld2 = 0.7MW is added (t = 3 sec.). The behavior of the system is analyzed in both cases i.e. when the DSTATCOM/FESS is disconnected and when it is connected. The variations in active power, injected into the system for both cases are shown in Fig. 7.

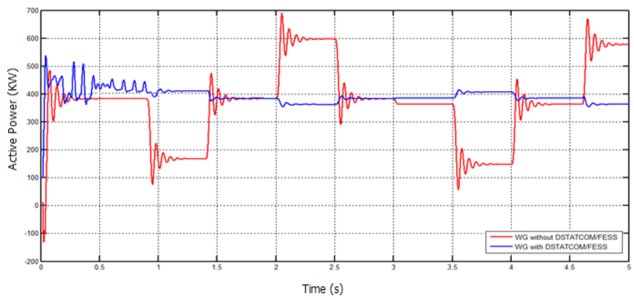

Fig.7. the active power of the WG-DSTATCOM/FESS.

It is obvious that when the DSTATCOM/FESS device is connected, the variations of power injected from the WG into the system, are reduced, indicating that the active power is approximately constant.

For the reactive power control, three different cases are observed: DSTATCOM/FESS disconnected, DSTATCOM/FESS connected working in Power Factor Control Mode (PFCM) and DSTATCOM/FESS connected working in Voltage Control Mode (VCM) as shown in Fig.8.

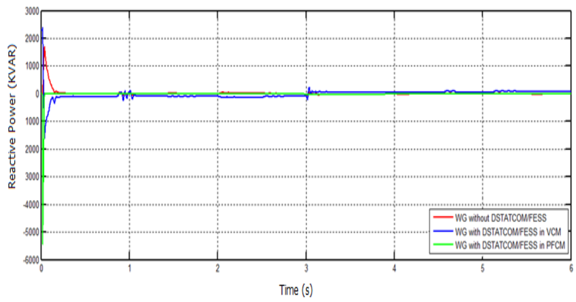

Fig.8. the reactive power of the WG-DSTATCOM/FESS.

When the DSTATCOM/FESS-connected working in PFCM, it is observed that the reactive power injected is zero. So, the device proposed has satisfactorily compensated the reactive power variations of the WG. When the DSTATCOM/FESS-connected working in VCM, the reactive power variations from the WG are also compensated in order to make the voltage at bus 4 equal to 1 pu.

The voltage at bus 4 can also be observed as shown in Figs. 9, 10, 11, 12, 13 and 14. When the DSTATCOM/FESS is disconnected, significant variations in voltage happen. This is due to both the variations of power from the WG and those of the load. When the DSTATCOM/FESS device is connected in PFCM, there are no voltage variations due to the variations in the wind power. However, in this mode, the voltage has a value different from 1 pu due to the load variation. When the DSTATCOM/FESS device is connected in VCM, the voltage is approximately maintained at 1 PU and does not change due to the variations in wind power or the variations of the load. So this control mode solves, in quite an effective way, the problem caused by the PFCM. Thus, the VCM is the most convenient mode when the connection point of the WG has no other device that controls the voltage.

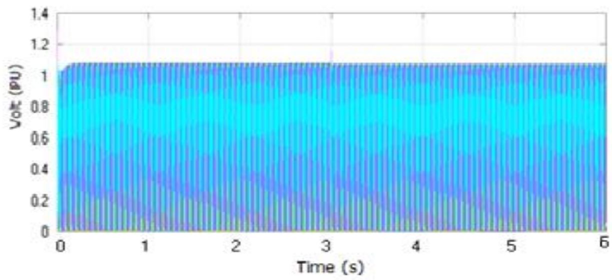

Fig.9. voltage at bus 4 without DSTATCOM/FESS connected.

