DESIGN OF AN ACTIVE DC FILTER FOR
A HVDC SYSTEM

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ABSTRACT

Active filters have become the most viable alternatives for the compensation of the harmonics in the power system analysis. These filters are able to reduce the harmonics percentage much lower than selective passive filters and also provide compensation for the loss occurring in the transmission system. This project basically deals with the operational characteristics of the active shunt filter design for a specific voltage rating irrespective of the load connected. This is basically used to reduce the harmonic component present in the output of the converter in the HVDC application. This basically deals with the detection of the percentage of harmonic content in the percentage of the fundamental by using the FFT analysis of the signal and the design the active filter with the concept of selective harmonics compensation for specific harmonic order.

Active filters are basically working with the concept of providing the same negative current in the passive filter part to cancel out the harmonic current making the load current/voltage harmonic free. This is being done by using a transformer in series with the passive filter branch.

KEYWORDS: HVDC, ADF (Active DC Filter), FFT (Fast Fourier Transform)
INTRODUCTION

1. Why HVDC

In an AC system voltage conversion is simple with the help of the transformer which allows high power level and high insulation level within one unit and has low loss. Apart from that a 3 phase synchronous generator is superior to that of a DC generator. However HVAC links have disadvantages which may compel a change to DC technology. Inductive and capacitive elements put limits to the transmission capacity and also to the link to the transmission. Depending upon the required transmission capacity the system frequency and the losses evaluation can change. Direct connection between two AC system of different frequencies is not possible.

Merits of HVDC

A DC link allows interconnection of two AC systems of different frequencies whose synchronization cannot be possible. Inductive and capacitive parameters don’t limit the transmission and also there is no loss due to skin effect (which is absent). Beyond a certain distance DC is less costlier than AC. Losses are less in HVDC transmission.

2. Types of DC links

2.1 Mono polar DC links Useful for very long distance transmission. Chances off breakdown are less It is more costlier compared to other transmission.

2.2 Bipolar link It is a combination in such a way that a common low voltage return path will only carry a small unbalance current during normal operation. This configuration is used if the capacity increased beyond that of a single pole. More than 50% of the transmission capacity can be utilized as well as there will be reduction in cost for high power transmission. Disadvantage is the unavailability of the return path will affect the operation of both the poles.
3. Converter operation

- Converters are basically the devices which converts AC to DC and vice versa.
- The devices doing the conversion from AC to DC are known as Rectifiers and the DC to AC conversion is done by the Inverters.
- Normally power electronics switches are connected in a combined fashion whose turn on and off made the total thing possible.
- Current flows through the valve when the anode is made more positive than cathode. The valves can made to turn on by applying proper gate pulses to the gate cathode terminal which are the pulses for short duration.
- In order to commutate a negative voltage is being developed across the conducting switches or a negative current is being applied to flow by turning on the other pair of switches in the bridge circuit.

4. Harmonics

Harmonics are generated both in AC side as well as DC side of the converter. As we can see that getting pure DC is difficult. Whatever DC we are getting that can be obtained by using a converter, which can be 6,12,24 or 32 pulse. The more the no of pulse, the less is the ripple content but at the same time it will be more complex.

As per the analysis made the harmonic content of a particular converter in the DC side will be np, where

n=the no of harmonics and p=no of pulses

That means there is the chance of occurrence of even harmonics in the output of the converter which has to be removed.
4.1 Causes of Harmonics

- It can be caused by any electrical equipment that uses switched mode power supply.
- Due to improper switching of the converter switches, on linear loads, faults, etc.

4.2 Results of Harmonics

- Harmonic current can cause overheating of the distribution system.
- It will cause voltage distortion reducing the amount of voltage to the load circuit.
- It will add to the loss component of the system.
- Interference in telephone lines.

4.3 Harmonic Current Measurement

The load current is measured with the help of a current sensor made up of a Rogowski Coil mounted inside the aluminum case which provides the shielding and means for the connection to the line. The measured signal is digitized and transmitted to the control equipment by fiber optics link with a normal frequency range up to 3000Hz.

