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Comparison of Current Control Strategies for Four-Leg Shunt Active Power Filter in Matlab-Simulink

Streszczenie. *W artykule przedstawiono porównanie trzech metod sterowania dwupoziomowym czterogałęziowym aktywnym filtrem mocy. Dwie z metod stanowią rozwiązania klasyczne, natomiast trzecia metoda proponowana jest, jako rozwiązaniem alternatywne. W pierwszej metodzie zastosowano teorię mocy chwilowych oraz regulatory histerezowe; druga metoda bazuje na regulatorach PI oraz modulacji PWM. Trzecia metoda to sterowanie predykcyjne wykorzystujące model o ograniczonej ilości stanów (FS-MPC). Porównanie dokonane zostało na podstawie symulacji w programie Matlab-Simulink.* ***Porównanie trzech metod sterowania dwupoziomowym czterogałęziowym aktywnym filtrem mocy***

Abstract*. This paper presents a comparison of three control strategies that were applied in the simulation model of a four-leg Shunt Active Power Filter based on two-level voltage-source converter. The research considered two classical methods and one proposed as an alternative. In the first an instantaneous power theory is used for the references calculation and hysteresis controllers for gates signals generation. The second employs PI controllers and PWM modulation. The third method is Model Predictive Control with a finite control-states set number (FS-MPC). The comparison is based on simulations performed in Matlab-simulink.*

Słowa kluczowe: predykcyjne, równoległy aktywny filtr mocy, czterogałęziowy APF, sterowanie, symulacje.
Keywords: predictive, Shunt Active Power Filter, four leg SAPF, control, simulation.

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Introduction

Fast growth of electrical energy consumption increases an importance of energy quality aspect. This is a high significance issue, while the correct operation of electrical devices is usually dictated by delivered electrical energy parameters. Modern grid-side transistor based converters are controlled with the algorithms which assures a required value of the current THD and reactive power. Here, three control methods for two-level four-leg Shunt Active Power Filter (SAPF) are presented and compared in simulation model.

The first method is based on instantaneous power theory which is used to calculate the reference currents for SAPF. Gate signals are generated by hysteresis controllers, which compare current references with measured values [1-6]. The second requires coordinates transformation from the natural do rotating *d-q* with fundamental 50Hz frequency. It employs linear current controllers (proportional-integral, PI) to calculate the SAPF reference voltage for a pulse-width modulator [1,7-9].

The third method belongs to the category of predictive control. It's generally based on the model of the controlled system, which is used for calculation of future values of state variables. Depending on the type of application and desired control properties different ways of using prediction can be chosen. In the case of SAPF a Model Predictive Control with a finite control states set (FS-MPC) [1,11-18] has been selected as the most suitable. For this method it is assumed that the system can represent a finite number of control states in every time period which is correct for power electronics devices. It also offers a very high operation dynamics what meets SAPF control requirement. FS-MPC features make it competitive to the aforementioned strategies.

The comparison of three control methods was performed in Matlab-Simulink. The subsequent sections of this paper give a system overview and introduce the three methods, showing the advantages and disadvantages of each of them. Next, the simulation results will be presented. Finally, according to the chosen criterions, the results comparison is performed, giving the conclusions in the last section.

Four-Leg Shunt Active Power Filter – System Overview

Figure 1 presents the system overview. Four-leg SAPF is connected to the Point of Common-Coupling (PCC) through a passive inductive filter. SAPF compensates distortions introduced by the nonlinear and asymmetrical load, which, for the purpose of this comparison is represented by three-arm 6-pulse diode-bridge with load and three-leg resistive-inductive load with the neutral point connected to the neutral line at PCC.

Instantaneous Power Theory Based Control With Hysteresis Controllers (P-Q Theory Based)

This type of SAPF control represents the classical approach to obtain the compensation of current harmonics, as well as the reactive power (see fig. 2). It requires load currents and grid voltages measurement. First, transformation to stationary coordinates is performed, using equation:

$$(1)\quad \begin{bmatrix} x_\alpha \\ x_\beta \\ x_0 \end{bmatrix} = \mathbf{C}\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}, \text{ where } \mathbf{C} = \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

and $\boldsymbol{x}$ is a vector of instantaneous values of grid voltage u_{PCC} or load current i_L.

