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Analysis of voltage sag compensation in distribution systems using a multilevel DSTATCOM in ATP/EMTP

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Abstract
Voltage sags are the most common power quality disturbances in electrical facilities. It may cause malfunction in sensitive equipment and process interruption. The distribution static compensator (DSTATCOM) is a device that can compensate voltage sags by injecting reactive power into distribution systems. This paper shows the influence on voltage sags characteristics by the presence of twelve-pulse DSTATCOM in the modified IEEE-13 distribution system. The analysis is performed by means of a random generation of disturbances using a MATLAB routine to identify the critical buses of the test system. Further, the DSTATCOM model taking advantage of the available elements from ATP/EMTP software is described. Simulations show that when DSTATCOM is placed directly to an affected bus it is possible to obtain a complete mitigation of the voltage sag. Finally, the relation between the reactive power injected by DSTATCOM, the type of voltage sag and the location of the affected bus is considered.

Keywords: voltage sags; DSTATCOM; voltage compensation; ATP/EMTP; power quality

Análisis de la compensación de hundimientos de tensión en sistemas de distribución usando un DSTATCOM multinivel en ATP/EMTP

Resumen
Los hundimientos de tensión (sags) son perturbaciones de calidad de potencia comunes en los sistemas eléctricos. Estos pueden causar daños en equipos sensibles y la interrupción de procesos. El compensador estático de distribución (DSTATCOM) es un dispositivo que puede compensar sags inyectando potencia reactiva al sistema. Este artículo muestra la influencia que tiene la conexión de un DSTATCOM de 12-pulsos sobre los sags que se presentan en el sistema de distribución IEEE-13 modificado. El análisis se realiza mediante la generación aleatoria de perturbaciones usando una rutina de MATLAB para identificar los nodos críticos del sistema de prueba. Además, se describe el modelo del DSTATCOM usando los elementos disponibles en el software ATP/EMTP. Las simulaciones muestran que cuando el DSTATCOM se conecta al nodo afectado es posible mitigar el sag completamente. Finalmente, se considera la relación entre la potencia reactiva inyectada por el DSTATCOM, el tipo de sag y la ubicación del nodo afectado.

Palabras clave: hundimientos de tensión (sags); DSTATCOM; compensación de tensión; ATP/EMTP; calidad de potencia

1. Introduction

Voltage magnitude is one of the major factors that influence the quality power conditions in distribution systems. Voltage sags are among the most frequent and one of the main power quality (PQ) problems that exist in power systems [1]. They are defined as a decrease in RMS voltage at power frequency, between 0.1 and 0.9 in p.u. of the nominal value with durations from 0.5 to 30 cycles [2].

Usually this disturbance is characterized by the retained voltage (deep), its duration and the phase jump. Furthermore, its presence increases the current in remote locations of an electrical system, produces mal operations or interruptions on sensitive equipment, leads to complete interruptions of the industrial process and affects the proper operation of electrical systems [3].

The most severe voltage 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. Although voltage sags are less harmful than interruptions, they are more frequent, for this reason their effects can be as important as those produced by an interruption.

Currently, several works have been developed to preventing or reducing the effect of voltage sags in distribution systems. Most of these works focus on installing mitigation devices and use conventional methods such as 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.

The distribution static compensator (DSTATCOM) is a shunt-connected compensation equipment which is capable of generating and absorbing reactive power. This equipment can be used to mitigate voltage sags and other PQ solutions such as power factor correction, voltage stabilization, flicker suppression and harmonic control [4,5]. In addition, DSTATCOM 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 analysis of voltage sag compensation on modified IEEE-13 (IEEE-13M) bus test feeder using a twelve-pulse DSTATCOM is presented. To understand DSTATCOM operation and the IEEE-13M system response, modeling and digital simulations are made with Alternative Transient Program (ATP/EMTP). Further, the relation between the reactive power injected by DSTATCOM, the sag features and the location of affected buses is considered.

The paper is structured as follows: The ATP/EMTP model of IEEE-13M bus test feeder and its main features are detailed in section 2. Section 3 describes the method used to identifying the critical buses that highly affect the voltage profiles in the IEEE13-M system. The case studies (under voltage sag conditions) obtained by a scheme of random generation of disturbances are presented in section 4. The configuration and operation of DSTATCOM are briefly explained in section 5. Section 6 shows the model parameters of DSTATCOM in ATP/EMTP. Simulation results and analysis of DSTATCOM connection and its influence on voltage profiles of the test system are presented in Section 7. Finally in section 8, some conclusions of this work are presented.

2. Description and modeling of test system

In order to analyze the DSTATCOM impact on voltage sags in distribution systems, this performed simulations based on the IEEE-13 bus test feeder. This system consists of 13 buses which are interconnected by means of 10 lines (overhead and underground with a variety of phasing), one generation unit, one voltage regulator unit consisting of three single-phase units connected in wye, one main transformer $\Delta - Y$ to 115/4.16 kV (substation), one in-line $Y - Y$ transformer to 4.16/0.480 kV, two shunt capacitor banks, unbalanced spot and distributed loads [7]. On the other hand, in steady-state the IEEE-13 bus system presented three types of disturbances: (a) voltage imbalances, (b) load unbalance, and (c) reactive power flows. Fig. 1 shows the scheme of the IEEE-13 system.

