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Investigation of the line-reactor influence on the active power filter and hybrid active power filter efficiency: practical approach

***Abstract**. The shunt active power filter (SAPF) and hybrid active power filter (HAPF) efficiency does not only depends on their designed control system, but also on the parameters of the electrical system in which they are connected. In the electrical system for instance with diode or thyristor rectifier loads, the operating efficiency of the shunt active power filter may not be satisfied at the commutation times, when the rate of current change (di / dt) is high. In the topology of HAPF where the active and passive filters are connected in parallel, the passive filter efficient may depend on the grid parameters. Therefore, the efficiency of such filters can be in certain cases improved by connecting an additional line-reactor in the electrical system. This paper presents an investigation on the influence of the additional line-reactor on the SAPF and HAPF efficiency. The investigation is based on laboratory experiments.*

***Streszczenie.** Wydajność filtru aktywnego i hybrydowego zależy nie tylko od zaprojektowanego układu sterowania, ale także od parametrów obwodu elektrycznego, do którego są one podłączone. W układzie elektrycznym obciążonym na przykład prostownikiem diodowym lub tyrystorowym, efektywność pracy równoległego filtru aktywnego może nie być satysfakcjonująca w chwilach komutacji, gdy szybkość zmian prądu (di / dt) jest wysoka. W topologii HAPF, gdzie filtr aktywny i pasywny są połączone równolegle, skuteczność filtru pasywnego może także zależeć od parametrów sieci. W związku z tym, wydajność takich filtrów można, w niektórych przypadkach, poprawić przez dodatkowy dławik liniowy w obwodzie elektrycznym, do którego podłączone są filtry. W niniejszej pracy przedstawiono badania wpływu dodatkowego dławika liniowego na wydajność filtru aktywnego i hybrydowego, które opierają się na eksperymentach laboratoryjnych. (**Badanie wpływu dodatkowego dławika liniowego na efektywność pracy filtru aktywnego i hybrydowego: podejście praktyczne**).*

Keywords: shunt active power filter, hybrid active power filter, current commutation ripples, voltage and current distortion
Słowa kluczowe: równoległy filtr aktywny, hybrydowy filtr aktywny, komutacyjne tętnienia prądu, odkształcenie napięcia i prądu

Introduction

In the past few years, the increase of non-linear devices has become a serious problem for the electrical system because of the production of reactive power and disturbances such as harmonics, voltage fluctuation, asymmetry, etc. The harmonics generated by such of devices can cause in the electrical system the overloading, overheating, malfunction and even damage of its elements (e.g. cables, transformers etc.) and loads connected [1, 2]. To maintain the grid power quality in accordance with the standard, many devices are used to mitigate the quoted disturbances (e.g. passive harmonic filters (PHFs), active power filters, hybrid active power filters etc.) [3-9].

The PHFs in comparison to the SAPF and HAPF is less efficient in term of harmonics mitigation, even though they are low cost. The SAPF and HAPF are applied in the most cases to mitigate the fundamental harmonic reactive power as well as disturbances such as harmonics and asymmetry [10, 11].

The efficiency of SAPF and HAPF does not only depends on their designed control system, but also on the parameters of the electrical system in which they are connected. In the electrical system for instance with diode or thyristor rectifier loads, the efficiency of SAPF (with input line-reactor) can be affected by the fact that in the control system, the compensating current (from the feedback loop) is not able to track the reference current (mostly) at the points of commutation notches because of the high rate of reference current change. This problem can be solved by designing more complex control system [12-15]. But this paper proposes the solution of using at the rectifier load input, a line-reactor with inductance equal or higher than the one used at the SAPF input. The proposed solution can be used to avoid the design of a complex control system.

The main advantage of applying the topology of HAPF where the SAPF and passive harmonic filters (PHF) are connected in parallel, is to reduce the SAPF power rate which is higher when it is operating without the PHF [16-18]. But in that topology, the parallel resonance between the PHF and the grid inductance still exist and the PHF efficient may still depend on the electrical grid parameters (for instance when the impedance of harmonics to be eliminated, at the grid side is smaller than at the PHF side).