Transformed vectors are used for load power calculation, which for three-phase grid with symmetrical voltages is expressed with:

$$(2)\quad \begin{bmatrix} p_L \\ q_L \end{bmatrix} = \begin{bmatrix} u_{PCC\alpha} & u_{PCC\beta} \\ -u_{PCC\beta} & u_{PCC\alpha} \end{bmatrix}\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix}$$

Next, a variable component P_{vr} of P_L is extracted with a high-pass filter [2]. Finally, including SAPF DC-capacitor voltage control with P_{dUdc} component, the expression for the reference currents is given as:

$$(3)\quad \begin{bmatrix} i_{Cref\alpha} \\ i_{Cref\beta} \end{bmatrix} = \frac{1}{u^2_{PCC\alpha} u^2_{PCC\beta}}\begin{bmatrix} u_{PCC\alpha} & -u_{PCC\beta} \\ u_{PCC\beta} & u_{PCC\alpha} \end{bmatrix}\begin{bmatrix} -p_{comp} \\ -q_{comp} \end{bmatrix}$$

, where $P_{comp}=P_{vr}-P_{dUdc}$. In case of asymmetrical load, the non-zero neutral wire current must be also compensated by SAPF. Its reference value is calculated using the Kirchoff's law, as a sum of the three phase currents.

Calculated reference currents are delivered to hysteresis controllers which compare them with the measured compensation currents. This way the gates signals are generated.

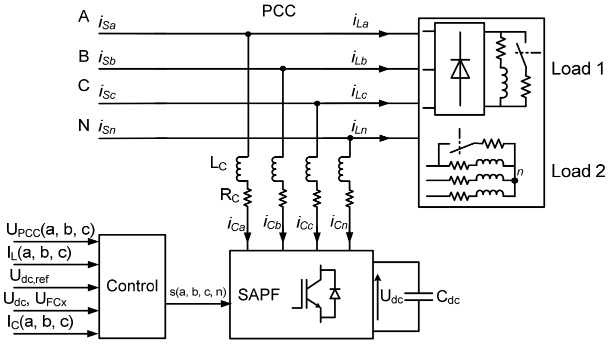

Fig. 1 General system overview

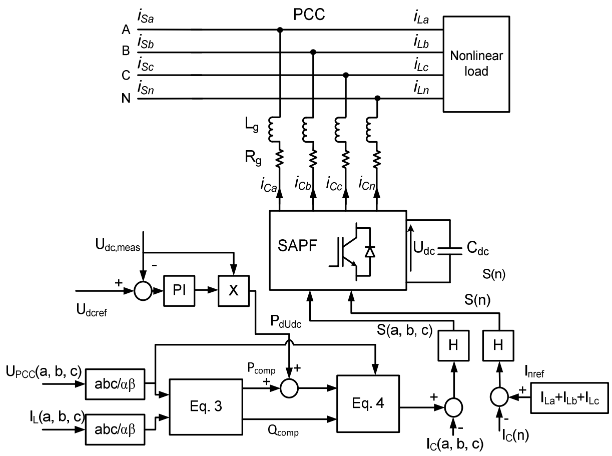

Fig. 2 Instantaneous power theory based control scheme for SAPF

This method gives a very simple solution for SAPF control. Thanks to the use of hysteresis controllers a high operation dynamics in transient states and very good reference tracking can be reached. The robustness is extremely high, what is a great advantage of this method. On the other hand, classical hysteresis controllers operate with a variable switching frequency, which is, in fact, a very important issue. Spectral analysis shows that a wide range of harmonic frequencies can be generated. As the main consequences, a problematic output filter design should be mentioned.

However, solutions for this problem have already been proposed. With a variable width of hysteresis band a fixed switching frequency can be achieved. The variation is dependent on the instantaneous output voltage and DC voltage, as described in [10]. It's realized with a phase-locked loop or a feed-forward loop.

Linear current controllers

Another classical approach represents the linear current control method. This solution is based on coordinates transformation and PI controllers. However, this method also brings several issues. The linear PI controllers have a limited bandwidth, what also brings limitation to the SAPF performance. It cannot reach a zero steady state error when operates on an alternate signal. A partial solution is to transform coordinates system from stationary to rotating [7-9]. This operation requires the grid voltage phase angle and low-pass filters for DC values extraction (fundamental frequency current becomes a DC value), what is similar to previous method. The block scheme is presented in figure 3. Load currents are transformed from the natural *abc* to rotating *d-q-0* coordinates system, synchronized with the grid voltage phase angle $\Phi(\mathbf{u}_{PCC})$ using equations:

