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Impact of Harmonics on Power System and Suitability of Its Mitigation Techniques

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ABSTRACT

This paper presents the study of harmonics present in the system and harmonic filters primarily used in electrical system. The main objective is to analyze and reduce harmonics in the system to get desired output and system response for particular operation. This paper describes the hardware design of active filter along with comparative study with simulation results of active filter in MATLAB.

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I. INTRODUCTION

The presence of harmonics in a power system can give rise to a variety of problems including equipment overheating, reduced power factors, deteriorating performance of electrical equipment, the incorrect operation of protective relays, interference with communication devices, and in some cases, circuit resonance to cause electric apparatus dielectric failure and other types of severe damage. Even worse, harmonic currents generated in one area can penetrate into the power grid and propagate into other areas, resulting in voltage and current distortions for the entire system. This phenomenon has become a major concern for power quality due to the ever-increasing usage of electronic devices and equipment in power systems.

The harmonic is defined in many literatures as "a component of a periodic wave having a frequency that is an integral multiple of the fundamental power line frequency". The meaning of the harmonic can be easily explained using the following example.

Let 'f' represents a fundamental frequency, the second harmonic has frequency 2f Hz, third harmonic has frequency 3fHz ,and so on. The 2nd ,4th,6th,etc.,are called even harmonics while the 3rd,5th,7th,etc.,are called odd harmonics. There are two types of harmonics:

1. Voltage Harmonics
2. Current Harmonics

The harmonic distortion occurs when non-linear loads, such as rectifier, inverter, adapters, etc., are feeded from power systems and changes sinusoidal wave at a fundamental frequency to different non-sinusoidal waves as shown in Fig.1.

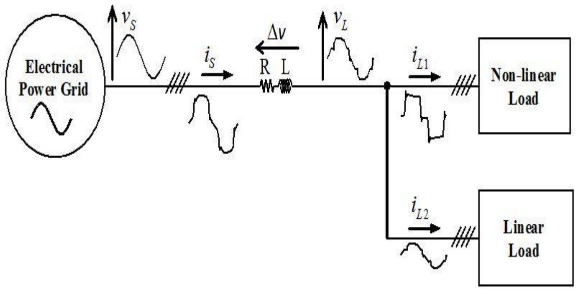


Fig.1 Effect of Non-linear load on electrical power system.

II. HARMONICS AND ITS EFFECTS

Table 1. Harmonics and its effects

Sr. No		Effects of Harmonics
1.	General	Heating,Thermal or voltage stress, aging of electrical insulations
2.	Motors	Flux distribution in air gap,cogging or crawling
3.	Generators	High stressed mechanical forces , temperature rise
4.	Transformers	Increases audible noise, Increases losses like Cu losses, stray flux losses, Iron losses, causes losses
5.	Power cables	Voltage stress and corona
6.	Electronic Equipment	Malfunctioning
7.	Metering	Erroneous operation
8.	Switchgear And Relaying	Increases heating and losses, slower operation ,changes in operating characteristics

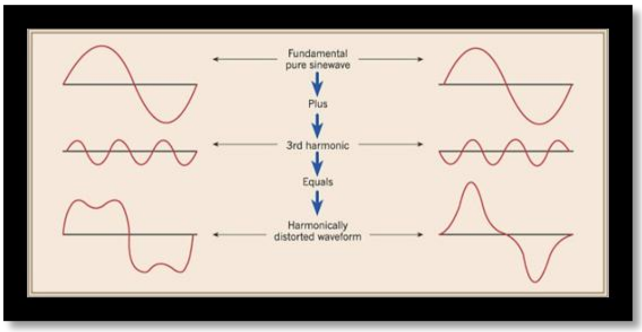


Fig.2 Effect of Harmonics

Non-linear loads:

The effects discussed above are because of the non-linear load. These are the loads in which the current wave form does not resemble the applied voltage waveform due to a number of reasons, for e.g. the use of electronic switches that conduct load current only during a fraction of power frequency period. Therefore,e can conceive non-linear loads as those which Ohm’s law cannot describe the relation between V and I.
Those loads are listed below:

