Integrated D-STATCOM with Supercapacitor Used in IEEE Industrial Distribution System

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ABSTRACT

In this paper, a new control method for D-STATCOM (Distribution STATIC Compensator) applied in IEEE 13-bus industrial distribution system is proposed. The operation of this control method enables D-STATCOM to mitigate every type of voltage distortions caused by Single Line to Ground (SLG), Double Lines to Ground (DLG) and Three Lines to Ground (TLG) faults. This new method is based on two factors; firstly, integrating D-STATCOM and supercapacitor energy storage system and secondly, using of feedback in controller system and determining proportional gain of Proportional-Integral (PI) controller, intelligently. In addition, the 12-pulse D-STATCOM configuration with IGBT is designed and the graphic based models of the D-STATCOM are developed using the PSCAD/EMTDC electromagnetic transient simulation program. As a case study, a 13-bus IEEE industrial distribution system is simulated to verify operation of proposed D-STATCOM.

Keywords: D-STATCOM, Supercapacitor, SCESS, PWM, VSC, Case study, 13-bus distribution system

1. INTRODUCTION

Voltage sags are the most important power quality (PQ) problems that many industries and utilities face it. It contributes more than 80% of power quality problems that exist in power systems. Voltage sags are not tolerated by sensitive equipment used in modern industrial plants such as process controllers; programmable logic controllers (PLC), adjustable speed drive (ASD) and robotics [1]. Reactive power compensation is another important issue in the control of distribution systems. Reactive current increases the distribution system losses, reduces the system power factor, shrink the active power capability and can cause voltage sags in the load-side voltage. Various methods have been applied to reduce or mitigate voltage sags. The conventional methods are based on using capacitor banks, introduction of new parallel feeders and installing uninterruptible power supplies (UPS). However, the PQ problems are not solved completely due to uncontrollable reactive power compensation and high costs of new feeders and UPS.

From 1988, custom power is introduced as a solution to power quality problems. D-STATCOM is one of the custom power devices, which locate shunt in network and applied to mitigate voltage sag and voltage swell [2-4]. The D-STATCOM has emerged as a promising device to provide not only for voltage sag mitigation but also for a host of other power quality solutions such as voltage stabilization, flicker suppression, power factor correction, and harmonic control. The configurations that are more sophisticated use multi-pulse and/or multilevel configurations. The voltage source converter (VSC) converts the dc voltage across the storage device into a set of three-phase ac output voltages. These voltages are in phase and coupled with the ac system of network through the reactance of the coupling transformer [5]. A control method based on RMS voltage measurement has been presented in [6] and [7] where they have been presented a PWM-based control scheme that requires RMS voltage measurements and no reactive power measurements are required. Also in this given method, Clark and Park transformations are not required. However, they have been investigated voltage sag/swell mitigation due to just load variation and using the same proportional gain for all types of voltage distortions while no SLG and DLG and TLG faults have been investigated.

In this paper, a new control method for mitigating the point of common connection (PCC) bus voltage sags caused by all types of faults is proposed. In this method, both dc side topology of the D-STATCOM is modified and the performance of control system is improved by leaving a feedback in out of PI controller and then the proportional gain of the PI controller is selected intelligently (based on the proposed Lookup Table in feedback) for mitigating voltage distortions. Moreover, system faults effects on the sensitive loads in a 13-bus IEEE industrial distribution system are investigated and the control of voltage sags are analyzed and simulated. The reliability and robustness of the control scheme in the system response to the voltage sags caused by SLG, DLG and TLG faults is obviously proved in the simulation results. In addition, effects of system faults on the sensitive loads (connected to PCC bus) are investigated and the con-

Manuscript received on August 1, 2011 ; revised on January 3, 2012.
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trol of voltage sags are analyzed and simulated.

2. THE STRUCTURE OF D-STATCOM

Generally, the D-STATCOM configuration consists of a typical 12-pulse inverter arrangement, a dc energy storage device; a coupling transformer connected in shunt with ac system, and associated control circuits, as shown in Fig. 1. The voltage source inverter converts an input dc voltage into a three-phase output voltage at fundamental frequency. These voltages are in phase and coupled with the ac system through the reactance of the coupling transformer. Fig. 2 shows a typical 12-pulse inverter arrangement utilizing two transformers with their primaries connected in series. The first transformer is in Y-Y connection and the second transformer is in Y-Δ connection. The Y-Δ inverter being delayed by 30 degrees with respect to the Y-Y inverter to reduce harmonics generated from the D-STATCOM [8].