4.4 FFT Method (Fast Fourier Transform)

As we know that the Fourier transform method is used to separate out the dc and the ac components in a particular signal. The FFT method reduces the duplicate terms in the mathematical algorithm to reduce the mathematical operation required. It also reduces the computation factor thereby saving the time and more accurate. [5]

\[ I_{\text{load}}(t) = I_d(t) + \sum_{n=1}^{\infty} I_n \sin(n \omega t + \phi) \]  (1)
where
\[ I_d(t) = \text{dc component of the signal selected} \]
\[ I_{\text{load}}(t) = \text{load component of the signal} \]
\[ I_h = \text{harmonic component of the signal} \]

Hence in this method after integrating and subtracting the dc component from the load value we can find out the harmonic component of the signal.

5. Filters

To reduce the harmonic content filters are used which are of two types such as

- Passive filter
- Active filters

5.1 Types of passive filters

5.1.1 High pass filter

A high pass filter is the type of filter which pass all the frequency above the cutoff frequency specified. The filter characteristics equation can be
\[ H(s) = \frac{s}{1 + sRC} \]

5.1.2 Band pass filter

A band pass filter is the type of filter which pass all the frequency within the band of the cutoff frequency specified. It is the combination of a high pass and low pass filter. The filter characteristics equation can be the combination of a low pass and a high pass filter that is
\[ H(s) = \frac{Ks}{s^2 + Ks + w^2} \]

Single tuned filter are the type of filter which has been tuned to a single frequency. Similary Double tuned filters can be tuned simultaneously to two specific frequencies. Same as the multi-tuned filter.
5.2 Selection of the passive filter

Selection of passive filter is a trivial task for any system. The method involve the percentage of harmonics in the signal without the filter and the required value with the filter. Normally a HVDC system has smoothening reactor on both side(rectifier and the inverter side). Hence the formula used for the calculation of the filter impedance can be given as

\[ Z_f = \frac{V_o \times Z_s}{V_s - V_o} \]  

Where

- \( Z_f \) = filter impedance
- \( Z_s \) = impedance of the smoothing reactor
- \( V_o \) = output voltage
- \( V_s \) = input/supply voltage

All the components can be calculated in the Laplace Transform form for better calculation. If the total value of the harmonic has to be removed then a LC filter can be used. But practically pure LC filter is not present some lumped resistance value will be there in the component. The formula holds good for the single harmonic content in the supply voltage but for more than one harmonic component in the supply voltage there will be interference in the filter output. Hence it has been observed that the selective harmonics are getting decreased but there will be generation of some more even as well as odd harmonics. Again the more no of filters means there will be chances of spikes in the output voltage as well as current waveform. Again it is also difficult to design for more than 2 harmonics because the calculation will be complicated and time consuming.

5.3 Limitations of Passive Filters

- The source impedance influences the compensation characteristics of the passive filters, which is not known and varies with the system configuration.
- The Passive filter act as a sink to the harmonics of the source voltage and harmonics generated elsewhere on the ac system.
- At specific frequency there is always an anti resonance between the source impedance and the passive filter, called load harmonics amplifying phenomenon.
- Designing is a trivial task so that sometimes it became so complex that practical meaning of using it will be lost.
- Constraint on the free choice of the values of the filter component there by making the design complex.
- Deviation of the ac fundamental frequency leads to the considerable mistuning of the filter circuit.

5.4 Active filter

The concept of shunt active filter was first introduced by Gyugyi and Strycula in 1976. Now a days a shunt active filter is not a dream but a reality and many shunt active filters are in commercial operation all over the world. Their controllers determine in the real time the compensating the current reference and force a power converter to synthesize it accurately. In this way the active filtering can be selective and adaptive. In other words a shunt active filter can compensate only for harmonics current of a selective harmonics, linear and non linear loads and also can continuously track changes in the harmonic content. A shunt active filter can be properly controlled to present selective compensation characteristics. In other words it is possible to select what current is to be compensated.

