ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering
Tome XX [2022] | Fascicule 3 [August]

[1.] Ion VONCILĂ, [1.] Elena SELIM, [1.] Ion PARASCHIV

RESEARCH ON ADAPTING CAPACITY OF THE SHUNT ACTIVE POWER FILTERS TO NON–LINEAR LOAD REQUIREMENTS

[1.] "Dunărea de Jos" University of Galați, ROMANIA

Abstract: This paper presents the results obtained within the project CRESC–INTEL regarding modeling, simulation, and design of active power filters (APFs), shunt type, for imposed control strategies. The main purpose of this study is to present, through modeling and simulation, the conditions that must be fulfilled for a certain control strategy by the APF component subassemblies, in order to obtain a high flexibility and dynamic adaptability at the requirements demanded by the non–linear load. To view the adaptability of the shunt APF, in this research it was used the method of instantaneous powers for control and the simulations were performed in PSIM, for single non–linear loads, but also for combined (multiple) non–linear loads. Identification of the conditions under which a proper operation of the APF, shunt type, can be obtained at non–linear load development or modification of its operation regime, was imposed by the laboratory testing process of several APFs that have implemented different control strategies, for given power supply, respectively given non–linear load. The testing required the adoption of similarity criteria and the visualization, a priori, on the virtual simulator, of the optimal conditions in which an efficient and qualitatively proper operation of the APFs, shunt type, can be obtained.
Keywords: active power filters, modeling of shunt active filters, optimal operation conditions, shunt active power filters

1. INTRODUCTION

Active power filters (APFs) are used, on a high scale, to attenuate the distortion regime in electrical networks. In principle, depending on the considered criteria in increasing the electricity quality circulated in the energy system, both active power filters – series type [2], [10] and active power filters – shunt type [3] can be used, [4], [5], [8]. To obtain performant APFs, the specific topology to each filter has a great importance but also the specific control strategy.

It is worth mentioning in this context that, in the project "Knowledge transfer regarding increasement of energy efficiency and intelligent power systems (CRESC–INTEL)" has been developed topologies especially for APFs, shunt type, and the variation has been accomplished through implementation of a control strategy typical for each prototype that was made.

The control strategies implemented by the project partners are specified in Table 1.

Table 1: The control strategies and the companies that implemented them in each prototype made

Control strategy of the shunt APF		The partner company that carried out the implementation
Developed on Instantaneous Power Theory (PQ)		SC Smartech Automation SRL
Developed on D–Q Synchronous Algorithm		SC Uniel Serv SRL
Developed on Principle of Maximum (MAX)		ICPE ACTEL SA
Developed on Indirect Control Principle (CI)		ELECTRO–TOTAL SRL
Developed on Principle of current synchronization with the positive voltage sequence component (POS–SEC)		SC Electrosistem SRL
Developed on the method of separating polluting components	Band pass filter – BPF	SPIRU ELECTRA SRL
	Low pass filter –LPF	DOCEROM SISTEM S.R.L.

One of the special problems encountered after prototypes realization, was the verification of the proper functioning of each power filter (with the specific control strategy implemented), for the given non–linear load. For the protection of each prototype made and human operators involved in the process also, the laboratory tests required the adoption of similarity criteria and staged testing, for various values of the quantities delivered by the special power supply used.

Subsequently, tests were performed under the conditions of keeping constant the quantities delivered by the power supply (given power supply) and changing the non–linear load.

The secondary goal pursued in these testing processes, was to find, from entire measurement chain, the conditions that must be met to demonstrate the ability of each APF to adapt to the requirements of non–linear load. To highlight the quality of the filtering process, and, implicitly, the continuous adaptation of the APF at the requirements of non–linear load, several indicators were used, of which two were more strongly highlighted: total harmonic distortion factor (*THD*), respectively fractal dimension of current supplied by filter [9]. In this paper, the efficiency of the active filtering process will be valued with total harmonic current distortion factor (*THDi*), due to the specificity of the shunt APF.

The a priori visualization of the APF behavior (shunt type) at the variation of either the measurements of the power supply for a given non–linear load, or of the non–linear load for a given source, can be done only on the virtual simulator. Moreover, the virtual simulator allows combinations that must then be put into practice very carefully.

In this article, to strengthen the ideas, was used the simulation in various conditions, of an APF, shunt type, in the PSIM environment, for a given control strategy (which is, in principle, a reference for the various control strategies used, on a large scale, at present). The agreed control strategy is the one developed on Instantaneous Power Theory (PQ) [1], [6], [7]. Through comparative analysis, the following are presented the results of the simulation performed in PSIM and, at the same time, is highlighted the primary condition that must be complied in the measurement/ filtering chain to obtain a special flexibility and an adaptability of the shunt APF, to the requirements of the non–linear load.