1. **Power Electronics:**
   - Variable frequency drives
   - Power converters
   - Cycloconverters
   - Cranes
   - Elevators
   - UPS
   - Battery Chargers
   - Inverters
2. **ARC Devices:**
   - Fluorescent Lighting
   - Arc furnaces
   - Welding machines

III. MITIGATION TECHNIQUES

1. Passive Filters:

Passive filters are very much helpful for mitigation of harmonic component & used traditionally. There is a continuous development has been reported in this technique for the better use of filter & convert the filter more useful to achieve the optimum approach to utilization with reduced rating & cost. The use of passive filter in the mitigation of harmonic in 3 phase system use the utilizing reactor & capacitor is the most significant development in the field of harmonic distortion mitigation.

2. Active Filter:

To reduce the harmonics conventionally passive L–C filters were used and also capacitors were employed to improve the power factor of the ac loads. But the passive filters have several drawbacks like fixed compensation, large size and resonance problem. To mitigate the harmonics problem, many research work development are developed on the active powerFilter (APF)

IV. CASE STUDY

- Set up :

We connected the power quality analyzer Fluke 430-II across various non-linear loads like makino A98, A99, CNC machine, vfd, etc.

Modelling and control of the single-phase THSeAF

A. Average and small-signal modeling

Based on the average equivalent circuit of an inverter, the small-signal model of the proposed configuration can be obtained as in fig.4. Hereafter, d is the duty cycle of the upper switch during a switching period, whereas v and i denote the average values in a switching period of the voltage and current of the same leg. The mean converter output voltage and current are expressed by following relations:

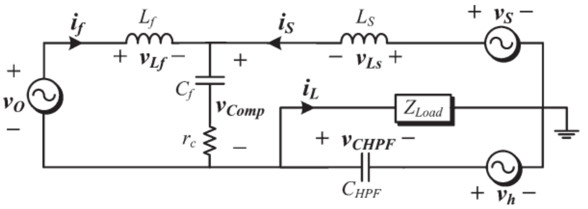


Fig.4. Small-signal model of transformer less HSeAF in series between the grid and the load

$$v_{O}=(2d-1)v_{DC}$$

Where the (2d-1) equals to m, then

$$i_{DC}=m i_{f}$$

Calculating the Thevenin equivalent circuit of the harmonic current source leads to the following assumption:

$$vh(j\omega)=\frac{-j\overline{ih}}{CHPF.\omega_h}$$

If the harmonic frequency is high enough, it is possible to assume that there will be no voltage harmonics across the load. The state-space small signal ac model could be derived by a linearized perturbation of the averaged model as follows:

$$\dot{x}=Ax+Bu$$

Hence we obtain,

$$\frac{d}{dt}\begin{bmatrix}\overline{vCf}\\ vCHPF\\ \overline{i_s}\\ \overline{i_f}\\ \overline{i_l}\end{bmatrix}=\begin{bmatrix}0 & 0 & \frac{1}{Cf} & \frac{1}{Cf} & 0\\ 0 & 0 & \frac{1}{CHPF} & 0 & -1/CHPF\\ -1/L_s & -1/L_s & -r_c/L_s & -r_c/L_s & 0\\ -1/L_f & 0 & -r_c/L_f & -r_c/L_f & 0\\ 0 & \frac{1}{Ll} & 0 & 0 & -\frac{Rl}{Ll}\end{bmatrix}$$

$$\times\begin{bmatrix}\overline{vCf}\\ vCHPF\\ \overline{i_s}\\ \overline{i_f}\\ \overline{i_l}\end{bmatrix}+\begin{bmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ \frac{1}{Ls} & 0 & \frac{1}{Ls}\\ 0 & \frac{1}{Lf} & 0\\ 0 & 0 & \frac{-1}{Ll}\end{bmatrix}\times\begin{bmatrix}vs\\ V_{DC}\\ \overline{vh}\end{bmatrix}$$

Moreover, the output vector is

$$y=Cx+Du$$

By means of the eqns, the state-space representation of the model is obtained as shown in Fig. 4.