3. PROPOSED CONTROL METHOD

The block diagram of the control scheme designed for the D-STATCOM is shown in Fig. 3. The basic control strategy is based on measurements of the voltage V_{RMS} at the load point.

The voltage error signal is obtained by comparing the measured V_{RMS} voltage with a reference voltage, V_{RMS_Ref}. A PI controller processes the difference between two signals (i.e. measured V_{RMS} and reference voltage, V_{RMS_Ref}) in order to obtain the phase angle delta that is required to drive the error to zero. The angle delta is used in the PWM generator as the phase angle of the sinusoidal control signal. The switching frequency used in the sinusoidal PWM generator is f_{sw}=1450 HZ and the modulation index is $M_a \approx 1$.

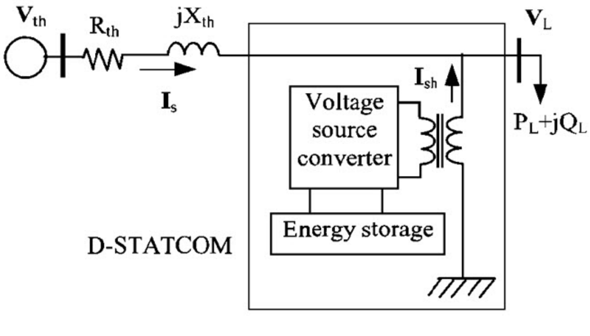

Fig.1: *Schematic representation of the D-STATCOM*

In this paper, in order to mitigate voltage sags caused by SLG, DLG and TLG faults, a new method is proposed that firstly, D-STATCOM and supercapacitor energy storage system (SCESS) are integrated and secondly, a feedback in out of PI controller is used to improve the control system performance under different types of operational conditions.

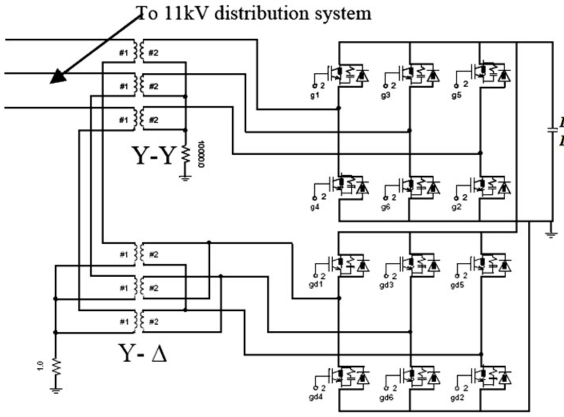

Fig.2: *The 12-pulse D-STATCOM arrangement*

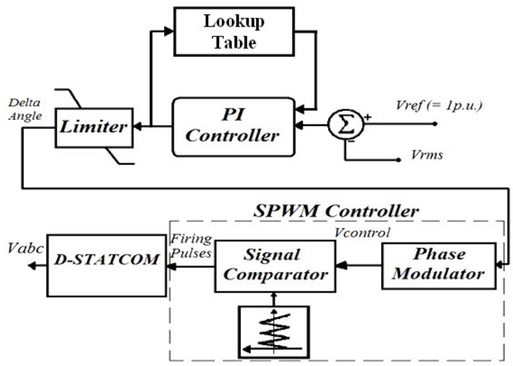

Fig.3: *Control scheme designed for the D-STATCOM*

Considering this fact that all types of fault may occur in distribution system, controller system must be able to mitigate any types of voltage sags. The integration and control of SCESS into a D-STATCOM is developed to mitigate such problems, enhance power quality and improve distribution system reliability [9]. The SCESS is explained as following:

