Voltage Unbalance Reduction by Distribution Static Compensator in a Case Study Network

[1]Seyed Hossein Hosseini, *Member, IEEE* and [2]Amin Nazarloo, *Student Member, IEEE*

[1]Department of Electrical Engineering, Tabriz Branch, Islamic Azad University, Tabriz, Iran
[2]Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz 51666-16471, Iran
hosseini@tabrizu.ac.ir, nazarloo@ieee.org

Abstract

This paper proposes a new control method for Distribution STATic COMpensator (D-STATCOM) in IEEE 13-bus industrial distribution network. Operating this proposed control method enables D-STATCOM to mitigate all types of fault. This paper validates the performance of D-STATCOM system to mitigate power quality problems and improve distribution system performance under all types of system related disturbances and system unbalanced faults, such as Line to Line (LL), Double Lines to Ground (DLG) faults and simultaneous fault. In this paper, 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 network is simulated to verify operation of proposed D-STATCOM. The reliability and robustness of the control schemes in the system response to the voltage disturbances caused by LL, DLG and simultaneous faults are obviously proved in the simulation results.

1. Introduction

Reactive power compensation is an 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 large-amplitude variations in the load-side voltage [1]. There are three types of unbalanced faults in power networks that cause to voltage sag, such as shunt, series and simultaneous faults. Shunt fault types involving one or two phases and ground are a single line-to-ground fault, a double line-to-ground fault and a line-to-line fault. These are called shunt faults.

The series type faults are one conductor opens and two conductors open. These faults are in series with the line and are called series faults. One or two conductors may be opened, due to mechanical damage or by operation of fuses on unsymmetrical faults [2]. Simultaneous faults are a combination of two or more faults that occur at the same time. They may be of the same or different types and may occur at the same or at different locations. A broken overhead line conductor that falls to earth is a simultaneous one-phase open-circuit and one-phase short-circuit fault at one location [3]. Various methods have been applied to reduce or mitigate voltage sags. The conventional methods are by using capacitor banks, introduction of new parallel feeders and by 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. 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 [4]. D-STATCOM is a shunt device that generates a balanced three-phase voltage or current with ability to control the magnitude and the phase angle [5]. Generally, the D-STATCOM configuration consists of a typical 6-pulse inverter arrangement, a dc energy storage device; a coupling transformer connected in shunt with ac system, and associated control circuits. The configurations that are more sophisticated use multi-pulse and/or multilevel configurations. The 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 [6].

A control method based on RMS voltage measurement has been presented in [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 mitigation due to just load variation while no balanced and unbalanced faults have been investigated. In this paper, a new control method for mitigating the voltage sags in point of common connection (PCC) bus caused by all types of shunt and simultaneous faults is proposed. In [8] and [9], a Lookup Table is used to detect the proportional gain of PI controller, which is based only on Trial and Error. While in this paper, the proportional gain of PI controller is fixed at a same value, for all types of faults, by tuning transformer reactance in a suitable amount. Then robustness and reliability of proposed method is more than mentioned methods. In this method, dc side topology of the D-STATCOM is modified for mitigating voltage distortions and 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.

2. The 12-Pulse D-STATCOM Configuration

Fig. 1 shows the schematic representation of the D-STATCOM. The basic electronic block of the D-STATCOM is the voltage source inverter that 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. Suitable adjustment of the phase and magnitude of the D-STATCOM output voltages allows effective control of active and reactive power exchanges between the D-STATCOM and the ac system.

The VSC consists of 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. Each inverter operates as a 6-pulse inverter, with the Y-Δ inverter being delayed by 30 degrees with respect to the Y-Y inverter. The IGBTs of the proposed 12-pulse D-STATCOM are connected anti parallel with diodes for commutation purposes and charging of the DC capacitor [10]. This is to give a 30 degrees phase shift between the pulses and to reduce harmonics generated from the D-STATCOM. The D-STATCOM is connected in shunt to the system.

3. D-STATCOM Control Strategy

The block diagram of the control scheme designed for the D-STATCOM is shown in Fig. 2. It is based only 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 these two signals in order to obtain the phase delta angle that is required to drive the error to zero. The delta angle 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 $M_a \approx 1$ [11].
The modulating delta angle is applied to the PWM generators in phase A. The angles of phases B and C are shifted 120 and 240 degrees, respectively.

