# Impact of Twelve-pulse D-STATCOM on Voltage Sags Mitigation in Distribution Systems

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***Abstract*— This paper presents a study about response of distribution system under presence of voltage sags implementing distribution static compensator (D-STATCOM). From simulations, it analyzes the modified IEEE-13 distribution system identifying those nodes that highly affect the voltage profiles in the distribution system using a method of fault positions (critical nodes). It presents D-STATCOM model based on twelve-pulse inverter, taking advantage of the available elements and the TACS-MODELS tool from ATP/EMTP. Further, the performance of the distribution system using D-STATCOM in several cases is analyzed, showing that this device is a good alternative for sags mitigation. In addition, the relation between the injected D-STATCOM reactive power, the type of sag and the location of affected nodes is considered.**

***Index Terms*— Voltage Sags, D-STATCOM, Sags Mitigation, Power Quality, Simulations, ATP/EMTP.**

## I. Introduction

In electrical distribution systems the most critical disturbance is the interruption of the power service due to economic losses that are produced over affected customers. However, the main concern for many commercial and industrial users is the mal-operation produced by voltage sags [1].

A voltage sag (or dip) is a sudden short duration drop of the RMS voltage at power frequency, between 10% and 90% of the nominal value with durations from half-cycle to a few seconds. Usually this disturbance is characterized by the retained voltage (deep), its duration and the phase jump [2], [3]. Furthermore, its presence increases the current in remote locations of electrical system and affects the operation of sensitive devices and equipment.

The most severe sags are caused by faults and short-circuit generally associated to bad weather conditions (i.e. lightning strokes, storms, wind, etc.), transformer energizing, motor starting, overloads and other load variations [3]. Although voltage sags are less harmful than interruptions, they are more frequent, besides their effects on sensitive devices and equipment can be as important as those produced by an interruption. For these reasons voltage sags are among the most frequent and one of the main power quality (PQ) problems [2].

Study of voltage sags has increased the interest on mitigation methods to preventing or reducing their effects. The conventional methods are by using capacitor banks, introduction of new parallel feeders (distributed generation-DG) and uninterruptible power supplies (UPS). However, due to high costs of these alternatives and the uncontrollable reactive power compensation, PQ problems are not solved completely.

Custom power technology was introduced in the 1980's decade as a solution to PQ problems. The distribution static compensator (D-STATCOM) is a device used to mitigate voltage sags and other PQ solutions such as power factor correction, voltage stabilization, flicker suppression and harmonic control [4], [5]. Additionally, D-STATCOM has the capability to sustain reactive current at low voltage, reduced land use and can be developed as a voltage and frequency support by replacing capacitors with batteries as energy storage [6].

In this paper, the response of modified IEEE-13 (IEEE-13M) distribution system using a twelve-pulse D-STATCOM for voltage sags mitigation is presented. To understand D-STATCOM operation and the distribution system response, modeling and digital simulations are made with Alternative Transient Program (ATP/EMTP). In addition, the relation between the injected D-STATCOM reactive power, the type of sag and the location of affected nodes is considered.

The document is organized as follows. Section II presents the description and modeling of the test system based on IEEE-13 node test feeder. The methodology used to identifying those nodes (critical nodes) that highly affect the voltage profiles in the distribution system is explained in section III. Section IV describes the process to determine, under voltage sag conditions, the cases studies using a scheme of random generation of disturbances. Section V and section VI show the configuration, operation and modeling of D-STATCOM using ATP/EMTP. Simulation results carried out for both cases where the D-STATCOM is connected and disconnected from test system are analyzed in section VII. Finally, some conclusions are presented in section VIII.

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## II. DESCRIPTION AND MODELING OF TEST SYSTEM

The distribution system used in this study is based on IEEE-13 node test feeder [7]. This system presents some interesting characteristics, such as: short and relatively highly loaded for a 4.16 kV feeder, one substation and one voltage regulator unit consisting of three single-phase units connected in wye, overhead and underground lines with a variety of phasing, two shunt capacitor banks, one in-line transformer, unbalanced spot and distributed loads. Fig. 1 shows the scheme of IEEE-13 system.

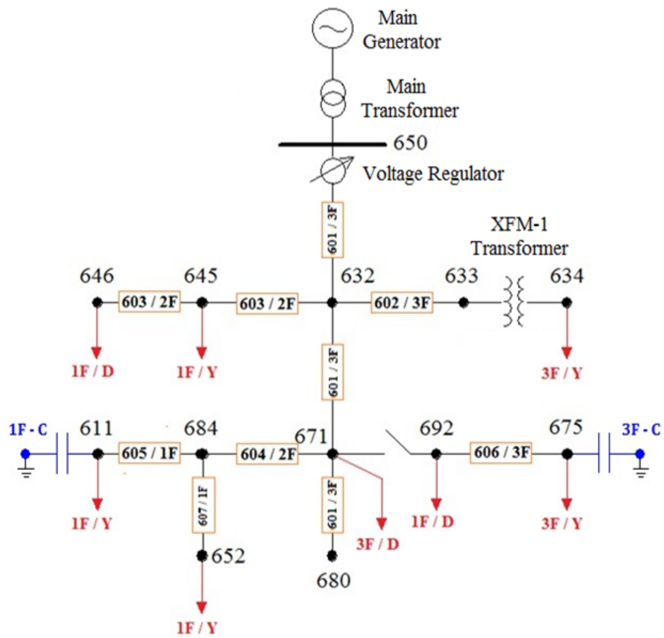


Figure 1. Scheme of IEEE-13 node test feeder

Due to IEEE-13 system is a distribution network with a radial configuration, any fault produced near to the substation transformer (node 650) significantly affects all voltage profiles of the system. This behavior observed in the system allows identifying easily the points or zones that under fault conditions most disturbing the voltage profiles of the nearby nodes (critical nodes). To avoid this condition, the IEEE-13 system is modified connecting other substation-voltage regulator unit, with the same characteristics of the original one in the node 680 where no loads are connected.

