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Study of the Dynamic Behavior of a DSTATCOM Installed in a Distribution Network in Case of Single and Multiphase Short Circuit

Hassane OUSSEYNI IBRAHIM[1,a*], Francois-Xavier FIFATIN[2,b]
and Arouna OLOULADE[3, c]

[1]University Institute of Technology, University Dan Dicko Dankoulodo, of Maradi, BP 465. Maradi, Niger

[2]Polytechnic School of Abomey-Calavi (EPAC), University of Abomey-Calavi, BP 123. Cotonou, Benin

[3]Electrotechnic, Telecommunication and Informatic Laboratory (LETIA), University of Abomey-Calavi, BP 123. Cotonou, Benin

[a]hassane2025@yayoo.fr, [b]fifatinf@gmail.com, [c]olouarou@yahoo.fr

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Abstract. The quality of the electricity delivered to consumers depends in particular on the stability of the distribution system. Any faults that appear on the distribution lines must be automatically controlled and eliminated as quickly as possible. These requirements lead electrical system operators and planners to look for modern equipment adapted to their system. This paper investigated the behavior of a DSTATCOM in the face of contingencies that may arise in an electrical power distribution network. It shows that DSTATCOM is an effective attenuator to limit the impacts of perturbations on the distribution network. The model equations are simulated in a MATLAB environment and have shown that the exactitude of the network parameters is a determining factor in the capacity of a perturbed distribution network to absorb voltage variations in the presence of a DSTATCOM optimally positioned at a node. The capacitive current of the DSTATCOM increases inversely with a bad power factor and a critical voltage drop. The DSTATCOM in a network is therefore more solicited when the operating parameters of this network degrade as a result of single-phase or multiphase short circuits. Distribution system operators must therefore design protection plans that truly and sustainably limit the impacts of short circuits on distribution systems.

1. Introduction

Most power systems in developing countries are faced with difficulties related to the proper management of various faults that generally compromise their reliability and availability. The introduction of digitalization in the operation of these networks is still very slow in view of the heavy financial resources that are required. These faults are generally single-phase, two-phase and three-phase short circuits, the consequences of which are disastrous if the protection plans are not effective and optimal to eliminate them as soon as possible. The selectivity of the protection of these networks is still problematic. It is not uncommon to find that faults in the distribution networks are not eliminated there, but instead end up in the EHV/HV (Extra High Voltage / High Voltage) source substations with enormous material consequences. These consequences include fires in some equipment, drastic voltage drops and sometimes faulty EHV/HV power transformers. They sometimes involve physical damage such as facial burns, hand burns and others. Operators are constantly looking for appropriate solutions to limit these consequences. In the very agglomerated African cities, excessive loads are transmitted on the cables and lines, which are the cause of voltage drops that exceed the permitted limits. That is, below plus or minus 5% in HV and plus or minus ten percent in LV (Low Voltage). To prevent voltage instabilities and stabilize the delivery, operators usually install equipment on the network such as capacitors, Distributed Static Synchronous Compensator (DSTATCOM), Distributed Static Var Compensator (DSVC) and other power electronics components that can help correct the network power factor. When these faults occur on the networks in the presence of one of these compensators, it results either in an attenuation of the short-circuit impact on the network or sometimes in an acceleration of the electromagnetic phenomena which have consequences on the power transit and the reactive current. The problem for the operators is to maintain the voltages within the tolerances in the case of the occurrence of faults in the presence of compensators or to be able to manage surges in the same situations. Short circuits are evidently the cause of voltage sags, drops, harmonics and fluctuations. In the case of single-phase and polyphase short circuits, the DSTATCOM presents different behaviors that may vary according to the intrinsic characteristics of the network and or the location of the short circuit.