This paper presents an investigation on the influence of the additional line-reactor on the SAPF and HAPF efficiency. Three cases of study are considered: the first on presents the influence of the rectifier input line-reactor on the SAPF efficiency, the second on presents the influence of the grid side line-reactor on the SAPF efficiency and third one is about the HAPF efficiency when the additional line-reactor is connected between the SAPF and the PHF and when it is connected at the grid side. The investigations are based on laboratory experiments.

Laboratory model description

The laboratory set up together with its equivalent circuit are presented respectively in Fig.1 and Fig.2. During the laboratory studies, the smart meter “PQ-BOX 200” have been used for measurements. The equivalent parameters of the electrical grid in Fig.2 show that the grid equivalent inductance is very small. The electrical grid voltage waveform and its spectrum measured in the laboratory at the PCC (point of common coupling) before the load and filters connection are presented in Fig.3.

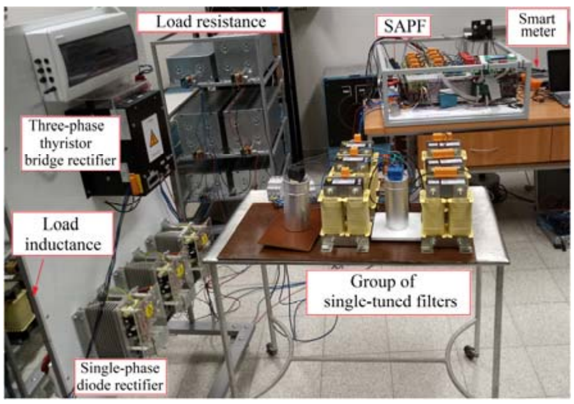

Fig.1. Laboratory set up

The load is composed of three-phase thyristor rectifier with resistance and reactor at its DC side and of single-phase diode rectifier with 24 Ω resistance at the DC side. The single-phase diode rectifier, connected between phase and neutral, is used to obtain the current asymmetry. At the rectifiers input there is a line-reactor L_T.

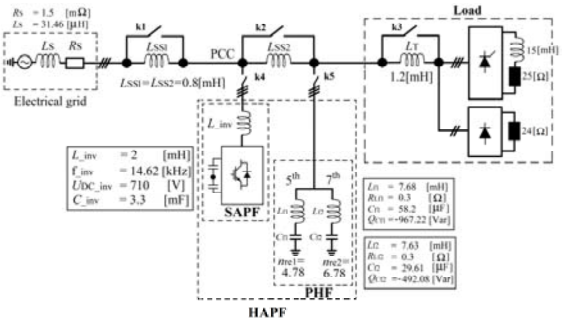

Fig.2. Equivalent circuit of the laboratory set up

The SAPF used to perform the laboratory studies is three legs four wires structure with reactor $L_{\_inv}$ at its input (Fig.2). The input reactor value 2 mH has been chosen for a better switching ripples filtration and better respond of the feedback signal in the control system. The control system is based on the instantaneous p-q theory algorithm [10] and PWM control method. In the control loop where the inverter output current $I_{\_inv}$ is compared to the reference current, the conventional PI controller is used. The SAPF switching frequency 14.63 kHz has been chosen basing on the transistor losses and control system hardware conditions.

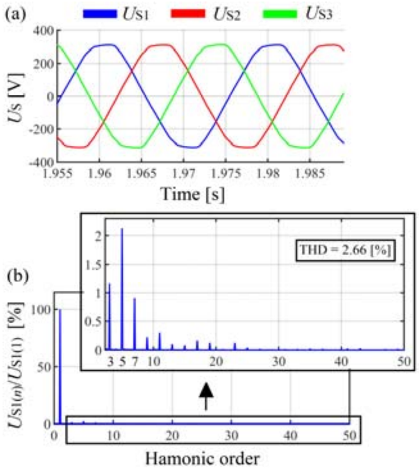

Fig.3. Electrical grid voltage waveform (a) and its spectrum (b), measured in the laboratory before the load and filters connection on

