Impact of STATCOM Design Parameters on Voltage Distortion at the PCC

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***Abstract*— The subject of this work is the investigation of the power quality impact resulting from connecting a STATCOM to a distribution system. The STATCOM is used to provide voltage regulation, however, this device has an impact on the power quality at the PCC. This impact will be quantified for different STATCOM configurations (including two-level and multilevel inverter), output filter design and modulation techniques. The main conclusion of the analysis is that the STATCOM does not significantly impact the low frequency harmonics, however, for some configurations the THD limits are exceeded. It will be shown that changing the modulation technique does not change significantly voltage distortion at the point of common coupling (PCC), while increasing the number of levels and modifying the output filter design have a more evident effect. Future work on this topic will include the study of more complex system with existing harmonic distortion prior to connecting the STATCOM, to evaluate interaction of this device with other sources of harmonics.**

***Index Terms*— Distribution System, STATCOM, Voltage Regulation, Harmonics, Multilevel Converters, PCC, VSC**

I. Introduction

The STATCOM is a shunt connected compensator, which performs rapid reactive power exchange with an ac power system, to improve transient voltage stability and dynamic voltage control, prevent voltage collapse and damp power oscillations [1],[2],[3]. Both voltage amplitude and phase angle at the STATCOM terminals are controllable and this device has the capability to generate inductive and capacitive reactive power [4]. If the STATCOM is coupled with an energy source, it can also exchange active power with the AC system. However, since the STATCOM is based on the fast commutation of power electronic switches, there is a concern that this device may cause increasing voltage distortion [1].

Different parameters are available when designing a STATCOM, and they impact both transient and steady-state performance, including harmonic distortion. These parameters are, for instance, control system coefficients, inverter topology and output filter design. Therefore, the STATCOM designer can choose among different configurations to achieve the desired performance, taking into account requirements and limitations such as cost and space.

This paper will consider the impact of three different parameters on the harmonic distortion: number of levels, output filter design and modulation technique. The control system gains and constant are kept the same for all configuration studied (with an exception that will be explained in Section V) to allow a straightforward comparison between the different cases. This work is an extension of the analysis carried out in [5], where different modulation techniques have been investigated.

II. STATCOM Operation and Configuration

A. STATCOM operation within a distribution system

Fig. 1 is used to describe the power flow between a simple distribution system and a STATCOM. The apparent power flow S_{ST} between Bus 3 and Bus ST is given by [6], [7]:

$$S_{\mathrm{ST}} = \frac{V_3 V_{\mathrm{ST}}}{X_{\mathrm{ST}}} \sin(\delta_{\mathrm{ST}} - \delta_3) - j\frac{V_3(V_3 - V_{\mathrm{ST}})}{X_{\mathrm{ST}}} \cos(\delta_{\mathrm{ST}} - \delta_3) \quad (1)$$

For the present analysis, the objectives of the STATCOM are to improve transient voltage stability and to perform voltage control. Therefore, only reactive power exchange is required. In the practice, because of the internal losses, the power system voltage leads the STATCOM voltage by a small angle [8]. However, it can be assumed that those losses are small and therefore no active power flow occurs. This lead to the condition $\delta_{\mathrm{ST}} = \delta_3$ in (1).

Based on the amplitude of the voltage at Bus 3 and of the voltage at Bus ST, reactive power flow is defined according to the notation shown in Table 2.

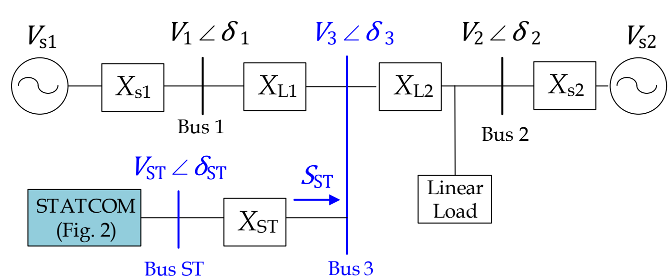

Figure 1. A simple distribution system with a STATCOM connected to Bus 3. The voltage magnitude and phase angle for each bus are indicated.

