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Improving Compensation Performance in Three-Phase Active Power Line Conditioners by DC-Voltage Control

This paper analyses the influence of the prescribed DC-link voltage on the filtering efficiency, in terms of current harmonic distortion after compensation, in a three-phase three-wire shunt active power line conditioner. The AC voltage controller as nonlinear load and two configurations of the coupling filter are taken into consideration. It is pointed out that, for each rms current to be compensated, there is an optimal set value of the DC-link voltage which minimizes the supply current distortion after compensation. Experimental tests validate the simulation results.

Keywords: Power conditioning, Harmonic distortion, Voltage control

1. Introduction

Improving the power quality in electrical systems with nonlinear loads is a concern for many decades. Fulfilling the provisions of existing standards and recommendations, such as IEC 61000 and IEEE 519 – 1992, is the ultimate goal and finding solutions as efficient as possible is a stated goal.

Although the passive filtering is a handy solution, it is mainly adopted in hybrid compensating systems due to the limited performance and lack of adaptation to the dynamic changes of the load [1].

As for the newer solution referred as active power line conditioners (APLCs) or active power filters (APFs), it allows compensating the reactive power and obtaining the desired waveform of the supply current, by implementing the compensation strategy in the control system of the power inverter which provides the compensating power [2].

In the shunt structure of APLC, the prescribed output current of the voltage source inverter is generated based on the measured supply voltages and load currents, in accordance with the adopted compensation strategy (Fig. 1).

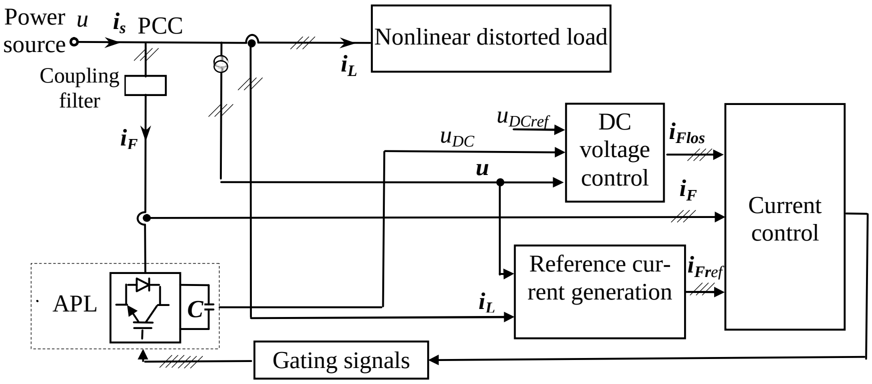

Figure 1. Shunt APLC structure.

The current tracking accuracy depends especially on performance of the control system, but it is also influenced by the structure and parameters of the coupling passive filter which is intended to attenuate the high order switching harmonics.

As regards the DC side of the voltage inverter, it is necessary to impose and maintain the voltage across the capacitor in order to ensure the energy required in the compensation process and the coverage of power losses. Thus, the voltage control loop provides an additional reference current (i_{Floss}). There are different approaches on the DC-link design and voltage control, but they do not take into account the possibility of adapting the prescribed DC-voltage according to compensating conditions [3], [4], [5].

The attention in this paper is directed towards finding the optimal DC-voltage value in order to minimize the harmonic distortion of the supply current after compensation. The coupling filters of L and LCL type are taken into consideration.

2. The DC-voltage value

In the adopted inner control loop of the DC-voltage, a Proportional Integral (PI) controller designed in accordance with the Modulus Optimum criterion provides the magnitude of the additional reference current [6]. As regards the design of the DC-link circuit, the conditions of limiting both the voltage ripple and the integral of the current lead to [7]:

$$C = \frac{\varepsilon_i \cdot S_{DC}}{\varepsilon_u \cdot f \cdot U_{DC}^2}, \tag{1}$$

where ε_i is imposed capacitor charge (pu), ε_u is imposed capacitor voltage ripple (pu), S_{DC} is the capacitor apparent power and f is the fundamental frequency of the capacitor current.