The transfer function of the compensating voltage versus the load voltage, *TV _CL*(s), and the source current, *TCI* (s), are developed in the Appendix. Meanwhile, to control the active part independently, the derived transfer function should be autonomous from the grid configuration. The transfer function *TVm* presents the relation between the output voltages of the converter versus the duty cycle of the first leg converter's upper switch

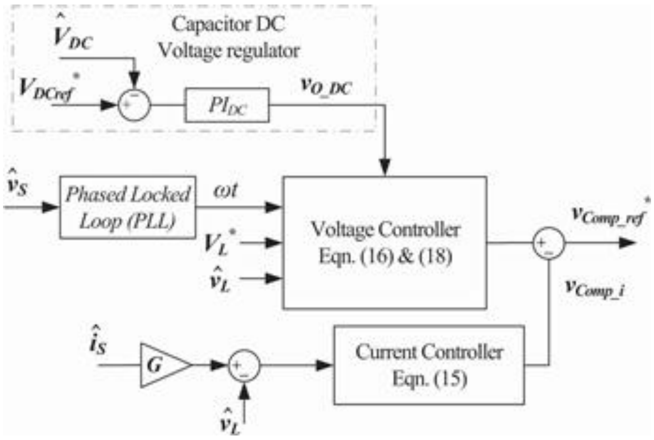


Fig. 5. Control system scheme of the active part.

$$T_V(s)=\frac{V_{comp}}{V_O}=\frac{rC_f s+1}{LfCf\,s2+rCCf\,s+1} \quad 13$$

$$TVm(s)=\frac{Vcomp}{m}=VDC\cdot TV\,(s). \quad 14$$

The further detailed derivation of steady-state transfer functions is described in Section V.

A dc auxiliary source should be employed to maintain an adequate supply on the load terminals. During the sag or swell conditions, it should absorb or inject power to keep the voltage magnitude at the load terminals within a specified margin. However, if the compensation of sags and swells is less imperative, a capacitor could be deployed. Consequently, the dc-link voltage across the capacitor should be regulated as demonstrated in Fig. 5.

B. Voltage and Current Harmonic Detection

The outer-loop controller is used where a capacitor replaces the dc auxiliary source. This control strategy is well explained in the previous section. The inner-loop control strategy is based on an indirect control principle. A fast Fourier transformation was used to extract the magnitude of the fundamental and its phase degree from current harmonics. The control gain ***G*** representing the impedance of the source for current harmonics has a sufficient level to clean the grid from current harmonics fed through the nonlinear load.

The second proportional integrator (PI) controller used in the outer loop was to enhance the effectiveness of the controller when regulating the dc bus. Thus, a more accurate and faster transient response was achieved without compromising the compensation behaviour of the system. According to the theory, the gain ***G*** should be kept in a suitable level, preventing the harmonics from flowing into the grid. As previously discussed, for a more precise compensation of current harmonics, the voltage harmonics should also be considered. The compensating voltage for current harmonic compensation is obtained from

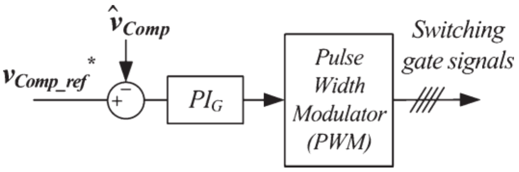
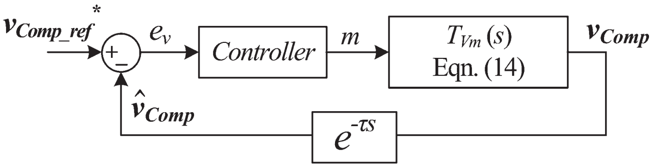


Fig. 6. Block diagram of THSeAF and PI controller.