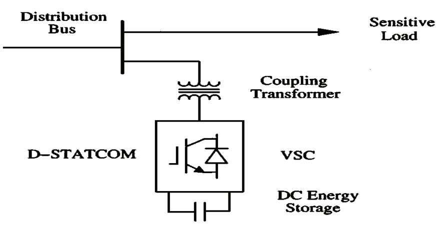

Fig. 1. Schematic representation of the D-STATCOM as a custom power controller

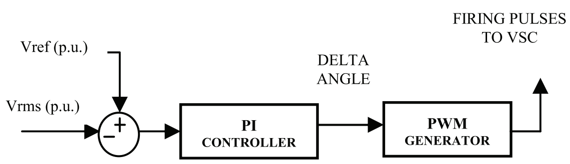

Fig. 2. Control scheme designed for the FD-STATCOM

4. Proposed Control Method

In this paper, in order to mitigate voltage sags caused by shunt and simultaneous faults, a new method is proposed that at first the D-STATCOM and Super-capacitor energy storage system are integrated and secondly, a feedback from out of the PI controller is situated for detecting the suitable proportional gain for any specific fault that is shown in Fig. 3. The Lookup Table arrangement in feedback is based on qualitative testing by individual parameter alterations as shown in Table 1. The proposed feedback improves the speed of dynamic responce of controller system and mitigate the transient states fastly. 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 energy storage systems, such as super capacitor energy storage system (SCESS) into a D-STATCOM is developed to mitigate such problems, enhance power quality and improve distribution system reliability.

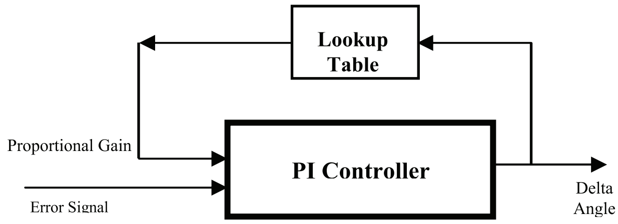

Fig. 3: Proposed feedback for improving the dynamic response

Table 1. Arrangment of Lookup Table in feedback

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

The SCESS is explained as following:

The SCESS is a relative recent technology in the field of energy storage systems based on the electric double layer capacitor (EDLC or simply DLC). The construction and theory of operation of a DLC can be understood by examining the schematic view of its internal components presented in Fig. 4. The elementary structure consists of two activated porous carbon electrodes immersed into an electrolytic solution, and a separator that prevents physical contact of the electrodes but allows ion transfer between them. Energy is stored in the EDLC as a charge separation in the double layer formed at the interface between the solid electrode material surface and the liquid electrolyte in the micro-pores of the electrodes.

This effectively creates two equivalent capacitors connected in series, which gives the name to the structure.

The SCESS performance is based mainly on an electrostatic effect, which is purely physical reversible, rather than employing faradic reactions, although includes an additional pseudo-capacitive layer contributing to the overall capacitance [12-14].

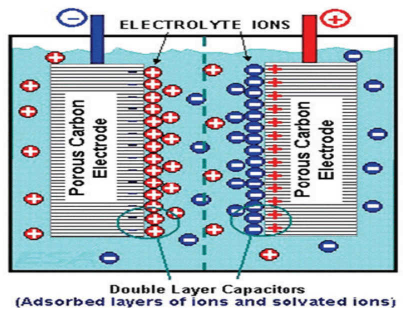

Fig. 4: Schematic representation of a supercapacitator

The new method develops the control concepts of charging and discharging the SCESS by D-STATCOM, and validates the performance of an integrated D-STATCOM/SCESS for improving distribution system performance under all types of system related disturbances and system faults, such as shunt and simultaneous faults. Fig. 5 shows a typical distribution system controlled by this method. The SCESS capacitance is determined by applying a constant-current discharge with

$C = I \times dt/dv$. Since dv/di is almost constant, SCESS capacitance can be modelled as a constant. The equivalent series resistance (ESR) is calculated by measuring the output voltage drop from no load to steady-state load and then dividing by the load current. Since the open-circuit voltage has no significant effect on the ESR, the ESR can be modelled as a constant [15]. The SCESS is modelled with 10 mF capacitance and 320 mΩ ESR. The speed of response and robustness of the control scheme are clearly shown in the simulation results.