Assuming that S_{DC} exceeds the apparent power to be compensated with about 10%, expression (1) can be written as:

$$C \cdot U_{DC}^2 = \frac{3.3 \cdot \pounds_i \cdot U_f}{\pounds_u \cdot f} \cdot I_F \,, \qquad (2)$$

where U_f is the rms phase voltage and I_F the rms compensating current.

The above expression suggests idea that the energy provided by the capacitor should be dependent on the rms compensating current in order to keep the filtering performance (ε_i, ε_u = constant). As the DC-capacitance is constant, it means that the prescribed DC-voltage should not remain constant when the compensating apparent power changes.

3. The DC-voltage influence on the filtering performance

First, the performance of the shunt APLC system for different DC-voltage values has been determined by simulation under Matlab-Simulink environment. In the Simulink model shown in Fig. 2, the three-phase power supply of rated line-to-line voltage of 380 V and 50 Hz supplies a nonlinear balanced load consisting of an AC voltage controller with back-to-back thyristors and RL load.

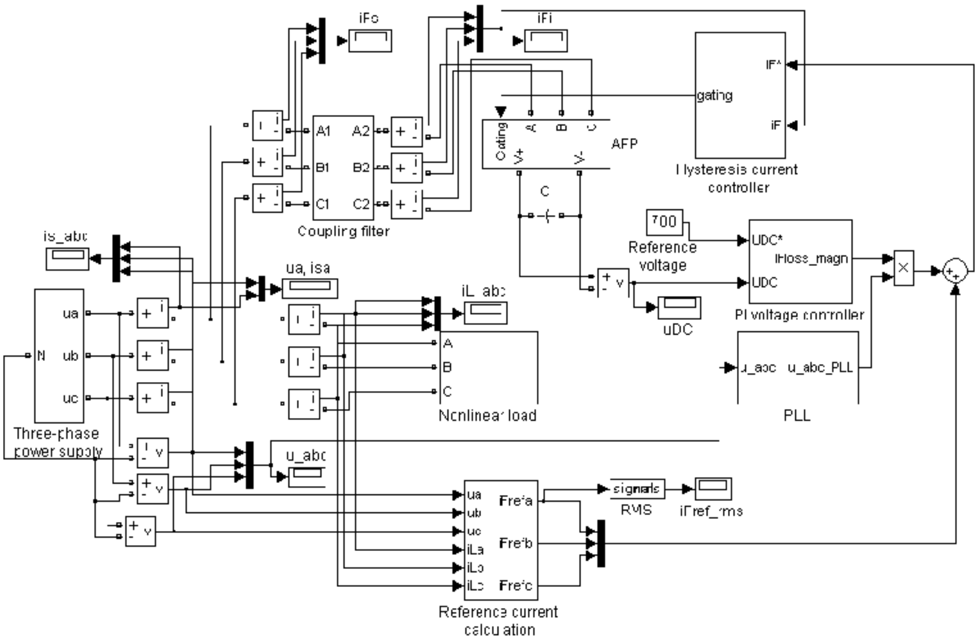

Figure 2. Simulink model of the shunt APLC system.

The reference current calculation block provides the prescribed compensating currents by implementing the partial compensation strategy based on p-q theory of the instantaneous reactive power, which means the current harmonic cancellation without the reactive power compensation [8].

