Synchronous Reference Frame Theory For Nonlinear Loads using Mat-lab Simulink

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Abstract: Nonlinear loads introduce the harmonics in the power system. Nonlinear load used in this paper is universal bridge which is a three leg circuit consisting of 6 diodes. To compensate the harmonics produced by this nonlinear load, filter is connected in parallel to the load .The paper presents detailed explanation of the design of three-phase shunt active power filter (SAF).This filter injects a suitable compensating current at a point of common coupling so that it cancels out the harmonics present in the line and restores the sinusoidal waveform. The technique used to extract the harmonic components is Synchronous Reference Frame (SRF) algorithm and Hysteresis controller is used to generate firing pulses to the inverter. This system is simulated using MATLAB/ Simulink and the results are presented.

Keywords: Shunt Active Filter, Synchronous Reference Frame, Hysteresis Controller.

1. Introduction

When a sinusoidal voltage is applied to a certain type of load, the current drawn by the load is determined by the voltage and impedance and follows the voltage waveform. These loads are referred to as linear loads; examples of linear loads are resistive heaters, incandescent lamps, and constant speed induction and synchronous motors. In contrast, some loads cause the current to vary disproportionately with the voltage during each cyclic period. These are classified as nonlinear loads, and the current taken by them has a non sinusoidal waveform. When there is significant impedance in the path from the power source to a nonlinear load, these current distortions will also produce distortions in the voltage waveform at the load. However, in most cases where the power delivery system is functioning correctly under normal conditions, the voltage distortions will be quite small and can usually be ignored. The issues and considerations associated with three-phase power harmonics are often misunderstood. With the advent of power electronics and proliferation of non-linear loads in industrial power applications, power harmonics and their effects on power quality are a topic of concern. Currently in the United States, only 15 to 20% of the utility distribution loading consists of non-linear loads. It is projected over the next ten years that non-linear loads will comprise approximately 70 to 85% of the loading on our nation's utility distribution systems. The characteristic harmonics are based on the number of rectifiers (pulse number) used in a circuit and can be determined by the equation: h = (n x p) + and – 1 where: n = an integer (1, 2, 3, 4, 5 …) p = number of pulses or rectifiers

High levels of stress or harmonic distortion can lead to problems for the utility's distribution system, plant distribution system and any other equipment serviced by that distribution system. Effects can range from spurious operation of equipment to a shutdown of important plant equipment, such as machines or assembly lines. Harmonics can lead to power system inefficiency. Active filters are used to reduce all the problems of harmonics and to provide a sinusoidal wave at point of common coupling. Active filter is connected in parallel so its name is shunt active filter.

2. Literature Survey

Active power filter connected in parallel to load is defined as "shunt active power filter" (SAF). It produces and injects current of opposite polarity to the harmonic component of load current resulting in cancellation of harmonic component and converting source current to be sinusoidal leading to reduction in THD [1].

Nonlinear loads are loads in which the current waveform does not take the shape of the applied voltage waveform due to a number of reasons, for example, the use of electronic switches that conduct load current only during a fraction of the power frequency period. Therefore, we can describe the nonlinear loads as those in which Ohm's law cannot describe the relation between V and I. These non-sinusoidal currents pass through different impedances in the power systems and produce voltage harmonics. These voltage harmonics propagate in power systems and affect all of the power system components. [2]

The synchronous reference frame theory or d-q theory is based on time-domain reference signal estimation techniques. It performs the operation in steady-state or transient state as well as for generic voltage and current waveforms. It allows controlling the active power filters in real-time system. Another important characteristic of this theory is the simplicity of the calculations, which involves only algebraic calculation. [3]

Synchronous reference theory and hysteresis controller.[4]

Voltage Source Inverter.[5]

3. Filters

By using filters which prevent currents of frequency above 50 Hz to pass into power distribution system, total harmonic distortion at the point of common coupling can be reduced. Basically there are two types of filter: a) passive filters and b) active filters.

3.1 Passive Filter

A passive filter is a filter that is made only from passive elements -- in contrast to an active filter; it does not require an external power source (beyond the signal). Since most filters are linear, in most cases, passive filters are composed of just the four basic linear elements --

resistors, capacitors, inductors, and transformers. Its major disability is that it introduces system resonance and cannot compensate for random load variations.