In the literature it is shown that DSTATCOM can protect the network against drops, surges, voltage fluctuations, current harmonics and bad power factor [1-8]. The above-mentioned consequences are those which evidently result from the occurrence of single-phase, two-phase and or three-phase short circuits on the distribution networks. It can therefore contribute to increasing the reliability and safety of the network while helping to maintain voltages within the recommended ranges and/or ensuring the resilience of the network in contingency and severe disturbance situations. In fact, in the event of a fault between the upstream EHV/HV substation transformer and the DSTATCOM, it can always remain connected and supply the load of the isolated part by maintaining the voltage at the coupling point within the range of admissible values. However, the performance of DSTATCOM in this case depends on the network parameters. In the literature, several modes of DSTATCOM operation associated with controllers, generators and techniques such as PI (Proportional-Integral), LQR (Linear quadratic regulator), PMW (Pulse Width Modulation), Neuro-Fuzzy, three-level cascade inverter and others [9-12], are proposed to improve the performance of distribution networks under fault conditions. For example, Brijesh Parmar et al [12], used a PI controller on a sinusoidal PWM-based DSTATCOM to substantially reduce the voltage drops that would be due to single-phase and polyphase faults in HV distribution systems connected to a non-linear load. The scheme ignored the random parameters of the distribution networks, although these have a significant influence on the effectiveness of the network protections. For example, the fictitious capacitance of an HV line can not only be the cause of untimely disturbances if not taken into account in the settings but can also have an effect on the values of the short-circuit currents. It was also observed that this study did not include any effect of network parameters on the output current of the DSTATCOM. Abdollah Shokri and al [13], used the equations of a simplified DSTATCOM model in a distribution system to handle voltage variations under different operating conditions that go only to proportions of the undervoltage. In this paper it appears that certain modelling uncertainties were not taken into account such as the characterization of the imprecision in the determination of inductances and network capacitances and probabilistic phenomena such as overvoltages which can also result from a discharge electrostatic or a short circuit on the distribution network. In reference [14], Chetan et al, used the model schemes of DSTATCOM and DVR (Dynamic Voltage Restorer) to correct voltage drops, surges and interruptions in a distribution system. In this research the performance of DSTATCOM was evaluated on the DC (Direct Current) energy storage device by incorporating the coupling transformer parameters. However, the effects of grid parameters were not discussed in this research, which are important factors in the behavior of the compensator in the face of different disturbances. Ravilla Madhusudan et al [15], proposed the control of DSTATCOM by Sinusoidal Pulse Width Modulation (SPWM) technique, to correct voltage drops and surges in distribution networks. It is also observed that the effects of network parameters have not been discussed in this application.

From the literature, it can be seen that several authors have addressed the problem of power line disturbances in the presence of DSTATCOM, but as an ensemble forming a DSTATCOM system in a control loop. These studies do not take into account network parameters such as line resistance and reactance. However, this problem is still relevant from the point of view of the behavior of the DSTATCOM in a network in the face of different types of short circuits. It becomes then imperative to complete our contribution by studying the dynamic behavior of a distribution line in the case of faults in the presence of the DSTATCOM with the consideration of the network parameters.

A distribution network has many nodes and branches due to the many loads it supplies. It is therefore very difficult to find a model that takes into account all nodes and branches. In this paper, we have used a simplified model to study the different situations mentioned above. The various faults that arise are studied in a MATLAB environment.

2. Materials and Methods

The distribution network is composed of medium voltage feeders, distribution substations, protection devices and other devices that may be connected to the networks. A single-phase equivalent model of the study network and the various equations arising from the simplified steady-state system will therefore be established.

2.1. Distribution Network Modeling in the Presence of a DSTATCOM

The equivalent single-phase model proposed in Figure 1 represents that of an electrical distribution network to which a DSTATCOM is connected. It will allow the study of voltage drops and surges by incorporating variations in the currents injected or absorbed by the DSTATCOM at its coupling node and in the characteristics of the network. The model includes the following elements:

- An EHV/HV source station, medium voltage at the feeder entrance.
- The distribution lines which can be characterized by three parameters which are resistance, inductance and capacitance. Since HV lines are generally short, less than 80 km in length and supplied at medium voltage not exceeding 60 kV, the effects of shunt capacitance can be ignored without considerable error. So, each line of the distribution network can be represented by a complex impedance composed of a resistor in series with a reactance and distributed by section along the length of the line.
- The HV/LV and HV/HV substations that supply the consumers are modeled as constant power type nodes [16].

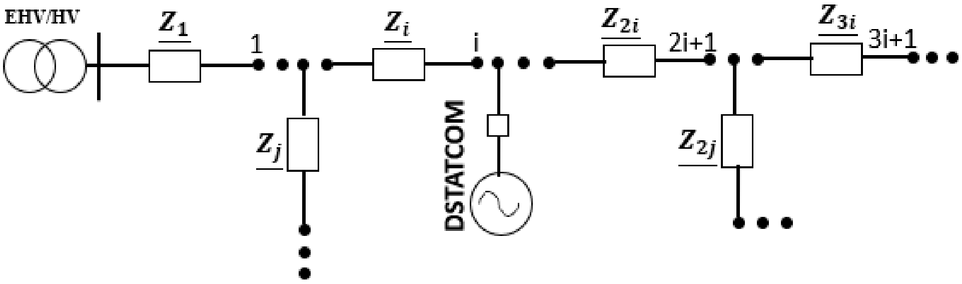

Fig. 1. Single-phase equivalent model of an electrical distribution network.

- The DSTATCOM, a voltage converter that connects in parallel to the grid to inject or absorb active or reactive current in order to improve the quality of power in distribution systems. It consists of an energy storage device, the Voltage Source Converter (VSC) and a grid coupling transformer. By varying the amplitude and angle of the DSTATCOM output voltage, the load voltage of the coupling bus can be controlled and the power factor corrected. In nominal operation with a short circuit or a large load, the DSTATCOM regulates the load bus voltage to a permissible value by injecting or absorbing the necessary current into the system [17]. In this project the DSTATCOM is modelled as a PQ node injecting or absorbing certain powers to the network.