2. SHUNT APF MODELING FOR ADAPTABILITY IDENTIFICATION AT NON–LINEAR LOAD REQUIREMENTS

On purpose to highlight this continuous ability of APF to adapt at the non–linear load requirements, two approaches were adopted in the paper, which were then employed during the simulation process: changing the value of unique non–linear load, respectively, changing parameters in the case of a combined load that involves controllable semiconductor devices (IGBTs) also. For each of these tasks, the efficiency of the filtering process was continuously monitored by identifying the key parameters responsible for achieving these filtering qualities.

In Figures 1 and 2 are presented the schematic diagrams in PSIM, for the two cases presented above. It should be noted that simulations were performed separately both for the case of non–linear load involving an uncontrolled rectifier and for the case of non–linear load involving an inverter with IGBTs. Subsequently, the case of reuniting the two types of loads, as shown in Figure 2, was also analyzed.

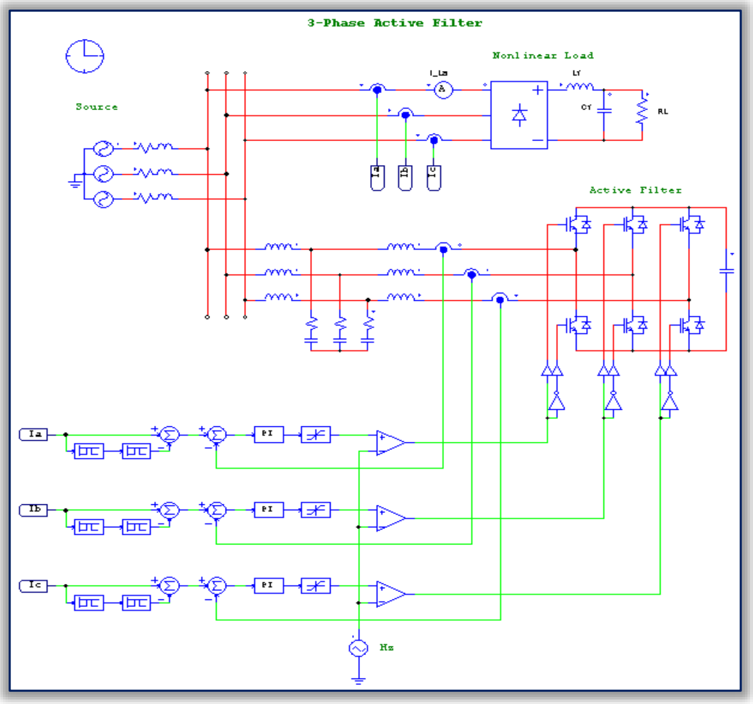


Figure 1. Schematic diagram in PSIM for shunt APF. Unique non–linear load case

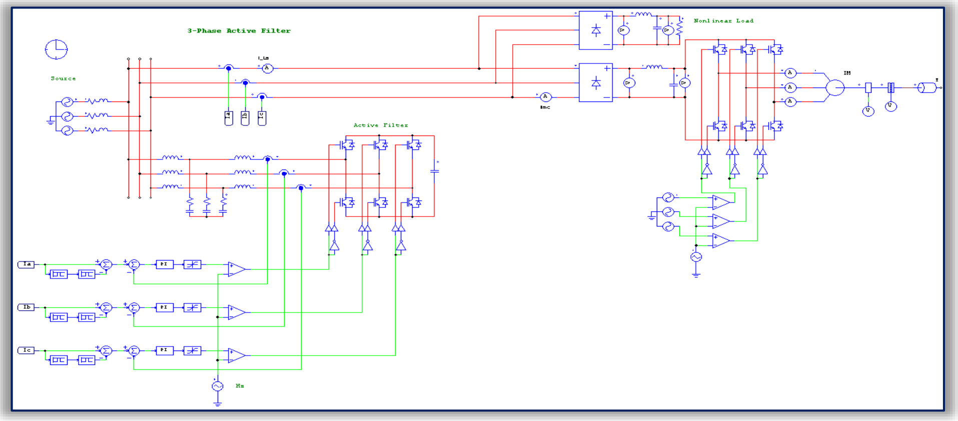


Figure 2. Schematic diagram in PSIM for shunt APF. Combined non–linear load case (additional – controlled semiconductor devices)

3. RESULTS OBTAINED. DISCUSSIONS

A. Unique non–linear load case

First of all, it was studied the behavior of shunt APF, to the development of non–linear load without controllable devices (Figure 1), with the aim of obtaining a total harmonic current distortion factor (*THDi*) as close as possible to the limit values indicated by standards. On this occasion, was identified the key parameter, which allows obtaining an adequate quality index of the current carried by the power supply, respectively, maintaining an adequate gap between the source voltage (maximum value) and the capacitor charging voltage on the inverter of shunt APF. In principle, the maximum value of the source voltage must always be lower than the voltage level at the capacitor terminals located on the APF.