Supercapacitor is a new energy device emerged in recent years. It is also known as electrical double-layer capacitor. The electrical double-layer capacitor is a novel energy storage component developed in 1970s. Its pole boards are made of activated carbon, which have huge effective surface so the capacitance could attain several farad even thousands farad. When it is charged, the electric charges are spontaneously distributed negative and positive ion layers on the interface between pole boards and electrolyte, so the supercapacitor doesn't have electrochemical reaction and only have electric charges adsorption and desorption when it is charged and discharged, as shown in Fig. 4. At the same time, its small leakage current enables it has long time of energy storage and the efficiency could exceed 95% [10, 11]. Energy storage unit, i.e. supercapacitor energy storage arrays, is composed of many monolithic supercapacitors. If a large number of supercapacitors be in parallel, at the same time improving capacity of power electronics devices in power conversion system can be easily composed of more large capacity SCESS, but operational reliability and control flexibility will not be affected. Supercapacitor is very easily modularized, when required, and it is very convenient in capacity expansion.

The whole control process is very simple, compared with SMES in technology it is simpler. Because it has no moving parts in the process of work, little maintenance, compared with flywheel energy storage and SMES, it is more reliable. Compared with battery it has high charge-discharge frequency, long life time, a wider range of voltage and may directly be connected to the bus, though its energy density is less than battery, but its power is larger than battery, which makes supercapacitor very ideal for short pulse power, it can act as battery. Therefore, supercapacitor substituted for battery has become reality.

Determining the number of energy storage module can save supercapacitors, and further reducing volume, quality and cost of the energy storage unit. It is assumed that each supercapacitor is represented as an equivalent resistance r_{eq} and equivalent ideal capacitor c_e in series, R and C of supercapacitor bank respectively are $R = n_s.r_{eq}/n_p C = n_p.c_e/n_s$; that n_s and n_p are the number of monolithic supecapacitors connected in series and parallel for constituting storage energy module. In this paper, SCESS is made of 10 arrays in parallel with $c_e = 1000$ μF and $r_{eq} = 1$ Ω for every array.

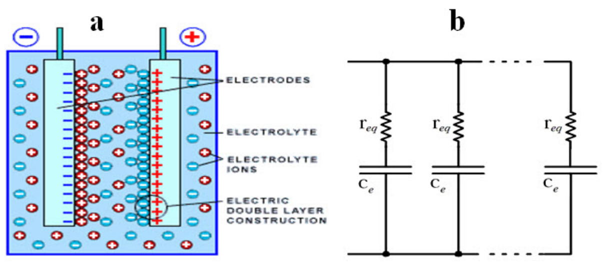

Fig.4: *a) Principle of a supercapacitor b) DC model of a supercapacitor*

Every PI controller has a proportional gain that is playing an important role in D-STATCOM correct performance. Therefore, it is necessary to use a separated proportional gain for each type of operational conditions. The second part of this method uses a feedback in out of PI controller to improve control system performance. Regarding that PI controller needs different proportional gains for special conditions, such as no fault and fault conditions, therefore this paper proposes a Lookup Table to present separated proportional gains for each special operational conditions. Therefore, the presented Lookup Table operates as a feedback for adjusting the proportional gain of the PI controller in D-STATCOM for mitigating of the voltage distortions, intelligently. As shown in Fig.5, angle delta of PI controller is exerted to Lookup Table, a suitable proportional gain is selected (in accordance with Table 1), and eventually, the suitable proportional gain is exerted to PI controller for creating an improved angle delta. The Lookup Table arrangement in feedback that is based on qualitative testing by individual parameter alterations, is shown in Table 1. From Table 1, it is observed that the angles between -10 and 10 degree are usually involved in no fault conditions, then a low proportional gain is needed, while the angles from -50 to -10 degree are usually involved in voltage sags caused by fault conditions and hence the high proportional gain is needed, and the angles between 10 and 20 degree are usually involved in transient states caused by condition changes from fault state to ordinary state and hence a higher proportional gain is needed for mitigating the transient states. The proposed feedback improves the speed of dynamic response of controller system and mitigates the transient states rapidly. The speed of response and robustness of the control scheme are clearly shown in the simulation results.