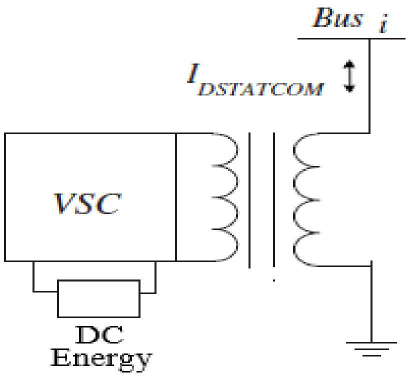

Fig. 2. DSTATCOM equivalent model connected to bus [17].

2.2. Simplified System Model

Any electrical network can be represented using a load bus and an equivalent Thevenin model seen from a point [18]. It is then described by two parameters, namely, the Thevenin voltage V_T and the equivalent complex Thevenin impedance Z_T. The V_T voltage is the secondary voltage of the EHV/HV substation. The equivalent impedance Z_T is the network impedance seen from the load bus to which the DSTATCOM is connected. This impedance is also assimilated to the short-circuit impedance, the modulus of which is calculated at a point from the amplitude of the short-circuit current Icc that would flow at this point in the event of a short-circuit to ground at voltage V_T [19]. This value is given by the three-phase short-circuit power.

$$\mathrm{S_{cc}} = 3\mathrm{V_T}\mathrm{I_{cc}} = \sqrt{3}\mathrm{U_T}\mathrm{I_{cc}} = \frac{\mathrm{U_T^2}}{|\mathrm{Z_T}|} \tag{1}$$

When the V_T system voltage exceeds the permissible limitations (drop, surge, flicker and other variations), the DSTATCOM injects or absorbs an $I_{DSTATCOM}$ shunt current through the grid- coupling transformer to keep the V_L load voltage within the permissible ranges. The schematic of the equivalent distribution network in Thevenin's approximation with DSTATCOM is shown in Figure 3.

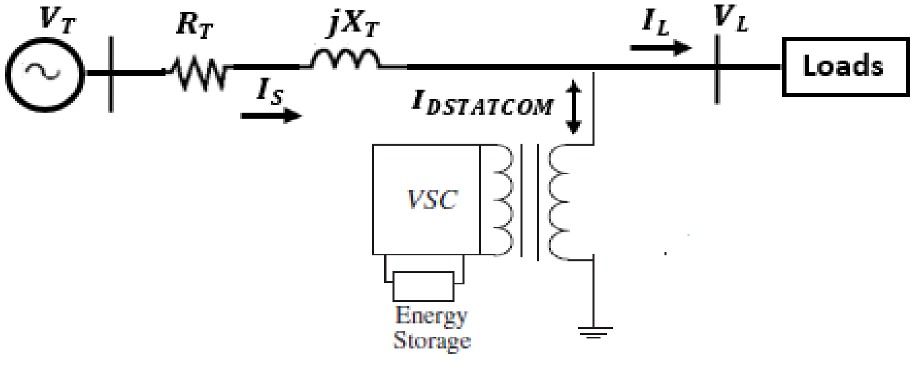

Fig. 3. Thevenin's equivalent model of the distribution network with DSTATCOM

2.3. System Equations

The load voltage V_L and the injected $I_{DSTATCOM}$ shunt current can be written:

$$V_L \angle 0 = V_T \angle \delta - Z_T \angle \beta (I_L \angle - \theta \pm I_{DSTATCOM} \angle \phi) \tag{2}$$

$$I_{DSTATCOM} \angle \phi = I_L \angle (-\theta) - \left(\frac{V_T \angle \delta - V_L \angle 0}{Z_T \angle \beta}\right) = I_L \angle (-\theta) - \left(\frac{V_T}{Z_T}\right) \angle (\delta - \beta) + \left(\frac{V_L}{Z_T}\right) \angle (-\beta) \tag{3}$$

With respectively V_T, V_L, I_S, I_L, $I_{DSTATCOM}$, δ, β, θ, ϕ, source voltage, load voltage, source current, load current, DSTATCOM current, source voltage angle, equivalent impedance angle, load current angle and DSTATCOM current angle. For a voltage drop with depth λ from source side to load point, we can write:

$$V_T(p.u) = 1 - \lambda \tag{4}$$

$$\delta = 0 \tag{5}$$

$$V_L = (1-\lambda) - Z_T\angle\beta\big(I_L\angle(-\theta) - I_{DSTATCOM}\angle(\phi)\big) \tag{6}$$

$$V_L = (1-\lambda) - Z_T\big(I_L\angle(\beta-\theta) - I_{DSTATCOM}\angle(\beta+\phi)\big) \tag{7}$$

In symbolic writing we obtain:

$$V_L = (1-\lambda) - Z_T[I_L\cos(\beta-\theta)] + jI_L\sin(\beta-\theta) - I_{DSTATCOM}\cos(\beta+\phi) - jI_{DSTATCOM}\sin(\beta+\phi)] \tag{8}$$

$$V_L = (1-\lambda) - Z_T[I_L\cos(\beta-\theta) - I_{DSTATCOM}\cos(\beta+\phi)] + jZ_T[I_{DSTATCOM}\sin(\beta+\phi)] - I_L\sin(\beta-\theta)] \tag{9}$$