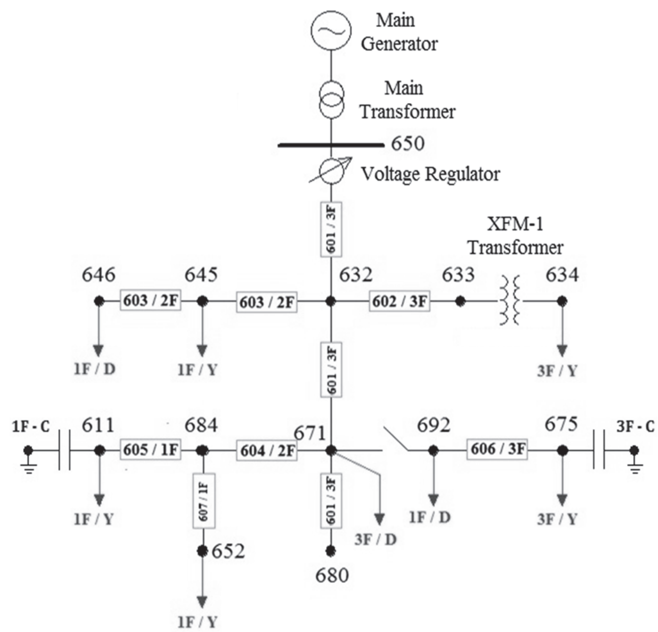

Figure 1. Configuration of IEEE-13 bus test feeder.
Source: the authors

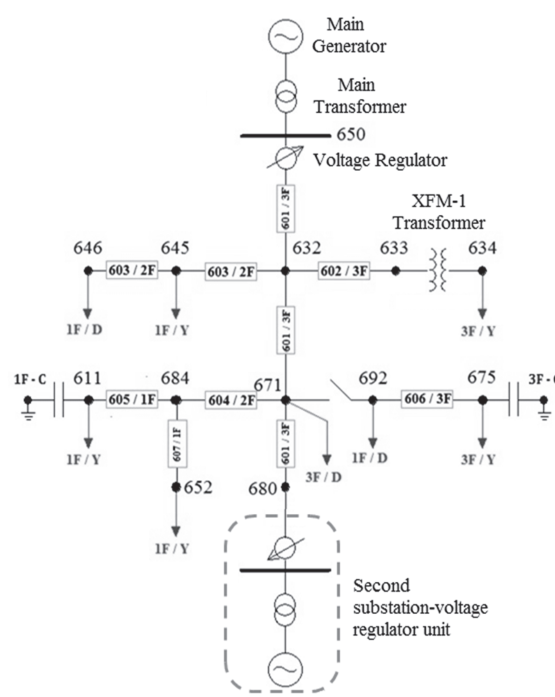

Figure 2. Configuration of IEEE-13M distribution system.
Source: the authors

Table 1.
Fault types

Fault Type	Involved Phases	Fault Code (F)
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

Source: the authors

Table 2.
Critical buses identification (a) local functions and overall function for bus 632, (b) overall functions for IEEE-13M buses

(a)		(b)	
Fault Type	Bus 632	Affected Bus	OF
1	5.207	671 – 692	121.174
2	6.624	632	112.017
3	7.966	680	101.604
4	12.378	675	86.287
5	14.144	633	79.702
6	12.874	650	74.157
7	4.073	684	25.123
8	4.370	634	24.508
9	4.177	645	22.038
10	19.751	646	16.335
11	20.389	611	3.742
$\boldsymbol{OF_{632}}$	**112.017**	652	2.283

Source: the authors

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

Fig. 2 shows the configuration of the IEEE-13 modified test system (IEEE-13M). The use of a new generation unit guarantees that critical buses are distributed in different points of the system reducing the importance of buses 650 and 632 in the study of effects produced by voltage sags.

Although several tools have been used to simulate voltage sags, this paper has been based on the development of models in ATP/EMTP and its ability to analyze systems in time-domain. The capability of this software to analyze voltage sags is shown in [8].

3. IEEE-13M critical buses identification

The critical bus of a system is a load connection point where the occurrence of faults will cause the reduction of voltage profiles in all buses of the system and produce deeper voltage sags. To analyze how much the IEEE-13M system is affected by the occurrence of a fault condition F in a specific bus b, the following local function is used:

$$\boldsymbol{L_{Fb}} = \sum_{i=1}^{13}\sum_{j=1}^{3}(V_{pre-ij} - V_{fault-ij})^2 \qquad (1)$$

Where, F is the shunt fault type according to the information given in Table 1, b is the bus where the fault is produced, i is each bus of the system, j is the phase, V_{pre-ij} is the reference (pre-fault) voltage in p.u. and $V_{fault-ij}$ is the voltage in p.u. fault condition. The use of a squared difference in (1) prevents negative values in local function when $V_{fault-ij} > V_{pre-ij}$.