The Fig. 2 shows the scheme of IEEE-13 Modified (IEEE-13M) test system. The use of a new distributed generation (GD) unit guarantees that critical nodes are located in different points of the system reducing the relevance of nodes 650 and 632 in the study of effects produced by voltage sags.

Although several tools have been used to simulate voltage sags, only those based in a time-domain solution can reproduce the main features of voltage sags and their effects. The present work has been based on the development of models in ATP/EMTP. The capability of this tool to the voltage sags analysis is shown in [8].

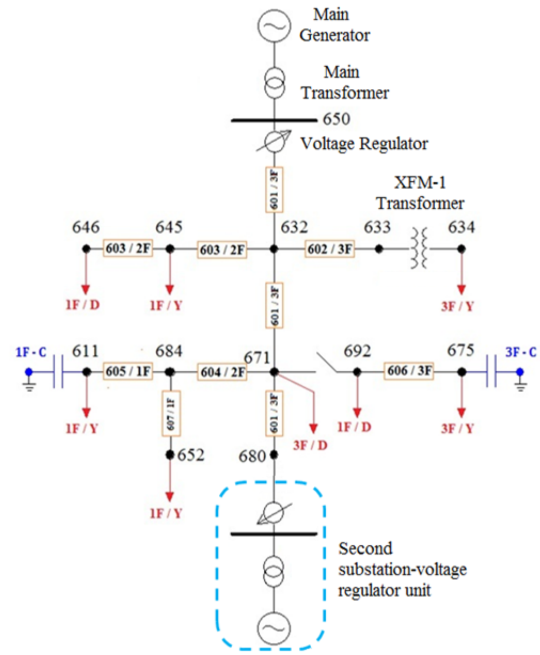


Figure 2. Scheme of IEEE-13M distribution system

## III. IEEE-13M CRITICAL NODES IDENTIFICATION

The vulnerability zones of IEEE-13M distribution system are defined as those critical nodes, that under fault conditions, disturbing the voltage of all nodes in the test system and producing deeper voltage sags. To analyze how much IEEE-13M system is affected by the occurrence of a fault condition $A$ in a specific node $k$, the following local function is used

$$LF_{Ak} = \sum_{i=1}^{13} \sum_{j=1}^{3} (V_{Ref-ij} - V_{Fault-ij})^2 \qquad (1)$$

Where, $A$ is the shunt fault type according to the code shown in Table 1, $k$ is the node where the fault is produced, $i$ is each node in the system, $j$ is the phase (A, B or C), $V_{Ref-ij}$ is the pre-fault voltage in p.u. and $V_{Fault-ij}$ is the voltage in p.u. during the fault. The use of a squared difference in Eq. (1) prevents negative values in the $LF$ function when $V_{Fault-ij}$ is greater than $V_{Ref-ij}$.

TABLE I
FAULT TYPES

| Fault type | Involved phases | Fault code (A) |
|---|---|---|
| single line-to-ground (LG) | A | 1 |
| | B | 2 |
| | C | 3 |
| line-to-line (LL) | AB | 4 |
| | BC | 5 |
| | AC | 6 |
| Double line-to-ground (2LG) | AB | 7 |
| | BC | 8 |
| | AC | 9 |
| Three line (3L-3LG) | ABC | 10 |
| | ABC to-ground | 11 |

Eq. (1) shows that the local function is greater when a specific fault in a node of interest produce deeper voltage sags. For each node of IEEE-13M system simulations for all fault types in the worst fault condition (fault impedance equal to zero) are performed. In total 102 cases are simulated considering that IEEE-13M system is unbalanced and in some nodes cannot perform certain faults.

To assess the complete effect that each node has on the others nodes in the system an overall function ($OF$) is proposed. This function takes into account all local functions ($LF$) obtained by fault type for each node of interest. The equation of this function is given by:

$$OF_k = \sum_{A=1}^{11} LF_{Ak} \qquad (2)$$

where, $A$ is the shunt fault type, $k$ is the node where the fault is produced and $LF$ is the local function. Table 2 (a) shows the local functions of node 650 by fault type and its overall function $OF_{650} = 74.157$. Furthermore, the Table 2 (b) shows a summary with all overall functions of IEEE-13M nodes organized in descendent order.