Voltage amplitude :

$$V_L = \Big[\big((1-\lambda) - Z_T[I_L\cos(\beta-\theta) - I_{DSTATCOM}\cos(\beta+\phi)]\big)^2 + (Z_T[I_{DSTATCOM}\sin(\beta+\phi)] - I_L\sin(\beta-\theta)])^2\Big]^{\frac{1}{2}} \tag{10}$$

The amplitude and angle of the current $I_{DSTATCOM}$:

$$I_{DSTATCOM}\angle(\phi) = I_L cos(\theta) - \frac{V_T}{Z_T}\cos(\beta) + \frac{V_L}{Z_T}cos(\beta) + j\left[\frac{V_T}{Z_T}\sin(\beta) - I_L sin(\theta) - \frac{V_L}{Z_T}sin(\beta)\right] \tag{11}$$

$$I_{DSTATCOM} = \left[\left(I_L\, cos(\theta) - \frac{V_T}{Z_T}\cos(\beta) + \frac{V_L}{Z_T}cos(\beta)\right)^2 + \left(\frac{V_T}{Z_T}\sin(\beta) - I_L\, sin(\theta) - \frac{V_L}{Z_T}sin(\beta)\right)^2\right]^{\frac{1}{2}} \tag{12}$$

$$\phi = arctang\,\frac{\frac{V_T}{Z_T}\sin(\beta) - I_L\, sin(\theta) - \frac{V_L}{Z_T}sin(\beta)}{I_L\, cos(\theta) - \frac{V_T}{Z_T}\cos(\beta) + \frac{V_L}{Z_T}cos(\beta)} \tag{13}$$

DSTATCOM power rating:

$$S_{DSTATCOM} = V_L I_{DSTATCOM} \tag{14}$$

2.4. Active Power Transfert in the System

The active power transfer characteristic between the two ends of the system is described by equation (15) [20].

$$P_T = P_L = \frac{V_T V_L \sin\delta}{(X_T + X_L)}\left(1 + \frac{I_{DSTATCOM} X_T X_L}{\sqrt{V_T^2 X_L^2 + V_L^2 X_T^2 + 2V_T V_L X_T X_L \cos\delta}}\right) \tag{15}$$

3. Results and Discussions

In order to analyse the performance of DSTATCOM on fault attenuation and the impact of network parameters on DSTATCOM performance, we implemented the above equations in Matlab.

3.1. DSTATCOM Performance Evaluation Under Different Faults

According to equation (15), the active power transfer capability in the considered distribution network is not only directly related to the $I_{DSTATCOM}$ current, but also related to the source voltage V_T, the load voltage V_L and the transfer angle δ [20]. The active power transfer characteristic in the network with and without DSTATCOM is shown in Figure 4, for some values of $I_{DSTATCOM}$ current. It is observed that the active power transfer (or voltage drop) between two ends of a line is related to the transit of the reactive power consumed by the load. For example, in the event of a voltage drop in the network due to a fault, the DSTATCOM acts in capacitive mode by injecting a capacitive current (e.g. 0.5 p.u or 1 p.u or 1.5 p.u), to correct the transferred active power and regulate the voltage drop. The same applies to an overvoltage, where the DSTATCOM reacts in (inductive current absorption) mode, to correct the fault. It can be deduced that DSTATCOM can increase the active power transfer capability of an electrical system. This has the advantages of reducing losses, mitigating voltage drops, surges and fluctuations, improving the power factor and supplying additional loads if required.

