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Voltage Regulation Using D-STATCOMs in Rural Distribution Feeders

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SUMMARY

An increase in load growth in rural distribution systems poses challenges to power utilities in order to manage the voltage along the feeders within admissible limits. In low-voltage long distribution lines with high R/X ratio characteristics, the voltage can drop significantly even with a slight fluctuation of the loading conditions. One of the remedial options to relieve the voltage drop problem is reactive power provision. The reactive power can be provided by Distribution Flexible AC Transmission System (FACTS) devices such as D-STATCOMs. However, in systems exhibiting high R/X ratios, the amount of reactive power injected by the device can be too large and require large equipment ratings upstream of the deployment location. Therefore, it is very important to minimize the reactive power flow to reduce any stress on the upstream devices while at the same time ensuring the voltage within the allowable range. In view of this and other concerns, this paper develops an analytical method that estimates the minimum amount of required reactive power to regulate the voltage with user specified voltage tolerance. It also shows how the proposed formulation can be applied to determine the required size of the D-STATCOM device. A case study has also been conducted on a real rural distribution feeder to validate the proposed analytical approach and reactive power compensation method using D-STATCOM.

KEYWORDS

Reactive Power, Voltage Fluctuation, Voltage Sag, Distributed Control, D-STATCOM

INTRODUCTION

Distribution utilities are required to maintain power quality to customers within the allowable band. One of the basic requirements is to keep the service voltages per the standard limits. Utilities may also further develop conservative voltage limits in their internal procedures based on the type of customer loads. There are several voltage control solutions to help regulate the voltage within the desired range at the location of interest on distribution feeders. These solutions can be generally classified into two broad categories as passive and active methods.

Passive methods include the use of on-load or off-load tap changer transformers inside substations and in-line voltage regulators installed on distribution lines. These devices neither inject nor draw active/reactive power, hence, they are referred as passive solutions. The active methods, on the other hand, make use of active/reactive power for voltage regulation. Energy storage systems and reactive power compensation devices such as switched capacitor and inductor banks can be considered as active solutions. Each of these mitigation options has their own drawbacks and advantages. For instance, the in-line voltage regulators need to handle the full downstream load side current due to their mode of connection with the distribution line; hence, high current/thermal rating requirement. Installation and maintenance complexity with potential customer interruptions is another drawback of these devices. On/off-load tap changers and voltage regulators can only increase or decrease the voltage. They can't be used to minimize system losses or improve power factor by managing the reactive power flow. On the other hand, shunt-connected devices such as switched capacitors and Distribution Static Synchronous Compensators (D-STATCOMs) do not to seem to suffer from either of the above-mentioned drawbacks of traditional in-line voltage regulators [1]. The most popular ones among these devices is the switched capacitor banks. Given the relatively low costs of these devices and operational flexibility, they have been used for several years and are still being deployed by distribution utilities around the world. The focus of this paper is the use of reactive power exchange for voltage drop mitigation considering one of these apparatuses as a source of reactive power.

Capacitor banks are usually switched in discrete steps mechanically to regulate the local voltage by injecting reactive power to the system. Hence, it isn't possible to control the voltage within tight ranges as this would require impractical small step sizes and large number of switching actions. Another drawback of switched capacitor banks is the reactive power being supplied to the system is proportional to the square of the voltage at the installation site. Thus, these devices are less efficient when they are needed the most during peak load (low voltage) hours. D-STATCOMs, on the other hand, are inverter-based devices which do not come with any mechanical switching operations. They employ semiconductor switches such as Insulated Gate Bipolar Transistors (IGBT) as part of their internal components and can perform voltage regulation with much faster speed, lower losses, and higher reliability [2]. In addition, their reactive power output is not affected by the voltage magnitude as opposed to switched capacitor banks. A number of research papers have shown the use of D-STATCOMs in various types of loads such as variable industrial loads [3]. Their application has also been tested in systems with large adoption of solar and wind generation [4].