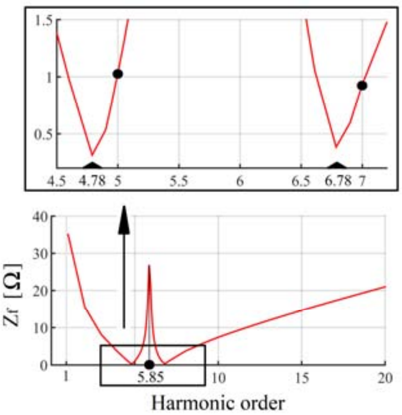

Fig.4. PHF group impedance versus frequency characteristic measured in the laboratory

In the PHF group, the first single-tuned filter is tuned to the frequency of 239 Hz (n_{re1} = 4.78) (which is at 95.6 % near the 5th harmonic frequency) and the second one is tuned to the frequency of 339 Hz (n_{re2} = 6.78) (which is at 96.85 % near the 7th harmonic frequency). n_{re} is the harmonic order of the PHF resonance frequency. The PHF group impedance versus frequency characteristic measured in the laboratory is presented in Fig.4.

The PHF group and SAPF when connected together formed the HAPF (Fig.2). In that HAPF topology, the goal of the PHF group is to mitigate the 5th, 7th and higher harmonics and to compensate the fundamental harmonic reactive power (which reduces the current level of SAPF). The SAPF goal is to filter the remaining harmonics, compensate the remaining reactive power and mitigate the current asymmetry. In such of HAPF configuration, the SAPF demand less power for it good functionality than when it is operating alone.

The value of the line-reactors (L_{SS1} = L_{SS2} = 0.8 mH) has been chosen in such a way to decrease the electrical grid short-circuit power therefore increasing the grid inductance (see Table 1 with comments).

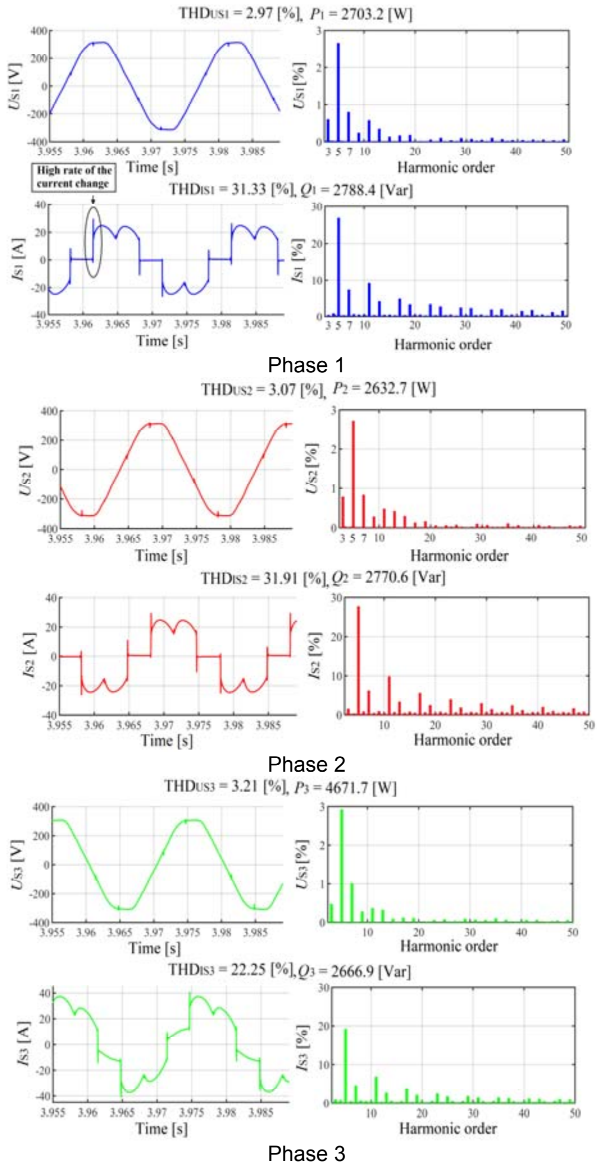

Fig.5. Measured grid voltage and current waveforms with spectrums before the SAPF connection (k3 closed)

Influence of the rectifiers input line-reactor L_T on the SAPF performance

Table 1. The 5[th] and 7[th] harmonics impedances of the PHF group ($Z_{PHF(5)}$ and $Z_{PHF(7)}$) are compared to those estimated from the electrical grid without ($Z_{S(5)}$ and $Z_{S(7)}$) and with ($Z_{SS(5)}$ and $Z_{SS(7)}$) the line-reactor L_{SS1} (no filters and no load are connected at the PCC, k2– closed – Fig.2).

