Design and Control of Hybrid Filter for Power Quality Enhancement of the Distribution System

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Abstract—This paper presents the analysis, systematic design and control of the hybrid parallel filter (active series filter in series with passive shunt filter) to enhance the quality of power in the distribution system. It consists of a three phase load commutated inverter fed synchronous motor (LCI-fed SM) drive as a nonlinear load, a series active filter (SAF) and a passive shunt filter (PSF) at point of common coupling (PCC) connected to three phase AC grid. A low rating SAF is in series with PSF forces harmonics of all orders into this PSF of the three phase LCI-fed SM drive. The proposed hybrid filter provides satisfactory performance in steady state and dynamic conditions with optimal design of PSF and SAF. A simple synchronous to rotating reference control with reduced sensors is used to control the low rating SAF. To validate the design and control of the proposed parallel hybrid filter system, the proposed system is modelled and its performance is simulated in MATLAB along with SPS toolbox.

Keywords— Harmonics, PSF, SAF, hybrid filter, LCI-fed SM, power quality.

I. INTRODUCTION

Nowadays, load commutated inverter fed synchronous motor (LCI-fed SM) drives have been used in number of applications with wide range speed control in high power level due to advancement and development of solid state devices of high power rating and robust in nature. SM has high power factor and efficiency but LCI-fed SM drive consisting of three phase controlled rectifier and SM pollute the distribution system by drawing large amount of harmonics and reactive power from three phase AC grid and deteriorate the efficiency and power factor. In addition to contaminating the distribution system, they also disturb the nearby consumers and components such as electronic communication networks, protective devices, etc. The mal-operation of communication network and protective devices leads to the disruptions in the system [1]. These power quality problems in the distribution system violate the limits imposed power quality standards. So proper method and techniques should be used to design the filters to improve the quality of power in accordance to IEEE and IEC standards etc [1].

Passive shunt filters (PSFs) are connected at the PCC (Point of Common Coupling) to enhance the quality of power in the distribution systems consisting of LCI-fed SM drives but they are not very effective to eliminate the harmonics [2-3]. So series active filter (SAF) is tied in series with PSF connected at PCC, called as a hybrid parallel filter [1, 4]. The SAF element of hybrid parallel filter forces the harmonics of all orders into the PSF thereby enriches the capability of the filter. The various configuration and control algorithms of hybrid filters have been proposed in the literature [1, 4-9]. To enhance the power quality in the distribution system comprising of large industrial drives, the design of both SAF and PSF are very important [10-12].

This paper presents the analysis, design and control of a hybrid filter consisting of hybrid parallel filter (a SAF is in series with PSF) for power quality enhancement of a three phase controlled rectifier of LCI-fed SM drive. The PSF elements are designed in such a way that it reduces the harmonics and provides the reactive power and
a SAF with a low rating forces these harmonics of all orders into the PSF of LCI-fed SM. A simple stationary to rotating reference control is used to control the SAF with reduced sensed signals [1, 4-5]. The proposed hybrid filter provides satisfactory performance in steady state and dynamic conditions with optimal design of PSF and SAF and its performance is simulated in MATLAB along with SPS toolbox.

II. PROPOSED SYSTEM CONFIGURATION

The proposed system configuration shown in Fig. 1, consists of a three phase 50 Hz, 415 V, distribution system, a 85 kVA LCI-fed SM with a firing angle of 30°, a SAF connected in series with PSF through injection transformer (n=1:6), passive shunt filter (5th, 7th and high pass filters), interfacing inductor L, ripple filter (C1) connected at PCC with AC mains. The SAF is a voltage source converter (VSC) based filter. The combination of SAF and PSF is called as hybrid parallel filter. All the parameters of the system are given in Appendix.

III. DESIGN OF PROPOSED SYSTEM

The design of the hybrid parallel filter for the proposed system is given in terms of two stages as PSF and SAF. In first stage, the PSF eliminates harmonics and compensates the reactive power. In second stage, a SAF is used to force harmonics currents of all orders into this PSF of LCI-fed SM drive load. The design of both SAF and PSF are as follows.