This paper demonstrates the use of D-STATCOMs in long rural distribution feeders for voltage management. Nevertheless, it is also important to reduce the reactive power flow originated from these devices to avoid exceeding the thermal limits of upstream network equipment especially in feeders with large R/X ratio. Therefore, a detailed analytical investigation is carried out to estimate the minimum level of reactive power that would guarantee the voltage to be within user-defined tolerances. This will also help to prevent oversizing the required D-STATCOM, hence, reduce investment costs. Several papers are written on sizing and siting of D-STATCOMs [5]-[6], however, their proposed approaches cannot be easily adopted in commercially available distribution analysis software tools. On the other hand, the proposed formulations developed in this paper can be easily incorporated in load flow packages such as CYME using simple Python scripting. The method has the following multiple distinct advantages: 1) the formulations only require system R/X ratio and fault level at D-STATCOM deployment location, and a user defined voltage tolerance. As these parameters are usually available to distribution planners, the method can be used as a quick screening tool to help identify potential installation sites; 2) the expressions can be directly applied to determine the size of the D-STATCOM; and 3) the expressions can provide the instantaneous reactive power outputted from the D-STATCOM at given voltage tolerance when loading condition is passed as additional parameter in the formulas.

An actual rural distribution feeder that suffers from severe low voltage during contingency situations is considered to validate the applicability of the proposed analytical expressions. The results of the developed formulations were compared against the results of load flow tools. Furthermore, the accuracy of the method was tested in determining the required size of the D-STATCOM.

VOLTAGE CHARACTERISTICS IN TYPICAL LONG DISTRIBUTION FEEDERS

In rural systems, distribution lines are extended over long distances to supply power to several distributed loads covering large customer areas. The main challenge here is that the reduction in magnitude and the increase in variation of the service voltage will become more pronounced as the customer connected to the feeder is farther way from the substation. The fundamental cause for the large voltage drop issue is the high system impedance associated with the long conductor length. This phenomenon can be better explained using a representative distribution feeder shown in Fig. 1 and subsequent mathematical expressions adopted from common power flow equations.

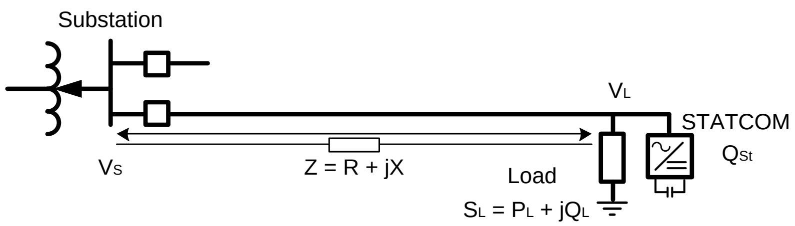

Fig. 1. Single line diagram of a distribution feeder with an equivalent load connected at the end of the feeder

By simplifying power flow equations, a relationship can be easily derived between the voltages at the source and load locations as follows:

$$\Delta V = V_S - V_L \cong \frac{RP_L + X(Q_L - Q_{St})}{V_L} \quad (1)$$

where Q_{St} is the reactive power exchange provided by the D-STATCOM, P_L and Q_L are the active and reactive power demands and $R + jX$ is the equivalent source impedance at the load location, composed by the sum of the utility source impedance, substation transformer impedance, and feeder conductor impedance. From Eq. (1), it can be observed that the reactive power injected by the D-STATCOM can regulate the load voltage to match the source voltage by full compensating the voltage. The voltage can even be raised higher if more reactive power is supplied from the D-STATCOM device.

A. Simplified Approximations of Non-linear Power Flow Equations

The expression provided in Eq. (1) allows the impact of D-STATCOM on the voltage to be decoupled from the other factors and separately considered:

$$V_L \cong \left[V_S - \frac{RP_L + XQ_L}{V_L}\right] + \left[\frac{XQ_{St}}{V_L}\right] \quad (2)$$

The left-hand side term in Eq. (2) is the baseline voltage V_{bc}, where the impact of loading level, source voltage and inline voltage regulators is accounted for. The right-hand side term represents the voltage boost or reduction achieved as the result of reactive power flow from or to the D-STATCOM device. Eq. (2) can be further re-written by reflecting the baseline voltage V_{bc} in the expression:

$$V_L \cong V_{bc} + \left[\frac{XQ_{St}}{V_L}\right] \tag{3}$$

Rearranging (3) yields a compact equation where the required amount of reactive power flow from the D-STATCOM for the desired voltage boost ΔV_{rq} can be easily estimated:

$$Q_{rq} \cong \frac{\Delta V_{rq} V_d}{X} \tag{4}$$

where $\Delta V_{rq} = V_d - V_{bc}$, and V_d is the new desired voltage to be achieved after the D-STATCOM installation. Converting all quantities to per unit, (4) can be re-written as:

$$Q_{rq} \cong \frac{\Delta V_{rq}}{X} \tag{5}$$

It is worthwhile to mention that Eq. (5) can be effective in systems with low R/X ratio where the amount of required reactive power for voltage control is minimal. However, for long rural distribution feeders that could potentially exhibit large R/X ratios, it may overestimate the requirement as its development involves multiple bold mathematical approximations. Overcompensation can cause increased system losses, device overloads, inaccurate equipment sizing, etc.