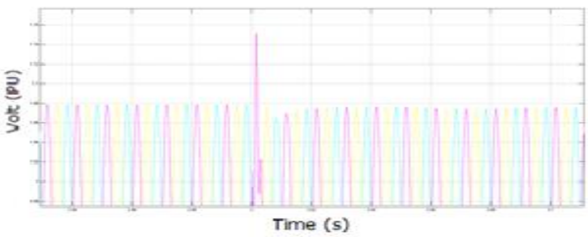

Fig.10. Expanded scale of voltage at bus 4 without DSTATCOM/FESS connected at time = 3 sec

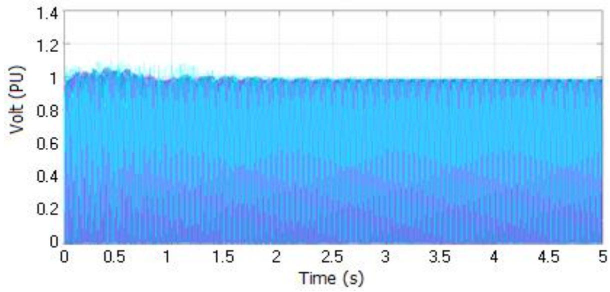

Fig.11. voltage at bus 4 with DSTATCOM/FESS connected in VCM.

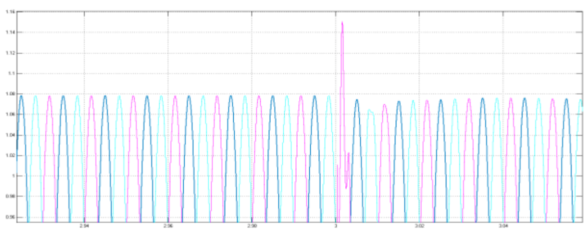

Fig.12. Expanded scale of voltage at bus 4 with DSTATCOM/FESS connected in VCM at time = 3 sec

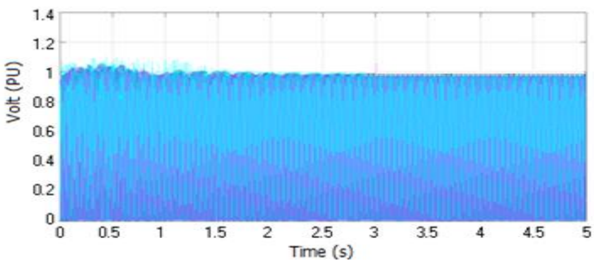

Fig.13. voltage at bus 4 with DSTATCOM/FESS connected in

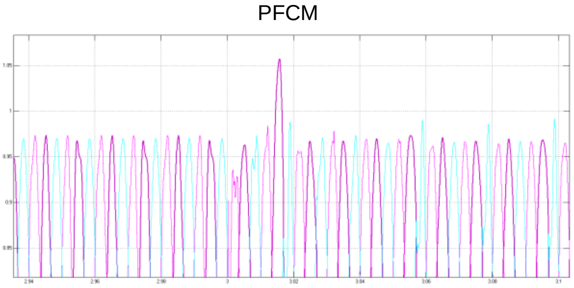

Fig.14. Expanded scale of voltage at bus 4 with DSTATCOM/FESS connected in PFCM at time = 3 sec.

2. OPERATION UNDER DIFFERENT TYPES OF FAULTS

For the system of Fig. 5, different types of faults are applied at bus 4; such as line to ground fault, line to line fault, line to line to ground fault, three lines to ground fault, and the system is studied under each case of them in details. In the following the simulation results of the foregoing types of faults are given

A. LINE TO GROUND FAULT

For line to ground fault, assumed to happen at t = 3 sec., and then be removed after 0.5 sec., three cases are observed: in the case when the DSTATCOM/FESS is disconnected, significant variations in voltage happen. These are shown in Fig. 15.When the DSTATCOM/FESS is connected, and working in VCM, the variation in voltage is mitigated as shown in Fig. 16. When the DSTATCOM/FESS is connected; working in PFCM, as shown in Fig. 17, voltage variation is mitigated, as well. In all cases when the DSTATCOM/FESS operates in VCM mode the dynamic performance of the system is best.