5. 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 system is extracted from a common system that is being used in many of the calculations and examples in the IEEE Color Book series. The plant is fed from a utility supply at 69 kV and the local plant distribution system operates at 13.8 kV [16]. The system is shown in Fig.5. A 12-pulse D-STATCOM is connected to the tertiary winding by closing Brk. 1 at 0.2 s, for maintaining load RMS voltage at 1pu in PCC bus. 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 simulations of the D-STATCOM in fault condition are done using LL, DLG and simultaneous faults. In LL and DLG faults the faulted phases are phases A and B. In simultaneous fault, one phase of the 69 kV line has been interrupted (by Brk. 2) and the transformer side and the source side conductors have fallen on the ground, thus creating a combined phase-to-earth and open-circuit fault. In this paper, the D-STATCOM by using proposed control method mitigates voltage sags at the PCC bus (BUS 3) due to all types of faults. The simulations are done for all types of faults introduced in IEEE 13-bus industrial distribution system as follows:

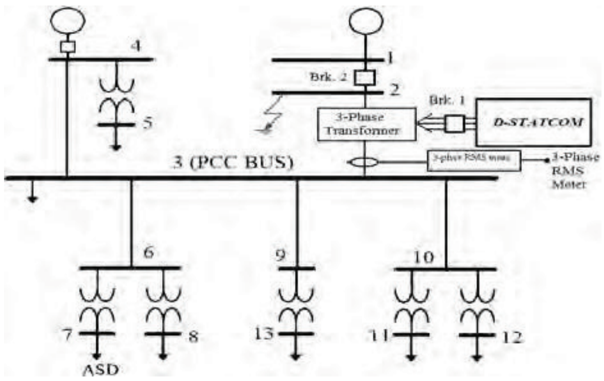

Fig. 5. IEEE 13-bus test system simulated by PSCAD/EMTDC

5.1. Simulation results for shunt faults

The LL and DLG 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.

5.1.1. Simulation results for LL fault

Fig. 6 shows the RMS and line voltages at PCC bus for the case when the system operates without D-STATCOM and under LL fault.

In t = 0.2 s, D-STATCOM is connected to the distribution system. The voltage drop of the sensitive load at PCC bus is mitigated using the proposed control method. Fig. 7 shows the compensated RMS and line voltages at the PCC bus under LL fault using proposed method where a very effective voltage regulation is provided. Fig. 8 shows the supplied reactive power by D-STATCOM to the distribution system. It is observed that in during fault mitigation the D-STATCOM supplies reactive power to the system.

Fig. 9 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 8 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. 9, 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.