TABLE II
CRITICAL NODES IDENTIFICATION (A) LOCAL FUNCTIONS AND OVERALL FUNCTION FOR NODE 650 (B) OVERALL FUNCTIONS FOR IEEE-13M NODES

**(a)**

| Fault Type | Node 650 |
|---|---|
| 1 | 3.451 |
| 2 | 4.048 |
| 3 | 5.083 |
| 4 | 3.218 |
| 5 | 3.473 |
| 6 | 3.265 |
| 7 | 7.979 |
| 8 | 8.808 |
| 9 | 8.274 |
| 10 | 13.27 |
| 11 | 13.288 |
| $OF_{650}$ | **74.157** |

**(b)**

| Affected Node | OF |
|---|---|
| 671 - 692 | 121.174 |
| 632 | 112.017 |
| 680 | 101.604 |
| 675 | 86.287 |
| 633 | 79.702 |
| 650 | 74.157 |
| 684 | 25.123 |
| 634 | 24.508 |
| 645 | 22.038 |
| 646 | 16.335 |
| 611 | 3.742 |
| 652 | 2.283 |

Since the overall function is a parameter that totalizes the effect of local functions, the critical node can be considered as the one with the largest overall function. In the case of IEEE-13M system the most critical is node 671 with an overall function $FG_{671} = 121.174$. By other hand, the less critical is node 652 which overall function is $FG_{652} = 2.283$. Observing the IEEE-13M topology shown in Fig. 2 is possible to notice that node 671 is the most critical because is a central node located in a zone with many lines and spot loads connections.

With the aim to choice several case studies to analyze the response of IEEE-13M system in presence of sags using D-STATCOM, in this work the five nodes with the largest overall function are selected. These nodes are 671, 632, 680, 675 and 633. However, depending on the number of nodes in the system can be selected a greater number of critical nodes or use a different selection criteria.

## IV. CASE STUDIES UNDER VOLTAGE SAGS CONDITIONS

In literature several alternatives to analyze and to assess the number of voltage sags and the impact produced by faults in power systems have been proposed. The most widely used are the "method of fault positions" and the "method of critical distances", for more details see Ref. [3], [9–12]. The work presented in this paper is based on the stochastic generation of disturbances. Although this method cannot determine the exact number of voltage sags that may occur in the IEEE-13M system, allows determine the voltage profile of the test system produced by voltage sags.

The application of the method requires the generation of random numbers with a probability density that are used to obtain the location of disturbance, the type of fault and the fault resistance. In addition, the procedure assumes that the voltage sags are originated only by faults, and they are rectangular.

The test system has been simulated in 200 different voltage sag scenarios. The characteristics of the faults have been randomly generated with a Matlab® function using the following parameters:

- Location of fault: a fault may occur at any critical node selected in section III (nodes 671, 632, 680, 675 and 633) or at the 25%, 50% and 75% of any line that connect the critical nodes (L632-633, L632-645, L632-671, L671-675, L671-680, L671-684 y LRG60-632). So the location is selected by a uniform random number
- Probability of each type of fault: LG:63.4%, LL and 2LG: 22.1%, 3L and 3LG: 14.5%
- Fault resistance: eight different values between 0.04Ω and 0.6Ω are established, so the fault resistance is selected by generating an uniform random number
- Initial time and duration of the fault: for simulations the start-time is 50 ms and the duration of the fault is 150 ms

Simulation procedure can be summarized as follows: every time the Matlab® function is run, several quantities are randomly generated (location of fault, type of fault and fault resistance); these parameters are modified in the ATP/EMTP simulation and the voltage sag characteristics in all nodes of the system are recorded (output information). To improve the simulation speed, no protection devices have been included and the effect of transformer simulation will be neglected.

In each simulation scenario, the results of the fault configurations are used to estimate a new $LF$ and to compare the voltage profiles before and after the voltage sag condition using Eq. (1). Table 3 presents the three cases with the worst voltage sag conditions, i.e. the cases with the largest local function. These are the case studies where DSTATCOM for voltage sags mitigation will be evaluated. Taking into account that the presence of voltage sags in the system has a random nature and the most critical conditions are produced by three-line faults these case studies are valid examples of IEEE-13M system response.

TABLE III
CASE STUDIES FOR D-STATCOM IMPLEMENTATION

| Case | Node | Fault Type | Resistance Value [Ω] | Local Function |
|---|---|---|---|---|
| 1 | N671 | 3LG – 11 | 0.07 | 13.580 |
| 2 | N632 | 3L – 10 | 0.07 | 13.278 |
| 3 | N633 | 3LG – 11 | 0.04 | 11.930 |

## V. CONFIGURATION AND OPERATION OF D-STATCOM

### *A. Basic structure of D-STATCOM*

Static compensator D-STATCOM is a three-phase and shunt connected electronic power device. It is connected near to the load at distribution systems [6]. The basic structure of a D-STATCOM is shown in Fig. 3. It consists of a DC energy storage device (DC source or DC capacitor), a three-phase inverter module (based on IGBT, thyristor, etc.), a control stage, an AC filter, and a step-up coupling transformer [13].

