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Research Article

Effect of Network Parameters on the Injection Current Requirement of D-STATCOM Designed to Mitigate Voltage Sag

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Abstract: The Distribution Static Compensator (D-STATCOM) can be used as a parallel voltage sag mitigation device at distribution systems. The D-STATCOM is also able to regulate and balance the bus voltage by absorbing or generating the required reactive power at specific buses. This study presents an overview on D-STATCOM structure and its simplified model that can be used for voltage sag analysis. In addition, this study also investigates the effect of various load and network parameters on the nominal power requirement D-STATCOM and its ability to compensate voltage sag. The results illustrate the performance of D-STATCOM by using an injection current to various conditions for voltage sag mitigation. In addition, the result shows that the D-STATCOM is not economical and effective in high voltage networks with low inductance feeder.

Keywords: D-STATCOM, power quality, power quality disturbances, voltage sag, voltage sag compensation

INTRODUCTION

Due to the recent increase in the number of sensitive devices and controllers such as microcontrollers, computers and motor drives, most of the industrial customers prefer to receive an improved level of electrical energy with high quality. Delivered energy with poor quality and especially voltage sag may cause severe problems such as process interruption or equipment failure for these sensitive customers (Arrillaga *et al.*, 2000). According to a study in U.S., the total damage caused by voltage sag may pose about 400 billion dollars losses/year to industries (Da Costa Teixeira, 2004). Therefore, voltage sag mitigation in power systems is necessary. Nowadays, various types of Custom Power Devices (CPD) such as D-STATCOM, Dynamic Voltage Restorer (DVR) and Static Transfer Switch (STS) are introduced and used as a mitigation device to improve power quality. The D-STATCOM and DVR are most effective Voltage Source Converter (VSC) based devices among other types of CPDs which are used for power quality improvement (Da Costa Teixeira, 2004; Nielsen and Blaabjerg, 2007). The main difference between the D-STATCOM and DVR is that the DVR injects voltage in series with the system, while the D-STATCOM injects current in parallel to the system to compensate the voltage sag, swell and interruption (Ramsay *et al.*, 1996; Wei-Neng and Kuan-Dih, 2003). However, the parallel compensation is more advantageous than the series one due to its requirement to a simpler protection system and its fewer losses. Furthermore, parallel compensator can be used to mitigate balanced and imbalanced harmonic currents produced by loads (Wei-Neng and Kuan-Dih, 2003), removal of produced flickers from large nonlinear loads, compensating reactive power and power factor correction (Choma and Etezadi-Amoli, 2002). Therefore, the D-STATCOM implementation is easier to protect the system against the balanced and unbalanced voltage fluctuations, current harmonics (Escobar *et al.*, 2000; Choma and Etezadi-Amoli, 2002; Wei-Neng and Kuan-Dih, 2003) flickers, voltage sags, swells and low power factor (Mohan and Kamath, 1995; Kumar and Nagaraju, 2007). Nonetheless, D-STATCOM has some limitations, which is dependent on the network parameters. In other words, this type of compensation can be used only in low voltage networks with significant feeder impedance (Ye *et al.*, 2005; Bilgin and Ermis, 2010). Otherwise, the amplitude of the required current, which must be injected into the network through D-STATCOM, is high and harmful for the device (Deniz *et al.*, 2010).

Various controllers and arrangements of D-STATCOM to compensate voltage sag have been proposed in the literature. In 2005, a current-source converter topology based D-STATCOM was proposed using a decoupled state-feedback control technique with a reduced-order state estimator in balanced systems (Yang *et al.*, 2005). The advantage of the proposed topology includes the fast response and low harmonic distortion in the injected current (Nazarloo *et al.*, 2011).