[Ω]	Electrical grid without additional line-reactor L_{SS1} (k1– closed)	Electrical grid with additional line-reactor L_{SS1} (k1 – opened)	PHF
$Z_{S(5)}$	0.049	-	-
$Z_{S(7)}$	0.069	-	-
$Z_{SS(5)}$	-	1.30	-
$Z_{SS(7)}$	-	1.82	-
$Z_{PHF(5)}$	-	-	1.03
$Z_{PHF(7)}$	-	-	1.25
The grid without considering the line-reactor L_{SS1} Presents lower impedance of the 5[th] and 7[th] harmonics than the PHF group.			

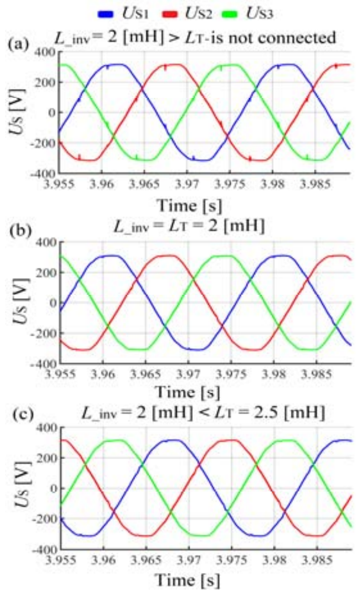

Fig.6. Comparison of grid voltage (U_S) waveforms: (a) $L_{\_inv} > L_T$ (not connected), (b) $L_T = L_{\_inv}$ and (c) $L_T > L_{\_inv}$

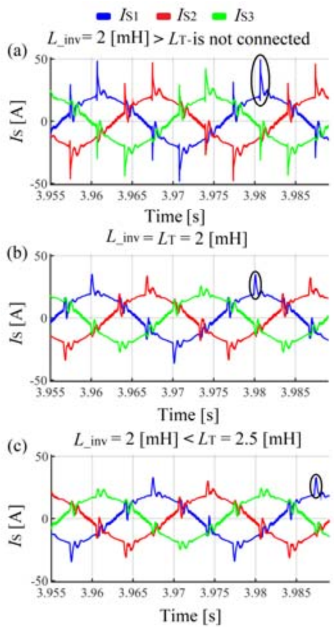

Fig.7. Comparison of grid current (I_S) waveforms: (a) $L_{\_inv} > L_T$ – (not connected), (b) $L_T = L_{\_inv}$ and (c) $L_T > L_{\_inv}$

In this case study, only the SAPF is considered. The connectors k1, k2, and k4 are closed and the connector k5 is opened (see Fig.2.). The influence of the rectifiers input line-reactor L_T (Fig.2.) on the SAPF efficiency is investigated.

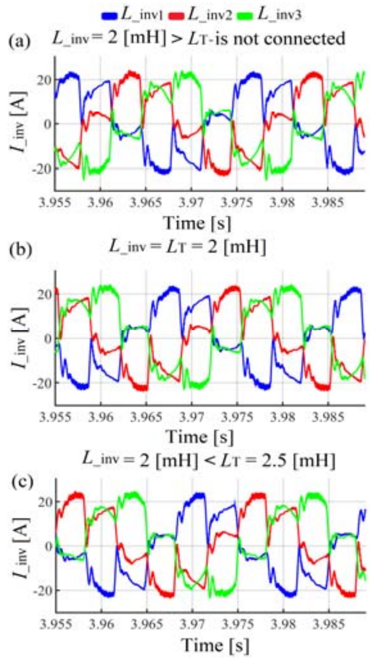

Fig.8. Comparison of SAPF input current ($I_{\_inv}$) waveforms: (a) $L_{\_inv} > L_T$ – (not connected), (b) $L_T = L_{\_inv}$ and (c) $L_T > L_{\_inv}$