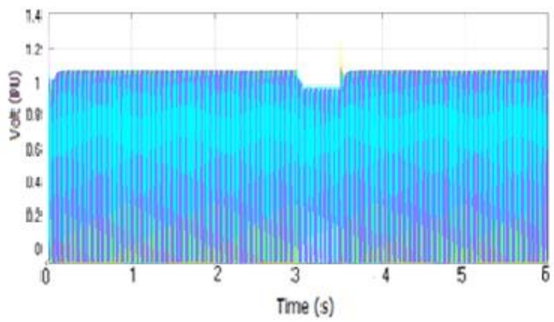

Fig.15. voltage at bus 4 without DSTATCOM/FESS connected of line to ground fault.

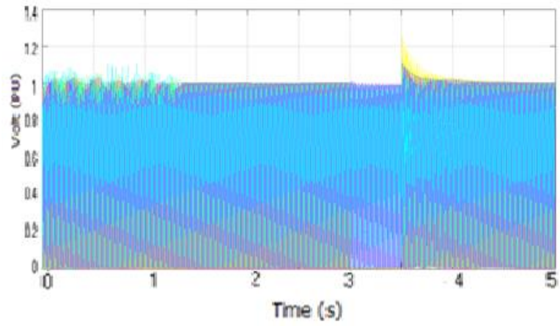

Fig.16. voltage at bus 4 with DSTATCOM/FESS connected.in VCM of line to ground fault.

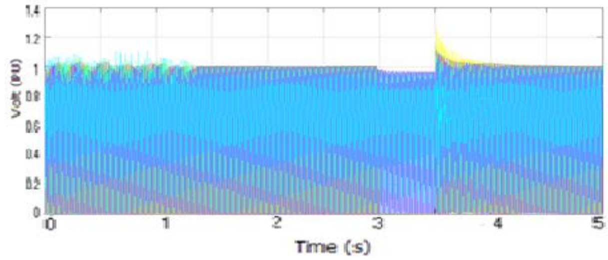

Fig.17. voltage at bus 4 with DSTATCOM/FESS connected.in PFCM of line to ground fault.

B. LINE TO LINE FAULT

For line to line fault, assumed to happen at t = 3 sec., and then be removed after 0.5 sec., three cases are observed: in the case when the DSTATCOM/FESS is disconnected, significant variations in voltage happen. These are shown in Fig. 18.When the DSTATCOM/FESS is connected, and working in VCM, the variation in voltage is mitigated. In addition, the time taken by the system to return to stability decreased as shown in Fig. 19. When the DSTATCOM/FESS is connected; working in PFCM, as shown in Fig. 20, voltage variation is mitigated and the time taken to regain stability decreased as well. In all cases when the DSTATCOM/FESS operates in VCM mode the dynamic performance of the system is best.

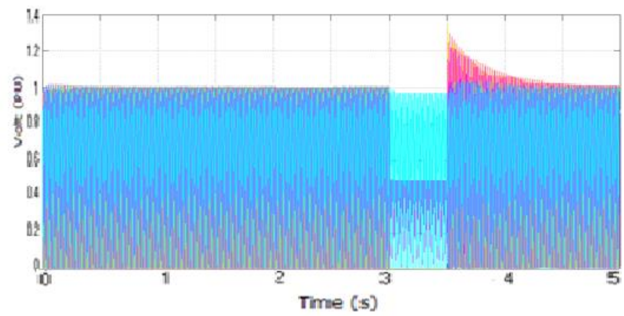

Fig.18. voltage at bus 4 without DSTATCOM/FESS connected of line to line fault.