Eq. (1) shows that the local function is greater when a specific fault in a specific bus produces deeper voltage sags. For each bus of IEEE-13M system simulations for all fault types connecting an impedance-to-ground equal to zero are performed. In total 102 cases are simulated considering that the IEEE-13M system is unbalanced and some buses just have a single-phase or two-phases.

In this paper, an overall function (OF) to assess the complete effect that each bus has on the other buses in the IEEE-13M system is proposed. This function takes into account all local functions (L_{Fb}) obtained by fault type for each bus of interest. The equation of this function is given by:

$$\boldsymbol{OF_b} = \sum_{F=1}^{11} L_{Fb} \qquad (2)$$

where, L_{Fb} is the local function for each fault condition F in the bus b. Table 2(a) shows an example of local functions for bus 632 by fault type and its overall function $OF_{632} = 112.017$. In addition, the Table 2(b) shows a summary with all overall functions of IEEE-13M buses organized in descendent order.

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

To analyze the response of the test system in presence of voltage sags using DSTATCOM, in this paper five buses with the largest overall function are selected as the most critical. These buses are 671, 632, 680, 675 and 633. However, depending on the number of buses in the system or for different case studies other selection criteria can be used.

4. Case studies

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]. In this paper, a method of stochastic generation of disturbances based on the distribution system model and statistical data of faults is applied [13]. Although this method cannot determine the exact number of voltage sags that may occur in the IEEE-13M system, it enables the voltage profile of the test system produced by voltage sags to be determined.

This method selects the location of disturbance (critical buses identified in section 3), the fault type and the fault resistance based on the generation of random numbers with a probability density. In addition, the method assumes that 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 bus (B671, B632, B680, B675 and B633) or at the 25%, 50% and 75% of any line that connect the critical buses (L632-633, L632-645, L632-671, L671-675, L671-680, L671-684 y LRG60-632). The density function for buses and lines is 60% and 40%, respectively.
- Probability of fault types: 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. The fault resistance is selected by a uniform density function.
- Initial time and duration of the fault: for simulations the start-time is 50 ms and the duration of the fault is 10 cycles.

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 profiles in all buses of the system are recorded. To improve the simulation speed, no protection devices have been included and the effect of transformer simulation will be neglected.

For each simulation, the results of fault configurations are used to estimate a new L_{Fb} function. Later, in order to analyze the difference between voltage profiles before and after, voltage sag condition Eq. (1) is used. Table 3 shows three of the worst cases that present voltage sag conditions in IEEE-13M. These are the case studies (with large local functions) 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.

5. Configuration and operation of DSTATCOM

5.1. Basic structure of DSTATCOM

The distribution static compensator (DSTATCOM) is a shunt connected reactive compensation device that can be used to improve the PQ in power systems. This device is connected near or directly to the load buses at distribution systems and its installation can completely mitigate voltage sags and it may reduce the number of sensitive equipment failures [6].

Table 3.
Case studies for DSTATCOM implementation

Case	Bus	Fault Type	Resistance Value [Ω]	Local Function
1	N633	3LG – 11	0.04	11.913
2	N675	3L – 10	0.04	11.556
3	N632	3LG – 11	0.10	10.857

Source: the authors

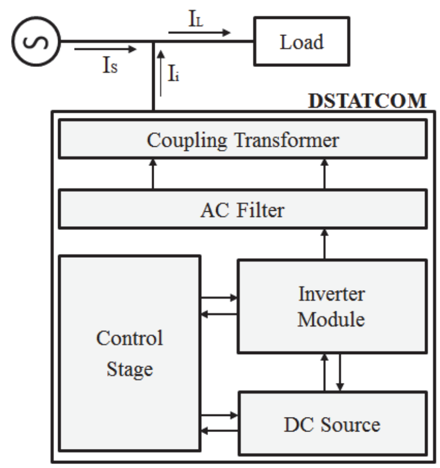

Figure 3. Basic structure of DSTATCOM.
Source: the authors

The basic structure of a DSTATCOM 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 [14].

The main unit of DSTATCOM 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 distribution system through the reactance of the coupling transformer [5]. The VSC is used to completely replace the voltage or to inject the difference between the rated voltage and the voltage during the sag condition.

Usually, the DSTATCOM 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 six-pulse inverters connected by two transformers with their primaries connected in series.

On the other hand, the control stage corrects the voltage drop at the affected bus by adjusting the magnitude and phase of the output voltage of the DSTATCOM during the voltage sag condition. 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 can also filter the harmonic current components that are produced by the power inverter module.

5.2. Operation of DSTATCOM

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

The block diagram of DSTATCOM and its connection scheme is shown in Fig. 4. 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 output voltage of the DSTATCOM (Vi) and the power system voltage (Vs) is dynamically adjusted so that the DSTATCOM absorbs or generates the desired reactive power at a specific point connection.