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \\ i_{L0} \end{bmatrix} = \begin{bmatrix} \cos\Phi(u_{PCC}) & \sin\Phi(u_{PCC}) & 0 \\ -\sin\Phi(u_{PCC}) & \cos\Phi(u_{PCC}) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \\ i_{L0} \end{bmatrix} \tag{4}$$

The components of compensation currents can be individually extracted, similarly to instantaneous power theory, with low-pass filters. Here, also the DC-capacitor voltage error component in ***d*** coordinate is injected. Next, the resulting reference currents are compared with measured values. Errors for *d* and *q* components are delivered to PI controllers. After decoupling of the ***d*** and ***q*** output components, the final reference voltage is delivered to the implemented modulation technique.

This technique, thanks to the modulation, has a great advantage of fixed switching frequency, what is very helpful in the matter of the output filter design. This control loop works quite well with reactive power compensation and low-order harmonics. However, higher-order harmonics exceed PI bandwidth, so the SAPF currents cannot track the references with a desired quality and thus the compensation becomes unsatisfactory.

Finite Control-States Set Model Predictive Control

This control strategy belongs to calculation demanding. In case of power electronics application it was a serious barrier. However, modern control platforms, at last brought solutions for an effective digital implementation, so the popularity of this control strategy grows [11-18]. Figure 4 depicts the scheme of a typical FS-MPC structure.

The idea is based on system model which is used for state variables values prediction [12,13,15]. So first of all, the model must be as exact as possible, because the control performance is highly dependent on the parameters (inductances, capacitances) precision. Using measured values of compensation currents, their values in the forthcoming sampling can be predicted using (5), with respect to available control states $S(a, b, c)$. It must be done for all switching states in every sampling period.

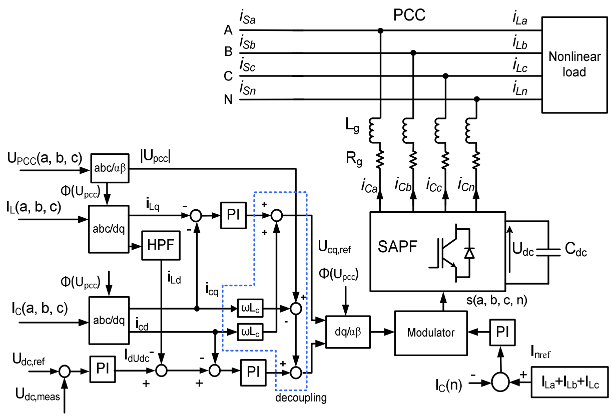

Fig. 3 Linear current control scheme for SAPF

The correction of the predicted value also improves the prediction precision [19]. In this simulation, the coefficient K was chosen 0,6 (see fig. 4), what gave the best operation performance. The reference values can be calculated with any available method. For this comparison the instantaneous power theory based method was employed with equations (2) and (3).

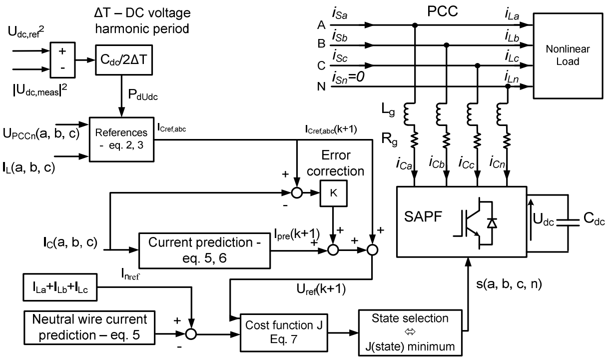

Fig. 4 FS-MPC scheme for SAPF

For each state predicted currents errors are summed up in the cost function (7). Whole Predictive Control can be expressed with equations:

$$I_{pre,m}(k+1) = C_v V_{C,m}(k+1) + C_i I_{C,m}(k) \tag{5}$$

$$V_{C,m}(k+1) = U_{DC} S_m(k+1) - U_{PCC,m}(k+1) \tag{6}$$

$$J(S_m) = \sum_{m \in a,b,c} \left(I_{Cref,m}(k+1) - I_{pre,m}(k+1)\right)^2 \tag{7}$$

, where m corresponds to phase a, b, c or neutral leg n; $I_{pre,m}(k+1)$, $I_{C,m}(k)$ – predicted and measured compensation current in, respectively (k) and $(k+1)$-th step; U_{DC} - SAPF DC capacitor voltage; S_m switching states; $U_{PCC,m}(k+1)=U_{PCC,m}(k)+(U_{PCC,m}(k)-U_{PCC,m}(k-1))$; $C_v=T_s/(L_g+R_gT_s)$, $C_i=L_g/(L_g+R_gT_s)$ - constants dependent on the output filter parameters and sampling time T_s.