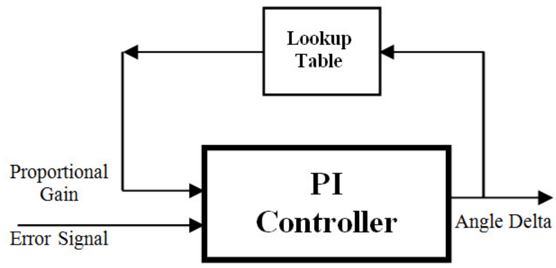

Fig.5: *The application of Lookup Table as a feedback*

Table 1: *basic parameters value of the power system*

Angle Delta	-50	-10	10	20
Proportional Gains	270	219	286	

4. SIMULATION RESULTS

To verify the proposed method, the IEEE 13-bus industrial distribution system is employed. This test case consists of 13 buses and is representative of a medium-sized industrial plant. The plant is fed from a utility supply at 69 kV and the local plant distribution system operates at 13.8 kV [12]. The system is shown in Fig.6. A 12-pulse D-STATCOM is connected to the tertiary winding by closing Brk. 1 at 0.2 s, for maintaining PCC bus RMS voltage at 1pu. A SCESS on the dc side provide the D-STATCOM energy storage capabilities. Simulations are carried out for both cases where the D-STATCOM is connected to or disconnected from the system. The main converter and load parameters used in simulations are defined in Table 2.

The SLG, DLG and TLG faults are exerted by Timed Fault Logic operation in BUS2, therefore, the D-STATCOM supplies reactive power to the system. The duration of the fault is set for about 0.3 s and the faults are exerted at 0.4 s. The total simulation time is 1.6 s. Specifications of test system under all types of fault are presented in Table 3.

The simulations are done for all types of faults introduced in IEEE 13-bus industrial distribution system as follows:

Table 2: *Main parameters of converter and distribution system used in simulations*

Parameters	Value
Utility supply voltage	69kV
Local plant distribution system voltage	13.8kV
Fundamental output voltage frequency	50Hz
Converter switching frequency ($f_{switching}$)	1.45kHz
Tertiary winding transformer ratio	69/13.8/13.8 kV
Modulation index	1
Proportional gain of PI controller	Using of proposed Lookup Table in TABLE 1

4.1 SIMULATION RESULTS FOR SLG FAULT

Figs. 7 and 8 show the RMS and line (Vab) voltages at the BUS3, PCC bus, respectively, for the case when the system operates without D-STATCOM and under SLG fault. In this case, the voltage drops by almost 30% with respect to the reference value. In $t = 0.2$ s, the D-STATCOM is connected to the distribution system. The voltage drop at the PCC bus is mitigated using the proposed control method. Figs. 9 and 10 show the mitigated RMS and line voltages using the new method where a very effective voltage regulation is provided. Fig. 11 shows the D-STATCOM injected reactive power to the system. It is observed that in during fault mitigation the D-STATCOM supplies reactive power to the system. Fig. 12 shows the dc voltage of the VSC. Before the D-STATCOM starts operating, the capacitor is charged to a steady state voltage level of approximately 7 kV. This initial condition of the capacitor improves the response of the D-STATCOM and simplifies the requirements of the control system. As shown in Fig. 12, in the periods 0.4-0.7 s, the D-STATCOM absorbs active power from the ac system to charge the capacitor and maintain the required dc link voltage level.

4.2 SIMULATION RESULTS FOR DLG FAULT

Figs. 13 and 14 show the RMS and line voltages at the PCC bus, respectively, for the case when the system operates without D-STATCOM and unbalanced DLG fault is occurred. The RMS voltage faces with 22% decrease with respect to the reference voltage. Figs. 15 and 16 show the compensated RMS voltage and mitigated voltage of Vab_BUS3 at the PCC bus, respectively. It is observed that the proposed method has mitigated voltage sag, correctly.

Fig. 17 shows the supplied reactive power by D-STATCOM to the distribution system. In addition, the dc voltage of the VSC is shown in Fig. 18.