Figures 3–6 show several results obtained in this case. For the reference, the value of load resistance – resistance supplied through three–phase diode bridge rectifier (not controlled) is R_L = 0,5 Ω. Under normal operating conditions of APF, according to Figure 3, total harmonic current distortion factors (THD_i), have following values: for the load current – $(THD_i)_L$ = 25,64 %; for the power supply current – $(THD_i)_S$ = 3,64 %. Must be point out that these normal operating conditions are characterized by a voltage on the APF capacitor, U_{dc} = 600 V, while the maximum voltage of the power supply is U_{max} = 155 V. The voltage difference for the reference case is $\Delta U = U_{dc} - U_{max}$ = 445 V.

In Figure 4 it is simulated the case when the voltage at the capacitor terminals on the APF, is only slightly higher than the maximum value of the voltage supplied by the source, respectively, U_{dc} = 175 V. In this case, the voltage difference is $\Delta U = U_{dc} - U_{max}$ = 20 V. Therefore, the total harmonic current distortion factors (THD_i) have following values: for the load current – $(THD_i)_L$ = 20,01 %; for the power supply current – $(THD_i)_S$ = 10,44 %.

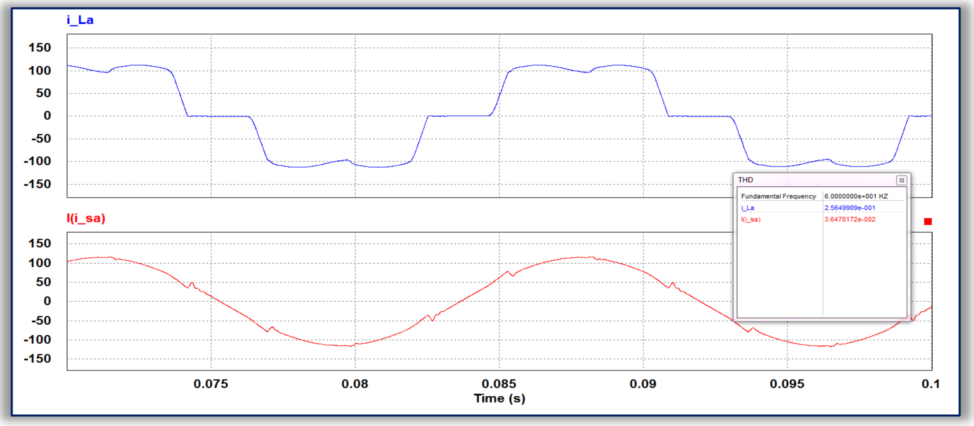


Figure 3. Time variation of load current (up), respectively power supply current (down) in the case of unique non–linear load – reference

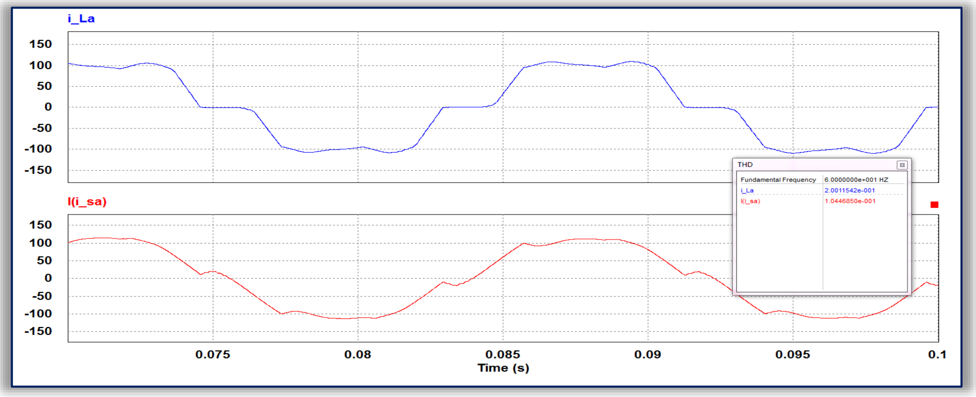


Figure 4. Time variation of load current (up), respectively power supply current (down) in the case of unique non–linear load – voltage difference ΔU = 20V