The cost function $J(S_m)$ can also include other parameters that should be covered like the number of switching, DC-capacitor voltage etc. Finally, the control output is the switching state that minimizes the cost function.

Considering power converters, it is clear that they can represent only a finite number of states (switching states). Focusing only on SAPFs applications, as it was described before, the main objectives are high precision in references tracking and thus high operation dynamics. FS-MPC, thanks to its capabilities can reach these high demands, while it naturally eliminates possible delays. It operates with a finite number of control states, choosing the converter's switching state that gives an optimal references tracking. However, it suffers from an inaccuracy of the given circuit parameters, what can possibly bring an error in every prediction.

This control strategy doesn't employ the modulation. The switching states are set directly, what leads to a variable switching frequency, if only currents control is considered. Nevertheless, how was mentioned above, the cost function can cover that issue, through including the number of switching as the parameter.

FS-MPC, thanks to the cost function, has great capabilities of control. However, for the comparison with the classical control strategies only the basic form was chosen. The prediction and cost function includes only compensation currents, while the references are obtained with the instantaneous power theory, which was described in the previous section.

Simulation Results

The comparison was performed in Matlab-Simulink using a SimPowerSystems library. To analyze the performances in the compensation of reactive power and current harmonics, two types of load were considered: three-phase 6-pulse diode-bridge with resistive load and asymmetrical three-phase resistive-inductive (Load 1 and Load 2 - see figure 1). The main system parameters are collected in the table 1.

Table 1. Main parameters of simulation model

Quantity	Value		
Load Power [kVA]	15		
Grid phase voltage [V_{rms}]	230		
SAPF DC voltage [V]	700		
Sampling frequency [kHz]	Hysteresis controllers	Linear current regulators	FS-MPC
	40	10	40
Passive filter inductance L_g[mH]	2.5		
Passive filter resistance R_g [Ω]	0.001		
Bridge load R/L [Ω]/[mH]	30/20		
Bridge switched load $R1$ [Ω]	60		
Three phase load R/L [Ω]/[mH]	20/30		
Three phase load – phase A switched load R [Ω]	30		

Results are in two groups. All the figures present system performance during a load step change. The first group corresponds to an asymmetrical three-phase load. Here, to standardize operating conditions in the comparison a criterion was chosen: reduction of Total Harmonic Distortion (THD) of phase A grid current below 4%. To reach this criterion, the sampling frequency of linear control was set to 10kHz, while FS-MPC and control based on instantaneous power theory operate on 40kHz. The other group corresponds to a nonlinear load, where each method operates with the same sampling frequency respectively.

Figures 5, 6 and 7 represent the first group. They compare phase shift compensation effectiveness, while the load is symmetrical and, after a load change in one phase, also compensation of neutral wire current. The classical methods give similar THD value 3,9%, however, with the instantaneous power theory based control, a number of switching is much lower. Comparing THD it must be noted, that FS-MPC gave the lowest value of this factor. The research showed that it was 3%. Moreover also this method required the lowest number of switching. All methods assured a similar and very good compensation of asymmetry.

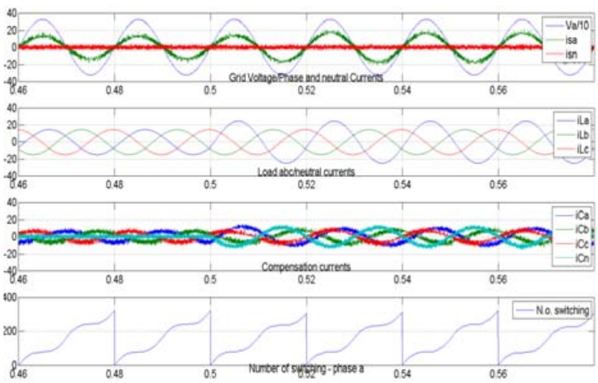

Fig. 5 SAPF with instantaneous power theory based control; Load 2 - operation performance, from the top: phase A grid voltage V_a and current i_{sa} (THD=3,9%) and neutral current i_{sn}, load currents with neutral current, compensation currents, number of switching in SAPF phase A per grid voltage period (20ms)