Table 2: Reactive power flow between STATCOM and power system, under different voltage magnitudes at Bus 3 and at Bus ST

Case	Condition	Reactive power Q
1	$V_3 > V_{ST}$	From ac system to STATCOM (Q<0)
2	$V_3 < V_{ST}$	From STATCOM to ac system (Q>0)
3	$V_3 = V_{ST}$	Q = 0

B. STATCOM configuration

Fig. 2 shows the main components of a STATCOM: dc-link capacitor, power converter, output filter, coupling transformer and control blocks, to generate switching pulses.

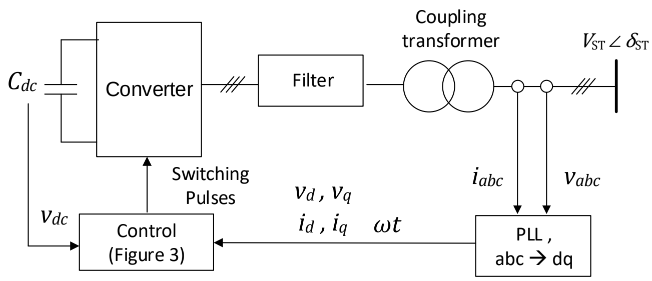

Figure 2. STATCOM configuration: power converter, filter, coupling transformer, control blocks

The control system operates to maintain a constant dc-link voltage while regulating the ac voltage to a set point. The dc-link voltage is controlled by forcing the output ac voltage to lag by a small angle. In this manner, the power converter absorbs a small amount of active power from the grid to feed its internal losses and preserve the capacitor voltage at the desired level [4].

Fig. 3 shows the main core of the control system developed for this analysis. This control system is quite standard, and includes the following main blocks: dc link voltage control, feed forward compensation, active and reactive power flow, modulation. Details on the STATCOM control can be found in numerous publications such as [9].

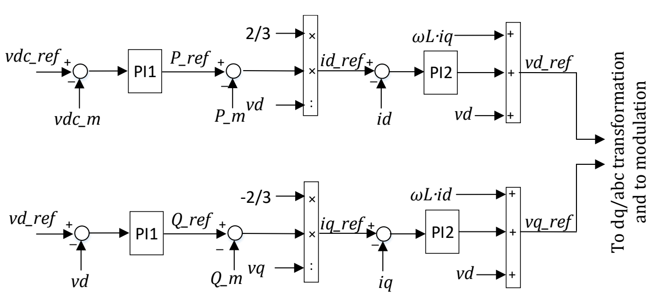

Figure 3: Overview of the proposed control system

Voltage-source converters (VSCs) are often preferred over line-commutated converters (LCCs) for different reasons related to cost and performance, including: reduced harmonic generation, the ability to independently control active and reactive power, and the lower space occupied by the converter station [1], [9]. With the aim of overcoming the poor harmonic performance of the two-level converter and increasing voltage and power handling capabilities, multilevel converters have been developed to become a well-established technology [10]. In multilevel converter topologies, the semiconductor devices are connected in series and parallel. Numerous modulating techniques have been developed [11],[12],[13] and some of them will be considered in the present analysis to address the impact of this parameter on the harmonic performance [14].

C. Objective of the analysis

The analysis presented in the rest of the paper will address how three different design parameters affect the levels of distortion of the output voltage for a STATCOM:

1. Output filter: the use of either a *LC* or *L* filter will be studied
2. Number of levels: two level (2L), three levels (3L) and five levels (5L) configurations will be considered
3. Modulating techniques: sinusoidal pulse-width modulation (SPWM) and some of its variations; space vector modulation (SVM) and third harmonic injection (3HI) [12], [13] will be modeled.