A shunt active filter generally consists of two distinct main blocks:

a. The PWM converter
b. The active filter controller
The PWM converter is responsible for power processing in synthesizing the compensating current that should be drawn from the power system. The active filter controller is responsible for signal processing in determining the instantaneous compensating current reference, which is continuously passed to the PWM converter. The shunt active filter controller works in a closed loop manner, continuously sending the load current and calculating the instantaneous values of the compensating current reference for the PWM converter. In ideal case the PWM converter may considered as a linear power amplifier where the compensating current track correctly its reference. The PWM converter should have high switching frequency ($f_{PWM}$) in order to reproduce accurately the compensating current. Normally $f_{PWM} > 10f_{hPWM}$, where $f_{hPWM}$ is the frequency of the highest order of the harmonic that is to be compensated. The dc capacitor and IGBT with anti parallel diode are used to indicate a shunt active filter that is build up from a voltage source converter. In fact voltage source converter or current source converter can be used in shunt active filters. Now a days VSC are most widely used in the shunt active filters. IGBT modules are the most suitable for the VSC because freewheeling diode is connected antiparallel to each device, that means it need not provide the capability of reverse voltage blocking in itself thus bringing more flexibility to device design in a compromise between conducting and switching losses and short circuit capability than the reverse blocking IGBT.

Active filter controller is a control algorithm implemented in the controller of the shunt active filter determines the compensation characteristics of the shunt active filter. There are many ways to design that algorithm one of them is the selective band pass filters in parallel.

Active filters are the type of filter which is using a transformer in series with the passive part. Basically the active filter is a combination of the passive and the active part. The active part is nothing but the source used to supply the transformer. The load current is taken as a feedback to a bank of selective band
pass filter in which the specific harmonics those have to be eliminated is selected within the band. Then the signal is fed to the amplifier there by given to the pulse generator which will give corresponding triggering pulses to a single or multi phase inverter depending upon the application required. The inverter is giving supply to the transformer which will be in series with the passive part supplying a negative value of the same current flowing in the shunt branch, there by nullifying the effect of harmonics.

5.5 Limitations of the Active filter

- It is difficult to realize large VA rating PWM converter with rapid current response and low loss, which is the main circuit of the active filter
- The initial running cost is high as compared to the passive filters
- The injection current from the active filter may flow into the inductor and capacitors of the circuit.

This is one of the factor by which we can find out what amount of the reduction of harmonic content in a particular signal has occurred in percentage. The THD is always calculated taking reference to the fundamental component for ac as well as dc.

This can be given as

\[
\text{THD} = \left( \sqrt[\infty]{ \sum_{n=2}^{\infty} V_h^2 (n) } \right) / V_1
\]

Where

- \( V_h \) = harmonic voltage other than fundamental
- \( V_1 \) = fundamental component of the voltage
Harmonic analysis is done w.r.t the fundamental component because

- The modulation and the demodulation of the same value has to be done in the conversion and the inversion process
- As $V_h$ is represented in percentage of the fundamental component as (we are considering the harmonics in the multiples of fundamental) hence it will get cancelled out in the THD calculation.
- The average value of the fundamental component is zero for a full cycle.

(as the average value of the fundamental component is zero for a full cycle hence the fundamental component is not considered for the harmonic analysis of the signal)

5.6 Control Principle

- The dc circuit of the HVDC can be simplified into a circuit consisting of a converter harmonic EMF, smoothing reactor, dc filter with harmonic impedance, line impedances.[1]
- The output current will be sensed by a sensing element and fed to the feedback path containing the active filter consisting of a transformer, an amplifier and the control circuit.
- The control circuit contains a pwm generator and the pi controller (to provide proportional output)
- The active filter is represented as a voltage source. The line current generated by the active filter will give a negative current to the harmonic value thereby it will cancel out the harmonic value.
- The FFT analysis of the signal without filter will give the amount of compensation required.
- As per that value the dc voltage to the control circuit and the no of turn is calculated.[4]
$$I_h(t) = I_{load}(t) - I_d(t)$$  \hspace{1cm} (4)