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Bilgin proposed a forced-commutated Current-Source Converter (CSC) type of D-STATCOM for industrial applications. In the proposed configuration, the power semiconductors device were designed to switch at 500 Hz based on the switching patterns generated by selective harmonic elimination method for mitigation of the most significant harmonic orders. In addition, the bipolar voltage-blocking capability was accomplished using an asymmetric Integrated Gate Commutated Thyristor (IGCT) and a fast-recovery diode, which maximizes the converter power rating (Bilgin and Ermis, 2010). Recently, a Neuro-Fuzzy Controller (NFC) was proposed with control a three-level cascaded inverter based D-STATCOM. In this method, the inputs of NFC is considered as error of d and q-axis current and in the output of NFC an anti-windup integrator is applied to eliminate steady state error at the output of the controller. In addition, the gating pulses are generated using a multilevel SPWM technique at 1.25 kHz frequency (Nazarloo *et al.*, 2011). Nazarloo proposed a new control method to compensate voltage sags caused by all types of fault using PI controller for 12-pulse inverter based D-STATCOM. In this method, the voltage error signal is obtained by comparing the measured voltage with a reference voltage at PI controller unit. To increase the robustness and reliability of the proposed method, the proportional gain of the PI controller is kept fixed for all types of faults by modifying the transformer reactance in a suitable value (Deniz *et al.*, 2010). In year 2011, a new current mode controller was proposed to compensate voltage sag by the D-STATCOM. In the proposed method, Goertzel algorithm is used as a signal processing tool to detect voltage sag. The proposed method has better harmonic performance than previous methods and can be easily implemented by digital gates (Ye *et al.*, 2005).

In this study, the performance of the D-STATCOM in compensation of voltage sag in a simple test system under different load and network conditions are investigated. The simulation results demonstrate that D-STATCOM is effective to mitigate voltage sags under specific conditions, but its usage in high voltage with low impedance networks is not economical.

D-STATCOM STRUCTURE AND MODELLING

Recently, D-STATCOM is widely applied as a power quality improvement device, which is connected in parallel with the system. D-STATCOM can also recover voltage levels during sags and swells conditions. The most common type of D-STATCOM is designed based on the Voltage Source Converter (VSC) using IGBT switches (Nazarloo *et al.*, 2011). Figure 1 shows the basic configuration of D-STATCOM, which consists of controller unit, IGBT switches, RL filter and coupling transformer (Escobar *et al.*, 2000). It should be noted that usually the impedance of transformer is considered as a part of RL filter impedance of the D-STATCOM as shown in (1) and (2):

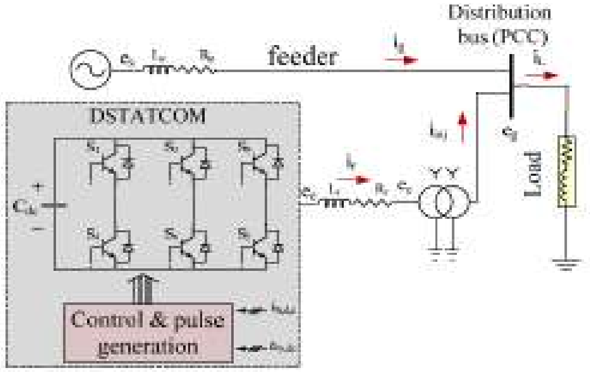

Fig. 1: The D-STATCOM structure (Hingorani *et al.*, 1999)

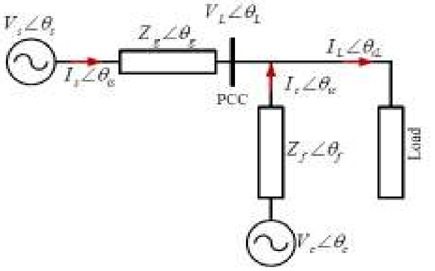

Fig. 2: Simplified model of D-STATCOM

$$R_f = R_r + R_t \tag{1}$$

$$L_f = L_r + L_t \tag{2}$$

where,

R_f and L_f : The total resistance and inductance of the filter
R_r and L_r : Internal resistance and inductance of the filter
R_t and L_t : Resistance and inductance of transformer

Figure 2 shows the simplified model of D-STATCOM in terms of filter impedance, Z_f and a voltage source converter, e_c in parallel with the network (Nielsen and Blaabjerg, 2007). With respect to the presented models in Fig. 1 and 2 and applying Kirchhoff's voltage law, the injected current, I_c into the network by D-STATCOM can be expressed as (Mohan and Kamath, 1995; Kumar and Nagaraju, 2007):

$$I_c\angle\theta_{ic} = I_L\angle\theta_{iL} - \frac{V_s\angle\theta_s - V_L\angle\theta_L}{Z_g\angle\theta_g} \tag{3}$$

where, θ, I_L, V_s, V_L, Z_g are the variables angle, load current, initial voltage of feeder, load voltages and feeder impedance, respectively.