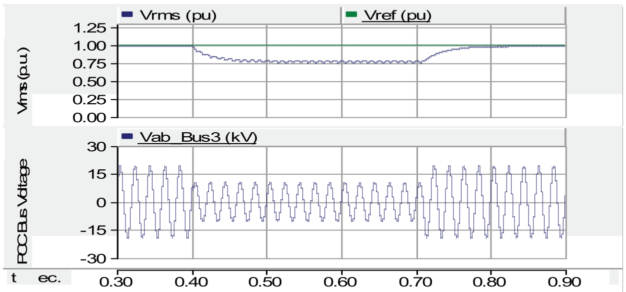

Fig. 6.RMS and line voltages at PCC bus without D-STATCOM

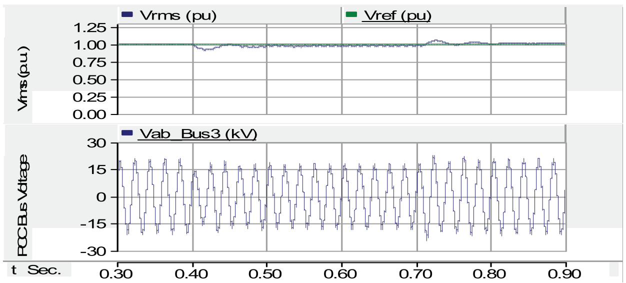

Fig. 7. RMS and line voltages at PCC bus with D-STATCOM

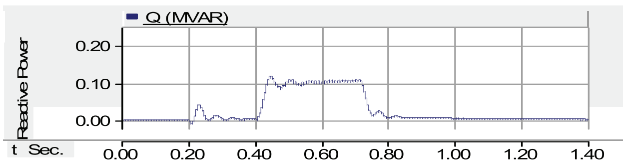

Fig.8. D-STATCOM injected reactive power to network

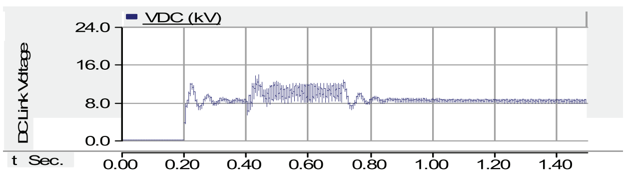

Fig. 9. DC link voltage under LL fault

5.1.2. Simulation results for DLG fault

Fig. 10 shows the RMS voltage and line voltages at the PCC bus for the case when the system operates without D-STATCOM and under DLG fault. Fig. 11 shows the mitigated RMS voltage and line voltages at the PCC bus using proposed method. It is observed that the RMS voltage is very close to the reference value, i.e., 1pu. Fig. 12 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. 13.

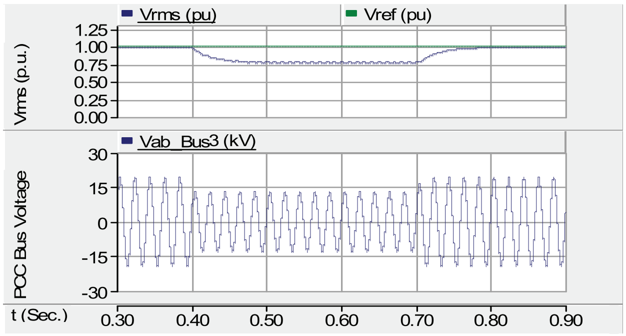

Fig. 10. RMS and line voltages at PCC bus without D-STATCOM

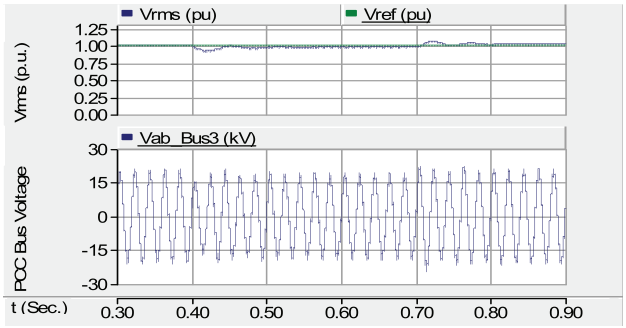

Fig. 11. RMS and line voltages at PCC bus with D-STATCOM

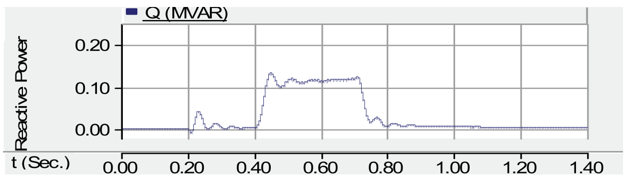

Fig.12. D-STATCOM injected reactive power to network

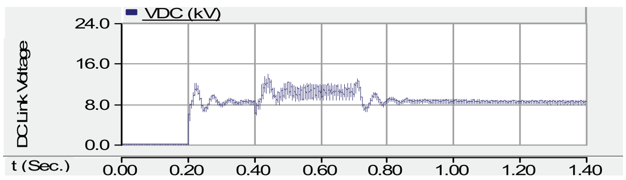

Fig. 13. DC link voltage under DLG fault

5.2. Simulation results for simultaneous faults

In simultaneous faults, phase A of the 69 kV line has been interrupted and the one side (for example transformer side) conductor or both side conductors has/have fallen on the ground, thus creating a combined phase-to-earth and open-circuit fault.

Fig. 14 shows the RMS and line voltages at PCC bus for the case when the system operates without D-STATCOM and under simultaneous fault. In this case, the RMS voltage drops by almost 30% with respect to the reference value.

Fig. 15 shows the compensated RMS and line voltages at the PCC bus under combined earth fault on transformer side and open-circuit fault simultaneously, using proposed method. It is observed that the proposed method has mitigated voltage sags, truly. Fig. 16 shows the supplied reactive power by D-STATCOM to the distribution system and the dc voltage of the VSC is shown in Fig. 17.