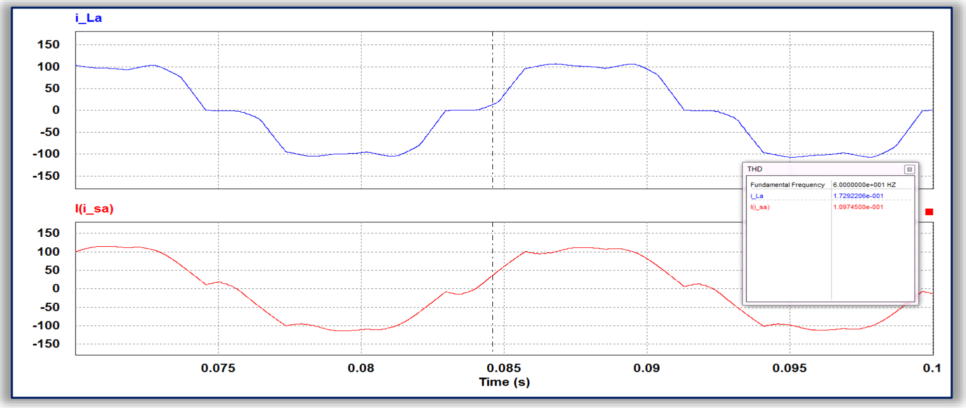
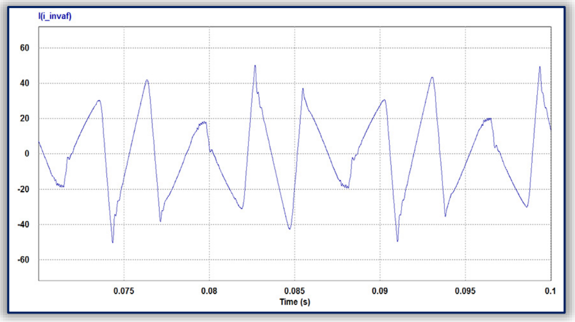


Figure 5. Time variation of load current (up) respectively, power supply current (down) for unique non–linear load – voltage difference ΔU = – 20 V

Figure 5 presents the results of simulation for the case when the voltage at the capacitor terminals on the APF, is only slighter smaller than the maximum value of power supply voltage, respectively U_{dc} = 135 V. In this case, the voltage difference is $\Delta U = U_{dc} - U_{max} = -20$ V. Then, the total harmonic current distortion factors (THD_i) have following values: for the load current – $(THDi)_L$ = 17,29 %; for the power supply current – $(THDi)_S$ = 10,97 %.

As per Figure 6, the APF works in each analyzed cases, but the quality of the filtering process, as indicated by the total harmonic distortion factors, is severely affected (being practically the weakest, if the voltage at the capacitor terminals is lower than the maximum value of the voltage delivered by the power supply).



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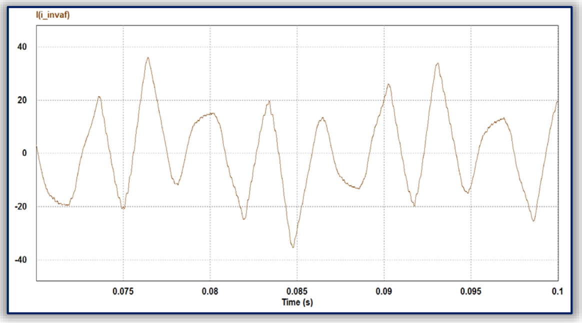

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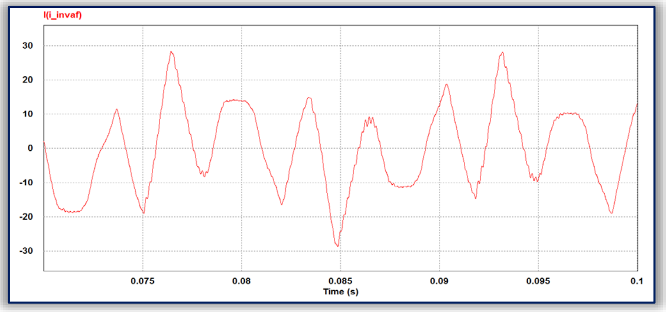


c)

Figure 6. Current variation delivered by APF in all 3 analyzed cases for unique non–linear load:
a) The reference value; b) voltage difference ΔU = 20 V; c) voltage difference ΔU = – 20 V

Table 1 – Comparative analysis of the ability of APF to adapt to the non–linear load requirements – the case of unique load

	R_L = 0,5Ω	R_L = 5Ω
	THD_i – reference	THD_i – reference
$(THD_i)_L$	25,64 %	81,48 %
$(THD_i)_S$	3,64 %	6,70 %
	THD_i – voltage difference ΔU = 20 V	THD_i – voltage difference ΔU = 20 V
$(THD_i)_L$	20,01 %	47,99 %
$(THD_i)_S$	10,44 %	20,03 %
	THD_i – voltage difference ΔU = – 20 V	THD_i – voltage difference ΔU = – 20 V
$(THD_i)_L$	17,29 %	35,73 %
$(THD_i)_S$	10,97 %	18,99 %

It was analyzed the ability of the shunt APF to adapt to the development of non–linear load (by increasing 10 times the load resistance values). The results of the comparative analysis, as regards the quality of the filtering process visualized by the total harmonic current distortion factor, $(THDi)$, are presented in Table 1.