Assuming the occurrence of voltage sag with depth of α at the feeder ($V_c\,(p.u) = (1-\alpha)$) and $\theta_s = 0$, Eq. (3) can be obtained as a below:

$$I_c\angle\theta_{ic} = I_L\angle\theta_{iL} - \frac{1-\alpha}{Z_g}\angle(-\theta_g) + \frac{1}{Z_g}\angle(\theta_L - \theta_g) \tag{4}$$

Therefore, (4) can be written in rectangular form as:

$$I_c\theta_{ic} = I_L\cos\theta_{iL} - \frac{1-\alpha}{Z_g}\cos_g + \frac{1}{Z_g}(\theta_L - \theta_g) + j \left[I_L\sin\theta_{iL} + \frac{1-\alpha}{Z_g}\sin\theta_g + \frac{1}{Z_g}\sin(\theta_L - \theta_g\right] \tag{5}$$

Then, the magnitude and angle of the injected current into the network can be expressed as:

$$I_c = \left[\left[I_L\cos\theta_{iL} - \frac{1-\alpha}{Z_g}\cos(\theta_g) + \frac{1}{Z_g}\cos(\theta_L - \theta_g)\right]^2 + \left[I_L\sin\theta_{iL} + \frac{1-\alpha}{Z_g}\sin(\theta_g) + \frac{1}{Z_g}\sin(\theta_L - \theta_g\right]^2\right]^{0.5} \tag{6}$$

$$\tan\theta_{ic} = \frac{I_L\sin\theta_{iL} + \frac{1-\alpha}{Z_g}\sin(\theta_g) + \frac{1}{Z_g}\sin(\theta_L - \theta_g)}{I_L\cos\theta_{iL} - \frac{1-\alpha}{Z_g}\cos(\theta_g) + \frac{1}{Z_g}\cos(\theta_L - \theta_g)} \tag{7}$$

Using (6), the nominal power of D-STATCOM can be introduced as:

$$S_D = V_L I_C \angle(\theta_L - \theta_{iC}) = V_L I_C \angle -\frac{\pi}{2} \tag{8}$$

Therefore, the produced voltage, V_c of the Voltage Source Convertor (VSC) of the D-STATCOM can be expressed as:

$$V_C\angle\theta_C = V_L\angle\theta_L + Z_f\angle\theta_f \cdot I_C\angle\theta_{iC} \tag{9}$$

expanding (9):

$$V_C\angle\theta_C = V_L\cos\theta_L - Z_f I_C\sin(\theta_f + \theta_L) + j(V_L\sin\theta_L + \angle Z_f I_C\cos(\theta_f + \theta_L)) \tag{10}$$

Therefore, the magnitude of V_c can be obtained as:

$$V_C = \begin{bmatrix} ((V_L\cos\theta_L - Z_f I_C\sin(\theta_f + \theta_L))^2 \\ +(V_L\sin\theta_L + Z_f I_C\cos(\theta_f + \theta_L))^2 \end{bmatrix}^{0.5} \tag{11}$$

Finally, the sensitivity of produced V_c to filter parameters of Z_f, (11) can be defined as:

$$S_{Z_F}^{V_C} = \frac{Z_f I_C}{V_C^2}(\text{Im}\,[V_C]\cdot\cos(\theta_f + \theta_L) - \text{Re}\,[V_C]\cdot\sin(\theta_f + \theta_L)) \tag{12}$$

and

$$S_{\theta_f}^{V_C} = \frac{Z_f I_C \theta_f}{V_C^2}(\text{Re}\,[V_C]\cdot\cos(\theta_f + \theta_L) - \text{Im}\,[V_C]\cdot\sin(\theta_f + \theta_L)) \tag{13}$$

PERFORMANCE ANALYSIS OF D-STATCOM

In this section, the performance of the D-STATCOM to compensate voltage sag in different conditions based on the presented equations in previous sections analysed. In addition, it is assumed that injecting active power to the network from D-STATCOM is not permitted and the voltage control is performed only by injecting reactive power to the network. The simplified one-line diagram of the applied test system is shown in Fig. 2.