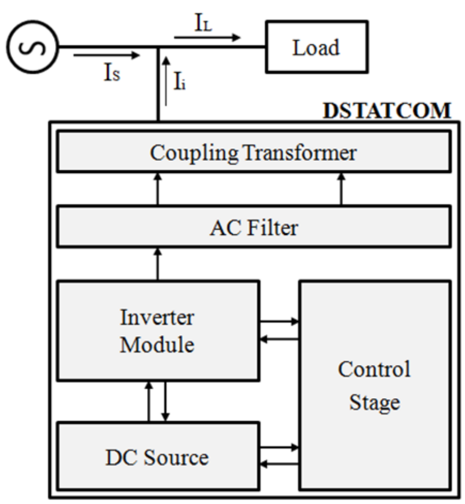


Figure 3. Basic structure of D-STATCOM

Basic electronic unit of D-STATCOM is the voltage source inverter (VSC) that convers 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 thought the reactance of the coupling transformer [5]. The VSC is used to completely replace the voltage or to inject the difference between the nominal voltage and the voltage during the sag condition.

Usually, D-STATCOM configuration consists of a conventional six-pulse inverter arrangement. The configurations that are more sophisticated use multi-pulse or multi-level configurations. In this paper a twelve-pulse inverter configuration is used. This arrangement has 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 being delayed 30° with respect to the Y-Y transformer. Each inverter is a six-pulse inverter connected in parallel and shares the same DC-source.

The twelve-pulse inverter removes the $5^{th}$ and $7^{th}$ harmonic, keeping only the $(n = 12m + 1)$ harmonic order for $m = 1,2,\ldots$ Using this configuration the pulses of the compensator can be extended to 24 or 48 by adding more primary windings with six-pulses inverters.

The aim of the control stage, under voltage sag conditions, is to maintain constant the voltage magnitude at the point of connection (PC) where a load is connected. The controller governs the magnitude and phase of the output voltage of the D-STATCOM.

Finally, the AC filter provides the signal conditioning and the coupling transformer allows the transfer of energy between the network and the power converter device. In a high voltage system, the leakage inductances of the power transformer can function as coupling reactances and also can filter the harmonic current components that are produced by the power inverter module.

### *B. Description of D-STATCOM operation*

The D-STATCOM is a solid state device with the ability to control the voltage magnitude and the phase angle, for this reason can be treated as a voltage controlled source but can also be seen as a controlled current source.

Fig. 4 shows the block diagram of D-STATCOM and its connection scheme. The controller regulates the reactive current that flows between the compensator and the distribution system in such a way that the phase angle between the inverter voltage ($Vi$) and the system voltage ($Vs$) is dynamically adjusted so that the D-STATCOM absorbs or generates the desire reactive power at a specific PC.

The active power ($P_{DST}$) and reactive power ($Q_{DST}$) that flow through an impedance can be calculated using the following equations,

$$P_{DST} = [(|Vs||Vi|)/X_{Trx}] * sen(\delta) \quad (3)$$

$$Q_{DST} = [\{(|Vs||Vi|)/X_{Trx}\} * cos(\delta)] - [|Vs|^2/X_{Trx}] \quad (4)$$

where, $Vi$ is the output voltage of the D-STATCOM, $Vs$ is the power system voltage, $X_{Trx}$ is the reactance of the coupling transformer and $\delta$ is the phase angle between $Vi$ and $Vs$.

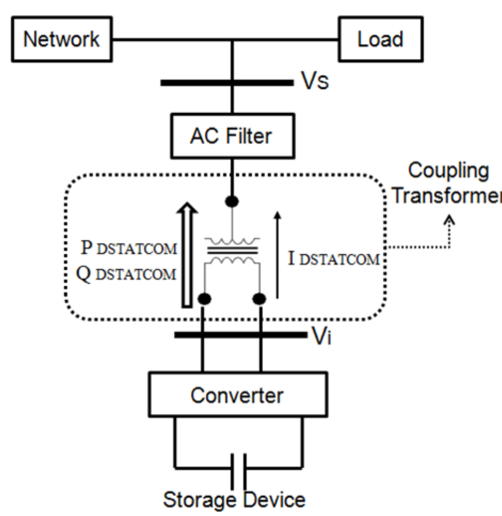


Figure 4. Block diagram of D-STATCOM

Equations (3) and (4) show that the basic operation of D-STATCOM varies depending upon $Vi$. The operation modes of the D-STATCOM are as follows:

- When $Vi > Vs$, the current flows from the D-STATCOM to the power system. In this condition the system sees the compensator as capacitance to its terminals and the D-STATCOM generates reactive power.
- When $< Vs$ , the current flows from the power system to the D-STATCOM. In this condition the system sees the compensator as inductance connected to its terminals and the D-STATCOM absorbs reactive power.
- If $Vs = Vi$, the reactive power exchange is zero and the D-STATCOM does not generate or absorb reactive power.
- When the phase angle $\delta = 0$ the active power exchange is zero. This can be achieved with the control stage.

## VI. D-STATCOM Modeling on ATP/EMTP

Tin this paper, the model of D-STATCOM is a three-phase, twelve-pulse inverter that is connected to the distribution system through a coupling transformer. The complete ATP/EMTP model of compensator is shown in Fig. 5. In this section the elements that conforms each stage of the compensator are described.

