Comparison of Current Control Strategies for Three-level Four-leg Shunt Active Power Filter

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Abstract— This paper presents a comparison of two control strategies for 3-level 4-leg Shunt Active Power Filter (SAPF). The first method is based on hysteresis controllers. The second, proposed method is the Model Predictive Control (MPC) with a finite control-states set (FS) based on phase-to-phase model. The two methods are described and simulation results are presented and analyzed. Comparison is performed in Matlab – Simulink.

I. INTRODUCTION

Fast industry development and increasing number of electrical energy consumers brings to the front an aspect of the energy quality [1]-[3]. In modern devices active converter supplies the load circuit. With a proper control, the issues like nonlinearities, asymmetry or reactive power demand, can be effectively reduced. On the other hand, if generated distortions are introduced to the grid, a possible solution to compensate them is to connect to the system a Passive and/or Active Power Filters. In the first group the elements must be selected for a specified frequency, dependent on the load characteristics and grid parameters in the point of common coupling (PCC). The second group for a proper operation requires a control algorithm that will assure a high dynamics and precision in references signals generation what implies a high sampling frequency [4].

Shunt Active Power Filters (SAPF) are designed to reduce the grid current THD and demanded reactive power. A good improvement to those operations is to apply a multilevel converter, which reduces output voltage step changes and switching ripples in currents. In the presented research a 3-level Flying Capacitor Converter (FCC) [5] was applied to 4-leg SAPF. In this topology each leg has an additional capacitor which is used for generation of level 0 of the output voltage. The capacitors voltages must be balanced to a proper level, half of the DC bus voltage. This operation is performed in each leg separately what simplifies the control and makes this multilevel topology very suitable for SAPF.

This paper is focused on the comparison of two control strategies. The first method is a classical approach, based on hysteresis controllers, which compare current commands with measured values. An instantaneous power theory is employed to calculate the SAPF references [6]-[15].

The second method belongs to the category of Predictive Control (PC) [16]. It is based on the model of the controlled system, which is used for calculation of future values of the state variables. In the case of SAPF a Model Predictive Control (MPC) with a finite number of control states (FS) was selected as the most suitable. In this method it is assumed that the system can be represented by a finite number of control states (like switching states) in every sampling period. It offers a high operation dynamics what meets SAPF control requirement and makes the strategy competitive to the classical approach.

The comparison of two control methods was performed in Matlab-Simulink. The subsequent sections of the paper present the system overview, the idea of SAPF operation and introduce the two methods, showing the advantages and disadvantages of each of them. Next, the simulation results are brought and they are analyzed and compared, giving the conclusions at the end.

II. FOUR-LEG SHUNT ACTIVE POWER FILTER – SYSTEM OVERVIEW

The system overview is presented in Fig. 1. Four-leg SAPF is connected to the PCC through an inductive filter (filter resistance $R_g$ can be neglected). It should be noted that in practice L filter is not enough and LCL filter should be used to reduce current ripples generated by SAPF itself. Compensated currents $i_{C,m}$ (where $m$ corresponds to $a$, $b$, $c$ or $n$ wire), generated by SAPF, compensate distortions introduced to the grid currents $i_{G,m}$ by load currents $i_{L,m}$, what can be expressed with:

$$i_{G,m}(t) = i_{C,m}(t) + i_{L,m}(t)$$

With an assumption that grid neutral wire current $i_{G,n}=0$ the whole load neutral wire current $i_{L,n}$ has to be compensated by $i_{C,n}$. Considering grid voltages as symmetrical, the equations are given:

$$i_{C,n}(t) = -(i_{L,a}(t) + i_{L,b}(t) + i_{L,c}(t))$$
$$i_{C,n}(t) = -i_{L,n}(t)$$
$$i_{G,n}(t) = 0$$

The above equations can be the mathematical description of a 4-leg SAPF operation.