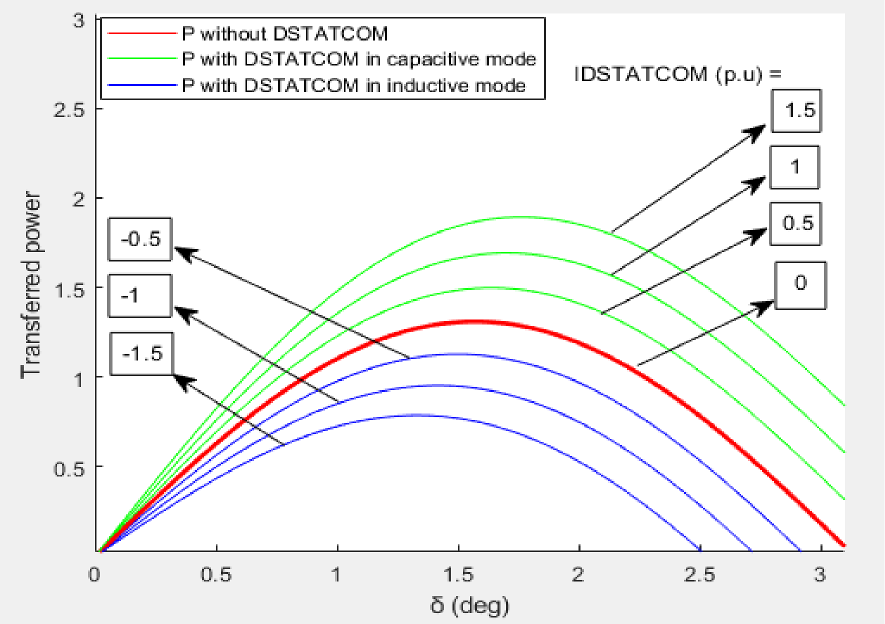

Fig. 4. Power transfer curves without and with DSTATCOM

3.1.1. Voltage Drop Compensation

Figure 5 illustrates three types of faults applied with and without DSTATCOM:

- A single-phase to ground fault generating a voltage drop at the point of load λ of 25 to 30% with respect to the reference voltage taken at 1 p.u and which we denote by 1L-G [12],
- A two-phase to ground fault λ=40% symbolized by 2L-G,
- A three-phase to ground fault λ=75% symbolized by 3L-G.

For the single-phase short circuit, without DSTATCOM ($I_{DSTATCOM} = 0$), the load voltage V_L drops to 0.75 p.u. On the other hand, when the DSTATCOM is in operation, it injects a capacitive current of about 2.2 p.u to regulate the voltage V_L to 1p.u.

For the two-phase short circuit, the capacitive current is 3.6 p.u.

For the three-phase short circuit the capacitive current is 6.7 p.u. It is observed in all three fault cases that the DSTATCOM can correct the load voltage V_L to 1 p.u by injecting the necessary capacitive current to correct the voltage drop.

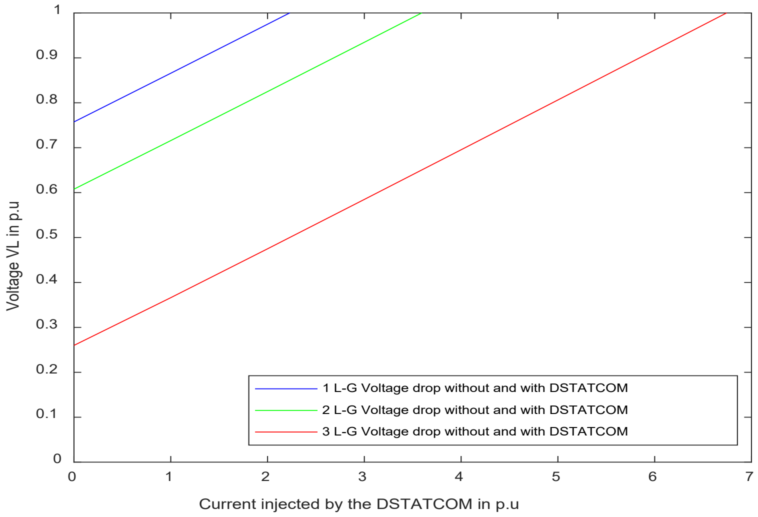

Fig. 5. Faults 1L-G, 2L-G, 3L-G, without and with DSTATCOM.

3.1.2. Mitigation of Surges in The Distribution Network

The introduction of distributed power generation (DG) in electrical networks, the fluctuations and failures often recorded on electrical networks and the occurrence of lightning can cause surges which are the cause of a considerable part of the electrical accidents and in particular of the fires which take place every year. This analysis considers the voltage rise at the point of load to be 30-40% above the nominal reference voltage of 1 pu. Figure 6 shows the performance of a DSTATCOM in the event of an overvoltage event. For example, for the 40% overvoltage without DSTATCOM ($I_{DSTATCOM} = 0$), the load voltage V_L is 1.4 p.u. Whereas with DSTATCOM the overvoltage is attenuated. The DSTATCOM acts in inductive mode and absorbs an inductive current of about 3.85 p.u, to correct the induced overvoltage and regulate the V_L voltage at 1p.u. The greater the rise, the greater the inductive current absorbed. It can therefore be deduced that the greater the amplitude of the surge, the greater the absorption of the reactive current. In the distribution networks, permanent surges on HV lines are rare, as these lines are short and therefore have low capacity. On the other hand, atmospheric surges are almost frequent, but are quickly capped with the operation of surge protectors such as surge arresters, spark gaps, arcing horns and others. Thus, given the very fast response time of these devices, it can be deduced that DSTATCOMs can be less stressed in the event of a surge.