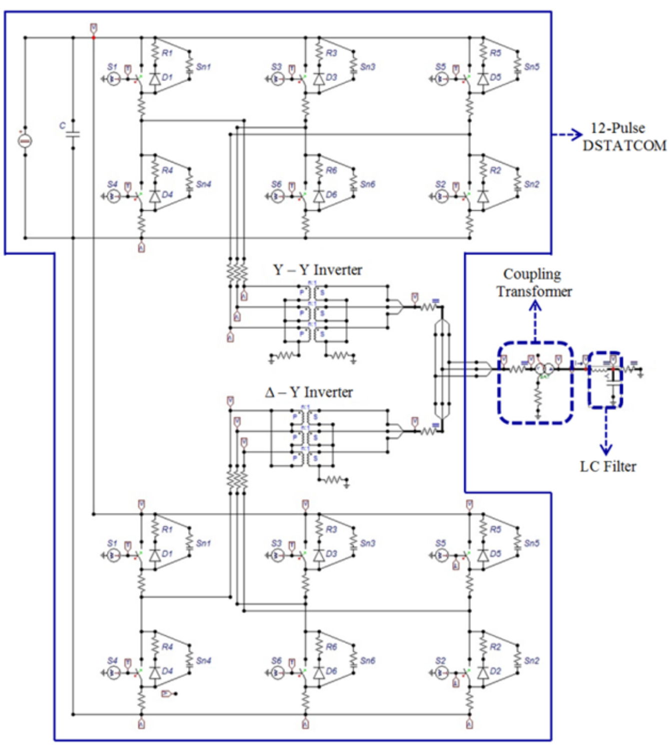


Figure 5. Model of 12-pulse DSTATCOM in ATPdraw

### A. DC energy storage device

DC voltage storage device is modeling as DC source connected in parallel with a capacitor $C_{DC}$. The sizing of this capacitor is referred to the fault current in the system, which is defined as the different between the current before and after the fault [14]. The importance of the capacitor sizing is that this element stores the energy needed to mitigate the voltage sag and is used by D-STATCOM to inject the reactive power. To determine the size of $C_{DC}$ in a three-phase system the following equation is used [15]

$$C_{DC} = 3 \times \left[ (V_{DSTAT} * \Delta I_L * T) / \left( {V_{C\,máx}}^2 - V_{DC}^2 \right) \right] \quad (5)$$

where, $V_{DC}$ is the voltage across $C_{DC}$ per phase, $V_{DSTAT}$ is the peak voltage per phase, $\Delta I_L$ is the difference between the current before and after the fault in the load, $T$ is the period of one cycle of voltage and current and $V_{C\,máx}$ is the upper limit of the energy storage in $C_{DC}$ per phase.

The value of $\Delta I_L$ can be determine by measuring the load current before and during the voltage sag [15]. The value of $V_{DC}$ is determined from ATP/EMTP simulation for each case study. The value of $V_{C\,máx}$ is the upper limit of $C_{DC}$ voltage and this can be two or three times of $V_{DC}$.

### B. Converter/Inverter design

The basic configuration of the D-STATCOM is the twelve-pulse inverter arrangement shown in Fig.5. This configuration uses two 6-pulse inverters connected in parallel and share the same DC-source. The circuit also uses two transformers with their primaries connected in series [16]. The first inverter is connected to the system through Y-Y arrangement, whereas a Y-Δ connection is used for the second inverter being delayed 30° with respect to the Y-Y inverter [17].

For each six-pulse inverter are used six bidirectional semiconductors that can be IGBTs or GTOs. However, for the D-STATCOM model proposed in this paper ideal type-13 switches controlled by TACS are used as valves. Followed to this element is connected a resistance in series that represents the inverter losses.

It is important to emphasize that the inverter model includes a snubber circuit with diodes connected in anti-parallel to each type-13 switch. This circuit is used to reduce $dv/dt$ and $di/dt$ due to the switches commutation. Fig. 6 shows the configuration in ATP/EMTP for one branch that conform a six-pulse inverter. The resistance R1 and R2 represent the inverter losses and the resistance Rsn and capacitor Csn complete the snubber circuit.

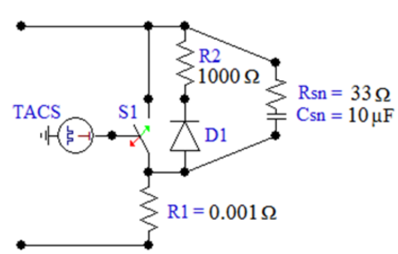


Figure 6. Configuration and values of a six-pulse inverter branch

### C. Controller scheme

Control stage used in simulations is divided in two parts. The first section controls the voltage of D-STATCOM varying the DC voltage of capacitor $C_{DC}$ that stores the energy. The second section controls the phase shift of D-STATCOM output voltages. This control is achieved by variations in the switching angle of each type-13 switch using a TACS–

Source–Pulse-23 as shown in Fig. 6. This TACS circuit produces a square signal or pulse train that acts as a pulse width modulation (PWM) generator.

In this work, the controller of D-STATCOM is configured in a discrete form, this means that for each case simulated the voltage magnitude of $C_{DC}$ and the commutation angles of electronic devices must be set manually. Besides, to obtain the reactive power flow from D-STATCOM to the system the compensator voltage should be greater than the system voltage. Finally, to reduce the active power exchange the output voltages of the D-STATCOM lag the system voltages by a small angle.

### *D. Coupling transformer configuration*

This device is a Y-Δ transformer that allows the energy exchange between the AC system and D-STATCOM. In applications that include electronic devices the coupling transformer is used to adapt the circuit impedances, change the values of inverter output voltages and connect to the next stage.