In the next section, a base case is developed, and then four different combinations of the parameters above will be studied to evaluate the impact of these variables on harmonic distortion at the PCC and to identify acceptable configurations.

III. STATCOM MODEL DEVELOPMENT AND VALIDATION

The system shown in Fig. 1 has been modeled using Matlab/Simulink. The 11 kV distribution network has a short circuit capacity of 25 MVA. The STATCOM is connected at bus B3 between two 20 km distribution lines – this bus will be considered the PCC for the analysis. The lines are built using a PI model. A 2.5 MW load is connected in proximity of the STATCOM. The dc rated voltage is 2 kV and the capacitor value is 9650 µf. The VSC for the base case uses an IGBT based two-level VSC adopting the SPWM technique. It includes a filter composed of a series inductive branch (2mΩ and 600 µH) and a shunt capacitive branch (R=0.1 Ω and C=2000 µF). The output voltage rating is 400 V and the transformer series reactance is 8% and rating is 2.5 MVA.

A control system similar to the one shown in Fig. 3 was developed for this configuration. The proportional and integral gains are as follows: 0.2 and 3.26 for PI1 (slower dc voltage and reactive power controller) and 10 and 250 for PI2 (faster current controls). The switching frequency is 2.6 kHz.

The STATCOM is installed to regulate the voltage at the PCC. Fig. 4 shows the step response of the STATCOM, and illustrates the robustness and effectiveness of the developed control system. The top graph shows the voltage in pu at Bus 1 and at the PCC. The grid voltage varies step-wise between +10% and -10%, but the voltage at the PCC is quickly restored at the reference value of 1 pu. A detailed analysis of the step response (calculation of rise time, settling time and peak voltage) is not carried out within this paper as the main focus of the analysis is to study the impact of the STATCOM on harmonic levels. The response shown in Fig, 4 is considered to be sufficiently accurate. If a different step response was required, the control system parameters could be further tuned.

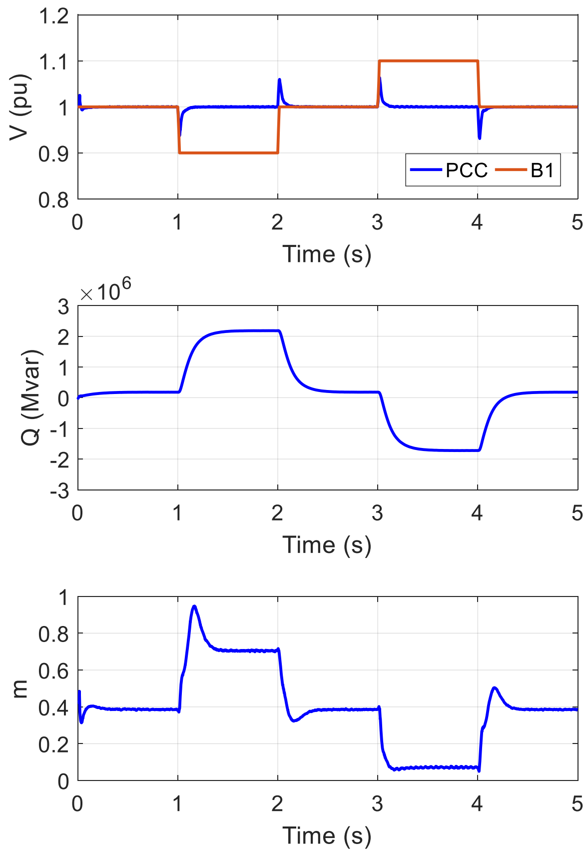

Figure 4: STATCOM response for varying voltage on the ac grid: normalized voltage at Bus 3 and at Bus 1, reactive power output Q and modulation index *m*.