Basically, when developing the load, the APF demonstrates flexibility/ adaptation to the requirements of the non–linear load, but the quality of the filtration process is not true even in the chosen reference case (the value of the quality indicator, *THDi*, is outside the recommended limits of the standards). It is noted that, the smallest total harmonic distortion factor, current, for R_L = 5Ω, was obtained for a value of U_{dc} = 1000 V at APF capacitor voltage, so, for a difference voltage of $\Delta U = U_{dc} - U_{max}$ = 845 V. In this case, $(THD_i)_S$ = 5,68 %.

B. Non–lineal combined load case

In this case, the problem is more complex, because in addition to the direct current (DC) load (the resistance supplied by the uncontrolled rectifier) it is also supplied an alternating current load (squirrel cage induction motor); due to these property, in the power diagram, steps in, a frequency converter that contains the three–phase uncontrolled rectifier but also an inverter with IGBTs (devices that are controlled by the basic current), Figure 2. The achieved results are presented in Figures 7–10.

Therefore, Figure 7 shows the results as regards not only the time variation of currents through the two types of loads (reunited in global non–linear combined load) but also the current from power supply in the case considered in terms of reference (the same as previous case). The voltage difference is certainly the same, respectively $\Delta U = U_{dc} - U_{max} = 445$ V, while the total harmonic current distortion factors, for the three viewed currents are: $(THDi)_{LDC} = 26{,}05$ %; $(THDi)_{LIM} = 14{,}55$ %; $(THDi)_S = 3{,}53$ %.

Figure 8 presents the obtained results when voltage difference is $\Delta U = U_{dc} - U_{max} = 20$ V (obtained in the same way as unique load case). This time, the quality indicators are: $(THDi)_{LDC} = 20{,}04$ %; $(THDi)_{LIM} = 205{,}10$ %; $(THDi)_S = 10{,}62$ %. Figure 9 approaches the negative voltage difference problem $\Delta U = U_{dc} - U_{max} = -20$ V, for combined non–linear load. The values of total harmonic current distortion factors, in this situation are: $(THD_i)_{LDC} = 17{,}45$ %; $(THD_i)_{LIM} = 102{,}79$ %; $(THD_i)_S = 11{,}11$ %.

Basically, the conclusions drawn are the same as for the unique non–linear load, in terms of the correlation between the voltage difference and the quality of the filtering process.

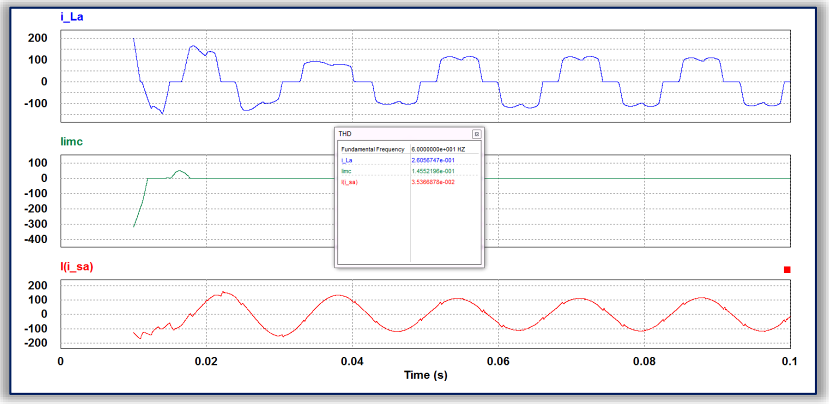


Figure 7. Time variation of load currents (up – first 2 positions), respectively, power supply current (bottom) for the case of the combined non–linear load – reference