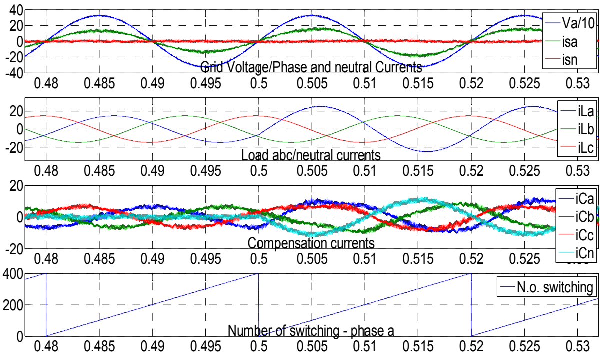

Fig. 6 SAPF with linear current control; Load 2 - operation performance, from the top: phase A grid voltage V_a and current i_{sa} (THD=3,9%) and neutral current i_{sn}, load currents with neutral current, compensation currents, number of switching in SAPF phase A per grid voltage period (20ms)

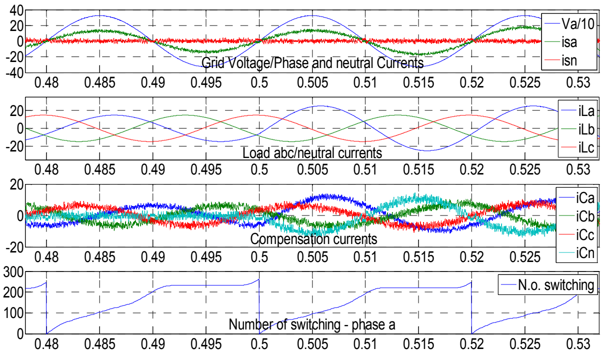

Fig. 7 SAPF with FS-MPC; Load 2 - operation performance, from the top: phase phase A grid voltage V_a and current i_{sa} (THD(i_{sa})=3%) and neutral current i_{sn}, load currents with neutral current, compensation currents, number of switching in SAPF phase A per grid voltage period (20ms)

The second stage of this comparison relates to the second type of load. This analysis gave a view on the three methods operations in dynamic states, with load currents step changes.

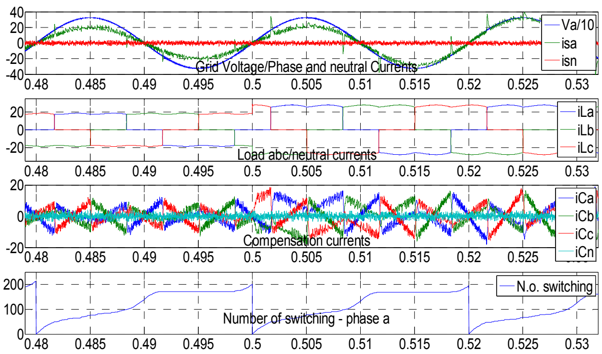

Fig. 8 SAPF with instantaneous power theory based control; Load 1 - operation performance, from the top: phase A grid voltage V_a and current i_{sa} (THD=9,5%), load currents, compensation currents, number of switching in SAPF phase A per grid voltage period (20ms)

As can be seen in figures 8, 9 and 10 the methods present different performances. Control based on instantaneous power theory and FS-MPC reduces THD to 9,5%. Taking a look on figures 8 and 10, it must be noted that FS-MPC requires much lower number of switching, what is noticeable on grid current ripples. The second classical method, linear control, gives much worse results. With this nonlinear load THD reached over 17%. It can be explained with a limited bandwidth of PI controllers, which cannot assure good error correction for rapidly changing references. Even though, it requires the highest number of switching it cannot reach the other two methods performances.