A. Design of PSF

The PSF of the orders 5th, 7th and high pass damped (HPD) filter for the proposed system are used to provide the reactive power compensation and to eliminate 5th, 7th harmonics and harmonics of all higher orders at the PCC. The following systematic design procedure is used to design the PSF for proposed distribution system.

The DC current of LCI-fed SM is estimated as, $I_{dc} = P_{L}/V_o = 85000/485.19 = 175.25$ A. (1)

Where $P_L = 85000$ kVA SM rating of the load, $V_o = 1.35*415*cos30^\circ = 485.19$ V.

The supply rms current of the three phase LCI-fed SM load is estimated as, $I_L = \sqrt{(2/3)}I_o = 0.8165*175.25 = 143.09$ A. (2)

The fundamental component of supply current of a three phase LCI-fed SM load is estimated as, $I_{L1} = \sqrt{(6/\pi)}I_o = 0.7796*175.25 = 136.6419$ A. (3)

The active component of supply current of a three phase LCI-fed SM load is obtained as, $I_{L1s} = I_{L1} = I_{L1} cos \alpha = 136.64cos30^\circ = 118.35$ A. (4)

The fundamental active power of the LCI-fed SM load is estimated as, $P_{s1} = 3*V_s^*I_{s1} = 3*239.6*118.35 = 85.06$ kW. (5)

The fundamental reactive power of the LCI-fed SM load is estimated as, $Q_{s1r} = 3*V_s^*I_{s1} \sin \alpha = 3*239.6*136.6419*0.5 = 49.109$ kVAR. (6)

The proposed three phase system requires total nine passive elements as 5th, 7th and HPD filter and three in each phase. The reactive power component of the LCI-fed SM load has to be provided by all elements of the PSF of hybrid filter. The capacitor value is assumed equal for all nine branches and is calculated as, $C = C_5 = C_7 = C_9 = Q/(9V_s^2\omega) = 49109/(9*239.6^2*314) = 302.55$ mF. (7)

1) Design of 5th Harmonic Tuned Filter (HTF) of PSF

The value of capacitor is estimated as, $C_5 = Q/(9V_s^2\omega) = 302.55$ mF. (8)

The inductor value is calculated as, $L_5 = 1/(\omega_5^2C_5) = 1.3$ mH. (9)

The resistance of the inductor is obtained as, $R_5 = X_s/Q_5 = 2.041 = 0.10205 \Omega$. (10)

Where $Q_5 = 20$, is quality factor. The 5th harmonic component of load current is estimated as, $I_5 = I_{L1}/5 = 136.6419/5 = 27.3284$ A. (11)
The 5th harmonic component of PCC voltage is estimated as,
\[ V_5 = I_5 \cdot R_5 = 27.3284 \cdot 0.10205 = 2.8752 \text{ V}. \]  
(12)

2) Design of 7th HTF of PSF

The value capacitor is estimated as,
\[ C_7 = Q/(9V_S^2\omega) = 302.55 \, \mu\text{F}. \]  
(13)

The inductor value is calculated as,
\[ L_7 = 1/(\omega^2C_7) = 0.6834 \, \text{mH}. \]  
(14)

The inductor resistance is estimated as,
\[ R_7 = X_7/Q_7 = 0.1502/20 = 0.0751 \, \Omega. \]  
(15)

Where \( Q_7 \approx 20 \), is quality factor.

The 7th harmonic component of load current is calculated as,
\[ I_7 = I_{L1}/7 = 136.6419/7 = 19.52 \, \text{A}. \]  
(16)

The 7th harmonic component of PCC voltage is calculated as,
\[ V_7 = I_7 \cdot R_7 = 19.52 \times 0.0751 = 1.4669 \, \text{V}. \]  
(17)

3) Design of 11th HTF (HPD filter) of PSF

The capacitor value is calculated as,
\[ C_h = Q/(9V_S^2\omega) = 302.55 \, \mu\text{F}. \]  
(18)

The inductor value is calculated as,
\[ L_h = 1/(\omega^2C_h) = 0.2767 \, \text{mH}. \]  
(19)

The resistance of the inductor is estimated as,
\[ R_h = X_h/Q_h = 0.9557/2 = 0.4782 \, \Omega. \]  
(20)

Where \( Q_h \approx 2 \), is quality factor of HPD filter.