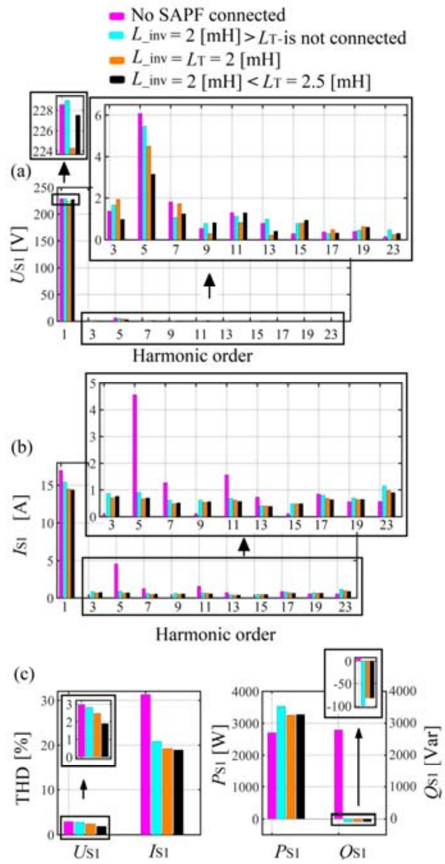

Fig.9. Comparison of: (a) PCC voltage spectrums, (b) PCC current spectrums and (c) PCC voltage and current THDs, active (P_1) and reactive powers (Q_1) (one-phase)

The laboratory results (PCC) obtained when the inverter reactor ($L_{\_inv}$) is bigger than the rectifiers input line-reactor ($L_{\_inv}$ = 2 mH > L_T – k3 closed) are compared to those when the inverter reactor is equal to the rectifiers input line-reactor ($L_{\_inv}$ = L_T = 2 mH – k3 opened) and to those when the inverter reactor is smaller than the rectifiers input line-reactor ($L_{\_inv}$ = 2 mH < L_T = 2.5 mH - k3 opened) (see Fig.6 to 9).

The PCC voltage and current waveforms and spectrums before the SAPF connection are presented in Fig.5. It can be observed: the current asymmetry, the voltage and current distortion as well as high level of fundamental harmonic reactive power.

Fig.6.(a) in comparison to Fig.6(b)(c) shows that when the inverter input reactor is equal or smaller than the rectifier input line-reactor L_T, the PCC voltage waveforms commutation notches are better reduced.

In Fig.7(b)(c), it can be seen that with the inverter input reactor inductance equal or smaller than the rectifiers input line-reactor, the grid current waveforms ripples (commutation ripples) at the high rate of current change (see also the current of Fig.5 – phase1) are better reduced by the SAPF. The inverter input current is presented in Fig.8.

Fig.9 presents a comparison of PCC voltage and current spectrums and THD as well as the PCC fundamental active and reactive powers. Only one-phase is considered since the PCC current is balanced after the SAPF connection. For $L_{\_inv}$ equal or smaller than L_T, the PCC voltage and current 5^{th} harmonic as well as THD are better mitigated (Fig.9 (a) to (c)). It is important to notice that the PCC voltage (without any load connected see Fig.3.) contains harmonics which can affect the results at the grid side after the filter connection (e.g. the 7^{th} harmonic in the grid voltage spectrum (Fig.9(a)) behaves differently from the 7^{th} harmonic in the grid current spectrum (Fig.9(b))).

Influence of the grid side line-reactor L_{SS1} on the SAPF performance

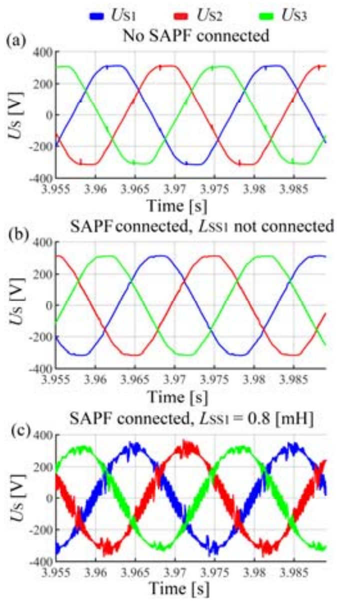

Fig.10. Comparison of PCC voltage waveforms when: (a) the SAPF is not connected, (b) the SAPF is connected but the line-reactor L_{SS1} is disconnected and (c) the SAPF is connected as well as the line-reactor L_{SS1}

The goal of these studies is to present what would happened if the SAPF together with the load were connected to the PCC through or without an additional line-reactor (e.g. L_{SS1} – see Fig.2.). In this case study, the connectors k2 and k4 are closed and the connectors k3 (L_T = 2.5 mH) and k5 are opened (see Fig.2.).