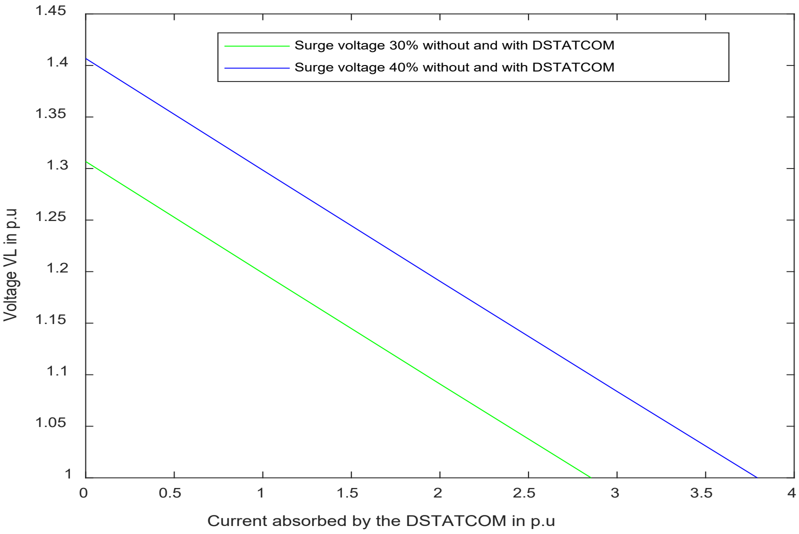

Fig. 6. Surge conditions without and with DSTATCOM.

3.2. Impacts of Network Parameters on DSTATCOM Performance

In networks, it is often difficult for operators extending their networks to accurately determine the actual impedance of distribution lines. Given the diversity of the line cross-sections used and their nature, which vary from country to country and from area to area depending on the power distribution per km². This inaccuracy introduces a random parameter in the determination of the impacts of the network parameters on the performance that a DSTATCOM could have on the mitigation of short circuits and other phenomena detrimental to the quality of an electrical network. This paper deals with the influence of the line inductance and resistance as well as the power factor of the load, in case of a fault and in the presence of the DSTATCOM in the network.

3.2.1. Influence of the Line Inductance

Figure 7 shows the influence of the inductance of a line during a fault in a network in the presence of a DSTATCOM. It can be seen that the $I_{DSTATCOM}$ capacitive current injected by the shunt compensator to correct the different voltage drops is higher with a low inductance. For example, for a voltage drop of 5%, the capacitive current injected by the DSTATCOM to correct the voltage drop is about 2 p.u with an inductance of 0.10 p.u, while it is 1.4 p.u with an inductance of 0.15 p.u. It can be deduced that the higher the network inductance, the lower the reactive current injected by the DSTATCOM to compensate for the voltage drops. The influence of the inductance on the performance of a DSTATCOM in the event of a single-phase short circuit causing a 25% dip is further illustrated in Figure 8. It can be seen that the capacitive current to be injected to regulate the voltage V_L at 1 p.u, decreases for an inductance of 0.15 p.u compared to the one injected when it is an inductance of 0.10 pu. It is 1.6 p.u and 2.3 p.u respectively. It can therefore be deduced that the current injected by the DSTATCOM in the event of a short circuit is less as high as the network inductance is high. In the same way, the V_L voltage without DSTATCOM ($I_{DSTATCOM}$=0), decreases more in case of a fault for a low inductance. In conclusion, in order to restore the voltage to 1 pu in the case of a single-phase short circuit (1L-G), the DSTATCOM is used less when the network inductance is high.

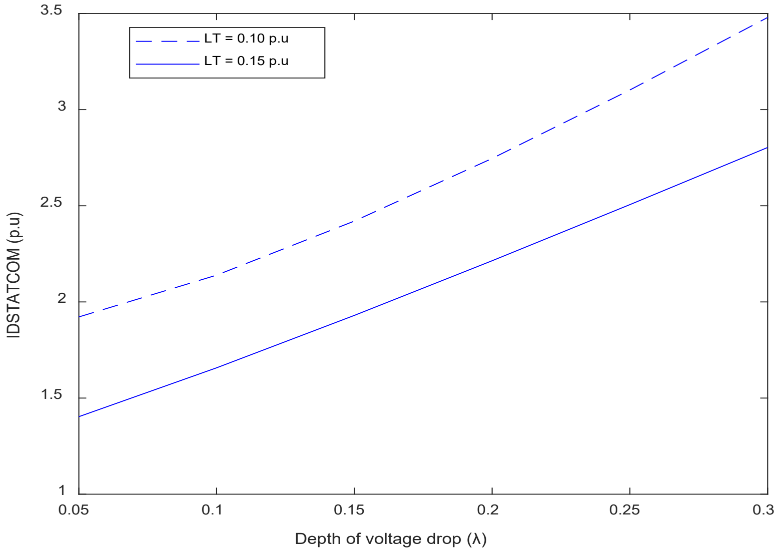

Fig. 7. Capacitive current of DSTATCOM as a function of voltage drops for two values of line inductance