The rms value of all higher order harmonics currents flowing in to HPD harmonic filter is calculated as,
\[ I_{h} = \sqrt{[I_{11}\times I_{11}\times I_{13}\times I_{13}]} = \sqrt{[143.09^2-136.642^2-27.33^2-19.52^2]} = 26 \, \text{A}. \]  
(21)

The rms voltage of all higher order harmonics component of PCC voltage is calculated as,
\[ V_h = I_h \cdot R_h = 26 \times 0.4782 = 12.4353 \, \text{V}. \]  
(22)

The rms value of all harmonics voltages at PCC is calculated as,
\[ V_{lh} = \sqrt{(V_5^2+V_7^2+V_h^2)} = 12.8474 \, \text{V}. \]  
(23)

B. Design of SAF

To force harmonics currents of all orders into the PSF, the SAF must inject all harmonics voltages \( V_{lh} \). The design of SAF is explained as,

1) Design of Voltage Rating of SAF

The voltage rating of SAF is calculated as,
\[ V_{fs} = \sqrt{(V_5^2+V_7^2+V_h^2)} = 12.8474 \, \text{V}. \]  
(24)

2) Design of Current Rating of SAF

The current rating of SAF is same as the PSF current and it is calculated as,
\[ I_{fs} = I_{psf} = \sqrt{[I_{11}^2-1]} = \sqrt{[143.09^2-118.355^2]} = 80.41 \, \text{A}. \]  
(25)

3) Design of VA Rating of SAF

The VA rating of SAF is calculated as,
\[ S_{fs} = 3 \times V_{fs} \times I_{fs} = 3 \times 12.847^2 \times 80.41 = 3.099 \, \text{kVA}. \]  
(26)

The per unit rating of the SAF is estimated as,
\[ S_{ps} = S_{fs}/P_L = 3099/1.85000 = 3.646 \, \% \] of the load rating.  
(27)

4) Design of Interfacing Inductor of SAF

The interfacing inductor of SAF is calculated as,
\[ L_f = \{(\sqrt{3})/2\} \times m_a V_{dc} / (6a_i \times \Delta I_f) = \{(\sqrt{3})/2\} \times 0.9 \times 250 / (6 \times 1.2 \times 20000 \times 0.15 \times 118.3556) = 0.45732 \, \text{mH} = 0.5 \, \text{mH}. \]  
(28)

Where \( \Delta I_f = 15 \, \% \) of \( I_{11a} \) is ripple current in the inductor, \( m_a \approx 0.9 \) is modulation index, \( a \approx 1.2 \) is overloading factor and \( f_s = 20 \, \text{kHz} \) is switching frequency for VSC.

5) Design of DC Bus Voltage of SAF

The DC link voltage of SAF connected in series with the PSF is estimated from its injected voltage. The voltage injected at the VSC end is estimated as,
\[ V_{inj} = V_{fs} \times n_2/n_1 = 12.8474^2 \times 6 = 77.0855 \, \text{V}. \]  
(29)

The DC link voltage is estimated as,
\[ V_{dc} = 2\sqrt{2}V_{inj}/m_a = 2\sqrt{2} \times 77.0855/0.9 \]  
\[ = 242.25 \approx 250 \, \text{V}. \]  
(30)

6) Design of DC Bus Capacitor of SAF

The DC bus capacitance \( C_{dc} \) of SAF is estimated as from the following relation,
\[ \Delta E = \frac{1}{2} C_{dc} (V_{dc}^2-V_{dcem}^2) = 3 \times V_{fs} \times I_{fs} \times \Delta t \]  
\[ \Delta E = \frac{1}{2} C_{dc} (250^2-230^2) = 3 \times 12.8474^2 \times 80.41 \times 0.1 \]  
\[ C_{dc} = 6456.6 \, \mu\text{F} \approx 7000 \, \mu\text{F}. \]  
(31)

Where \( \Delta E \) is the change in energy stored in the DC bus capacitor during dynamics and \( V_{dcem} \) is \( 8 \% \) of \( V_{dc} \) and Consider, \( \Delta t = 10 \, \text{ms} \).  