The middle graph of Fig. 4 shows the STATCOM reactive power injection: based on the notation of Table 2, the reactive power is positive when the STATCOM is required to raise the grid voltage, and, conversely, it is negative when the STATCOM is required to lower the grid voltage. The maximum reactive power injected by the STATCOM is approximately 2 MVA for this case. This value is close to the STATCOM rated power, thus confirming that the designed device is adequate for the system under consideration, assuming a maximum grid voltage variation of +/- 10%.

The last graph of Fig. 4 shows that for all operating conditions, the modulation index *m* is always between 0 and 1 (the modulation index is the ratio between the peak reference voltage and the carrier voltage), and this is the normal behavior expected for a fully-controlled device [9].

The voltage total harmonic distortion index (THD) is defined as follows [15]:

$$\mathrm{THD} = \sqrt{\frac{\sum_{h=1}^{n} V_h}{V_1}}$$

where V_1 is the voltage fundamental component, V_h is the voltage harmonic component at frequency h and n is the maximum number of harmonics studied. For the present analysis, n=50, in line with the international standards [15].

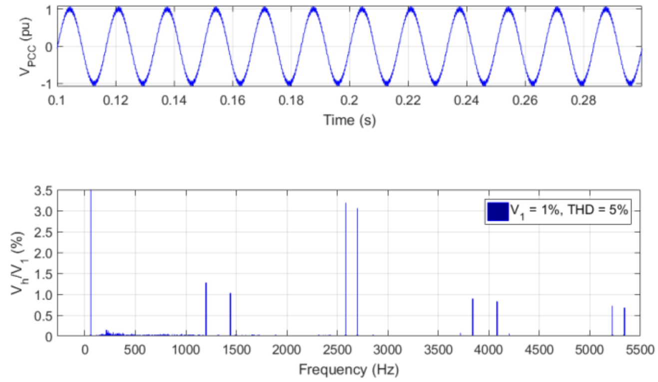

Figure 5: Voltage at the PCC and harmonic analysis.

Fig. 5 shows the voltage at the PCC: the first graph presents the time-domain variation, while the second graph illustrates the harmonic spectrum. Due to the use of a LC output filter, the main harmonic components are at frequencies in the order of kHz, in accordance with the formulae in [12]. The THD for this configuration is equal to 5%: this value is the upper limit for acceptable voltage distortion according to [15], and therefore this result will be used as a base case for the comparison carried out in the next section.

IV. Comparison of Different Configurations

Using as a base case the STATCOM developed in Section III, numerous combinations of modulation techniques, VSC configurations, and output filters were studied. Among these cases, four will be presented as they are representative of the findings of the analysis. For each case, the total voltage harmonic distortion at the PCC is monitored and only configurations which results in a THD lower than 5% will be considered acceptable.

A. *Two-level (2L) VSC with three modulation techniques*

Three modulation techniques are compared for the base case with 2L VSC: SPWM, third harmonic injection (3HI) and space-vector modulation (SVM). The topology and control system parameters are the same described in Section III: the modification required is implemented after the modulation signals m_d and m_q are obtained. For each modulation technique, two output filters are considered: *LC* and L, with the parameters given in Section III (the *L* filter is obtained by simply removing the capacitor, to allow for a straightforward comparison between the two designs and to quantify the effect of the shunt capacitor).

Fig. 6 summarizes the results in terms of output voltage harmonic distortion. For all cases, the *LC* filter is required to meet harmonic distortion, and the modulation technique doesn't seem to have much impact on the THD. A careful analysis of the internal control signals indicates that the modulation index is lower for the 3HI method. This means that the dc-voltage level could be decreased while still being able to provide the required voltage regulation. This property may be a design criterion which allows choosing between the three modulation techniques.