The active power (P_{DST}) and reactive power (Q_{DST}) that flow through the reactance of the coupling transformer X_{Trx} can be estimated 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, δ is the phase angle between Vi and Vs. The expressions presented in (3) and (4) show that the basic operation of DSTATCOM varies depending upon Vi. The operation modes of this device are as follows:

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

6. DSTATCOM modeling on ATP/EMTP

In this paper, the model of DSTATCOM is a three-phase, twelve-pulse inverter that is connected to the distribution system through a coupling transformer. Fig. 5 shows the ATP/EMTP model of the compensator. In this section, the elements that conform to each stage of the compensator are described.

6.1. DC energy storage device

DC voltage storage device is modeling as DC source connected in parallel with a capacitor C_{DC}. The importance of the capacitor sizing is that this element stores the energy

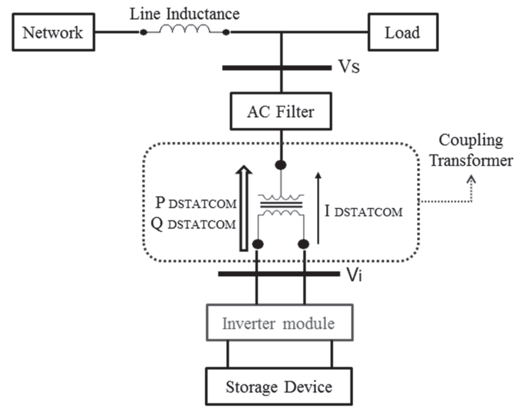

Figure 4. Block diagram of DSTATCOM.
Source: the authors

needed to mitigate the voltage sag and is used by DSTATCOM to inject the reactive power. To determine the size of this capacitor it is necessary to determine the fault current in the system, which is defined as the difference between the current before and after the sag condition [15]. Thus, the following equation is used in a three-phase system [16]:

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

where, V_{DC} is the voltage across C_{DC} per phase, V_{DSTAT} is the peak voltage per phase, ΔI_L is the difference between the current before and after the fault condition 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 ΔI_L can be determine by measuring the load current before and during the voltage sag [16]. The value of

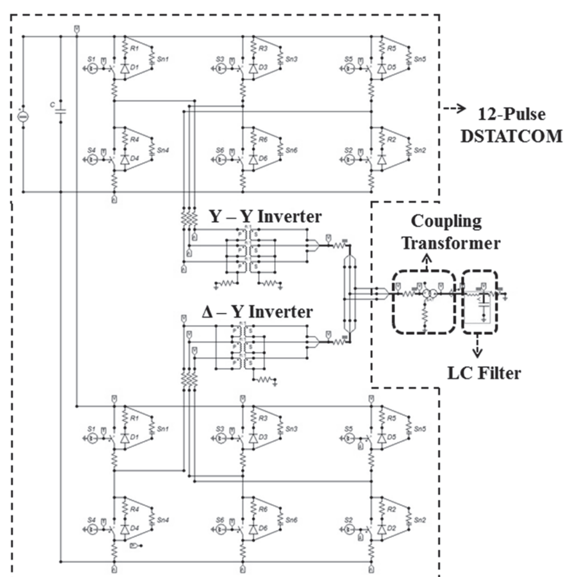

Figure 5. Scheme of 12-pulse DSTATCOM in ATPdraw.
Source: the authors

V_{DC} is determined from the ATP/EMTP simulation for each case study. The value of $V_{C\,máx}$ is the upper limit of C_{DC} voltage that in this case can be two or three times of V_{DC}.

6.2. *Converter/Inverter design*

The basic configuration of the DSTATCOM is the twelve-pulse inverter arrangement shown in Fig.5. This configuration uses two 6-pulse inverters connected in parallel and which share the same DC-source. The arrangement has two transformers with their primaries connected in series. The first transformer is in the $Y-Y$ connection and the second transformer is in the $Y-\Delta$ connection being delayed 30° with respect to the $Y-Y$ transformer [17]. The twelve-pulse inverter removes the 5th and 7th harmonic, keeping only the $(n = 12m + 1)$ harmonic order for $m = 1,2 \ldots$

For each six-pulse inverter six bidirectional semiconductors are used that can be IGBTs or GTOs. However, for the DSTATCOM model presented in this paper, ideal type-13 switches controlled by TACS are used as valves. Following 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 illustrates the configuration in ATP/EMTP for one branch that conforms a six-pulse inverter. The resistance R_1 and R_2 represent the inverter losses and the resistance R_{SN} and capacitor C_{SN} complete the snubber circuit.

6.3. *Controller scheme*

The control stage used in simulations is divided into two sections. The first part controls the voltage of DSTATCOM varying the DC voltage of capacitor C_{DC} that stores the energy. The second part controls the phase shift of DSTATCOM 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.

In this paper, the controller of DSTATCOM is configured in a discrete form. This means that for each case 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 DSTATCOM to the IEEE-13M system the compensator voltage should be greater than the system voltage. Finally, to reduce the active power exchange the output voltages of the compensator lag the system voltages by a small angle.