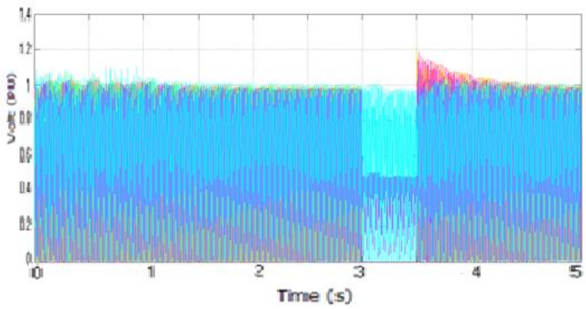

Fig.19. voltage at bus 4 with DSTATCOM/FESS connected.in VCM of line to line fault.

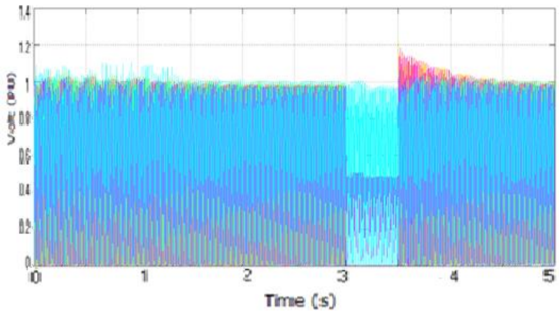

Fig.20. voltage at bus 4 with DSTATCOM/FESS connected.in PFCM of line to ground fault

C. LINE TO LINE TO GROUND FAULT

For line to line to ground fault, assumed to happen at t = 3 sec., and then be removed after 0.5 sec., three cases are observed: in the case when the DSTATCOM/FESS is disconnected, significant variations in voltage happen. These are shown in Fig. 21.When the DSTATCOM/FESS is connected, and working in VCM, the amplitude of faulty voltage increased as shown in Fig. 22. When the DSTATCOM/FESS is connected; working in PFCM, as shown in Fig.23, the amplitude of faulty voltage increased, as well. In all cases when line to line fault happen it is better to disconnect the DSTATCOM/FESS.

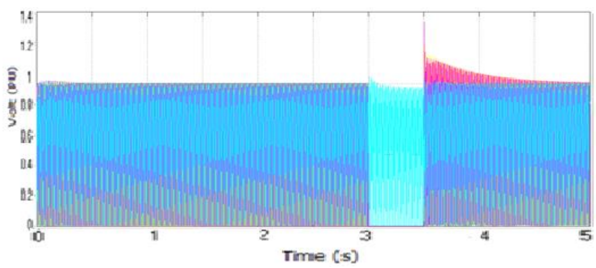

Fig.21. voltage at bus 4 without DSTATCOM/FESS connected of line to line to ground fault.

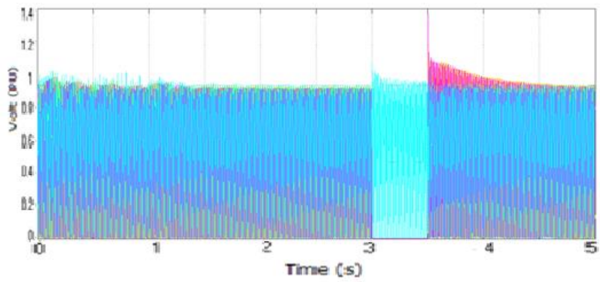

Fig.22. voltage at bus 4 with DSTATCOM/FESS connected.in VCM of line to line to ground fault.

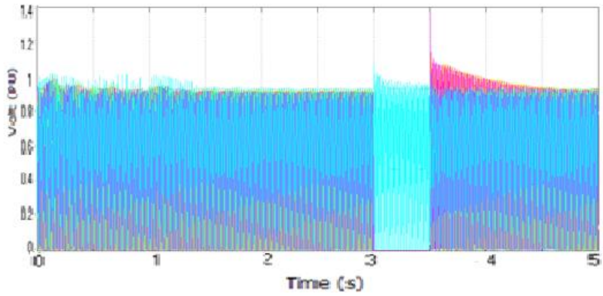

Fig.23. voltage at bus 4 with DSTATCOM/FESS connected.in PFCM of line to line to ground fault.