The laboratory results (PCC), obtained when the SAPF is not connected in the power system are compared to those when it is connected with L_{SS1} disconnected (k1 close) and to those when it is connected with L_{SS1} connected (k1 opened) (see Fig.10 to 12).

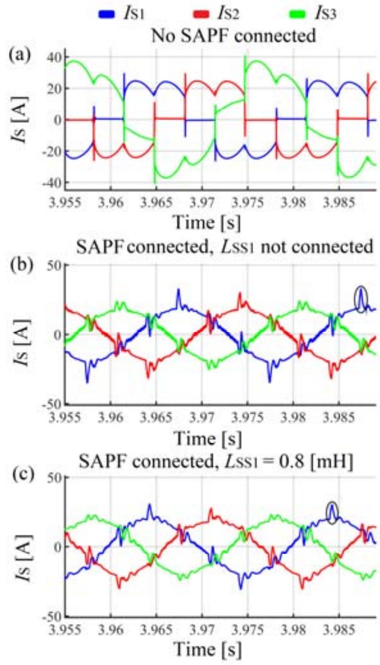

Fig.11. Comparison of PCC current waveforms when: (a) the SAPF is not connected, (b) the SAPF is connected but the line-reactor L_{SS1} is not connected and (c) the SAPF is connected as well as the line-reactor L_{SS1}

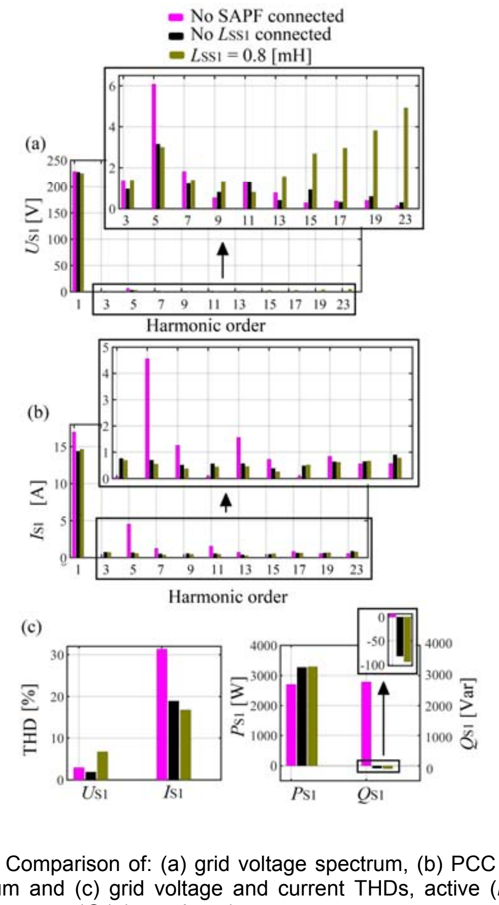

Fig.12. Comparison of: (a) grid voltage spectrum, (b) PCC current spectrum and (c) grid voltage and current THDs, active (P_1) and reactive power (Q_1) (one-phase)

On the one hand, the increase of the grid inductance (decrease of the grid short-circuit power) by adding the line-reactor L_{SS1} has improved the PCC current waveform (better reduction of ripples at the commutation points (Fig.11(c)) as well as the 5^{th}, 7^{th} and 11^{th} harmonic amplitudes (Fig.12(b) and the THD (Fig.12(c)). On the other hand, it has made the grid voltage more distorted by increasing the higher harmonic amplitudes from the 13^{th} (Fig.12(a)) as well as the THD (Fig.12(c)). In comparison to Fig.10(a)(b), the grid voltage waveform in Fig.10(c) is more distorted by switching ripples since the additional line-reactor L_{SS1} is considered. The PCC fundamental harmonic active and reactive power are presented in Fig.12(c).