$v$comp_$i(t) = (-G\hat{}iS + \hat{}vL) - [| - GiS1 + vL1| \cdot \sin(\omega St - \theta)]$. Hereby, as voltage distortion at the load terminals is not desired, the voltage sag and swell should also be investigated in the inner loop. The closed-loop equation (16) allows to indirectly maintain the voltage magnitude at the load side equal
to $V * L$ as a predefined value, within acceptable margins
$v$comp_$v = \hat{}vL - V{*}L \sin(\omega St)$. (16)
The entire control scheme for the THSeAF presented in Fig. 5 was used and implemented in MATLAB/Simulink for real-time simulations and the calculation of the compensating voltage. The real-time toolbox of dSPACE was used for compilation and execution on the dsp-1103 control board. The source and load voltages, together with the source current, are considered as system input signals. According to Srianthumrong *et al.* [25], an indirect control increases the stability of the system.
The source current harmonics are obtained by extracting the fundamental component from the source current
$v\ {*}$com_ref $= v$comp_$v - v$comp_$i + v$DC_ref where the vDC_ref is the voltage required to maintain the dc bus voltage constant
vDC_$ref\,(t) = VO$_DC $\cdot \sin(\omega St)$. (18)
A phase-locked loop was used to obtain the reference angular frequency (ωs). Accordingly, the extracted current harmonic contains a fundamental component synchronized with the source voltage in order to correct the PF. This current represents the reactive power of the load. The gain G representing the resistance for harmonics converts current into a relative voltage. The generated reference voltage $v$comp_i required to clean the source current from harmonics is described in eqn.
According to the presented detection algorithm, the compensated reference voltage $v*$
Comp_ref is calculated. Thereafter, the reference signal is compared with the measured output voltage and applied to a PI controller to generate the corresponding gate signals as in Fig. 6.

C. Stability Analysis for Voltage and Current Harmonics



configuration is mainly affected by the introduced delay of a digital controller. This section studies the impact of the delay first on the inclusive compensated system according to works cited in the literature. Thereafter, its effects on the active compensator is separated from the grid. Using purely inductive source impedance (see Fig. 4) and Kirchhoff's law for harmonic frequency components, is derived. The delay time of the digital controller, large gain G, and the delay time τ high stiffness of the system seriously affect the stability of the closed-loop controlled system.

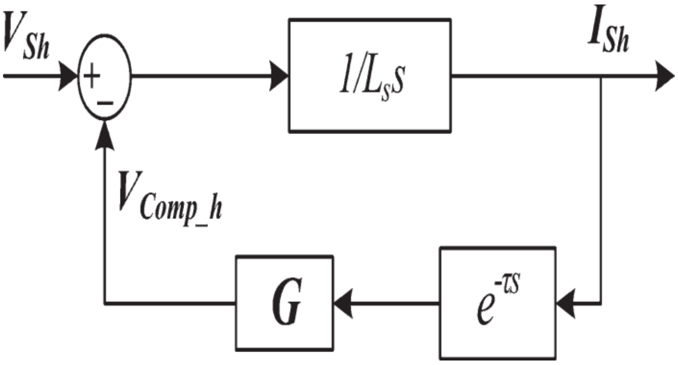


Fig. 7. Control diagram of the system with delay.