Figure 1 : Block Diagram of the Active filter

5.7 Design of ADF

- $U_s$: harmonic voltage output of the converter
- $U_{adf}$: voltage output of ADF
- $Z_{f(s)}$: impedance of the passive filter
- $L_s$: impedance of the smoothing reactor
- $U_d$: ADF dc voltage supply
- $n:1$: transformer ratio of the coupling transformer
  (n can be any number including fraction)
- $G$: Gain
- $I_s$: harmonic current output of the converter circuit
- $I_F$: harmonic current output of the filtering branch
- $I_L$: harmonic current output of the transmission line

5.7.1 Design of DC voltage

To cancel all the harmonics the DC voltage requirement can be given by the formula

$$U_{dc} = -I_h Z_{fh}$$  \hspace{1cm} (5)
Design of an Active DC Filter for a HVDC System

Where

\[ I_h = \text{harmonic current of the order } h \]
\[ Z_{th} = \text{impedance of the associated passive filter} \]

Or

\[ U_{adf}(s) = -\sum_{i=1}^{h} \left[ \frac{Z_f(j2\pi f_i)}{(j2\pi f_i L_s)} \right] U_{si}(s) \]  \hspace{1cm} (6)

where \[ U_{si} = \text{the harmonic voltage output of the converter} \]

5.7.2 Design of \( F(s) \)

\[ F(s) = \sum K_i H_{fi}(s) \]  \hspace{1cm} (7)
\[ H_{fi} = \frac{2\xi_i w_i s}{s^2 + 2\xi_i w_i s + w_i^2} \]  \hspace{1cm} (8)

where

\[ K_i = \text{Control coefficient of each harmonic term} \]
\[ w_i = \text{Passband center angular frequency} \]
\[ \xi_i = \text{Parameter to adjust the pass band width} \]

5.8 Circuit Diagram

5.8.1 Circuit of the active filter without load

![Figure 2](image-url)
5.8.2 Circuit without Filter (Bipolar HVDC line)

![Figure 3](image)

5.8.3 Circuit Active Filter (Bipolar HVDC line)

![Figure 4](image)

5.9 Waveforms and Table

5.9.2 For T Network

5.9.2.1 fft of the line voltage without filter
Design of an Active DC Filter for a HVDC System

Without Filter

waveform of the line voltage (top) and current (bottom) without filter

5.9.2.2 (fft of the line voltage with adf)

With Active Filter

waveform of the line voltage (top) and current (below) after adf
5.9.2.3 Comparison of the THD among circuits without filter, with passive filter and with ADF

5.9.3 For PI Network

5.9.3.1 fft of the line voltage without filter

waveform of the line voltage(top) and current (below) without filter
5.9.3.2 \textbf{fft of the line voltage with adf}

With Active filter

waveform of the line voltage (top) and current (bottom) with adf

5.9.3.3 \textbf{Comparison of the THD among circuits without filter, with passive filter and with ADF}
5.10 Comparison of the percentage of the harmonics on dc line voltage

5.10.1 T Network

<table>
<thead>
<tr>
<th>HARMONICS</th>
<th>12(^{\text{TH}})</th>
<th>24(^{\text{TH}})</th>
<th>36(^{\text{TH}})</th>
<th>48(^{\text{TH}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>WITHOUT FILTER1</td>
<td>7.69</td>
<td>1.07</td>
<td>1.44</td>
<td>-0.82</td>
</tr>
<tr>
<td>WITH ADF1</td>
<td>0.02</td>
<td>0.23</td>
<td>0.1</td>
<td>0.03</td>
</tr>
<tr>
<td>WITHOUT FILTER2</td>
<td>5.48</td>
<td>-2.23</td>
<td>-0.5</td>
<td>0.69</td>
</tr>
<tr>
<td>WITH ADF2</td>
<td>0.24</td>
<td>0.02</td>
<td>0.03</td>
<td>-0.07</td>
</tr>
<tr>
<td>WITHOUT FILTER3</td>
<td>-7.69</td>
<td>-1.07</td>
<td>-1.44</td>
<td>0.82</td>
</tr>
<tr>
<td>WITH ADF3</td>
<td>-0.06</td>
<td>-0.22</td>
<td>-0.06</td>
<td>-0.08</td>
</tr>
<tr>
<td>WITHOUT FILTER4</td>
<td>-5.48</td>
<td>2.23</td>
<td>0.5</td>
<td>-0.69</td>
</tr>
<tr>
<td>WITH ADF4</td>
<td>-0.23</td>
<td>-0.03</td>
<td>-0.03</td>
<td>0.03</td>
</tr>
</tbody>
</table>