6.4. *Configuration of coupling transformer*

This device is a $Y-\Delta$ transformer that allows the energy exchange between the AC system and DSTATCOM. 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.

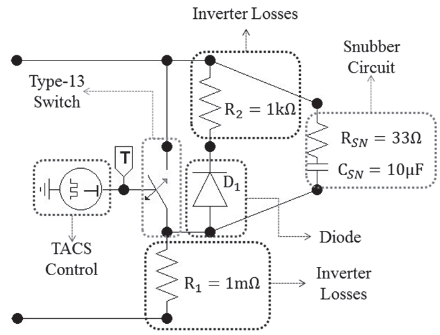

Figure 6. Configuration and values of a six-pulse inverter branch. Source: the authors

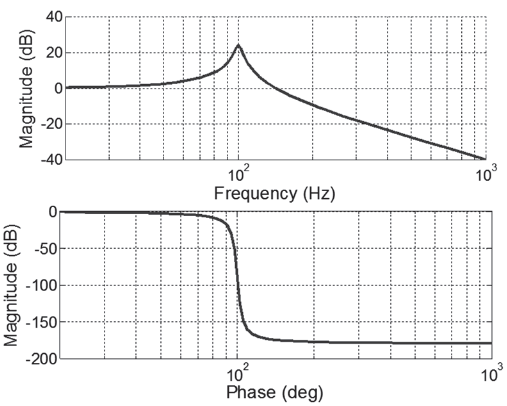

Figure 7. LC filter response. Top: magnitude in dB -- Bottom: phase in deg. Source: the authors

6.5. *Harmonic filter*

Due to DSTATCOM, output voltages are signals composed by rectangular pulses, a LC filter to reduce the harmonic distortion is implemented. The values of the inductance and the capacitance of the filter are 10 mH and 253 µF, respectively. Fig. 7 shows the frequency response of the LC filter with a cut-off frequency of 100 Hz. In addition, the input signal (DSTATCOM output voltages) and the output signal of the LC filter are illustrated in Fig. 8

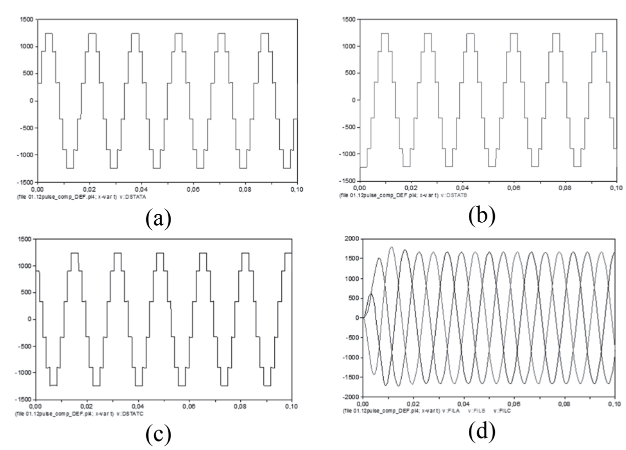

Figure 8. Filter input and output signals (a) Input voltage phase A (b) Input voltage phase B (c) Input voltage phase C (d) output three-phase voltage. Source: the authors

Table 4.
Voltage profiles of IEEE-13 and IEEE-13M systems without DSTATCOM

Bus	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

Source: the authors

The THDv in percent for the output three-phase voltages is 0.283%. Because a twelve-pulse DSTATCOM is used in this paper, then the THDv is small.

7. Simulation results

7.1. Reference case: simulations without DSTATCOM

Initially, the IEEE-13 and IEEE-13M test systems have been verified without installing the DSTATCOM. Table 4 shows the voltage profiles of the IEEE-13 system presented in [7] and the results provided by ATP/EMTP simulations for the IEEE-13 system and IEEE-13M system.

This table illustrates that all buses of the IEEE-13 system have voltages between 0.96 and 1.06 in p.u., while the buses of IEEE-13M system have voltages between 0.97 and 1.05 in p.u. Note that even with the additional generation unit the maximum absolute error obtained from simulations is 3.5%. This error supports the validity of the distribution system modeling.

7.2 Case studies using DSTATCOM under voltage sag conditions

In order to evaluate the performance of DSTATCOM and the response of IEEE-13M system under voltage sag conditions, the following procedure is developed for each case study defined in section 4:

- Step 1: Connect the DSTATCOM at bus in which the voltage sag occurs (bus with the deeper voltage).
- Step 2: Adjust the angles of DSTATCOM output voltages with the distribution system voltages to reduce the active power exchange.
- Step 3: Change the capacitor C_{DC} voltage (V_{DC}), in order to find a solution in which the local function described in (1) is the smallest possible and the voltage of IEEE-13M buses satisfying the condition $V_{bus} \geq 0.9$ in p.u.
- Step 4: Determine the value of C_{DC} from V_{DC} value and the output voltages of DSTATCOM.