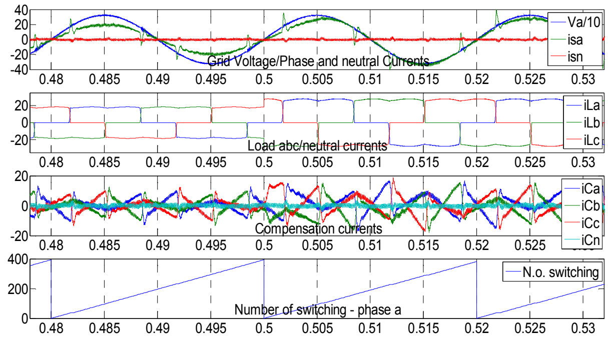

Fig. 9 SAPF with linear current control; Load 1 - operation performance, from the top: phase A grid voltage V_a and current i_{sa} (THD(i_{sa})=17,5%), load currents, compensation number of switching in SAPF phase A per grid voltage period (20ms)

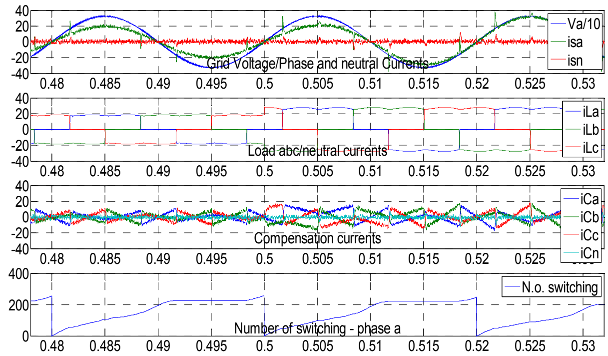

Fig. 10 SAPF with FS-MPC; Load 1 - operation performance, from the top: phase A grid voltage V_a and current i_{sa} (THD(i_{sa})=9,5%), load currents, compensation currents, number of switching in SAPF phase A per grid voltage period (20ms)

The analysis of figure 10 shows clearly that FS-MPC gives a better operation precision, than the other two methods. It gives the same THD value as control based on instantaneous power theory, but keeps the number of switching at the lowest level. The compensation currents can trace references with a high accuracy.

Table 2. Comparison of the three SAPF control methods proprieties.

Criterion	P-Q Theory based	Linear Current Control	FS-MPC
Calculations complexity	• Low complexity	• High complexity	• Low complexity (depends on model)
Calculation intensity per sampling	• High intensity (high switching frequency)	• Low calculation intensity	• High calculation intensity
Sensitivity to system parameters	• Low sensitivity	• Sensitive	Very sensitive to (output filter)
Gate signals generation	• Hysteresis controllers (variable switching frequency)	• Modulator (constant switching frequency)	• Direct states set (variable switching frequency)

Table 2 collects and gives comparison of the proprieties of the three control methods.

Conclusions

This paper presented a comparison of three Shunt Active Power Filter control technique performances. Two of proposed techniques are considered as the basic form of the classical approach to the SAPF control issue. These are: linear current control and instantaneous power theory based control with hysteresis controllers. The third method was Finite Control-State Set Model Predictive Control (FS-MPC). The idea was to compare MPC with the classical methods, as a possible alternative for the control strategy. This comparison was based on the SAPF simulation model, built in Matlab-Simulink. It considered two types of operation, regarding to the type of load. The first stage of research was focused only on a three phase RL load with the neutral wire connected to the grid neutral point. At the next point a diode-bridge with an RL load, connected in parallel with switched resistive load was considered.

To standardize operating conditions the criterion was chosen: reduction of phase A grid current THD to 4% for a symmetrical linear load. It was reached with a sampling frequency of 10kHz for linear control and 40kHz for the other two methods. Next a current phase shift compensation of a three phase symmetrical linear load was simulated and studied. In this case, with sinusoidal references, FS-MPC operated with the best precision, what can be noticed on the grid current THD of 3%. This result was reached with a significantly lower number of switching (per grid voltage period), than the other two methods. Linear control and instantaneous power theory based control gave a similar THD 3,9%, however, the linear control required more switching. At the next point, the analysis was performed for an asymmetrical load. It showed that all methods assured very similar compensation of a current phase shift and very good neutral wire current compensation.

The second type of load gave the results of the three control methods operation with a nonlinear load. This comparison showed that the best operation performance is given by FS-MPC. Although, similarly to control based on instantaneous power theory, THD increased to 9,5%, for FS-MPC the number of switching is significantly lower. Linear control presents much worse performance. With a limited bandwidth of PI controllers it cannot assure a good tracking of dynamically changing references, worsening compensation effectiveness.

This comparison shows that, proposed FS-MPC can be a good alternative to the classical methods. With a lower switching frequency, this method assured better compensation performance than the other two methods. Considering the idea of predictive control and FS-MPC, this method can assure a very high operation and filtration dynamics what is highly required in SAPF applications.

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