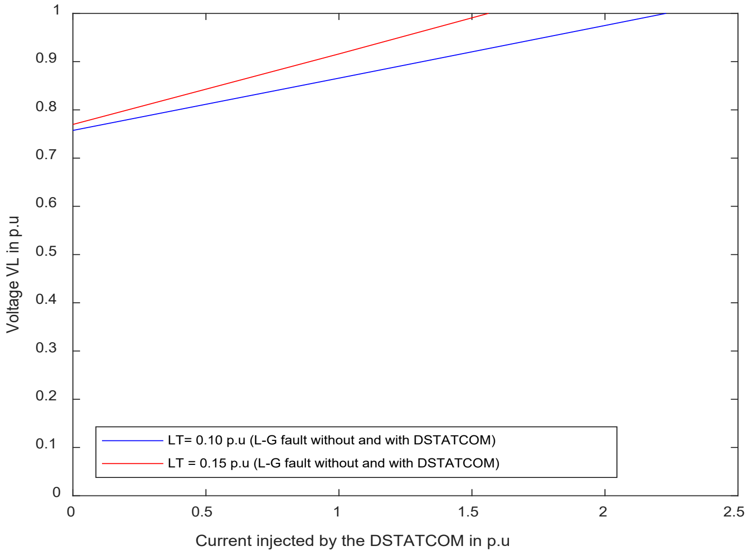

Fig. 8. Load voltage V_L as a function of the capacitive current of the DSTATCOM for two-line inductance values

3.2.2. Influence of The Line Resistance

The influence of the line resistance on the current injected by the DSTATCOM is shown in figure 9. It is observed, without DSTATCOM ($I_{DSTATCOM} = 0$), that a voltage drop of 25% caused by a single-phase 1L-G short-circuit, lowers the V_L voltage to 0.75 p.u for a resistance of 0. 05 p.u, to 0.72 p.u for a resistance of 0.1 p.u, and to 0.69 p.u for a resistance of 0.3 p.u. It can be deduced that contrary to what is observed as an influence of the inductance, the increase of the resistance worsens the voltage drop across the load. However, it is also observed that when the DSTATCOM is in operation, the capacitive current injected by the DSTATCOM to regulate the voltage across the V_L load at 1 p.u is higher for a low resistance. It is about 2.4 p.u for a resistance of 0.05 p.u, while it is 1.2 p.u for a resistance of 0.3 p.u. Similarly, for a voltage drop of 5%, shown in figure 10, the current injected by the DSTATCOM is 1.8 p.u for a line resistance of 0.05 p.u, while it is 0.85 p.u for a line resistance of 0.1 p.u. It can be concluded that a low line resistance can increase the capacitive current of the DSTATCOM to mitigate the voltage drop across the load during a fault.

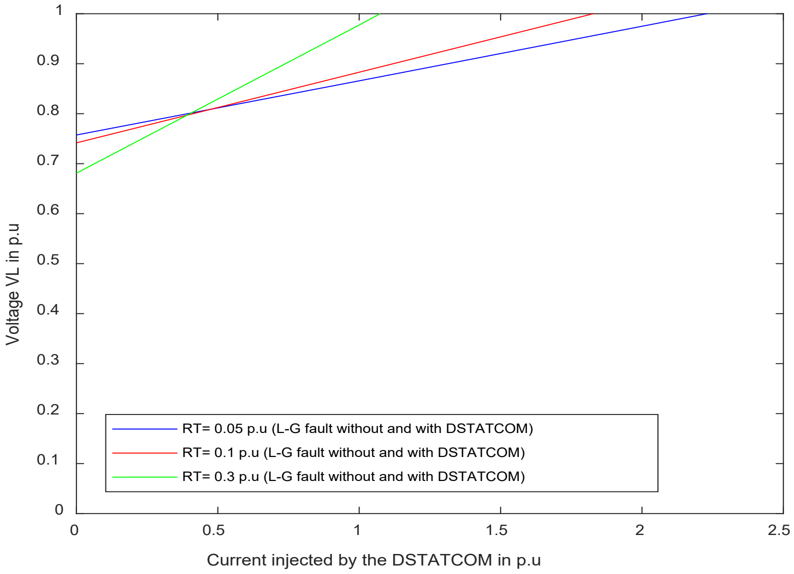

Fig. 9. Load voltage V_L versus capacitive current of the DSTATCOM for three-line resistance values

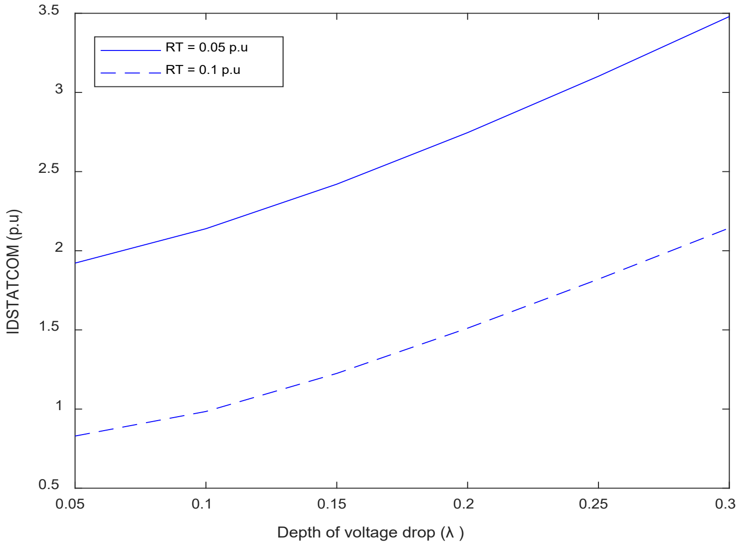

Fig. 10. Capacitive current of DSTATCOM as a function of voltage drop for two values of line resistance