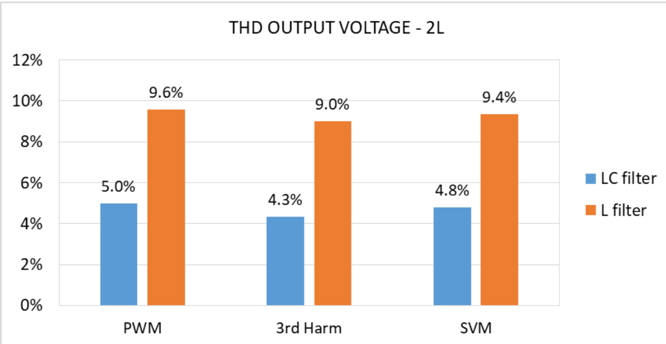

Figure 6: Voltage THD of two level inverter STATCOM with 3 modulation techniques and 2 harmonic filter configurations

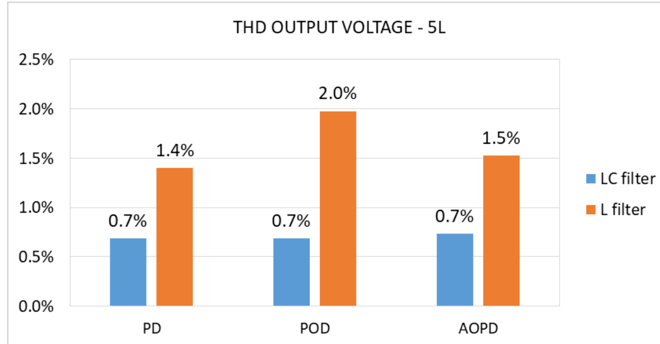

Figure 8: Voltage THD of five levels inverter based STATCOM with three variations of PWM

B. Two levels, three levels and five levels with SPWM

The reference case is the model developed in Section III. The same control and modulation technique is used, but the number of levels is increased. As in the previous case, two different output filters are considered.

The THD value for the different cases is shown in Figure 7. As expected, with increasing number of levels, the THD value is reduced. The 2L configuration requires a *LC* filter to meet THD requirements, while this is not necessary with the other two configurations. This case indicates that an increase of the number of levels will result in a smaller and simpler output filter design.

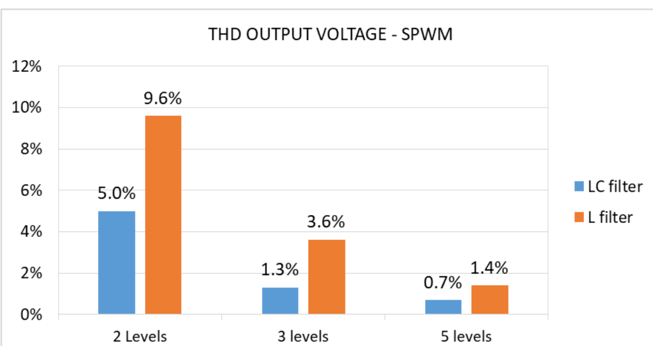

Figure 7: Voltage THD for two, three and five levels inverter based STATCOM with two different type of harmonics filters

C. Five level VSC with different PWM techniques

SPWM is the basic PWM technique, and different variations have been developed as discussed in Section II. Among these variations, the following are considered in this section: phase disposition PD-PWM, phase opposition disposition POD-PWM, and alternative phase opposition disposition APOD-PWM [16]. The base case is the 5L VSC developed in Section B, and the analysis considers two types of filters.

Figure 8 summarizes the THD values for the 5L SVC: the THD is always below 5%, and the comparison of the three PWM approaches shows that no significant difference can be observed, in particular when the *LC* filter is used (blue bars in Figure 8).

D. 5L-PDPWM inverter STATCOM with different output filters

The results presented in the previous section indicate that when the number of levels is increased, the shunt filter (capacitor) can be removed while still meeting THD requirements. This section investigates the impact of reducing the value of the inductor in the *L* filter with the purpose to identify the lower limit of *L* which allows meeting THD requirements.