7) Design and Selection of Ripple Filter of SAF

The ripple filter of the SAF is selected as \( C_f = 5 \, \mu\text{F} \). All these filter parameters are given in Table I.

IV. CONTROL ALGORITHM

A simple control algorithm with reduced sensors is proposed for SAF of the hybrid parallel filter of the proposed distribution system as shown in Fig. 2. To extract the fundamental positive sequence component from supply currents, the stationary to
TABLE I  PARAMETERS OF HYBRID SEIRES ACTIVE AND SHUNT PASSIVE FILTER

<table>
<thead>
<tr>
<th>SAF (Series Active Filter)</th>
<th>PSF (Passive Shunt Filter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V(_{dc})</td>
<td>250 V</td>
</tr>
<tr>
<td>C(_{dc})</td>
<td>7000 (\mu F)</td>
</tr>
<tr>
<td>C(_f)</td>
<td>5 (\mu F)</td>
</tr>
<tr>
<td>L(_i)</td>
<td>0.5 mH</td>
</tr>
</tbody>
</table>

Fig. 2 SRF based control algorithm of SAF.

rotating reference is used with synchronized phase locked loop (PLL). Using Park’s transformation, the supply currents (\(i_{sa}, i_{sb}\) and \(i_{sc}\)) are converted into the d-q (\(i_d, i_q\)) frame as follows,

\[
\begin{bmatrix}
i_d \\
i_q \\
i_0
\end{bmatrix} = \begin{bmatrix}
\cos \theta & -\sin \theta \\ \frac{1}{2} \cos \left(\frac{\theta - 2\pi}{3}\right) & \frac{1}{2} \sin \left(\frac{\theta - 2\pi}{3}\right) \\ \frac{1}{2} \cos \left(\theta + \frac{2\pi}{3}\right) & \frac{1}{2} \sin \left(\theta + \frac{2\pi}{3}\right)
\end{bmatrix}
\begin{bmatrix}
i_{sa} \\
i_{sb} \\
i_{sc}
\end{bmatrix}
\]

(32)

To extract the fundamental positive sequence components (\(i_{dq1}\)) of the supply currents, the \(i_d\) and \(i_q\) are passed through LPFs (Low Pass Filters).

The DC bus controller is used to regulate the DC link voltage across the VSC to set reference value by comparing the sensed and reference DC voltages and the output of PI controller \(i_i\) is estimated as,

\[i_i(t) = i_i(t-1) + K_P(V_{dc,r}(t) - V_{dc}(t-1)) + K_I V_{dc}(t)\]

(33)

where, \(V_{dc,r}\) is the reference (\(V_{dc,*}\)) and sensed (\(V_{dc}\)) DC voltage at sampling instant \(t^\text{th}\). \(K_I\) and \(K_P\) are the integral and proportional gains of the PI controller.