Table 5.
DSTATCOM angles adjustment for case 1

	Angles (degrees) Phase A	Phase B	Phase C
Sag Condition (system)	-71.5	-168.6	48.2
DSTATCOM	-70	-170	50

Source: the authors

- Step 5: Calculate the reactive power injected by DSTATCOM that mitigates the voltage sag condition in the IEEE-13M system.

7.1.1. Case study 1: voltage sag condition at bus 633

In this case, a three line-to-ground fault (type 11) at bus 633 with a fault resistance of 0.04 Ω is analyzed. This scenario has a local function of 11.913 and produces an average voltage sag per phase of 0.104 in p.u. To reduce the active power exchange, the output voltages of the system lag the DSTATCOM voltages by a small angle as shown in Table 5.

After the angles adjustment, V_{DC} is varied from 2 kV to 14 kV to obtain a reduction in the local function. This variation is illustrated in Fig. 9. In this case, the lowest local function obtained is 0.008 applying a DC voltage of 12 kV.

In this case, the use of compensator improves the voltage of bus 633 (affected bus) reaching an average value of 1.018 p.u. per phase. In addition, all voltages of IEEE-13M system are also improved achieving a minimum value of 0.936 p.u. at bus 650-phase B and a maximum value of 1.068 p.u. at bus 632-phase A. Fig. 10 shows the impact of the DSTATCOM connection on voltage profiles (average per phase) of IEEE-13M system obtained with ATP/EMTP.

The RMS voltage per phase at bus 633 before and after the connection of DSTATCOM is shown in Table 6. Note that the compensator connection contributes to mitigating completely the voltage sag in all phases of affected bus.

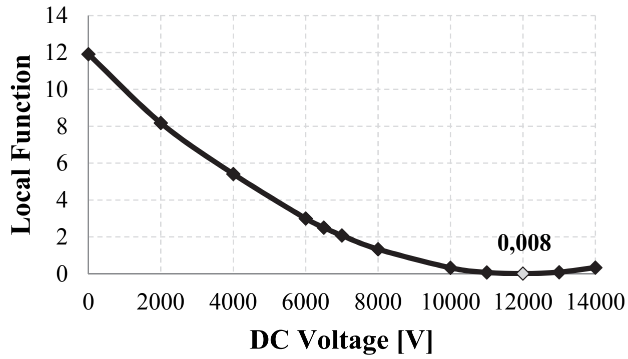

Figure 9. Local function vs. DC voltage for case 1. Source: the authors

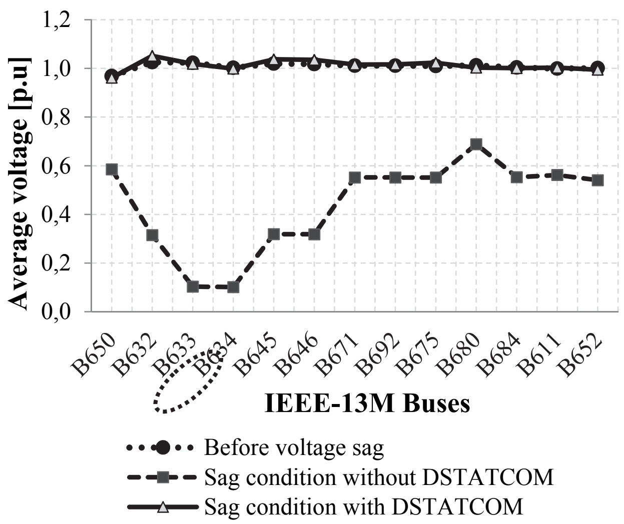

Figure 10. Voltage profiles of IEEE-13M system for case 1.
Source: the authors

Table 6.
Voltage comparison at bus 633 for case 1

	Angles (degrees)		
	Phase A	Phase B	Phase C
Without DSTATCOM	0.107	0.105	0.099
With DSTATCOM	1.025	1.017	1.014

Source: the authors

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} size using the Eq. 5 is 197 μF. Finally, the reactive power of the DSTATCOM is calculated as follows,

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

where, $\omega = 377$ rad/s and V_{L-L} is the nominal line-to-line voltage of the system at the point connection. For IEEE-13M system $V_{L-L} = 4.16\,kV$. Using the Eq. 6 the rating reactive power injected by DSTATCOM is 1285 kVAR.

Table 7.
DSTATCOM angles adjustment for case 2

	Angles (degrees)		
	Phase A	Phase B	Phase C
Sag Condition (system)	-66.6	-174.7	53.5
DSTATCOM	-70	-170	50