Table 1 summarizes the main parameters of the APLC system, including the coupling passive filter in the two structures taken into consideration (L and LCL with damping resistor)

Table 1. The main parameters of APLC

DC-capacitance	1100 μF
Proportional constant of the voltage controller	4.18
Integral constant of the voltage controller	232.56 s^{-1}
Hysteresis band of the current controller	0.4 A
Inductance of the coupling filter of L type	4.4 mH
Parameters of the LCL coupling filter: Supply side inductance – 0.4 mH; Inverter side inductance – 4 mH; Capacitance - 1 μF; Damping resistance – 100 Ω	

The APLC is charged, by turn, to compensate the high distorted current drawn the AC voltage controller of about 7 A rms (THD = 84%) and 17 A rms (THD = 73%) respectively. The associated compensating powers correspond to the compensating current values (I_{Fp}) of 4.5 A rms and 10 A rms respectively (Fig. 3).

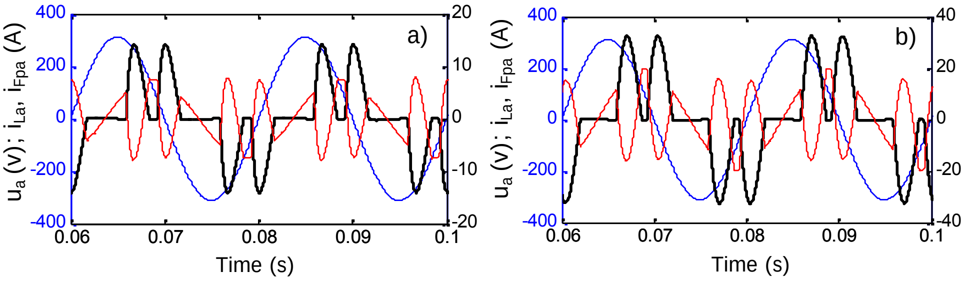

Figure 3. Waveforms of the supply voltage (blue line), load current (black line) and compensating current (red line): a) for I_{Fp1} = 4.5 A rms; b) for I_{Fp2} =10 A rms.

For each load current, different values of DC-link voltage are prescribed and the total harmonic distortion factor of the supply current is calculated as:

$$THD=\sqrt{\left(I_s/I_{s1}\right)^2-1}\,, \tag{3}$$

where I_s and I_{s1} are the rms values of the supply current and fundamental supply current.

In the first case study, the compensating current is injected to the point of common coupling through an inductive filter.

The dependences in Fig. 4 reveals the THD decrease as the prescribed U_{DC} increases up to a certain value which depends on the rms compensating current (700 V for I_{Fp1} =4.5 A and 750 V for I_{Fp2} =10 A). Compared to the case of 650 V, THD is reduced from 3.78% to 3.57% for I_{Fp1} and from 7.55% to 2.26% for I_{Fp2} (Fig. 4 and 5).

Over these optimal values, an increase of up to 50 V does not affect the supply current distortion. Further increase of the set DC-voltage leads to the THD increasing, which is more evident at low compensating current.

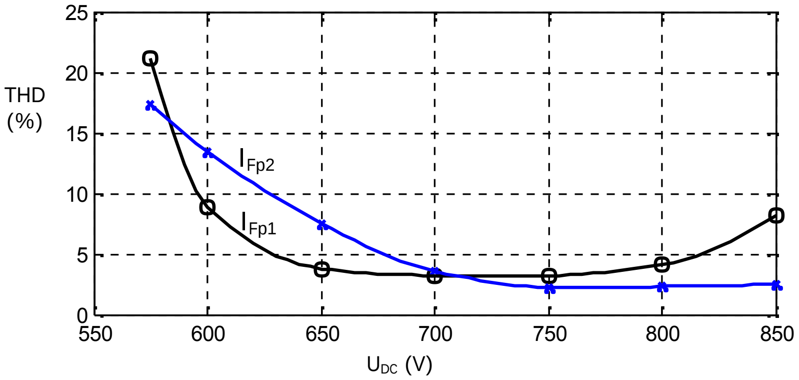

Figure 4. Supply current harmonic distortion versus DC-link voltage in the case of the inductive coupling filter