B. The Proposed Method for Enhancing the Accuracy of Reactive Power Estimation

The method proposed in this paper involves an analytical investigation and considers fewer assumptions to minimize the impact on the accuracy of the resulted expressions. The proposed formulations provide a better estimation of the required reactive power with few input network parameters needed to be known. The development of the formulations is presented in the procedures described below.

Given that the D-STATCOM in Fig. 1 injects Q_{rq} to keep the load voltage at the desired value V_d, the relationship among different parameters can be captured through the following voltage equation:

$$V_d^4 = \left[V_S^2 - 2RP_L + 2X\left(Q_{rq} - Q_L\right)\right]V_d^2 - \left(R^2 + X^2\right)\left[P_L^2 + \left(Q_{rq} - Q_L\right)^2\right] \tag{6}$$

As the D-STATCOM output will typically exceed the instantaneous load reactive power demand, the term $\left(Q_{rq} - Q_L\right)^2$ can be approximated by $\left(Q_{rq}^2 + Q_L^2\right)$. This allows decoupling the base case voltage and obtaining:

$$V_d^4 = \left[\left(V_S^2 - 2RP_L - 2XQ_L\right)V_d^2 - \left(R^2 + X^2\right)\left(P_L^2 + Q_L^2\right)\right] + \left[\left(2XQ_{rq}\right)V_d^2 - \left(R^2 + X^2\right)Q_{rq}^2\right] \tag{7}$$

Further manipulation on (7) results in:

$$V_d^2\left(V_d + V_{bc}\right)\left(V_d - V_{bc}\right) - 2\left(XQ_{rq}\right)V_d^2 + \left(R^2 + X^2\right)Q_{rq}^2 \cong 0 \tag{8}$$

Since $\left(V_d - V_{bc}\right) = \Delta V_{rq}$ and considering $V_d \cong V_N$, the nominal voltage, this relationship can be further simplified as:

$$\frac{2\Delta V_{rq}}{V_N} - \frac{2XQ_{rq}}{V_N^2} + \frac{\left(R^2+X^2\right)Q_{rq}^2}{V_N^4} \cong 0 \tag{9}$$

Rearranging (9) yields:

$$\frac{2\Delta V_{rq}}{V_N} - \frac{2XQ_{rq}}{V_N^2}\left(\frac{ZQ_{rq}}{\sqrt{1+(R/X)^2}}\right) + \frac{Z^2}{V_N^4}\left(Q_{rq}^2\right) \cong 0 \tag{10}$$

Eq. (10) is a simple quadratic equation which can be easily solved for Q_{rq} as shown in (11):

$$Q_{rq} \cong \frac{1}{\alpha} - \sqrt{\frac{1}{\alpha^2} + 2\Delta V_{rq}}, \tag{11}$$

where Q_{rq} is expressed in per unit of the fault level at the installation site and $\alpha = \sqrt{(R/X)^2 + 1}$.

The development of (11) has three useful implications: 1) only few approximations are involved, hence, exhibits high estimation accuracy; 2) it only requires few input parameters to be known by the user prior to applying the formulations, which are R/X ratio and short circuit level at the point of D-STATCOM connection; and 3) it can be easily encoded into common load flow and short circuit analysis tools available to utilities.

Eq. (11) can also be further modified to reflect loading conditions ($P_L, @Q_L = 0$) in the expression as follows:

$$Q_{rq} \cong \frac{1}{\alpha} - \sqrt{-P_L^2 - 2P_L\sqrt{1 - \frac{1}{a^2}} + \frac{1}{\alpha^2} + 2\Delta V_{rq}}, \tag{12}$$

A CASE STUDY: LOW VOLTAGE DURING CONTINGENCY IN A DISTRIBUTION FEEDER SUPPLYING RURAL TOWN

The case study involves a long distribution power line that feeds a town and a hospital about 70kms away from adjacent substation during contingency, as shown in Fig. 2. The main line conductor characteristics are tabulated in Table 1.