3.2.3. Influence of The Load Power Factor

The loads, in addition to their linear and non-linear characteristics, change rapidly in the distribution networks, thus changing the power factor. In such a situation, the voltage can drop excessively and lead to instability of the system voltage [20]. Figures 11 shows the simulation of the capacitive current of the DSTATCOM during a single-phase short circuit (1L-G) as a function of the power factor of the load. It is observed that the capacitive current injected by the DSTATCOM is 2.83 p.u for a power factor equal to 0.55, while it is 2.5 p.u for a power factor equal to 0.98. It can be deduced that the current injected by the DSTATCOM to compensate the voltage drop induced by a fault increases when the power factor decreases. Increased solicitation of the DSTATCOM in a disturbed regime can accelerate its ageing and therefore make it inefficient in the short term. This is why network operators must size the protection devices of the distribution networks in a very selective and reliable way to limit the duration of the contingencies on the networks and thus limit their disastrous impacts which are unfortunate.

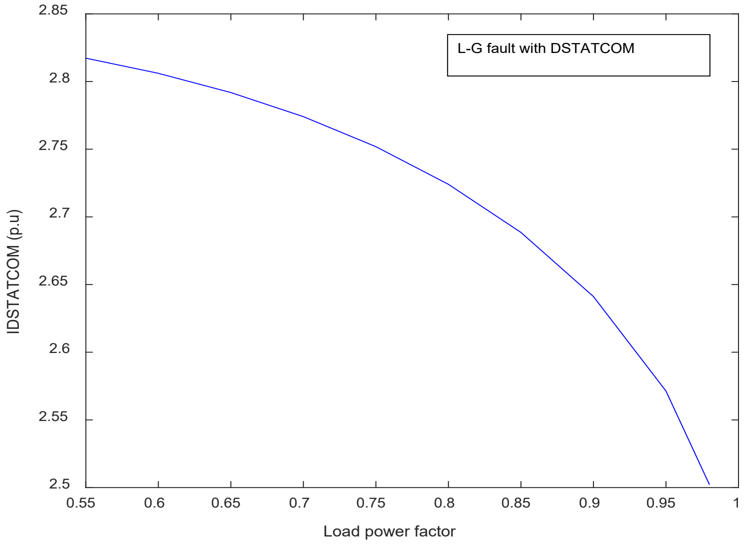

Fig. 11. Influence of the power factor on the capacitive current of a DSTATCOM.

Table.1. Summary of the influence of network parameters on the capacitive current of DSTATCOM

Parameters considered	Values	Fault	Capacitive current of DSTATCOM	Behavior of DSTATCOM
Line resistance	0.05 [p.u]	1L-G	2.4 [p.u]	The reactive power generated is higher with a low line resistance
	0.1 [p.u]		1.2 [p.u]	
Line inductance	0.10 [p.u]	1L-G	2.3 [p.u]	The reactive power generated is higher with a low line inductance
	0.15 [p.u]		1.6 [p.u]	
Power factor	0.55	1L-G	2.83 [p.u]	The reactive power generated is higher with a low power factor
	0.95		2.5 [p.u]	

From this table it can be seen that the intrinsic line parameters have an unfavorable influence on the behavior of DSATACOM if they are varied to decrease.

4. Conclusion

This study demonstrated the effectiveness of the DSTATCOM shunt compensator. DSTATCOM corrects voltage drops and surges. However, the characteristics of the power line influence the capacitive current of the DSTATCOM. A low resistance and a low inductance of the power line increase the capacitive current injected by the DSTATCOM, as does a low power factor of the load. It can be concluded that the random parameters of the network and the load have a considerable impact on the rated compensation power of the DSTATCOM when faults occur. Network managers and designers should give priority to symmetrical inductances and resistances on distribution networks so that the impacts of these effects on the networks are similar. To facilitate flexible settings, network operators need to develop suitable tools to enable them to accurately and automatically determine the actual impedance of the distribution lines in view of its effects on the DSTATCOM compensation current. Also this analysis did not take into account the capacitive effects of the lines which are supposed to be negligible in the case of short HV lines contrary to the case of long HV lines for which the capacitance effect must be considered. Similarly, the study of dynamic behaviour was carried out on a simplified model of the distribution network based on a Thevenin model. However, it would be interesting to continue this work on a real model by integrating the constraints linked to protection systems.

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