Effect of feeder impedance: Assuming that the resistive part of the feeder impedance shown in Fig. 2 has a constant value, (i.e., R_g = 0.05 p.u), while the inductive part of the feeder impedance (i.e., L_g) varies between 0 and 0.6 p.u. The effect of this variation of L_g on the injected current of D-STATCOM under normal and 25% voltage sag conditions is shown in Fig. 3. It should be noted that the occurred voltage sag is created using a symmetric 3 phase short circuit at the utility side. From Fig. 3, it can be seen by increasing the inductance L_g and consequently increasing the angle θ_g, the required current to be injected by the D-STATCOM is decreased to recover the PCC voltage and keep it constant. Therefore, the required nominal power of D-STATCOM to stabilize load voltage in a low voltage network with a large impudence is less than a high voltage with low impedance. Resultantly, the feeder inductance in two operation levels may cause severe limitations in the operation criteria of D-STATCOM. In addition, increasing the line inductance force the compensator to constantly operate for providing voltage sag compensation caused by feeder impudence. Therefore, the depth of occurred voltage sag and produced current harmonics by D-STATCOM are increased. On the other hand, decreasing the feeder inductance may resolve the problem but it may force the D-STATCOM to compensate the voltage sag with

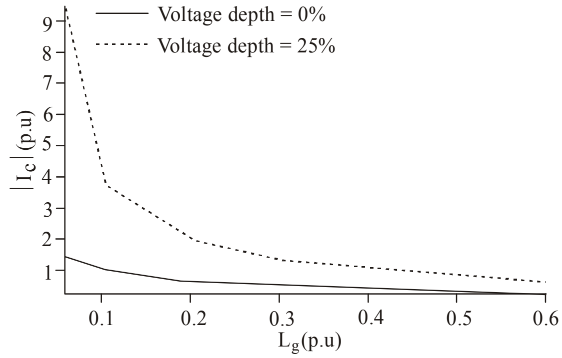

Fig. 3: The effect of feeder inductance L_g on injected current by D-STATCOM

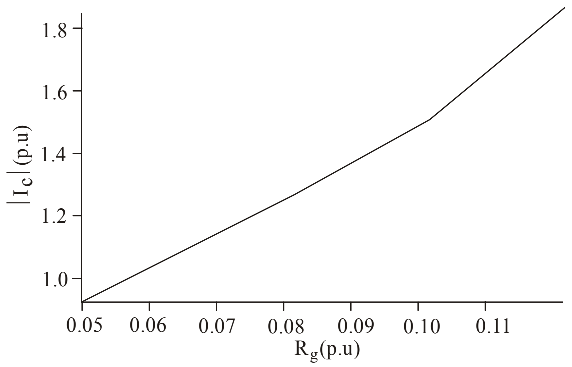

Fig. 4: The effect of feeder resistance R_g on the injected current of D-STATCOM

higher nominal power (about 10 times of the load power in some cases).

Figure 4 shows the effects of variation of line resistance, R_g on the injected current of D-STATCOM. Unlike the effect of L_g and by increasing R_g, the nominal power of D-STATCOM is rapidly increase due to the rising of the active power losses in the network resistance, R_g. Therefore, by increasing the value of R_g, the voltage drop caused by this resistance is increased. Furthermore, if the network resistance is small, the D-STATCOM has to inject more current to the network in order to compensate not only the network voltage sag but also the voltage drop caused by large resistance of the feeder.

The effect of the voltage dips depth: Assuming feeder impudence, $Z_g = 0.05 + j$ (0.18 and 0.15) p.u, in this section the effect of voltage sag depth on the injected current of the D-STATCOM and resultantly its nominal power is investigated as shown in Fig. 5. It is assumed that feeder impedance Z_g is fixed to $0.05 + j$ 0.1. From Fig. 5, it can be seen that increasing the feeder inductance can extremely reduce the injected current.