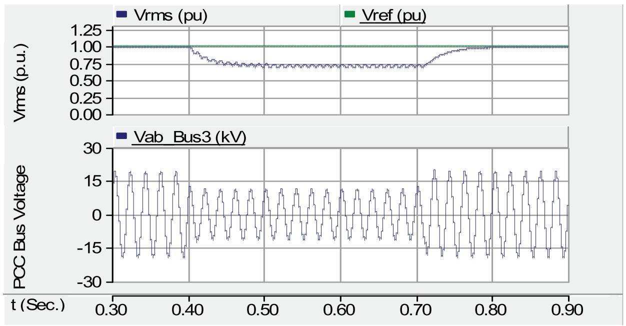

Fig. 14. RMS and line voltages at PCC bus without D-STATCOM

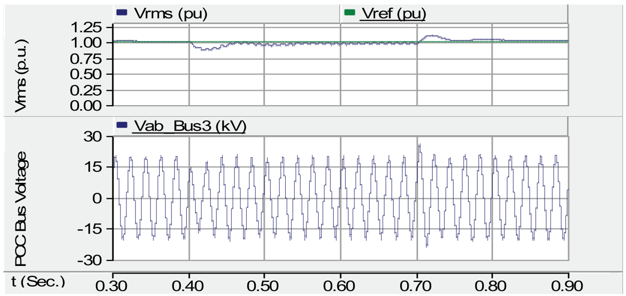

Fig. 15. RMS and line voltages at PCC bus with D-STATCOM

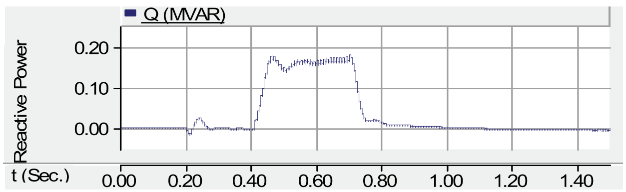

Fig.16. D-STATCOM injected reactive power to network

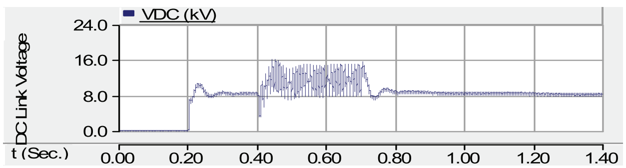

Fig. 17. DC link voltage

Fig. 18 shows the compensated RMS and line voltages at the PCC bus under combined earth fault on both sides and open-circuit fault simultaneously. It is observed that the PCC bus voltage is very close to the reference value, i.e., 1pu. Fig. 19 shows the D-STATCOM injected reactive power to the distribution system and the dc voltage of the VSC is shown in Fig. 20.

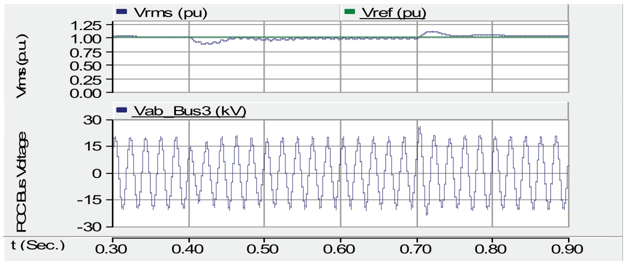

Fig. 18. RMS and line voltages at PCC bus with D-STATCOM

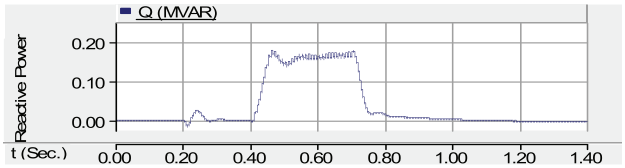

Fig.19. D-STATCOM injected reactive power to network

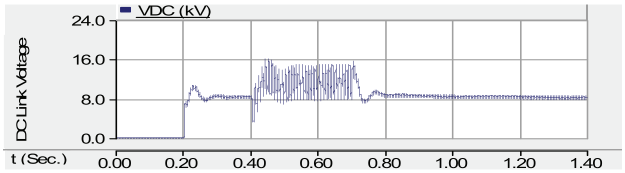

Fig. 20. DC link voltage

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 LL, DLG and simultaneous 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.

6. Conclusions

In this paper, a new control method is proposed for mitigating the voltage sags, caused by LL, DLG and simultaneous faults at the PCC bus. The proposed method is based on integrating D-STATCOM and SCESS. This proposed control scheme is tested under a wide range of operating conditions, and it is observed that the proposed method is very robust in every case. In addition, the regulated V_{RMS} 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 hence the response of the D-STATCOM is fast.

7. References

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