Any changes in the inductor value affect the performance of the closed-loop compensators parameter K_p, since the value of L is present in the equivalent circuit of the STATCOM mathematical model. The following equation represents the closed-loop transfer function:

$$G(s) = \frac{1}{s\frac{L}{K_p} + 1}$$

Equation 1: Closed-loop transfer function

In physical terms, an increasing value of the *L* filter inductance will increase the time it takes to charge and discharge the dc capacitors, hence a variation in the response of the STATCOM will occur.

As a result, in this analysis, the value of k_p is updated with any variation of L and the simulations are performed for three different options:

- 5L VSC with an *LC* filter using an inductance of half of the value used in the base case 2L inverter (300 µH).
- 5L VSC with a *L* filter using an inductance of half of the value used in the 2L inverter (300 µH).
- 5L VSC with a L filter using an inductance of one quarter of the value used in the 2L inverter (150 µH).

For all configurations, PD-PWM is used. The simulation results are summarized in Fig. 9. As expected, with reduced values of the series inductance *L*, the THD at the PCC increases. However, even when the inductor value is equal to ¼ of the one used in the original case and the capacitor is removed, the THD is still below 5%.

This case confirms the advantage brought by the multilevel inverter: the overall physical dimension and space that the STATCOM occupies is reduced due to a smaller size of the passive components of the harmonics filter.

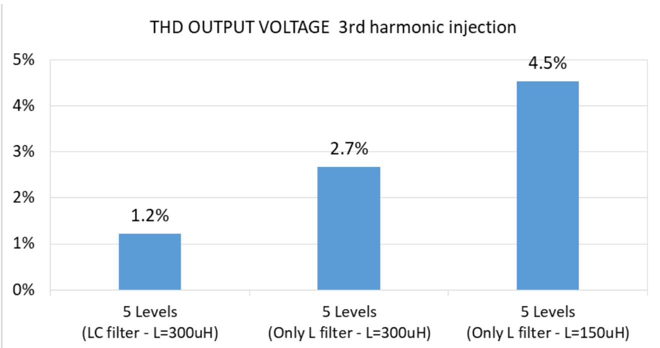

Figure 9: 5L-PD PWM inverter with different output filters.

V. CONCLUSION

This paper described the configuration and control system for a 2.5 Mvar STATCOM that exchanges reactive power with a distribution network to provide voltage stability.

The base scenario developed was a two-level VSC-based 2.5 Mvar STATCOM. The step response was analyzed to confirm the adequate operation of the designed control filter. Different topologies, output filters and modulation techniques have been compared, to verify under which conditions THD at the PCC was below the limit described by the standards. The same control system was used for all cases, except the last one where a change in the output filter inductance required a modification of the proportional gain. The following conclusions can be made from the analysis:

- An increasing number of levels reduce the harmonic impact on the grid. Therefore, the increased complexity in the VSC topology is compensated by the use of a smaller output filter.
- The use of different modulation techniques does not have a significant impact on the harmonic performance, in particular when a high number of levels is used.
- A closer analysis of the control system signals gives further insights of possible further optimization with regards to the modulation technique. For example, in one of the cases it was observed that for 3HI modulation technique, the modulation index is always much lower than unity. This means that for this configuration, the dc-link voltage may be reduced while maintaining an acceptable performance in terms of both steady-state and transient analysis.

The distribution system considered in this analysis is simple as no sources of harmonics are included; therefore the STATCOM output voltage distortion includes harmonics in the order of the switching frequency. The next step of the analysis will study a system where both low-order and high-order harmonic sources are present prior to connecting the STATCOM, to identify the effect of this device on pre-existing harmonic levels, and possible harmonic interactions.

The next steps of this research will also include a comparative analysis in terms of reliability and maintenance. The overall STATCOM reliability does not depend on the number of components only, since each component has a different failure rate and replacement time. Therefore, a detailed analysis needs to carried out for each configuration. For the case of multi-level converters, while the large number of power electronic switches may decrease the overall reliability of the VSC, the elimination or simplification of the output filter may have a positive effect on overall reliability of the STATCOM device.

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