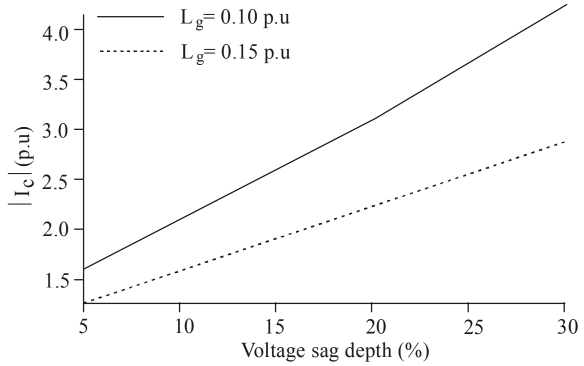

Fig. 5: The effect of voltage sag on the injected current of D-STATCOM

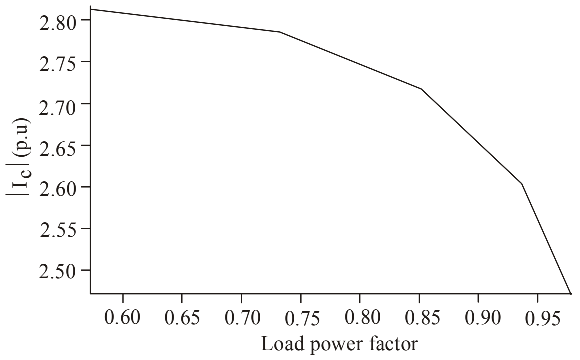

Fig. 6: The effect of power factor variation on the injecting current of the D-STATCOM under 25% voltage sag

Effect of load coefficient: In this section, it is assumed that the D-STATCOM should compensate voltage sag with depth of 25% under the worst condition. The feeder impudence is also assumed to be $Z_g = 0.05 + j$ 0.15/u.

Figure 6 shows the effect of variation of load power factor on the injected current of D-STATCOM. From the Figure, it is clear that by increasing of the load coefficient (power factor), the injected current and nominal power of D-STATCOM are decreasing.

Effect of load rating: Similar to the previous section, the feeder impudence is assumed to be $Zg = 0.05 + j$ 0.15 p.u and the depth of occurred voltage sag is considered as 25%. The effect of load power variation on the injected current into the network is shown in Fig. 7. As shown in the Figure, by increasing the nominal power of the load, the nominal power of the D-STATCOM is linearly increased. In addition, the carve slope is one which means that the required injected current by D-STATCOM to compensate voltage sag under the load rating equal to one should be at least 270% of the load power.

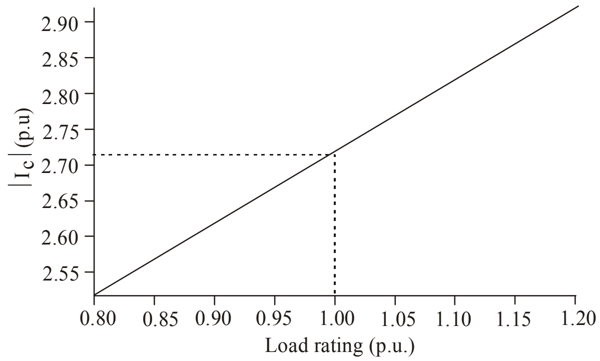

Fig. 7: The effect of nominal power of the load on the injected current of D-STATCOM

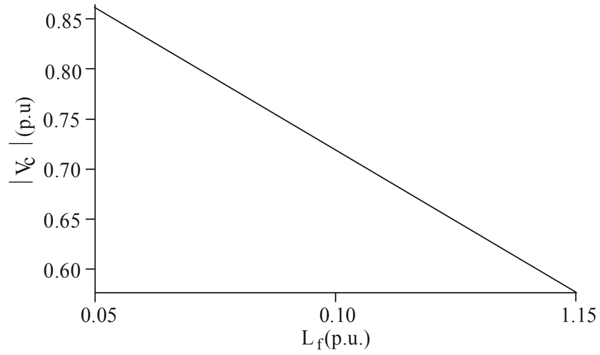

Fig. 8: The effect of L_f on D-STATCOM voltage source

ANALYSIS OF VOLTAGE MAGNITUDE OF THE D-STATCOM VOLTAGE SOURCE

In this analysis, it is assumed that the D-STATCOM is designed to compensate voltage sag with maximum depth of 25%. Feeder impudence is considered as $Z_g = 0.05 + j\ 0.15$/u and the load operates at power of 1 p.u with power factor 0.8. Figure 8 shows the effect of variation of filter inductance, L_f on the produced voltage by VSC. From the Figure, it is obvious that increasing L_f can reduce the magnitude of the produced voltage of D-STATCOM and consequently, decrease the level of voltage of its switches. In addition, the PCC voltage can be kept constant by increasing the value of filter impudence. Nonetheless, increasing the inductance of the filter may enlarge the harmonics current magnitudes, decrease injected current into the network and reduce the level of VSC voltage.