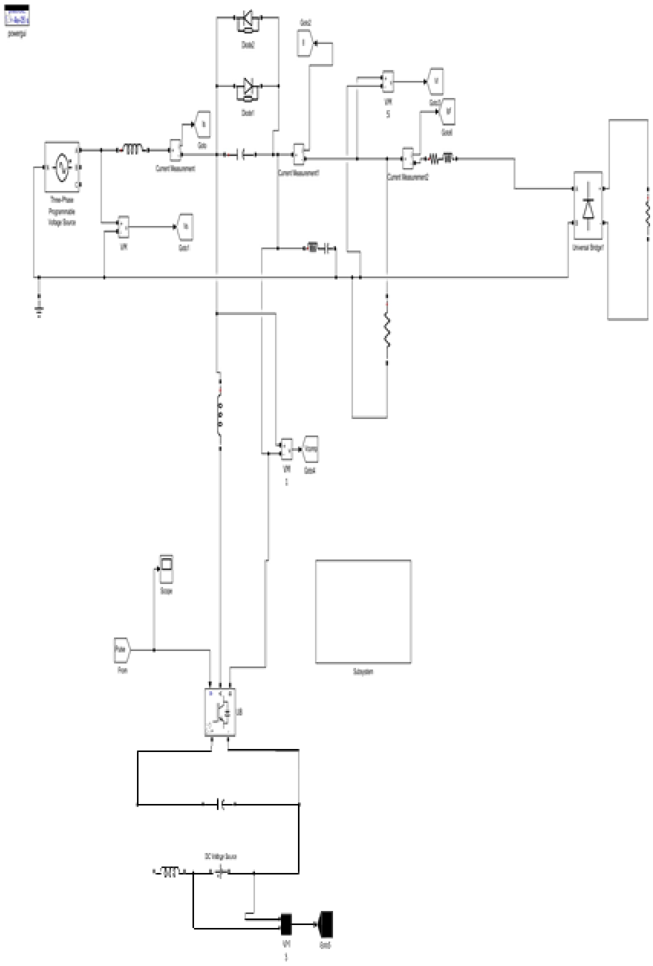


Fig. 8. Closed-loop control diagram of the active filter with a constant

$$I_{Lh}(s) = \frac{V_{sh} - V_{Comp} - V_{Lh}}{L_{s}s}$$

The compensating voltage including the delay time generated by the THSeAF in the Laplace domain [see (1)] is $v\mathrm{Comp} = G \cdot Ish \cdot e - \tau s - VLh.$ (20)

Considering (19) and (20), the control diagram of the system with delay is obtained as in Fig. 7.

For the sake of simplicity, the overall delay of the system is assumed to be a constant value τ. Therefore, the open-loop transfer function is obtained

$$G(s) = \frac{G}{L_{ss}} e\tau s.$$

From the Nyquist stability criterion, the stable operation of the system must satisfy the following condition:

$$G(s) < \frac{\pi L_s}{2\tau} e\tau s.$$

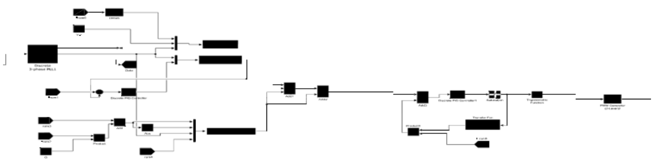
A system with a typical source inductance Ls of 250 μH and a delay of 40 μs is considered stable according to (22) when the gain ***G*** is smaller than 10Ω. Experimental results confirm the stability of the system presented in this paper. Moreover, the influence of the delay on the control algorithm should also be investigated. According to the transfer functions given above, the control of the active part is affected by the delay introduce by the digital controller. Thus, assuming an ideal switching characteristic for the IGBTs, the closed-loop system for the active part controller is shown in Fig. 8.

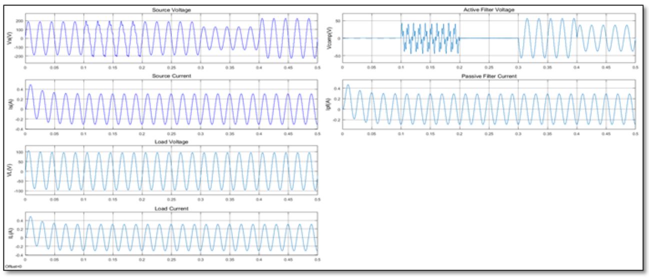
The open-loop transfer function in Fig. 8 turns to another eqn, where the τ is the delay time initiated by the digital controller

$$F(s) = PIG \cdot TVm \cdot e\tau s$$
$$= \frac{(rCCfVDCs + VDC).(Kps + Ki)e\tau s}{s \cdot (LfCf\, s2 + rCCf\, s + 1)}$$

A *PI* controller with system parameters described in Table I demonstrates a smooth operation in the stable region. By means of MATLAB, the behavior of the system's transfer function *F*(*s*) is traced in Fig. 9. The root locus and the Bode diagram of the compensated open-loop system demonstrate a gain margin.

V. SIMULATION RESULTS





VI. CONCLUSION

Harmonics generated from the non-linear load were analyzed using the hardware of power filter along with its MATLAB simulation. The Active power filter gives better results as compared to Power filter and this is observed with the help of waveforms obtained from MATLAB simulation models. Thus we can say that these harmonic mitigation techniques can be applied to various fields to mitigate or reduseharmonicc content present in the electrical system, so as to improve power quality and power factor.

VII.ACKNOWLEDGEMENT

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