The output of the DC link controller \(i_{ii}\) is subtracted from the fundamental quadrature component of the supply current \(i_{iq1}\) to generate reference supply current fundamental quadrature component \(i_{iq1,*}\) and is calculated as,

\[i_{iq1,*} = i_{iq1} - i_{i1loss}\]

(34)

Using inverse Park’s transformation, the reference supply currents \((i_{sa,*}, i_{sb,*}\) and \(i_{sc,*}\)) are estimated by transforming the \(i_{dq1,*}\) and \(i_{iq1,*}\) as,

\[
\begin{bmatrix}
i_{sa} \\
i_{sb} \\
i_{sc}
\end{bmatrix} = \begin{bmatrix}
\cos \theta \\
\cos \left(\theta - \frac{2\pi}{3}\right) \\
\cos \left(\theta + \frac{2\pi}{3}\right)
\end{bmatrix}
\begin{bmatrix}
i_{dq1,*} \\
i_{iq1,*}
\end{bmatrix}
\]

(35)

To produce the pulses for VSC of SAF of hybrid parallel filter, the sensed supply currents \((i_{sa}, i_{sb}\) and \(i_{sc}\)) along with the reference supply currents \((i_{sa,*}, i_{sb,*}\) and \(i_{sc,*}\)) are fed to PWM based current controller.

V. MATLAB MODELLING

The proposed system is modelled and simulated in MATLAB software as shown in Fig. 1. The three phase controlled rectifier is used to feed the LCI fed SM of 85 kVA, 415V, 50 Hz and a hybrid parallel filter consisting of a SAF in series with a PSF connected to PCC is used to improve the quality of power connected to three phase AC grid. All the parameters of the system are given in Appendix.

VI. RESULTS AND DISCUSSION

Figs. 3-5 show the steady state responses of the proposed system with the hybrid filter at at different firing angles for controlling the speed of LCI fed SM of 85 kVA. The supply voltages \((v_s)\), supply currents \((i_s)\), active power \((P)\), reactive power \((Q)\), load current \((i_{L,a})\), DC link voltage \((V_{dc})\), PSF current \((i_{psfa})\), SAF voltage \((v_{fsa})\), and reference supply currents \((i_{s,*})\) are shown to validate its responses and DC link voltage is regulated at reference value. The harmonics current and reactive power are compensated using the PSF and SAF is used to force these harmonics of all order into the PSF. Fig. 3 shows the power factor of the proposed system with this hybrid filter having of the system which makes it economical option at firing angle of 30\(^\circ\). The SAF is used to force these around unity (0.999 lag) at firing angle of 30\(^\circ\). The SAF rating of the hybrid filter are observed 3.64 % of the load which makes it economical option at firing angle of 30\(^\circ\).
Moreover, power factor varies from 0.998 leading to 0.976 lagging as firing angles of LCI-fed SM vary from 20° to 40°.

Fig. 6 shows the harmonic spectra and waveforms of supply voltage, supply current and load current at firing angle of 30°. The THDs of supply voltage, supply current, and load current are 4.79 %, 3.72 % and 27.19 % respectively. The supply voltage THD and supply current THD are in accordance to IEEE 519 standard [1] in the proposed system with designed hybrid parallel filter at different firing angle for controlling the LCI-fed SM drive.

VII. CONCLUSION

The proposed distribution system consisting of three phase controlled rectifier LCI fed SM and a hybrid filter (a SAF in series with PSF) has been analyzed, designed and modelled. The proposed hybrid filter has been observed cost effective for the proposed system due to low rating of SAF (less than 5% of the motor load) and is verified through simulation. The proposed hybrid filter has validated enhanced power quality at different firing angles (20°, 30°, 40°) and it has worked satisfactorily with
Fig. 6. Waveforms and harmonic spectra of (a) supply voltage (b) supply current and (c) load current at firing angle of 30°

DC link voltage maintained at reference set value and harmonics and reactive power have been compensated. The PCC voltage and current are witnessed nearly sinusoidal with the THD in accordance to IEEE 519 standard at different motor loads. However, the power factor is observed leading 0.98 at firing angle 20° from designed value and the power factor is observed lagging 0.976 at firing angle 40° from designed value.

VIII. APPENDIX

Grid voltage 415 V, f = 50 Hz; Feeder: Short circuit level 150 MVA, X/R=3; Load: LCI-fed SM Drive, 85 kVA, 50 Hz, firing angle of controlled rectifier = 30°; PI controller gains: \( K_p = 0.96, \ K_i = .001 \).

REFERENCES