5.10.2 Pi Network

<table>
<thead>
<tr>
<th>HARMONICS</th>
<th>12(^{\text{TH}})</th>
<th>24(^{\text{TH}})</th>
<th>36(^{\text{TH}})</th>
<th>48(^{\text{TH}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>WITHOUT FILTER1</td>
<td>50.17</td>
<td>1.24</td>
<td>0.7</td>
<td>-0.81</td>
</tr>
<tr>
<td>WITH ADF1</td>
<td>-0.6</td>
<td>0.61</td>
<td>0.4</td>
<td>0.16</td>
</tr>
<tr>
<td>WITHOUT FILTER2</td>
<td>12.11</td>
<td>-0.25</td>
<td>-0.46</td>
<td>1.16</td>
</tr>
<tr>
<td>WITH ADF2</td>
<td>-0.02</td>
<td>-0.21</td>
<td>-0.77</td>
<td>-0.18</td>
</tr>
<tr>
<td>WITHOUT FILTER3</td>
<td>-50.17</td>
<td>-1.23</td>
<td>-0.7</td>
<td>0.81</td>
</tr>
<tr>
<td>WITH ADF3</td>
<td>0.6</td>
<td>-0.63</td>
<td>-0.4</td>
<td>-0.14</td>
</tr>
<tr>
<td>WITHOUT FILTER4</td>
<td>-12.11</td>
<td>0.25</td>
<td>0.46</td>
<td>-1.16</td>
</tr>
<tr>
<td>WITH ADF4</td>
<td>0.02</td>
<td>-0.21</td>
<td>0.76</td>
<td>0.17</td>
</tr>
</tbody>
</table>
With ADF1&2 = scope of the active filter on the rectifier & inverter side of pole 1 in Fig 5.9 respectively.

With ADF3&4 = scope of the active filter on the rectifier & inverter side of pole 2 in Fig 5.9 respectively.

Without filter1&2 = scope of the circuit on the rectifier & inverter side of pole 1 in Fig 5.7 respectively.

Without filter3&4 = scope of the circuit on the rectifier & inverter side of pole 2 in Fig 5.7 respectively.

The analysis has been carried forward in Mat Lab and Simulink for DC line generated from a 150KV, 3φ, 50Hz AC system having the line impedance of 0.01Ω and 1mH. The 12 pulse converter system is used to find out the DC output for 45 degree firing angle. The 250km transmission line has been done for both T and PI network having 0.0015Ω line resistance, 0.0752H line inductance and 1.42µF capacitance per km for T network and 0.0258Ω line resistance, 0.0752H line inductance and 0.0123µF line capacitance per km.

The load parameters are calculated by varying the line parameters and thereby giving the load to the line so that the line can be able to draw the current. Because in ideal case the line current has to be negligible as compared to the voltage developed.

5.11 CONCLUSIONS

As per the analysis given we can see that the active filter is able to reduce the THD of the output waveform appreciably than the normal passive filter used. The passive filter used in series with the active filter with a switch to isolate the active part in case of any short circuit due to fault. Some figures are taken as the design parameters whose values cannot be disclosed and are used due to confidentiality mentioned by the company.
5.12 FUTURE WORK

The Active filter has minimum limitation other than the initial installation cost. The future analysis can be done by analyzing the behavior of the circuit with different type of loading by varying the torque angle of the supply. In case the power transfer is required then the HVDC line is also helping to make the load draw current from the line. The behavior of that current can be studied.

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