D. THREE LINES TO GROUND FAULT

For three lines to ground fault, assumed to happen at t = 3 sec., and then be removed after 0.5 sec., three cases are observed: in the case when the DSTATCOM/FESS is disconnected, significant variations in voltage happen and at the time of fault the voltage reach zero, as shown in Fig. 24.When the DSTATCOM/FESS is connected, and working in VCM, the variation in voltage is increased as shown in Fig. 25. When the DSTATCOM/FESS is connected; working in PFCM, as shown in Fig. 26, voltage variation is increased, as well. In all cases when three lines to ground fault happen, it is better to disconnect the DSTATCOM/FESS

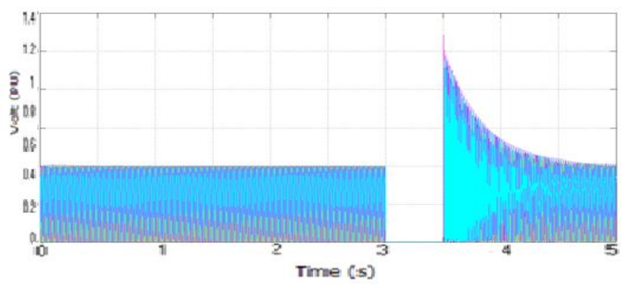

Fig.24. voltage at bus 4 without DSTATCOM/FESS connected of three lines to ground fault.

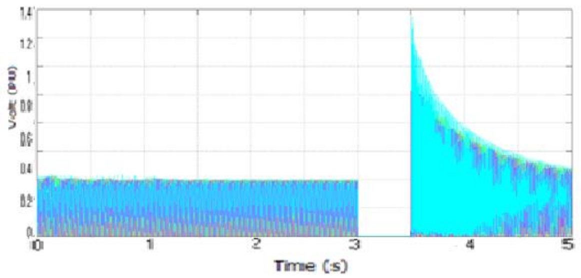

Fig.25. voltage at bus 4 with DSTATCOM/FESS connected.in VCM of three lines to ground fault

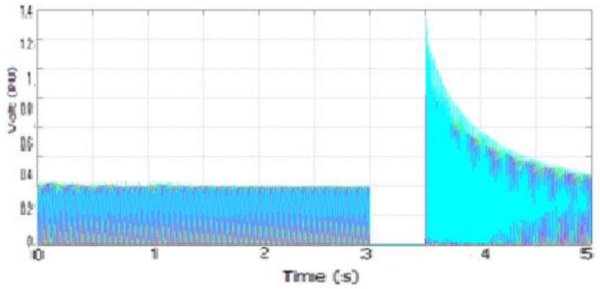

Fig.26. voltage at bus 4 with DSTATCOM/FESS connected.in PFCM of three lines to ground fault.

VI. CONCLUSIONS

This paper presents the control algorithms of a DSTATCOM controller coupled with a FESS System. A proposal is made of a fully detailed model with multilevel control algorithm based on the synchronous rotating d-q reference frame. The incorporation of the DSTATCOM/FESS with wind generation in the electric system was studied, and its behavior is analyzed in different control modes.

From the results obtained, it is concluded that with the proposed device, the power fluctuations coming from a WG are effectively mitigated. It was shown that the WG-DSTATCOM/FESS system can deliver an approximately constant active power in a time range of seconds or more. For the reactive power control, it was shown that the system is able to provide an approximately unity power factor or to maintain the voltage in the connection point. The voltage control operates satisfactorily in case of power disturbances in the WG and also for fluctuations in the system. The WG-DSTATCOM/FESS system is also studied under different types of faults, the results show that DSTATCOM/FESS is better to be connected during line to ground and line to line fault, while during line to line to ground and three lines to ground fault, disconnection of it is better. Therefore, the incorporation of DSTATCOM/FESS has shown that it can improve the power quality in wind systems, as well as, during some types of faults

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