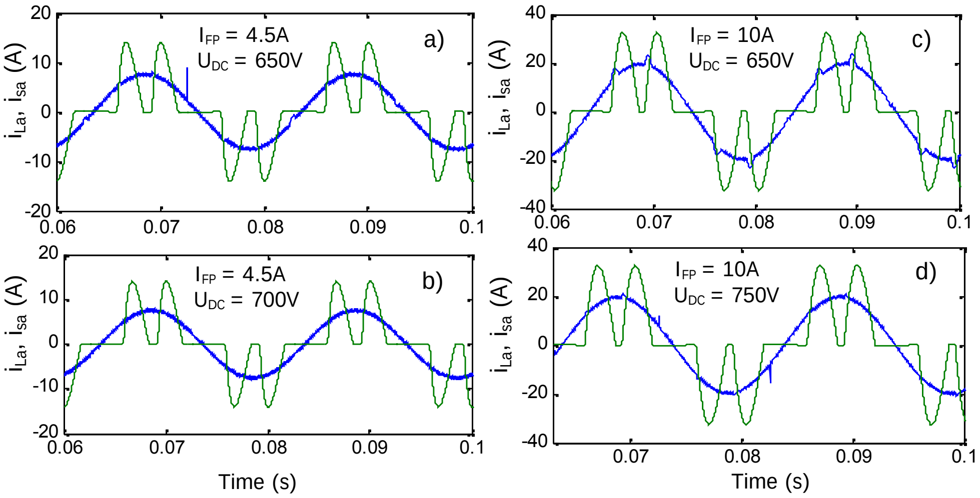

Figure 5. Waveforms of the supply current (blue line) and load current (green line) under different compensating current and DC-voltage conditions, in the case of the inductive coupling filter

In the second case study, the LCL coupling filter is used to mitigate the high order switching harmonics. As it can be seen in Fig. 6, the minimal values of THD are obtained for the same values U_{DC} as in the case of inductive filter. Thus, it is confirmed that the optimal value of U_{DC} does not depend on the type of coupling filter. Both the THD values and supply current waveforms (Fig. 7) show convincingly the benefic influence of the LCL filter.

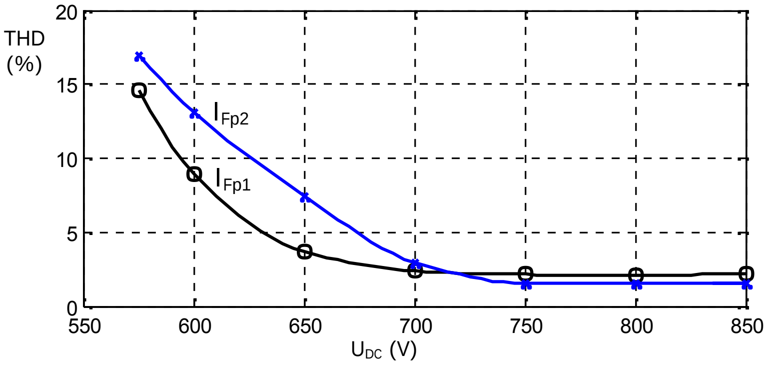

Figure 6. Supply current harmonic distortion versus DC-link voltage in the case of the LCL coupling filter