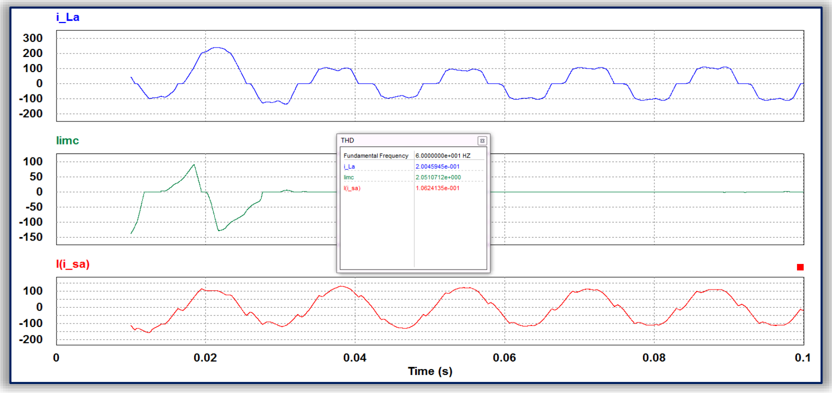


Figure 8. Time variation of load currents (up – first 2 positions), respectively, power supply current (bottom) for the case of the combined non–linear load – voltage difference $\Delta U = 20$ V

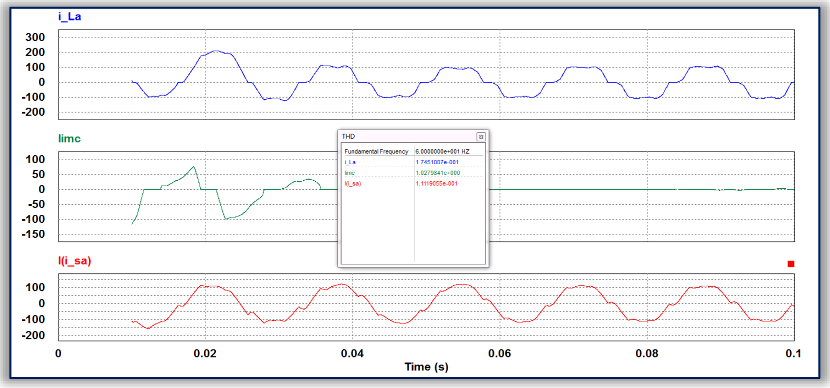
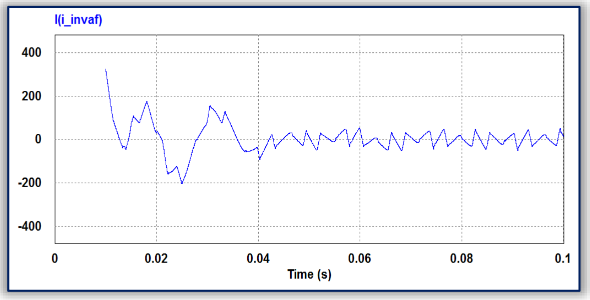


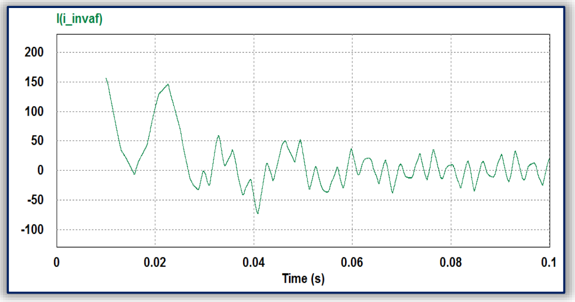
Figure 9. Time variation of load currents (up – first 2 positions), respectively, power supply current (bottom) for the case of the combined non–linear load – voltage difference $\Delta U = -20$ V

According to Figure 10, the APF works, again in all the analyzed cases, but the quality of the filtering process, as indicated by the total harmonic distortion factors, is strongly affected (being also the weakest, if the voltage at the capacitor terminals is less than the maximum value of the voltage supplied by the power supply).

It is worth noting that in the case of a relatively low DC load (R_{LDC} = 0,5 Ω), the character of the alternating current load is stronger at low voltages due to the inability of the squirrel cage induction motor to develop a suitable starting torque to allow the rotary shaft to be driven in rotational motion. When this is possible (reference case with U_{dc} = 600 V) and there is a corresponding speed at the shaft, due to the relatively high starting torque, the character of the AC load is less pronounced (Figure 7 and Table 2).



a)



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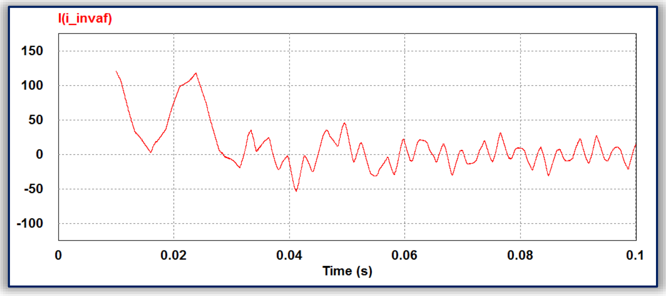

c)

Figure 10. Variation of current delivered by APF in the three cases analyzed for combined non–linear load:
a) reference; b) voltage difference ΔU = 20 V; c) voltage difference ΔU = – 20 V

The adaptability of APF, shunt type, to the development of non–linear load was analyzed in two ways:
- development of the DC load (by increasing 10 times the value of the load resistance);
- development of the alternative current (AC) load (by coupling a working machine to the shaft of the squirrel cage induction motor).