### *E. Harmonic filter connection*

Due to D-STATCOM output voltages are signals composed by rectangular pulses, a filter LC to reduce the harmonic distortion is implemented. The values of the inductance and the capacitance of filter are 10 mH and 253 μF, respectively. The THD in percent for the output three-phase voltages is 0.283%. Because a twelve-pulse D-STATCOM is used in this paper, then the THD is small.

## VII. Simulation Results

### *A. Simulations without D-STATCOM*

Firstly, the test system has been verified without using the D-STATCOM. Table 4 presents the voltage profiles of IEEE-13 system presented in [7] and the results obtained from ATP/EMTP simulations for IEEE-13 system and IEEE-13M system.

TABLE IV
RESULTS OF IEEE-13 AND IEEE-13M SYSTEMS WITHOUT D-STATCOM

| NODE | VOLTAGE [p.u] IEEE-13 REPORT | | | VOLTAGE [p.u] IEEE-13 ATP | | | VOLTAGE [p.u] IEEE-13M ATP | | |
|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | A | B | C | A | B | C |
| 650 | 1.00 | 1.00 | 1.00 | 0.97 | 0.97 | 0.96 | 0.97 | 0.97 | 0.97 |
| RG60 | 1.06 | 1.05 | 1.07 | 1.05 | 1.06 | 1.05 | 1.05 | 1.05 | 1.05 |
| 632 | 1.02 | 1.04 | 1.02 | 1.02 | 1.04 | 1.00 | 1.03 | 1.03 | 1.02 |
| 633 | 1.02 | 1.04 | 1.02 | 1.01 | 1.04 | 1.00 | 1.02 | 1.03 | 1.02 |
| 634 | 0.99 | 1.02 | 0.99 | 0.99 | 1.02 | 0.98 | 1.02 | 1.03 | 1.02 |
| 645 | - | 1.03 | 1.01 | - | 1.03 | 1.00 | - | 1.02 | 1.02 |
| 646 | - | 1.03 | 1.01 | - | 1.03 | 1.00 | - | 1.02 | 1.02 |
| 671 | 0.99 | 1.05 | 0.98 | 0.99 | 1.05 | 0.97 | 1.01 | 1.02 | 1.00 |
| 680 | 0.99 | 1.05 | 0.98 | 0.99 | 1.05 | 0.97 | 1.01 | 1.02 | 1.01 |
| 684 | 0.99 | - | 0.98 | 0.99 | - | 0.97 | 1.01 | - | 1.00 |
| 611 | - | - | 0.97 | - | - | 0.97 | - | - | 1.00 |
| 652 | 0.98 | - | - | 0.99 | - | - | 1.00 | - | - |
| 692 | 0.99 | 1.05 | 0.98 | 0.99 | 1.05 | 0.97 | 1.01 | 1.05 | 1.00 |
| 675 | 0.98 | 1.06 | 0.98 | 0.99 | 1.05 | 0.97 | 1.00 | 1.02 | 1.00 |

Table 4 shows that all nodes of IEEE-13 system have voltages between 0.96 and 1.06 in p.u., while the nodes of IEEE-13M system have voltages between 0.97 and 1.05 in p.u. Note that even with DG unit the voltage variation at some nodes reaches less than 3.5% of the rated voltage. The comparison between ATP/EMTP results for IEEE-13 system and for IEEE-13M system shows the validity of distribution system modeling.

### *B. Simulations using D-STATCOM under voltage sag conditions*

To analyze the response of IEEE-13M system for each case study defined in section IV and to evaluate the performance of D-STATCOM under voltage sag conditions, the following methodology is presented:

- The D-STATCOM is connected at node in which the voltage sag occurs (node with the deeper voltage).
- Adjusting the angles of D-STATCOM output voltages with the distribution system voltages to reduce the active power exchange.
- Varying the capacitor $C_{DC}$ voltage ($V_{DC}$), in order to find a solution in which the local function described in Eq. (1) is the smallest possible and the voltage of all IEEE-13M nodes satisfying the condition $V_{node} \geq 0.9$ in p.u.
- According to the $V_{DC}$ and the output voltage of D-STATCOM, determining the value of $C_{DC}$.
- Calculate the reactive power injected by D-STATCOM that improves the voltage profile of IEEE-13M system and mitigates the voltage sag condition.

#### *1) Case Study 1: voltage sag at node 671*

In this case, a three line-to-ground fault (type 11) at node 671 with a fault resistance of 0.07 Ω is analyzed. This scenario is the most critical of 150 simulated cases with a local function of 13.551, producing an average voltage sag per phase of 0.247 in p.u.

Table 5 shows the adjustment of D-STATCOM phase angles with respect to angles of IEEE-13M system during the voltage sag condition. This adjust reduces the active power flow between the compensator and the IEEE-13M system.

TABLE V
D-STATCOM ANGLES ADJUSTMENT FOR CASE 1

| | Angles [Degrees] | | |
|---|---|---|---|
| | Phase A | Phase B | Phase C |
| Sag Condition | -67.9 | 173.2 | 52.6 |
| D-STATCOM | -70 | 170 | 50 |

After the angles adjustment, $V_{DC}$ is varied from 900 V to 10 kV to obtain a reduction in the local function. This variation is illustrated in Fig. 7. In this case, the lowest local function obtained is 0.021 applying a DC voltage of 7 kV. In addition, the compensator improves the voltage of node 671 (affected node) reaching an average value of 1.017 p.u. per phase. With these changes all voltages of IEEE-13M system are also improved achieving a minimum value of 0.918 p.u. at node 650-phase C and a maximum value of 1.028 p.u. at node 680-phase A.