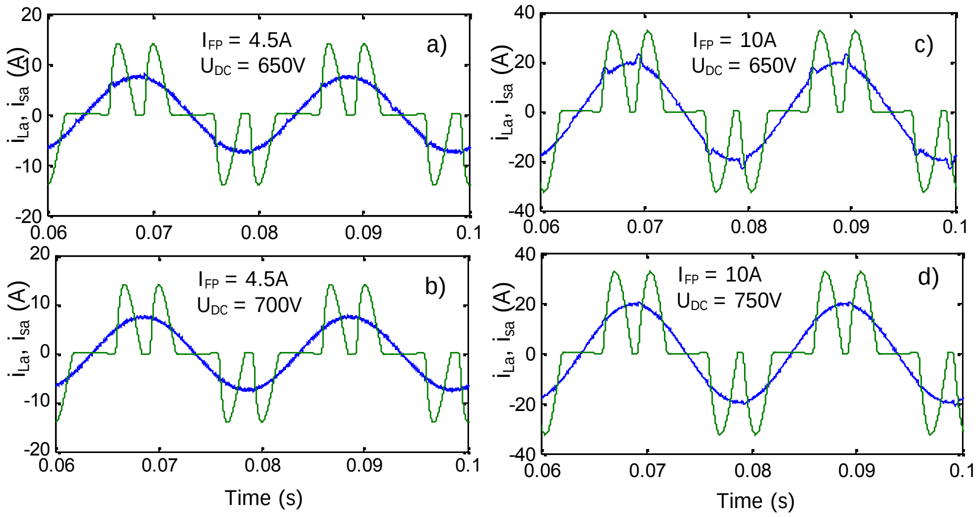

Figure 7. Waveforms of the supply current (blue line) and load current (green line) under different compensating current and DC-voltage conditions, in the case of the LCL coupling filter

The harmonic spectrum of the supply current in the case of the inductive coupling filter for the optimal DC-voltage of 700 V at I_{Fp1} =4.5 A (Fig. 8a) shows that the first significant harmonic is of about 0.35%. There are also three harmonics exceeding 0.2%. By comparison, when the LCL filter is used, only one harmonic is about 0.25%, while all others are below 0.2% (Fig. 8b).

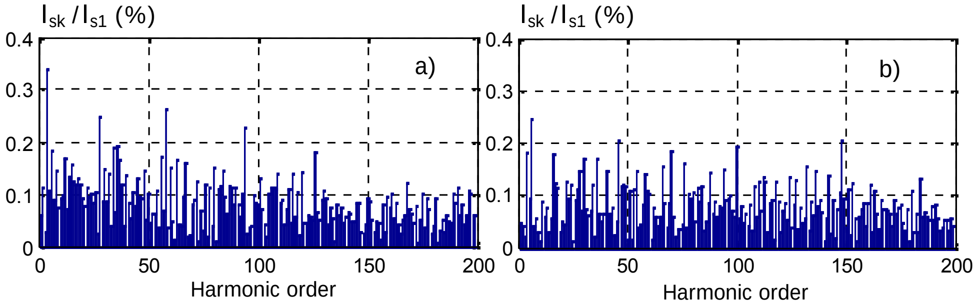

Figure 8. High-order harmonic spectra of the supply current for I_{Fp1} and U_{DC}=700V: a) in the case of the inductive coupling filter; b) in the case of the LCL coupling filter.

4. Experimental results

In the experimental setup, the three-phase IGBT-based voltage source inverter of 15 kVA rated power has a DC-link capacitor of 1100 µF on the DC-side and a configurable coupling filter on the AC-side (Fig. 9). The nonlinear load is an AC voltage controller manufactured by Nokian Capacitors Ltd. and especially aimed for testing.

Figure 9. Picture of the experimental setup

Based on dSPACE DS1103 PPC controller board, the real-time control system was implemented via Matlab/Simulink environment.

The APLC's parameters are identical to those used in simulation model (Table 1).

The nonideal supply voltage has an harmonic distortion of about 2.15 %. As illustrated in Fig. 10, the load current has a high level of distortion (about 126%). The associated rms compensating current to achieve the partial compensation is of about 5.25 A.

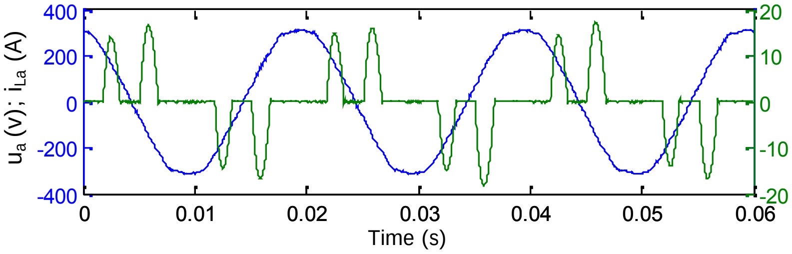

Figure 10. Acquired phase voltage (blue line) and load current (green line).