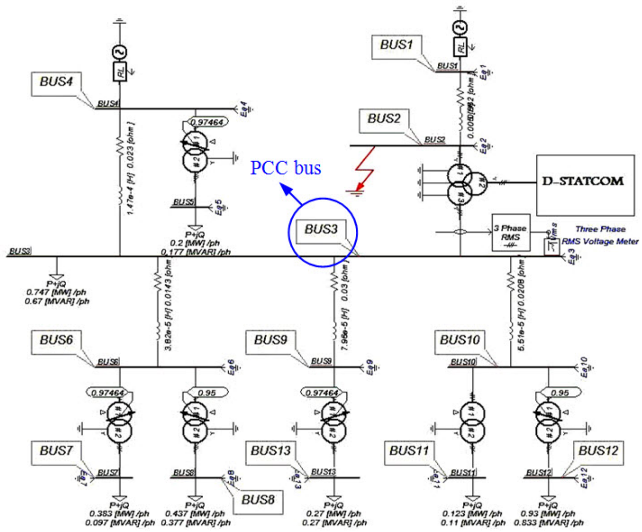

Fig.6: *IEEE 13-bus test system simulated by PSCAD/EMTDC software*

Table 3: *Conditions of test system under all type of faults*

Type Fault	Faulted Phases	Voltage Drop	Fault Interval
SLG	A	30%	0.4 - 0.7 s
DLG	A,B	22%	0.4 - 0.7 s
TLG	A,B,C	25.5%	0.4 - 0.7 s