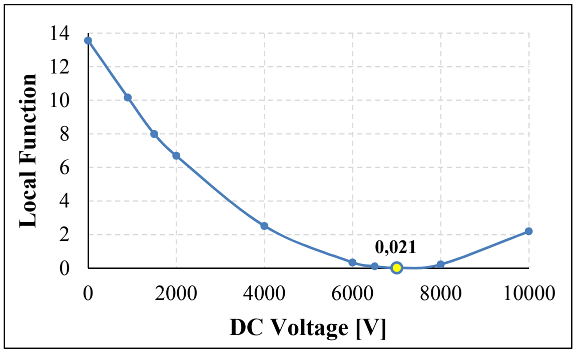


Figure 7. Local function vs. DC voltage for case 1

Table 6 presents the RMS voltage per phase at the node 671 before and after the connection of D-STATCOM during the voltage sag condition.

TABLE VI
VOLTAGE COMPARISON AT NODE 671 FOR CASE 1

| | Voltage [p.u] | | |
|---|---|---|---|
| | Phase A | Phase B | Phase C |
| Without D-STATCOM | 0.250 | 0.253 | 0.238 |
| With D-STATCOM | 1.021 | 1.020 | 1.009 |

For this case, $V_{C\,máx} = 15000\,V$, $V_{DSTAT} = 8206.2\,V$, $\Delta I_L = 63.6\,A$, $T = 16.67\,ms$ and $V_{DC} = 7000\,V$. From these values, the $C_{DC}$ value using the Eq. 5 is 148.3 µF. Finally, the reactive power of the D-STATCOM is calculated as follows,

$$Q = \omega * C_{DC} * V_{L-L}^2 \qquad (6)$$

Where, $\omega = 377$ and $V_{L-L}$ is the nominal line-to-line voltage of the system at the PCC. For IEEE-13M system $V_{L-L} = 4.16\,kV$. Using the Eq. 6 the rating reactive power injected by D-STATCOM is 967 kVAR.

*2) Case Study 2: voltage sag at node 632*

The voltage sag occurred at node 632 is due to a three line fault (type 10) with a resistance of 0.07 Ω. This condition produces an average voltage sag per phase of 0.226 p.u. The angles of D-STATCOM output voltages are adjusted with respect to the power system angles as shown in Table 7.

TABLE VII
D-STATCOM ANGLES ADJUSTMENT FOR CASE 2

| | Angles [Degrees] | | |
|---|---|---|---|
| | Phase A | Phase B | Phase C |
| Sag Condition | -95.7 | 114.3 | 23.9 |
| D-STATCOM | -100 | 140 | 20 |

In this case, the DC voltage is also varied from 900 V to 10 kV but the local function is reduced from 13.257 to 0.029 applying 7.2 kV. Fig. 8 shows the variation of the local function with respect to $V_{DC}$.

Table 8 presents the RMS voltage per phase at node 632 during the voltage sag condition with and without D-STATCOM. Voltages of node 632 are improved with the compensator obtaining an average increase of 0.824 p.u. In addition, all voltages of IEEE-13M system are also improved with values above 0.94 p.u., obtaining a minimum value of 0.942 p.u. at node 650-phase B and a maximum value of 1.094 p.u. at node 632-phase B.

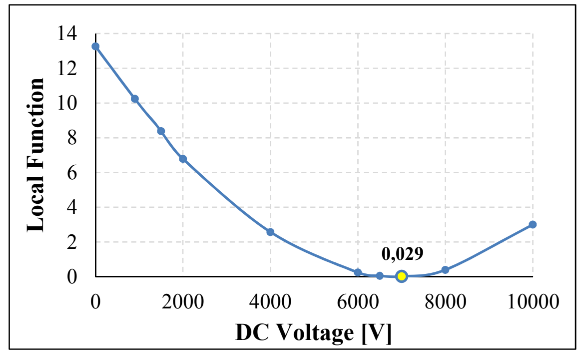


Figure 8. Local function vs. DC voltage for case 2

TABLE VIII
VOLTAGE COMPARISON AT NODE 632 FOR CASE 2

| | Voltage [p.u] | | |
|---|---|---|---|
| | Phase A | Phase B | Phase C |
| Without D-STATCOM | 0.212 | 0.253 | 0.212 |
| With D-STATCOM | 1.031 | 1.094 | 1.025 |

From ATP/EMTP simulation, $V_{C\,máx} = 15000\,V$, $V_{DSTAT} = 8659.5\,V$, $\Delta I_L = 26.4\,A$, $T = 16.67\,ms$ and $V_{DC} = 7208\,V$. Using Eq. 5 the calculated capacitance value is $C_{DC}$ = 65 µF. Finally, from Eq. 6 the injected reactive power of the D-STATCOM is 424 kVAR

*3) Case Study 3: voltage sag at node 633*

For this case, an average voltage sag of 0.104 p.u. is presented due to a three line-to-ground fault (type 11) at node 633 with a resistance of 0.04 Ω. The local function in this scenario is 11.913. To reduce the active power exchange, the output voltages of the system lag the D-STATCOM voltages by a small angle as shown in Table 9.