B1. Development of the DC load

The approach, in this case, was done only by changing the load resistance supplied by the three–phase uncontrolled rectifier and squirrel cage induction motor at no load operation. The results of the comparative analysis are summarized in Table 2.

Table 2 shows that, with the development of the DC load, a certain balance is obtained between it and the alternating current load, which is reflected in the values of the total harmonic distortion factors for the currents of the two load categories.

Table 2 – Comparative analysis of APF adaptability at combined non–linear load requirements in case of – by changing the parameters of the DC load

	R_{LDC} = 0,5 Ω and asynchronous motor at no load operation	R_{LDC} = 5 Ω and asynchronous motor at no load operation
	THD_i – reference	THD_i – reference
$(THD_i)_{LDC}$	26,05 %	49,92 %
$(THD_i)_{LIM}$	14,55 %	69,96 %
$(THD_i)_S$	3,53 %	4,70 %
	THD_i – voltage difference ΔU = 20 V	THD_i – voltage difference ΔU = 20 V
$(THD_i)_{LDC}$	20,04 %	35,24 %
$(THD_i)_{LIM}$	205,10 %	44,04 %
$(THD_i)_S$	10,62 %	12,46 %
	THD_i – voltage difference ΔU = – 20 V	THD_i – voltage difference ΔU = – 20 V
$(THD_i)_{LDC}$	17,45 %	29,80 %
$(THD_i)_{LIM}$	102,79 %	38,25 %
$(THD_i)_S$	11,11 %	16,46 %

B2. Development of AC load

The method chosen for the development of the alternating current load was the switching from no load operation of the squirrel cage induction motor to load operation. The results obtained, in this case, for maintaining the DC load at the reference value (R_{LDC} = 0,5 Ω), are presented in Table 3.

Table 3 – Comparative analysis of APF adaptability at combined non–linear load by modification of AC load

	R_{LDC} = 0,5 Ω and asynchronous motor at no load operation	R_{LDC} = 0,5 Ω and asynchronous motor at load operation (T_L = 0,5 Nm)
	THD_i – reference	THD_i – reference
$(THD_i)_{LDC}$	26,05 %	22,54 %
$(THD_i)_{LIM}$	14,55 %	180,94 %
$(THD_i)_S$	3,53 %	6,26 %
	THD_i – voltage difference ΔU = 20 V	THD_i – voltage difference ΔU = 20 V
$(THD_i)_{LDC}$	20,04 %	19,52 %
$(THD_i)_{LIM}$	205,10 %	183,20 %
$(THD_i)_S$	10,62 %	9,64 %
	THD_i – voltage difference ΔU = – 20 V	THD_i – voltage difference ΔU = – 20 V
$(THD_i)_{LDC}$	17,45 %	19,10 %
$(THD_i)_{LIM}$	102,79 %	181,68 %
$(THD_i)_S$	11,11 %	9,84 %

The following is important: although the voltage difference was kept the same as in A case, respectively B1, in order to ensure the starting torque of the three–phase asynchronous motor, it was necessary to increase the supply voltage and, proportionally, the APF capacitor voltage. Very important to mention that, in the case of combined non–linear loads, an additional correlation is needed between the amplitude of the power supply and the amplitude of the voltage at the APF capacitor (which requires the appropriate choice of both semiconductor devices on the APF inverter and of the equipment used for the connection to the common connection point (CCP) of the APF) along with complying the supplementary condition $U_{dc} > U_{max}$.

Starting from this idea, in this paper was analyzed, only for the case of DC load (Figure 1), the influence on the APF adaptability to the requirements of the non–linear load of the passive filter between the three–phase uncontrolled rectifier and the resistive load. Two cases were studied:

≡ modification of the passive filter inductance;

≡ modification of the passive filter capacity.

The reference values for the passive filter parameters are: L_f = 0,3 mH; C_f = 0,47 mF.

The acquired results are centralized in Table 4.