Influence of the line-reactors L_{SS1} and L_{SS2} on the HAPF performance

In this case study, the connector k3 is opened (L_T = 1.2 mH). The laboratory results (PCC), obtained when the line-reactor L_{SS2} is connected between the SAPF and PHF (k1 - closed) are compared to those obtained when the HAPF (k2 – closed) is connected to the electrical grid through the line-reactor L_{SS1} (k1 - opened) (see Fig.13 and Fig.15 to 17).

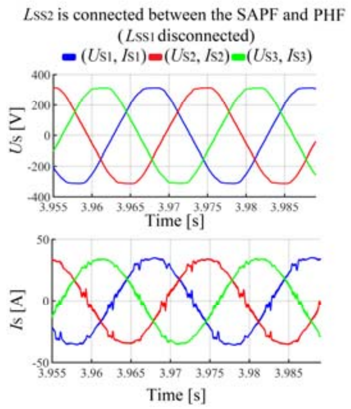

Fig.13. Voltage and current waveforms when the line-reactor L_{SS2} is connected between the SAPF and PHF (k1 closed and k2 opened – see Fig.2.)

The PCC voltage and current waveforms and spectrums measured when the HAPF was not connected are presented in Fig.14. Comparing the grid current and voltage THDs in Fig.14 to those in Fig.5, it can be noticed that in Fig.14, the grid voltage and current are less distorted. Because the rectifiers input line-reactor L_T, used in the case of Fig.14 (k3 – opened, k1 and k2- closed, Fig.2), is not used in the case of Fig.5. The rectifiers input line-reactor L_T plays also the role of harmonics filter as well as short-circuit current mitigation during the commutation between for instance thyristors rectifier in the electrical system.

In the case where the line-reactor L_{SS2} is connected between the SAPF and PHF (k1 - closed), the PCC current and voltage waveforms are less distorted (comparing Fig.13 to Fig.15). The connection of the HAPF (k2 - closed) to the grid through the line-reactor L_{SS1} (k1 - opened) presents the worst results in term of harmonics mitigation (Fig.16(a)(b) and Fig.17(a)) and fundamental harmonic reactive power compensation (Fig.17(b)). The PCC voltage and current are more distorted because of the additional voltage drops on the line-reactor L_{SS1} (Fig.16(a)(b)).

Connected between SAPF and the PHF group (case where the HAPF is connected directly to the grid without L_{SS1}), the line-reactor L_{SS2} has helped, on the one hand the group of PHFs to mitigate the 5^{th} and 7^{th} current harmonics. It has increased the grid equivalent impedance of the 5^{th} and 7^{th} harmonic forcing these harmonics to flow through the PHF group (see Table 1). On the other hand, it has helped the SAPF to better mitigate the ripples at the commutation points of grid current waveforms. Since with its co-nnection, the input rectifies inductance is increased ($L_T > L_{\_inv}$).