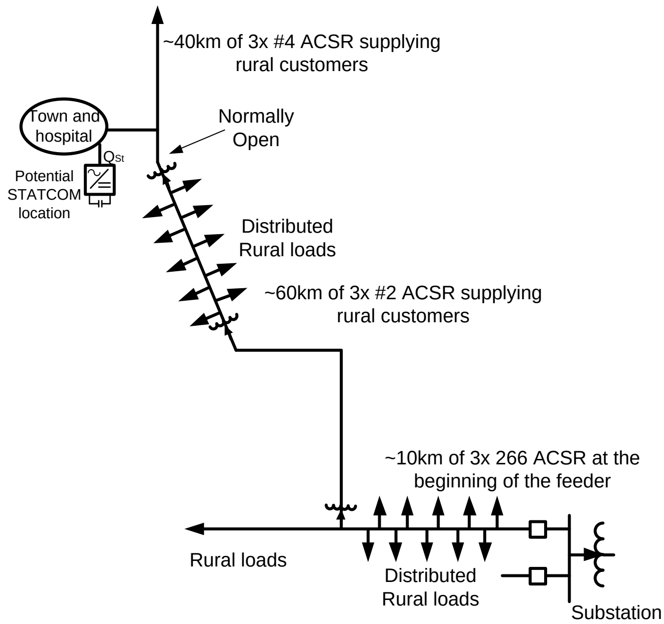

Fig. 2. Single line diagram of a potential three-phase D-STATCOM application

Table 1. The type, length and location of the main line conductor of the feeder under study

Type of Conductor	*Length (km)*	*Location*
3x266 ACSR	10	At the beginning of the feeder
#2 ACSR	60	From substation to the town tap-off
3x#4 ACSR	40	From town tap-off to end of feeder

The contingency feeding has the following two main concerns that require intervention to mitigate the problems:

1) The voltage drop along the line was so large that the voltage near the town reduced to 0.90 p.u. The voltage has even become lower at the end of the feeder (0.88 p.u.) where several distributed rural customers are connected. The allowable low voltage limit under contingency situations [7] is 0.92 p.u.; hence, this alternate feeding is unacceptable.

2) The alternate route caused three inline voltage regulators to be along the path between the town and the adjacent substation. This could result in high voltage (up to 1.23 p.u.) in a load rejection situation where an inline fuse near town tap-off is melted down. The voltage is beyond the acceptable utility standard where the upper boundary limit is 1.167 p.u.

The current practice for the contingency path to be able to feed the town within accept voltage limits is by dropping the rural loads to avoid severe undervoltage as well as high overvoltage in load rejection scenario. This solution obviously degrades the quality of service as it interrupts the continuity of the power supply for some customers. Therefore, it is prudent that other options need to be explored.

The proposed method was applied to determine the required D-STATCOM rating. The estimated size that would guarantee to bring the voltage within the admissible limits both in low and high voltage scenarios was about 1MVAR and the best installation site was found to be a location closer to the town, as indicated in Fig. 2. The system characteristics parameters required by the proposed formulations and other relevant information are provide in Table 2.

Table 2. System Characteristics and other data prior to D-STATCOM

$R0$ (pu)	$X0$ (pu)	$R1$ (pu)	$X1$ (pu)	V_{bc} (pu)	Peak feeder load	Village peak load
5.9	13.3	6.9	5.8	0.96	6,300 kW	480 kW

Fig. 3 shows the voltage profiles of the studied feeder before and after deployment of a 1MVAR D-STATCOM. As can be clearly seen from the figure, the voltage at the end of the feeder almost reduced to 0.88 p.u, when any mitigation action wasn't taken. On the other hand, with the D-STATCOM, it was possible to boost the voltage to get it closer to 0.92 p.u. without the need to curtail load on the feeder.

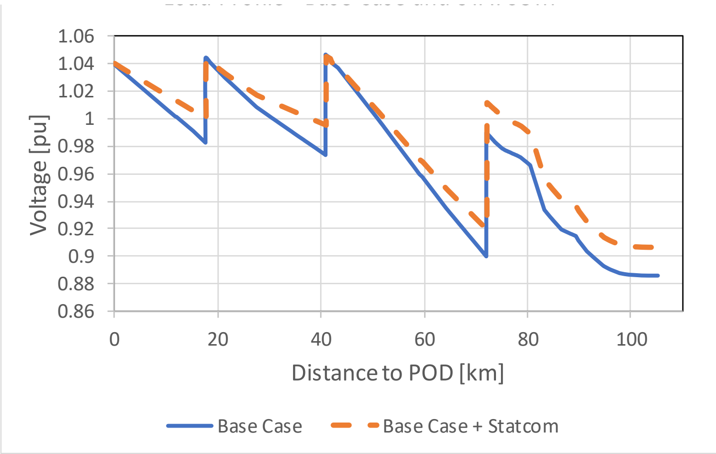

Fig. 3. Steady-state voltage profile under contingency scenario (before and after the use of D-STATCOM)