CONCLUSION

D-STATCOM can be used to compensate occurred voltage sag in distribution systems. This device is also able to control and regulate the PCC voltage and keeps it constant by injecting required reactive current into the network. In this study, the effect of various parameters of network and load on the injected current of the D-STATCOM is investigated. The simulation results show that increasing the values of L_g can decrease the required injected current, while increasing R_g can raise the amount of injected current to the network. Similar to L_g and R_g, load power factor and load rating have revere effect on injected current by D-STATCOM.

REFERENCES

Arrillaga, J., M.H.J. Bollen and N.R. Watson, 2000. Power quality following deregulation. Proceedings IEEE, 88(2): 246-261.

Bilgin, H. and M. Ermis, 2010. Design and implementation of a current-source converter for use in industry applications of D-STATCOM. IEEE Trans. Power Electr., 25(8): 1943-1957.

Choma, K.N. and M. Etezadi-Amoli, 2002. The application of a DSTATCOM to an industrial facility. IEEE Power Eng. Soc. Winter Meeting, 722: 725-728.

Da Costa Teixeira, C., 2004. Power quality solutions for low and medium voltage critical loads. Transmission and Distribution Conference and Exposition: Latin America, 2004 IEEE/PES, pp: 326-331.

Deniz, E., R. Coteli, B. Dandil, S. Tuncer, F. Ata, *et al*., 2010. Neuro-Fuzzy Current Controller for Three-Level Cascade Inverter Based D-STATCOM.

Escobar, G., A.M. Stankovic and P. Mattavelli, 2000. Reactive power, imbalance and harmonics compensation using d-statcom with a dissipativity-based controller. IEEE Conference on, Decision and Control, Proceedings of the 39th, 3054: 3051-3055.

Hingorani, N.G. and L. Gyugyi, 1999. Understanding FACTS: Concepts and Technology of flexible. AC Transmission Systems, New York.

Kumar, S.V.R. and Z.S.S. Nagaraju, 2007. Power quality improvement using d-statcom and DVR. Int. J. Electr. Power Eng., 1(3): 368-376.

Mohan, N. and G.R. Kamath, 1995. A novel, high-frequency, per-phase static var compensator. IEEE, 2583: 2581-2586.

Nazarloo, A., S.H. Hosseini and E. Babaei, 2011. Flexible D-STATCOM performance as a flexible distributed generation in mitigating faults. IEEE, pp: 568-573.

Nielsen, J.G. and F. Blaabjerg, 2007. A detailed comparison of system topologies for dynamic voltage restorers. IEEE Trans. Ind. Appl., 41(5): 1272-1280.

Ramsay, S.M., P.E. Cronin, R.J. Nelson, J. Bian and F.E. Menendez, 1996. Using distribution static compensators (D-STATCOMs) to extend the capability of voltage-limited distribution feeders. Rural Electric Power Conference, 1996. Papers Presented at the 39th Annual Conference, pp: A4/18-A14/24.

Wei-Neng, C. and Y. Kuan-Dih, 2003. Design and implementation of DSTATCOM with symmetrical components method for fast load compensation of unbalanced distribution systems. The Fifth International Conference on Power Electronics and Drive Systems, PEDS 2003, 1542: 1547-1551.

Yang, Y., M. Kazerani and V.H. Quintana, 2005. Current-source converter based STATCOM: Modeling and control. IEEE Trans. Power Deliver., 20(2): 795-800.

Ye, Y., M. Kazerani and V.H. Quintana, 2005. Current-source converter based STATCOM: Modeling and control. IEEE Trans. Power Deliver., 20(2): 795-800.