Table 4 – The influence of the passive filter on the APF adaptability to the requirements of non–linear load. The case of DC load

	R_{LDC} = 0,5 Ω				
	Reference – L_f, C_f are given	L_f – 10 times diminished	L_f – 10 times increased	C_f – 10 times diminished	C_f – 10 times increased
	THD_i – voltage reference				
$(THD_i)_{LDC}$	26,05 %	32,96 %	24,37 %	25,30 %	27,69 %
$(THD_i)_S$	3,53 %	6, 59 %	4,47 %	3,72 %	3, 68 %
	THD_i – voltage difference ΔU = 20 V				
$(THD_i)_{LDC}$	20,04 %	22,19 %	19,22 %	19,79 %	19,48 %
$(THD_i)_S$	10,62 %	11,36 %	9,53 %	10,27 %	10,26 %
	THD_i – voltage difference ΔU = – 20 V				
$(THD_i)_{LDC}$	17,45 %	18,25 %	17,03 %	17,22 %	16,63 %
$(THD_i)_S$	11,11 %	11,49 %	10,39 %	10,91 %	10,43 %

By comparative analyzing the values in Table 4, it can be concluded, first of all, there is a major influence of the passive filter, in the load circuit, on the quality of the active filtration process.

It appears the modification of the passive filter capacity (due, indeed, to the peculiarities of the non–linear load that contains a strong 5th order harmonic) has less influence on the adaptability and quality of the active filtering process than the modification of the passive filter inductance.

A special remark must be made if the condition $U_{dc} > U_{max}$ (ΔU = 20 V) is met, and the passive filter inductance increases 10 times compared to the reference when $(THD_i)_S$ = 9,53 %, a lower value than the chosen reference.

It is obviously that several elements of the chain designed to reduce the network deformation regime contribute to the ability of the APF to adapt to non–linear load requirements and the quality of the active filtering process: the capacity of the APF inverter, the APF connection subassemblies to the Common Connection Point (CCP) and even an additional passive filter placed in the non–linear load circuit. Ultimately, a good active filtering process depends on the set of parameters of all these elements.

4. CONCLUSIONS

The research undertaken regarding the adaptability of the APF, shunt type, at the non–linear load requirements, highlighted the following:

≡ The correct operation of the APF (which is reflected by a superior quality of the active filtering process) can only take place if the $U_{dc} > U_{max}$ condition is met (at any moment the voltage on the APF capacitor exceeds the maximum value of the power supply voltage);

- ≡ The existence even of a single non–linear DC load (load resistance supplied by an uncontrolled rectifier), allows, through its development, a significant deterioration of the quality of the active filtration process $((THD_i)_S$ increase strongly regardless of the play between U_{dc} and U_{max} voltage);
- ≡ In the case of combined (multiple) loads, the development, only, of the DC load, to the detriment of the alternating current load (asynchronous motor powered by frequency converter), allows to obtain a certain balance between it and the alternating current load, which is reflected in the values of the total harmonic distortion factors for the currents of the two load categories, regardless of the play between the voltage U_{dc} and U_{max});
- ≡ The development of alternating current load, by switching from no load operation to on load operation of asynchronous motor, powered by frequency converter, requires, due to the particularity of the chosen development solution, the change of both the power supply voltage level and the reference voltage level from the capacitor terminals on the APF, keeping the $U_{dc} > U_{max}$ condition and the same minimum voltage differences. The chosen development solution, for the alternating current load, allows a better adaptation of the APF to the increase of the load, which is reflected by the values $(THD_i)_S$;
- ≡ There is a strong influence on the quality of the active filtration process and other subassemblies in the chain designed to reduce the network distortion regime (subassembly used for PCC connection of APF, passive filter used both in the DC load circuit and in the intermediate circuit of frequency converter).

It should be mentioned that the research, whose results were presented in this present study, left open new avenues for new searches. Among the openings offered for the future, we can mention:

- ≡ Visualization of the particularities at the simultaneous development of loads, in case of combined non–linear loads, regarding the quality of the active filtering process;
- ≡ Visualization of the particularities regarding the adaptability of the APF, shunt type, to the development of the alternating current load by modifying the control strategy of the inverter with IGBTs in the structure of the frequency converter.

Indubitable, in the future, the research undertaken on the virtual simulator will have to be doubled by the validations on physical simulators, respectively, on the APFs carried out by the partners from the consortium set up for the implementation of the CRESC–INTEL project.

Acknowledgment

This study was presented in the project "Knowledge transfer regarding increasement of energy efficiency and intelligent power systems "(CRESC–INTEL), code SMIS 105803, project co–financed from European Funds for Regional Development through the Operational Program Competitiveness 2014–2020.

Note: This paper was presented at CNAE 2022 – XXth National Conference of Electric Drives, organized by University POLITEHNICA Timisoara, Faculty of Faculty of Electrotechnics and Electroenergetics (ROMANIA), in Timisoara, ROMANIA, in 12–13 May, 2022.

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