![Fig. 1. General system overview.](image-url)
III. INSTANTANEOUS POWER THEORY BASED CONTROL WITH HYSTERESIS CONTROLLERS (HYSTERESIS BASED)

This type of SAPF control is one of the classical approaches for compensation of current harmonics, as well as the reactive power (see Fig. 2) [6]-[15]. Firstly, load currents and grid voltages are transformed to stationary coordinates, using equation:

$$\begin{bmatrix} x_α \n x_β \n x_0 \end{bmatrix} = \mathbf{C} \begin{bmatrix} x_a \n x_b \n x_c \end{bmatrix}, \text{ where } \mathbf{C} = \begin{bmatrix} 1 & -0.5 & -0.5 \\ \sqrt{3} & 0 & -\sqrt{3} \\ 0 & 2 & 2 \\ \sqrt{2} & 1 & 1 \end{bmatrix}. \tag{3}$$

$x$ is a vector of instantaneous values of PCC voltage $U_{PCC}$ or load current $i_L$.

With the transformed vectors a load active and reactive power is calculated. Assuming phase voltages symmetry in three phase grid, it is expressed by:

$$P_L \equiv \begin{bmatrix} u_{PCCα} & u_{PCCβ} \end{bmatrix} \begin{bmatrix} i_{La} \\ -u_{PCCβ} & u_{PCCα} \end{bmatrix}i_{Lβ}$$

$$\begin{array}{l}
q_L = u_{PCCβ} \begin{bmatrix} i_{La} \\ u_{PCCα} \end{bmatrix} \\
\end{array} \tag{4}$$

Next, using a high-pass filter [7], [15] a variable component $P_{dc}$ is extracted from $P_L$. Finally, including SAPF DC-capacitor voltage control ($P_{dc(k)}$), the expression for the reference currents is given:

$$\begin{bmatrix} i_{Crefα} \\ i_{Crefβ} \end{bmatrix} = \frac{1}{u_{PCCα}u_{PCCβ}} \begin{bmatrix} u_{PCCα} & -u_{PCCβ} \end{bmatrix} \begin{bmatrix} -P_{comp} \\ Q_{comp} \end{bmatrix} \tag{5}$$

where $P_{comp}$ = $P_{dc(k)}$. SAPF must also compensate neutral wire current in case of asymmetrical load. The reference value is calculated as a sum of the three phase currents.

Calculated reference currents are then delivered to hysteresis controllers where they are compared with the measured SAPF currents. Generated gate signals are then delivered to the transistors.

This method represents a very simple approach to control SAPF. With the hysteresis controllers a high operation dynamics can be reached with a very good reference tracking. So the simplicity and dynamics are the main advantages of this method.

On the other hand, classical hysteresis controllers operate with a variable switching frequency, which is a very important issue. Wide range of harmonics is generated in SAPF currents. Due to that the output passive filter design becomes very problematic.

However, different modifications of algorithm have been described in the literature to solve that issue [10], [11]. The method based on a variable width of hysteresis band was proposed in [11]. The variations are dependent on the instantaneous output voltage and DC voltage. It’s realized with a phase-locked loop or a feed-forward loop. With this approach the switching frequency can be stabilized on the desired range. However, an additional loop complicates the algorithm and has in impact on its clarity.

IV. FINITE CONTROL-STATES SET MODEL PREDICTIVE CONTROL

Finite Control States-Set MPC (FS-MPC) belongs to calculation demanding algorithms. In case of power electronics application it was a serious barrier. However, modern control platforms bring a calculation power that can afford demands. The popularity of this control strategy in power electronics grows ([16]-[31]) and last few years brought several implementations, also for SAPF giving very promising results ([18]-[30]). With respect to that, in this research the idea was to develop the FS-MPC for 3-level 4-leg FCC operating as SAPF.

This method is based on system model which is used for state variables values prediction [16],[18]-[20]. First of all, the model must be exact and include all circuit elements. The control performance and prediction accuracy is highly dependent on the parameters evaluation precision. Next, using required measured values, the prediction of control variables values in the forthcoming sampling time is performed with respect to available control states.

Very important aspect is to understand how to model the system with mathematical equation using Kirchoff’s law. Fig. 3 depicts the scheme of FS-MPC structure for four-leg FCC [18]-[20]. Depending on the system functionality (rectifier, inverter etc.) different types of model can be used [20].