TABLE IX
D-STATCOM ANGLES ADJUSTMENT FOR CASE 3

| | Angles [Degrees] | | |
|---|---|---|---|
| | Phase A | Phase B | Phase C |
| Sag Condition | -71.5 | 168.6 | 48.2 |
| D-STATCOM | -70 | 170 | 50 |

From simulations the local function is reduced from 11.913 to 0.08 applying a DC voltage of 12 kV. Fig. 9 shows the behavior of the local function with respect to $V_{DC}$.

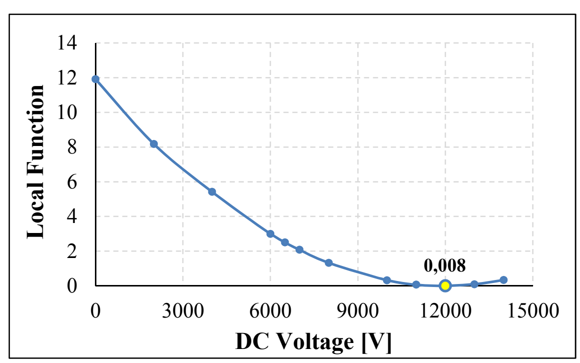


Figure 9. Local function vs. DC voltage for case 3

The RMS voltages at node 633 during the voltage sag condition are shown in Table 10. It can be observed that the presence of D-STATCOM improves the affected node voltages an average of 0.915 p.u. For this case, minimum voltage of IEEE-13M system is 0.936 p.u. at node 650-phase B and maximum voltage is 1.068 p.u. at node 632-phase A.

TABLE X
VOLTAGE COMPARISON AT NODE 633 FOR CASE 3

| | Voltage [p.u] | | |
|---|---|---|---|
| | Phase A | Phase B | Phase C |
| Without D-STATCOM | 0.107 | 0.105 | 0.099 |
| With D-STATCOM | 1.025 | 1.017 | 1.014 |

In D-STATCOM, the capacitor $C_{DC}$ is used to inject reactive power to the system during the voltage sag condition [14]. For this condition, $V_{C\,máx} = 15000\,V$, $V_{DSTAT} = 15.27\,kV$, $\Delta I_L = 20.9\,A$, $T = 16.67\,ms$ and $V_{DC} = 12\,kV$. From these values, the $C_{DC}$ value is 197 µF and the injected reactive power of D-STATCOM is 1285 kVAR.

### *C. Results comparison*

Fig. 10 shows a summary with the location of each node under sag condition, the capacitor $C_{DC}$ and the reactive power injected by D-STATCOM. Simulations show that the compensator inject the largest reactive power in case 3 with 1285 kVAR, while in cases 1 and 2 the D-STATCOM just inject 967 kVAR and 424 kVAR, respectively . From these results it is possible to notice that the D-STATCOM inject more reactive power in those cases where the affected node by voltage sag is farthest from generation zones.

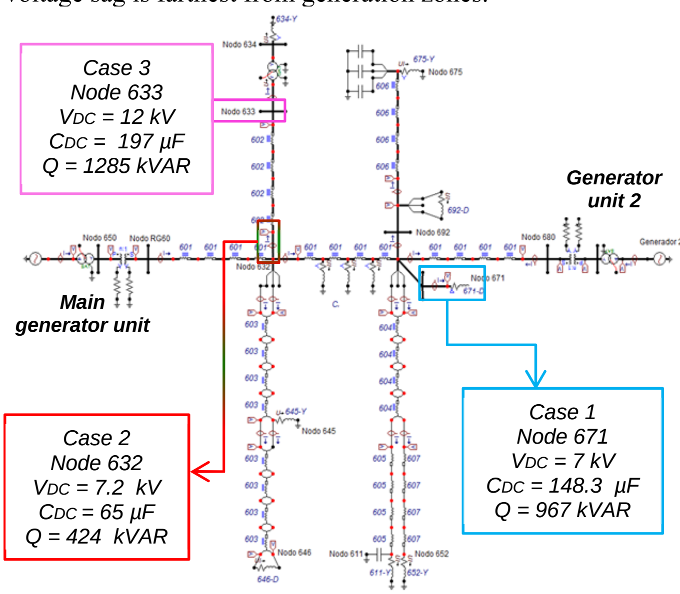


Figure 10. Results of case studies in IEEE-13M system using D-STATCOM

## VIII. CONCLUSIONS

In this paper, it was observed that the presence of D-STATCOM improve the voltage profiles not only in the affected node but also in all IEEE-13M system voltages. In fact, with this device the voltages in affected nodes (under voltage sag conditions) are close to the reference value, i. e. the pre-fault condition, and the voltage sags are completely mitigated. In addition, a 12-pulse D-STATCOM model is presented and applied it to the study of power quality problems. The developed features and graphic advantages available in ATP/EMTP were used to conduct all aspects of the D-STATCOM implementation, the IEEE-13M system modeling and to carry out extensive simulation results. Finally, the relation between the injected D-STATCOM reactive power, the size of $C_{DC}$ and the location of affected nodes is considered.

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