The oscillograms in Fig. 10 and 11 correspond to the APLC coupling through L and LCL filter for two values of the DC-link voltage. They confirm the simulation results related to the improvement of filtering performance by prescribing appropriate DC-voltage and by using an LCL coupling filter.

Although the remaining harmonic distortion of the supply current is over the value obtained by simulation, the filtering efficiency, in terms of ratio of harmonic distortion factors at the load and supply sides, is very good (about 12.5).

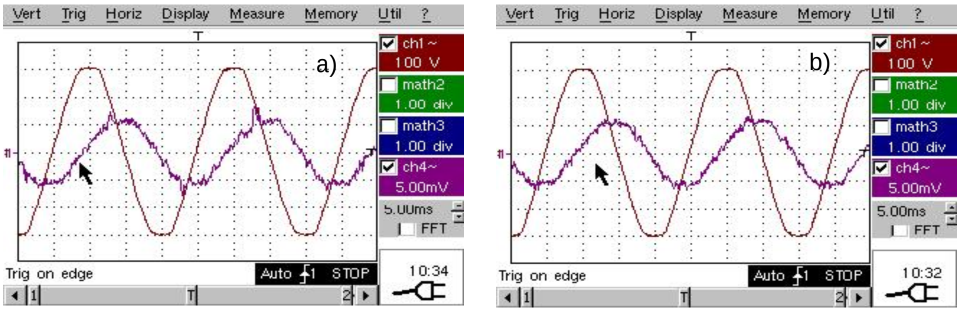

Figure 11. Experimental phase voltage and supply current in the case of the inductive coupling filter: a) for U_{DC} = 650 V; b) for U_{DC} = 700 V.

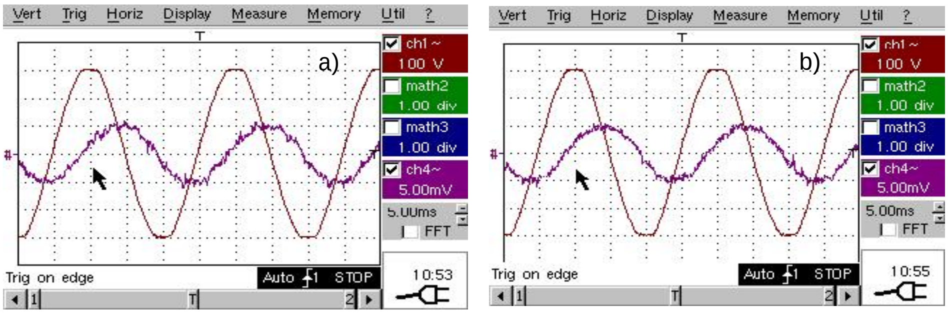

Figure 12. Experimental phase voltage and supply current in the case of the LCL coupling filter: a) for U_{DC} = 650 V; b) for U_{DC} = 700 V.

5. Conclusion

The simulation and experimental results justify the need for the analysis performed in this paper. It is mathematically justified, from the qualitative point of view, that the filtering performance depends on the rms compensating current when the voltage across the compensation capacitor is maintained constant. It is expected that the harmonic spectrum of the compensating current have some quantitative influences. To reveal this aspect, the analysis should be extended to many types of nonlinear load. It must be mentioned that, the load taken into consideration in this paper is an unfavorable case from this point of view.

Making evident the dependence of the optimal DC-voltage on the rms compensating current can be a solution for implementing the optimal voltage control.

Both the model-based and experimental analyses highlight the positive influence of a suitably designed LCL filter on the supply current after compensation. The LCL filter design is critical and could explain its limited use on the existing filtering systems on the market.

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