To test the effectiveness of the D-STATCOM solution for load rejection scenario, an inline fuse on the main feeder near the town tap-off is considered to be melted off, disconnecting several rural loads downstream. Fig. 4 shows the feeder voltage profile with and without D-STATCOM under load rejection scenario during contingency. The D-STATCOM solution was able to reduce the voltage and maintain it below 1.15 p.u., which is lower than the acceptable utility standard (1.167 p.u.).

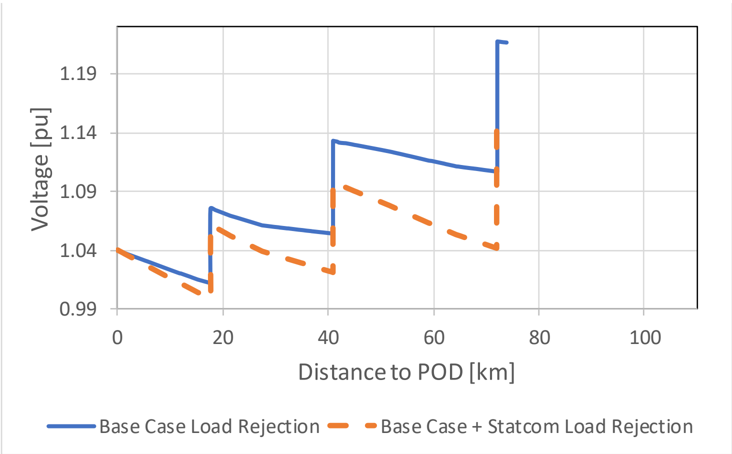

Fig. 4. Load rejection voltage profile under contingency scenario (before and after the use of D-STATCOM)

Simulation was also conducted to demonstrate the accuracy of the proposed formulations for sizing the D-STATCOM against the conventional method and load flow tools. The voltage boost needed to achieve the contingency lower voltage limit was 4%; hence, the required reactive power wasn’t too large in this particular case. However, the proposed method still outperforms the conventional approach, as shown Fig. 5.

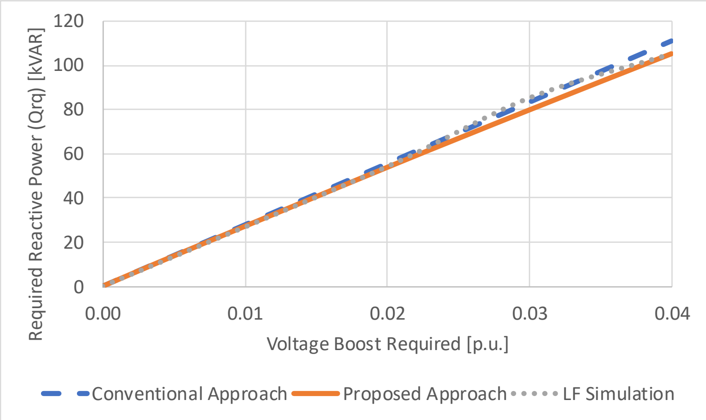

Fig. 5. Comparison of results among three different approaches to achieve contingency voltage limit

CONCLUSIONS

The paper has presented analytical formulations to estimate reactive power requirements for the purpose of voltage regulation in distribution feeders using D-STATCOMs. The developed method has three useful unique features: 1) it can be easily integrated in power system analysis software packages commonly used by electric utilities; 2) it only requires system R/X ratio and fault level as input network parameters; and 3) it provides flexibility in the formulations such that the amount of voltage tolerance can be varied to help a distribution planner make informed decisions. The proposed method can be used as a quick screening tool in planning activities for sizing and siting of D-STATCOMs. It can also be applied to determine the instantaneous reactive power output of these devices once they are sized and installed at the desired locations. The effectiveness of the proposed method is validated via a case study using an actual distribution line where an undervoltage problem and high overvoltage issue under load rejection scenario were highly pronounced.

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