In presented case of the SAPF circuit, to simplify the calculations a phase-to-phase model was used. With this approach, the following equation was given:

$$i_{pree,jm}(k+1) = T_s \left( U_{d,j} S_j - S_m \right) - \frac{T_s}{L_o} \left( u_{PCC}(k+1) - u_{PCCm}(k+1) \right) + i_{Cj}(k) - i_{Cm}(k) \tag{6}$$

where, indexes $j$, $m$ correspond to legs $a$, $b$, $c$ or $n$; $k$ - current step; $i_{pre}$ and $i_C$ - predicted and measured SAPF currents; $T_s$ - sampling time; $U_{d,j}$ - SAPF DC voltage; $u_{PCC(1)}$ - grid voltage at PCC (for leg $n$ $u_{PCCn}$ equals zero); $S_{jm}$ - switching state in corresponding SAPF leg; $L_o$ - inductance of the output filter (assumption that resistance $R_o=0$).

![Fig. 2. Instantaneous power theory based control scheme for SAPF.](Image)
Fig. 3. FS-MPC scheme for 4-leg SAPF.

Approximations in each part of the prediction equation are unavoidable and they sum up into errors between predicted and real values of state variables. The control uses measured values of compensation currents, grid voltages and DC-capacitor voltage and with (6) calculates (predicts) the values of SAPF current in forthcoming period with respect to control states \(S(a, b, c, n)\).

The further step is to calculate the absolute values of compensation currents errors, which are next summed up in the cost function, given by:

\[
J(S_{a b c n}(k + 1)) = w_f \sum_{j=a,b,c} |i_{Cref, jn}(k + 1) - i_{pre, jn}(k + 1)| + w_g \sum_{j=m=a,b,c,n} |i_{Cref, jm}(k + 1) - i_{pre, jm}(k + 1)|
\]

(7)

- where \(w_f, w_g\) are the weighting factors for errors; index \(n\) indicates the 4th leg of the converter.

Finally, the switching state that gives the smallest value of the cost function is applied for the next sampling period. Considering this simple structure, similarly to the classical method, the switching frequency is also variable so output filter design may be also problematic. However, the solution for this issue was described in [19], [20].

Considering the power converter the number of control states is defined by the number of available switching states, which for four-leg two-level converters equals \(2^4 = 16\). Application of three-level FCC will increase this number to \(2^4 = 256\) states, while each leg has two states for the voltage zero-level generation. So the prediction should also be done 256 times at every sampling time what might be very demanding with respect to high operation frequency.

To reduce that effect, it is proposed to identify the two redundant states used for voltage zero-level generation (see Table I) as a one state. With this approach, the available switching states are: ‘0’ and ‘2’ for \(-Ud/2\) and \(Ud/2\) level respectively and ‘1’ for the zero level. It reduces the overall number of states to 81, what is much lower than 256. Nevertheless, it is still much more demanding than the classical method.

The reference values were calculated using the instantaneous power theory. The algorithm is the same as for the first method and it’s described in Section III.

### Table I

<table>
<thead>
<tr>
<th>System state</th>
<th>Switching state for leg</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i_{Cref} \geq 0 ) (U_{Cref} \geq U_{Cref} )</td>
<td>(S(T_{in}, T_{no})=[0,1])</td>
</tr>
<tr>
<td>(i_{Cref} &lt; 0 ) (U_{Cref} &lt; U_{Cref} )</td>
<td>(S(T_{in}, T_{no})=[1,0])</td>
</tr>
<tr>
<td>(i_{Cref} \geq 0 ) (U_{Cref} &lt; U_{Cref} )</td>
<td>(U_{Cref} - FC) voltage in leg (m)</td>
</tr>
<tr>
<td>(i_{Cref} &lt; 0 ) (U_{Cref} \geq U_{Cref} )</td>
<td>(U_{Cref} - FC) reference voltage</td>
</tr>
</tbody>
</table>

### Table II

**Grid phase voltage RMS** 230
**SAPF DC-voltage** 700
**DC capacitor** 3.3mF
**Sampling frequency** 40kHz
**Output filter inductance** 2mH