Source: the authors

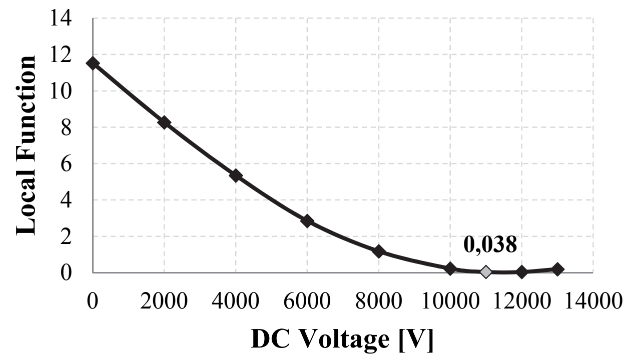

Figure 11. Local function vs. DC voltage for case 2.
Source: the authors

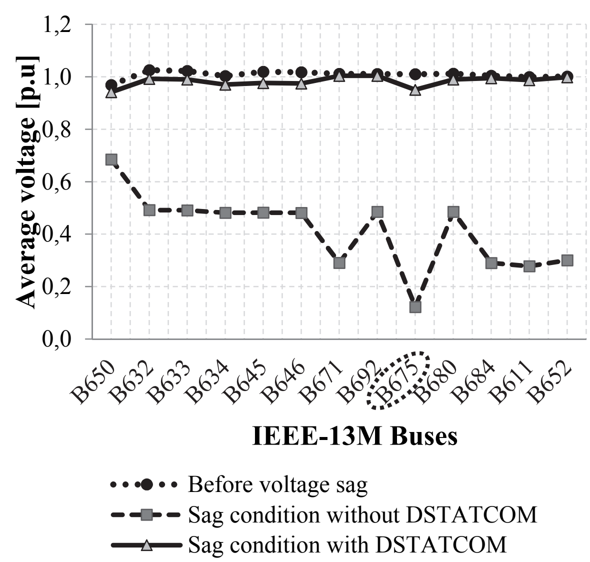

Figure 12. Voltage profiles of IEEE-13M system for case 2.
Source: the authors

7.1.2. Case study 2: voltage sag condition at bus 675

Average voltage sag of 0.123 p.u due to three-line fault (type 10) at bus 675 with a fault resistance of 0.04 Ω is presented. The angles of DSTATCOM output voltages are adjusted with respect to the power system angles as shown in Table 7.

In this case, the DC voltage is varied from 2 kV to 13 kV and the local function is reduced from 11.556 to 0.038 applying 11 kV. Behavior of local function with respect to V_{DC} is shown in Fig. 11.

Table 8.
Voltage comparison at bus 675 for case 2

	Angles (degrees)		
	Phase A	Phase B	Phase C
Without DSTATCOM	0.124	0.127	0.118
With DSTATCOM	0.953	0.952	0.948

Source: the authors

Table 9.
DSTATCOM angles adjustment for case 3

	Angles (degrees)		
	Phase A	Phase B	Phase C
Sag Condition (system)	-54.2	-174.2	65.4
DSTATCOM	-60	180	60

Source: the authors

The effect of DSTATCOM connection on voltage profiles (average per phase) of IEEE-13M system is illustrated in Fig. 12. For this condition, the minimum voltage of the IEEE-13M system is 0.921 p.u. at bus 650-phase B and maximum voltage is 1.019 p.u. at bus 680-phase B.

Table 8 presents the RMS voltage per phase at bus 675 during the voltage sag condition with and without DSTATCOM. It can be observed that the compensator connection improves the voltage of bus 675 obtaining an average increase of 0.828 p.u with respect to voltage sag.

From ATP/EMTP simulation, the compensator features are $V_{C\,máx} = 15000\,V$, $V_{DSTAT} = 13971\,V, \Delta I_L = 104.8\,A$, $T = 16.67\,ms$ and $V_{DC} = 11000\,V$. Using Eq. 5 the calculated capacitance value is C_{DC} = 704.06 µF. Finally, from Eq. 6 the injected reactive power of the DSTATCOM is 4593 kVAR.

7.13. Case study 3: voltage sag condition at bus 632

Voltage sag occurring at bus 632 is due to a three line-to-ground fault (type 11) with a resistance of 0.10 Ω. The local function in this scenario is 10.857 and produces an average voltage sag of 0.309 p.u. Table 9 shows the adjustment of DSTATCOM phase angles with respect to angles of the IEEE-13M system during the voltage sag condition. This adjust reduces the active power flow between the compensator and the IEEE-13M system.

From simulations the local function is reduced from 10.857 to 0.028 applying a DC voltage of 5 kV. Fig. 13 shows the variation of the local function with respect to V_{DC}.

The response of IEEE-13 M voltage profiles before and after the DSTATCOM installation is shown in Fig. 14. In this case, the compensator improves the voltage of the affected bus (B632) reaching an average value of 1.067 p.u. With these changes all voltages of the IEEE-13M system are also improved achieving a minimum value of 0.945 p.u. at bus 650-phase B and a maximum value of 1.074 p.u. at bus 632-phase B.

The RMS voltages of bus affected by sag condition using DSTATCOM are presented in Table 10. Note that the voltage sag is mitigated about 0.759 p.u. with respect to disturbance value (sag condition) connecting the compensation device.