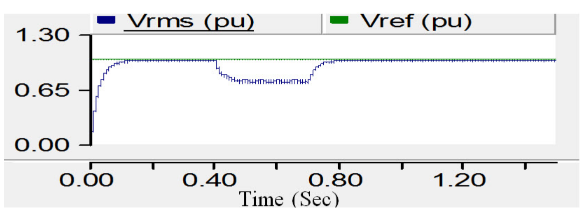

Fig.7: *The RMS voltage (V_{RMS}) at PCC bus without D-STATCOM*

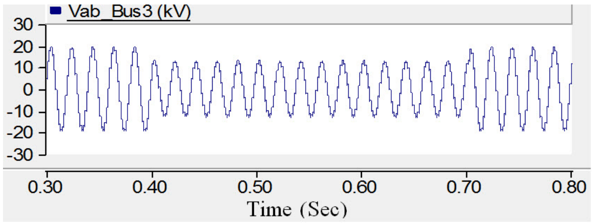

Fig.8: *Vab at PCC bus without D-STATCOM*

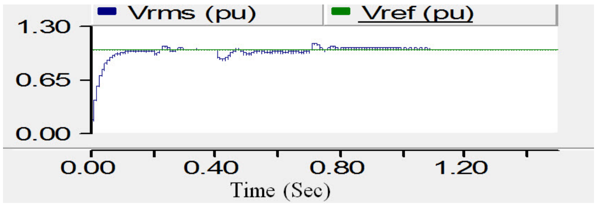

Fig.9: *Compensated RMS voltage under SLG fault*

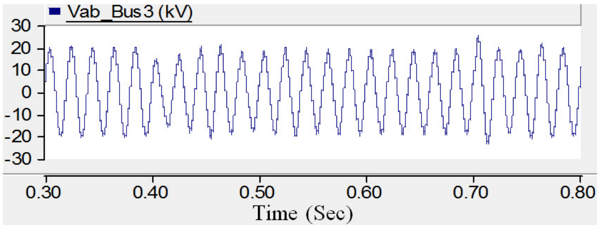

Fig.10: *Compensated line voltage (Vab) at PCC bus*

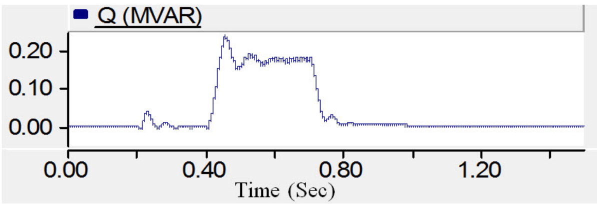

Fig.11: *D-STATCOM injected reactive power to the system under SLG fault*

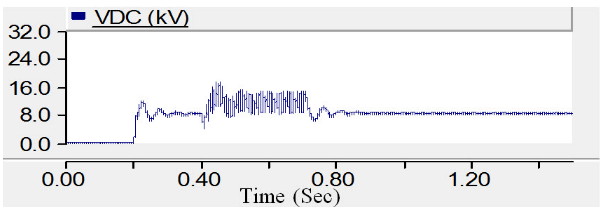

Fig.12: *DC link voltage under SLG fault*

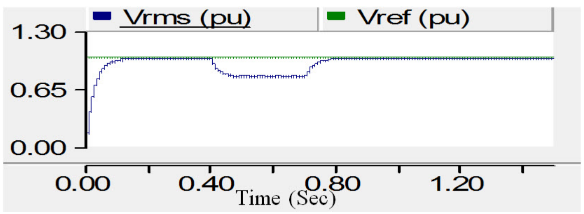

Fig.13: *The RMS voltage (V_{RMS}) at PCC bus without D-STATCOM*

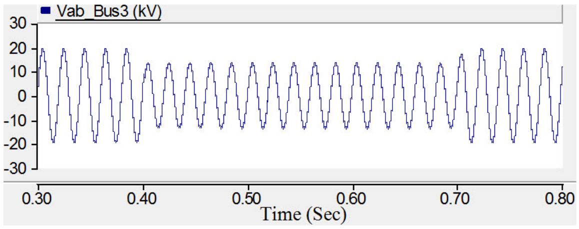

Fig.14: *Vab Line voltage at PCC bus without D-STATCOM*

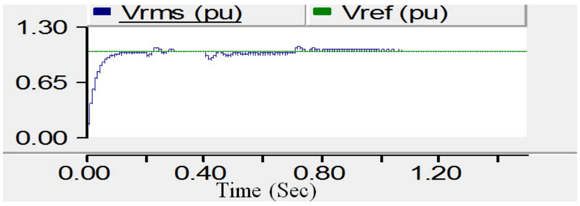

Fig.15: *Compensated RMS voltage*

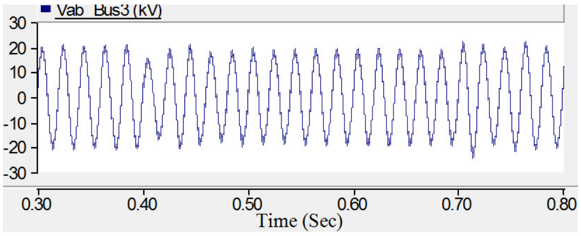

Fig.16: *Mitigated line voltage Vab at PCC bus*

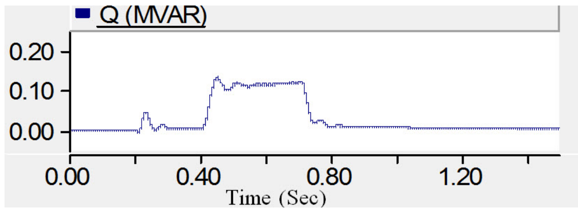

Fig.17: *D-STATCOM injected reactive power to the system under DLG fault*

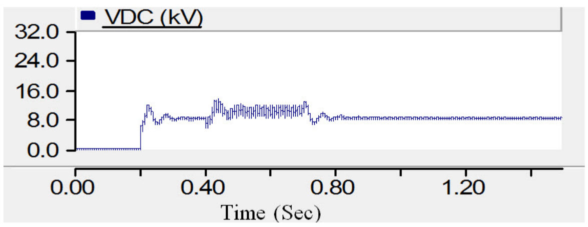

Fig.18: *DC link voltage under DLG fault*

4.3 SIMULATION RESULTS FOR TLG FAULT

Figs. 19 and 20 show the RMS and line voltages at the PCC bus, respectively, for the case when the system operates without D-STATCOM. In this case, the voltage drops by almost 25.5% with respect to the reference value. Figs. 21 and 22 show the mitigated RMS and line voltages at the PCC bus using proposed method. It is observed that the BUS3 voltage is very close to the reference value, i.e., 1pu.

Fig. 23 shows the injected reactive power by D-STATCOM to the distribution system. It is observed that the D-STATCOM is able to supply reactive power to system, correctly. In addition, the dc voltage of the VSC is shown in Fig. 24.