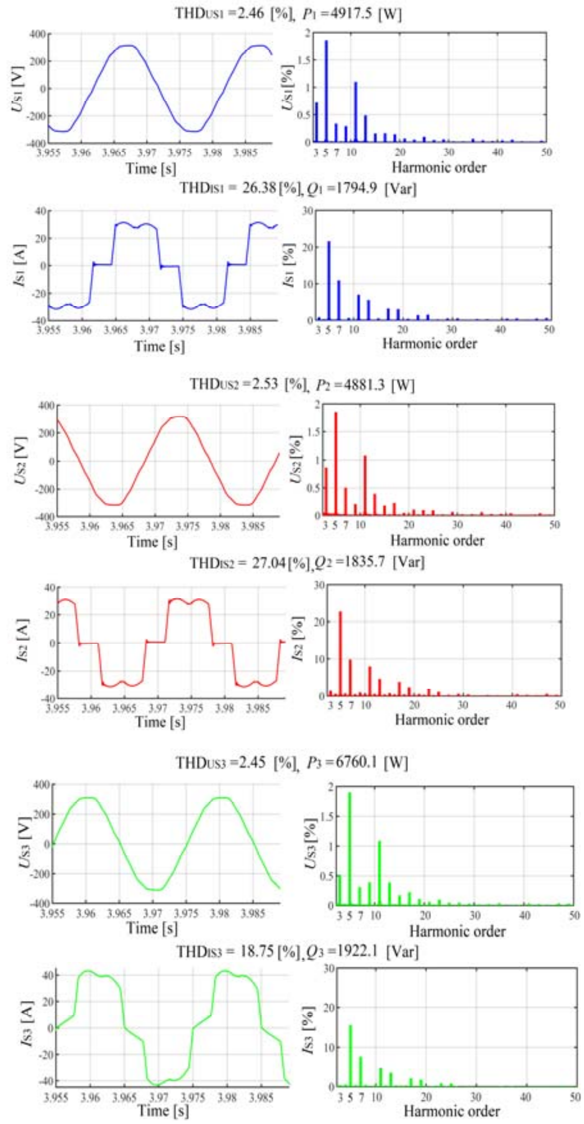

Fig.14. Measured grid voltage and current waveforms with spectrums before the HAPF connection (k3 - opened, k1 and k2- closed)

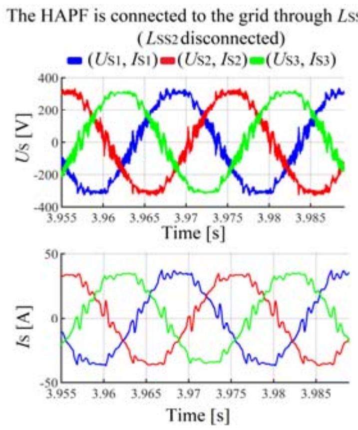

Fig.15. Voltage and current waveforms when the HAPF is connected to the grid through L_{SS1} (k1 opened and k2 closed - see Fig.2.)

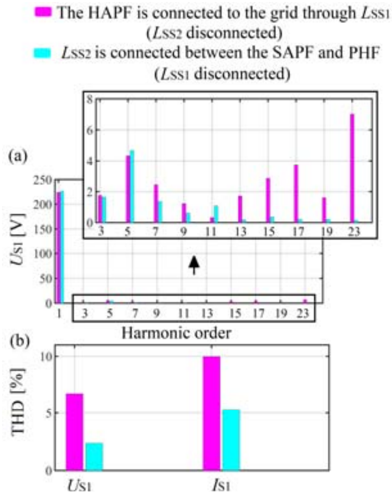

Fig.16. Fig.16. PCC voltage spectrum (a); grid voltage and current THD (b)

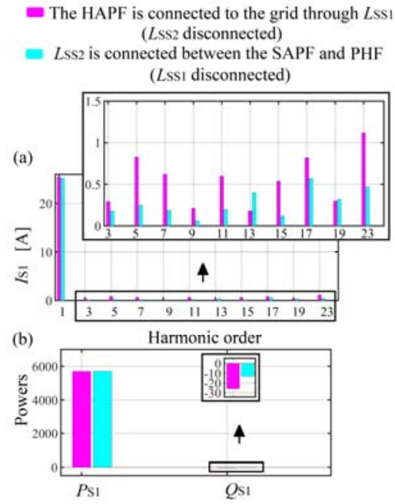

Fig.17. Grid current spectrum (a); PCC fundamental harmonic active and reactive powers (b)

Conclusion

The laboratory investigations presented in this paper have shown that the choice of the SAPF input reactor parameters should also depends on the rectifier input line-reactor parameters. In this case example, it has been demonstrated that the gird side voltage and current are better filtered when SAPF input reactor is equal or smaller than the rectifier input line-reactor.

The investigated topology of HAPF has shown that the connection of line-reactor between the SAPF and the PHF can be an advantage since it can increase the PHF and SAPF efficiency. When the SAPF (with input reactor (*L*-filter)) or the HAPF (investigated model) is connected at the PCC, the connection of an additional line-reactor between the PCC and the grid is not recommendable because the PCC voltage will be more distorted with inverter switching ripples.

The further researches will be about the investigation of the line-reactor influence on the SAPF and HAPF (active and passive filter connected in series) efficiency in the electrical system with more complex loads.

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