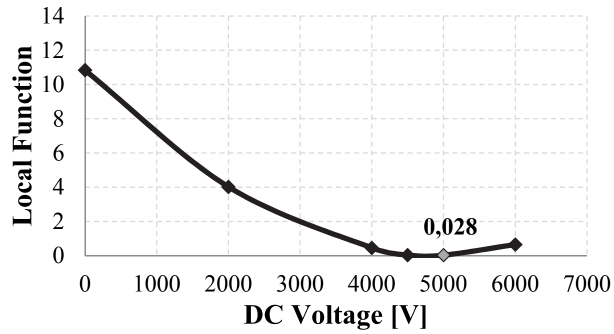

Figure 13. Local function vs. DC voltage for case 3.
Source: the authors

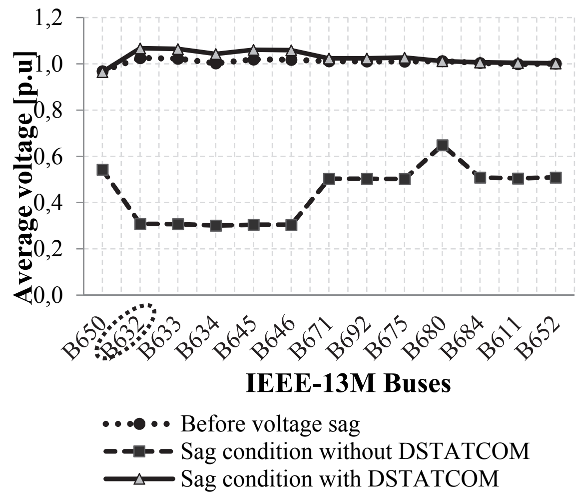

Figure 14. Voltage profiles of IEEE-13M system for case 3.
Source: the authors

Table 10.
Voltage comparison at bus 632 for case 3

	Angles (degrees)		
	Phase A	Phase B	Phase C
Without DSTATCOM	0.312	0.318	0.296
With DSTATCOM	1.068	1.074	1.060

Source: the authors

In DSTATCOM, the capacitor C_{DC} is used to inject reactive power to the system during the voltage sag condition. For this condition, $V_{C\,máx} = 15\,kV$, $V_{DSTAT} = 6.27\,kV$, $\Delta I_L = 47\,A$, $T = 16.67\,ms$ and $V_{DC} = 5\,kV$. From these values, the C_{DC} value is 73.71 µF and the injected reactive power of DSTATCOM is 480.9 kVAR.

8. Results comparison

A summary with the location of each bus under sag condition, the capacitor C_{DC} and the reactive power injected by DSTATCOM is shown in Fig. 15. Simulations show that the compensator injects the largest reactive power in case 2 with 4539 kVAR, while in cases 1 and 3 the compensator injects 1285 kVAR and 481 kVAR, respectively. From these results it is possible to notice that the DSTATCOM inject more reactive power in those cases where the affected bus by voltage sag is farthest from generation zones.

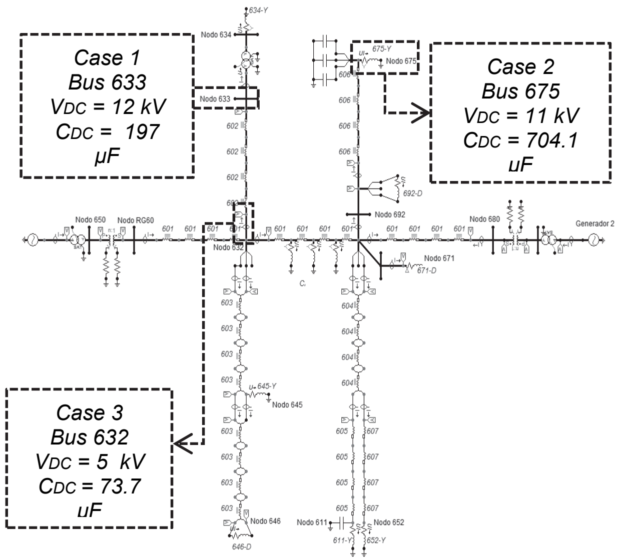

Figure 15. Results of case studies using DSTATCOM.
Source: the authors

9. Conclusions

In this paper, the influence of a 12-pulse DSTATCOM on compensation of voltage sags caused by faults in the IEEE-13M distribution system has been analyzed. In order to evaluate the effect of DSTATCOM installation, the relation between the size of capacitor C_{DC}, the reactive power injected by compensator and the location of affected buses has been taken into account. Further, a method to identify the critical buses based on a random generation of faults, the system characteristics and statistical data of faults was applied.

It was observed that the presence of DSTATCOM improved the voltage profiles not only in the affected bus but also in all IEEE-13M system voltages. In fact, with this device the voltage of buses during sag conditions are compensated close to the reference values (before voltage sag condition) and the voltage sags are completely mitigated.

Developed features and graphic advantages available in ATP/EMTP were used to conduct all aspects of the DSTATCOM implementation, the IEEE-13M system modeling and to carry out extensive simulation results. This work is still under development, the next step in research should consider the modeling of an online control stage and the improvement of the converter stage to 24 or 48-pulse multistage DSTATCOM.

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