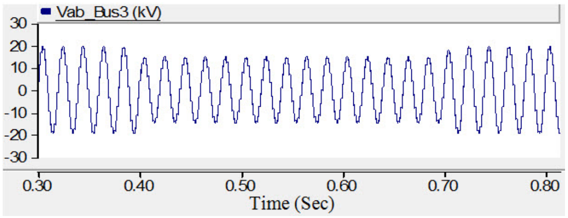

Fig.19: *The RMS voltage at PCC bus without D-STATCOM*

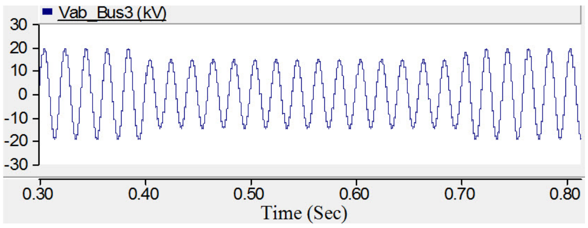

Fig.20: *Vab Line voltage at PCC bus without D-STATCOM*

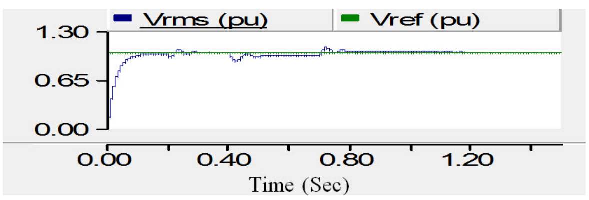

Fig.21: *Compensated RMS voltage*

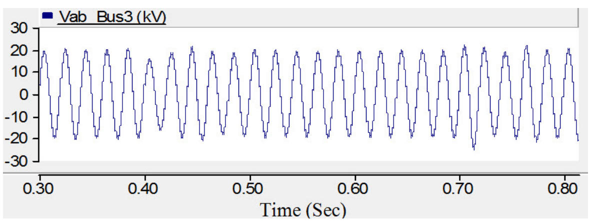

Fig.22: *Mitigated line voltage Vab at PCC bus*

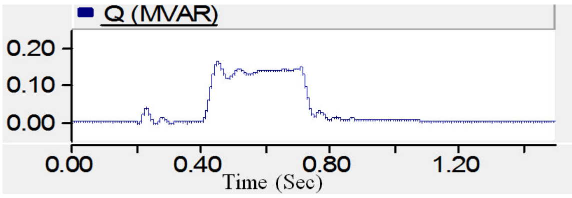

Fig.23: *D-STATCOM injected reactive power to the system under TLG fault*

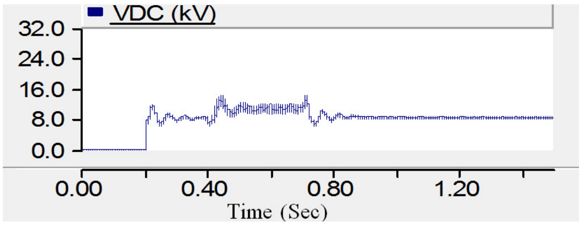

Fig.24: *DC link voltage under TLG fault*

The THD for Vab_BUS3 in during mitigation of SLG, DLG and TLG faults is presented in Table 4. Because of a 12-pulse D-STATCOM is used in this paper, then the THD for Vab is very small.

Table 4: *V_{AB}-THD in during mitigation of faults*

Type Fault	SLG	DLG	TLG
THD	0.0220%	0.0002%	0.0625%

Proposed method merits with respect to the classic methods are simplicity and control convenience and being flexible, i.e. it can mitigate voltage distortions caused by SLG, DLG and TLG faults only with the same control system setting. The presented results show that the proposed controller system could mitigate voltage distortions caused by all types of faults.

5. CONCLUSIONS

In this paper, a new control method is proposed for mitigating the voltage sags, caused by SLG, DLG and TLG faults at the PCC bus. The proposed method is based on two factors; firstly, integrating D-STATCOM and SCESS and secondly, using feedback in controller system and determining proportional gain of PI controller, intelligently. This proposed control scheme applied in IEEE 13-bus industrial distribution system and it is tested under a wide range of operating conditions, it is observed that the proposed method is very robust in every case. In addition, the regulated VRMS voltage at the PCC bus shows a reasonably smooth profile. It was observed that the PCC bus voltage is very close to the reference value, i.e., 1pu and the voltage sags are minimized completely. Moreover, the simulation results are shown that the charge/discharge of the capacitor is rapid through this new method (due to using

SCESS) and due to using a feedback in controller system, the response of the D-STATCOM is fast.

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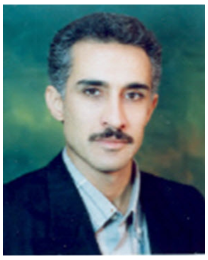

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