### Table III

<table>
<thead>
<tr>
<th>Type</th>
<th>phase</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Three-phase load</strong></td>
<td>A</td>
<td>(Roa=54\Omega; Loa=8mH)</td>
</tr>
<tr>
<td>A</td>
<td>(Roa=27\Omega; Loa=1mH)</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>(Rob=81\Omega; Lob=5.7mH; Cob=500uF)</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>(Roc=27\Omega)</td>
<td></td>
</tr>
<tr>
<td><strong>Two-phase to three-phase load</strong></td>
<td>A</td>
<td>(Roa=27\Omega; Loa=8mH)</td>
</tr>
<tr>
<td>B</td>
<td>(Rob=54\Omega; Lob=5.7mH; Cob=500uF)</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>(Roc=27\Omega)</td>
<td></td>
</tr>
</tbody>
</table>

As can be seen in both cases control compensates the asymmetry. Grid currents are in phase with grid voltages also in the dynamic state which occurs at 0.305. However, there are huge differences in grid currents THD\(_{90}\) values, which can be also noticed on the plots. For FS-MPC it is significantly
lower than for the classical method. In the simulation hysteresis bands were set to 0.75 and 1.5.

Even though that, two methods operate with a similar average number of switching events per second, which is about 16k, the difference is significant. Both methods handle FCs voltages balance effectively what can be seen on the bottom plots of the figures.

The second type of load is a 2-phase AB switched to 3-phase ABC at 0.305. The results for both control algorithms are presented in Fig. 7 and Fig. 8.

Similarly to the previous case, both methods compensate load asymmetry. Here also differences in THD values can be noticed. They are less than in the previous case. However, the average number of switching events per second is much higher for the control based on hysteresis controllers and crosses 18k, while FS-MPC keeps 16k.

The balance of FC voltages is performed well by both control algorithms. Considering presented results it can be seen that FS-MPC handles SAPF control much more effectively. Obtained THD values shows that the prediction and states selection assures better precision in the references tracking in steady and dynamic states.
CONCLUSIONS

This paper presented a comparison of two control strategies for 3-level 4-leg FCC operating as SAPF. The first was the classical approach to the SAPF control, based on instantaneous power theory and hysteresis controllers. The second method was the Finite Control-State Set Model Predictive Control (FS-MPC). The idea was to compare MPC with the classical method, as a possible alternative for the control strategy. Both methods were developed in the basic form, however, as it was explained in the previous sections, they can include additional functions.

This comparison was based on the SAPF simulation model built in Matlab-Simulink. The features of both methods are listed in Table IV. Two options of load were simulated. The first was asymmetrical 3-phase load with a step change in phase A, while the second was a 2-phase switched to 3-phase load by connection of phase C. Presented results shown that the proposed FS-MPC operates with a better precision that the hysteresis based control. Even though that both methods operate at the same sampling time with a variable switching frequency the comparison of THD values proves that FS-MPC is more accurate in the references tracking.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Instantaneous power theory and hysteresis controllers based</th>
<th>FS-MPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculations complexity</td>
<td>• Low complexity</td>
<td>• Low complexity (depends on model)</td>
</tr>
<tr>
<td>Calculation intensity per sampling</td>
<td>• High calculation intensity (high sampling frequency) but less than FS-MPC</td>
<td>• High calculation intensity (high sampling frequency and prediction)</td>
</tr>
<tr>
<td>Sensitivity to system parameters</td>
<td>• Low sensitivity</td>
<td>• Very sensitive to (output filter)</td>
</tr>
<tr>
<td>Gate signals generation</td>
<td>• Hysteresis controllers (variable switching frequency)</td>
<td>• Direct states set (variable switching frequency)</td>
</tr>
<tr>
<td>Implementation</td>
<td>• Easy</td>
<td>• Depends on model complexity</td>
</tr>
</tbody>
</table>

TABLE IV
COMPARISON OF THE TWO SAPF CONTROL METHODS FEATURES.
Moreover, the average number of switching events per second for single switch is less for MPC what demonstrates the effectiveness of SAPF switching states selection.

Both methods can also be developed to achieve some specified goals, like switching frequency stabilization. In the classical method it can be handled by additional loops, what lead to complication of the algorithm structure. In MPC a proper component of the cost function must be calculated. Then, depending on the necessity, a weighing factor can be chosen.

The above results and analysis prove that the proposed FSC-MPC can cope with FCC operating as SAPF effectively. The comparison with the classical method, based on hysteresis controllers, shows that the predictive control is very competitive and, as a result can be a good alternative in SAPF control.

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