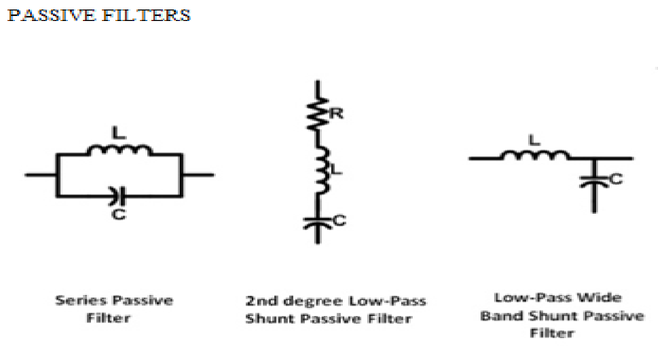

Figure 1: Passive Filters

3.2 Active Filter:

In this filter one or more compensating currents such as voltage source inverter (VSI) are used to provide the compensating currents or voltages to the nonlinear load. As a result of compensation, the non-linear load does not draw the non-sinusoidal components from the source and thus reduces harmonics.

4. Active filter types

Active filters are categorized into two main groups: single-phase and three-phase. Three-phase active filters may be with or without neutral connection. Single phase active filters are used to compensate power quality problems caused by single phase load, and three phase active filters are used for high-power nonlinear loads. Also active filter can be classified according to the connection of filter. The. Depending on the particular application or electrical problem to be solved, active power filters can be implemented as shunt type, series type, or a combination of shunt and series active filters (shunt-series type like UPQC). These filters can also be combined with passive filters to create hybrid power filters. The shunt-connected active power filter, with a self-controlled dc bus, has a topology similar to that of a static compensator (STATCOM) used for reactive power compensation in power transmission systems. Shunt active power filters compensate load current harmonics by injecting equal-but opposite harmonic compensating current. In this case the shunt active power filter a current source injecting the harmonic components generated by the load but phase-shifted by 180°.

5. Shunt active power filters

When the filter is connected parallel between the source and the load, is called as shunt active filter (SAF). These compensate current harmonics by injecting a compensating current harmonics equal in magnitude but opposite in direction, i.e. injecting the harmonic components generated by the load but phase shifted by 180. As a result, components of harmonic currents contained in the load current are cancelled by the effect of the active filter, and the source current remains sinusoidal and in phase with the respective phase to neutral voltage. This principle is applicable to any type of load considered as a harmonic source. It operates over a wide range of operating frequencies under varying load conditions. Equations are shown below [1].

IPCC = Iload + IInverter. … (1)

Now, Iload = Ifun (sinusoid) + I (harmonic component) … (2)

So, if IInverter = − {I (harmonic component)}, then IPCC = Iload = Ifun (sinusoid) … (3)

From equation (3), inverter generates current of equal magnitude but opposite polarity to the harmonic. This current generated by inverter is known as "compensating current" or "reference current". Equations are explained through following block diagram.

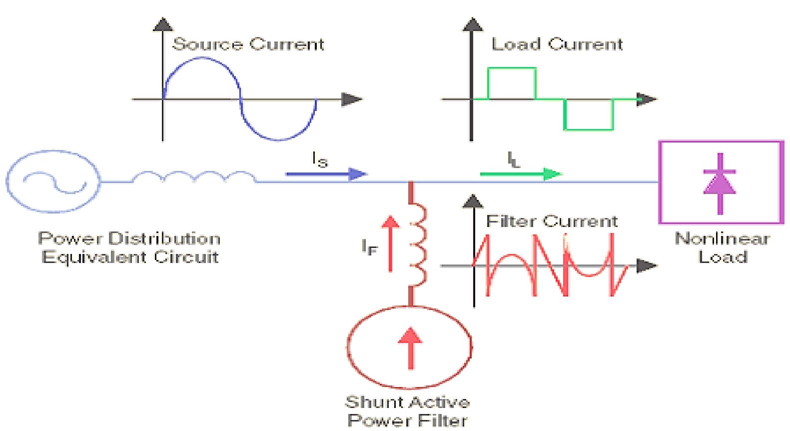

Figure 2: Block diagram of harmonic reduction process

6. Components of shunt active filter

The components of shunt active filter are Reference Current Generator, Control circuit and Voltage Source Inverter [1] .They are explained as below.

6.1 Reference current generator

This is the harmonic extractor. It estimates for what quantity of harmonics filter should compensate for. It determines all the multiple frequency components present in the current or voltage. The harmonics thus extracted become the reference for the controller circuit. There are different strategies or algorithms used for the calculation of reference currents in active power filter namely Instantaneous Reactive Power Theory (p-q theory), Unity Power Factor method, Fast Fourier Technique, One Cycle Control, etc. The paper describes the most common method used for harmonic extraction ie Synchronous Reference (SRF) Frame method to extract the three-phase reference currents (ica*, icb*, icc*) used by the active power filters.

6.1.1 Synchronous reference frame theory

Following figure explains SRF theory.

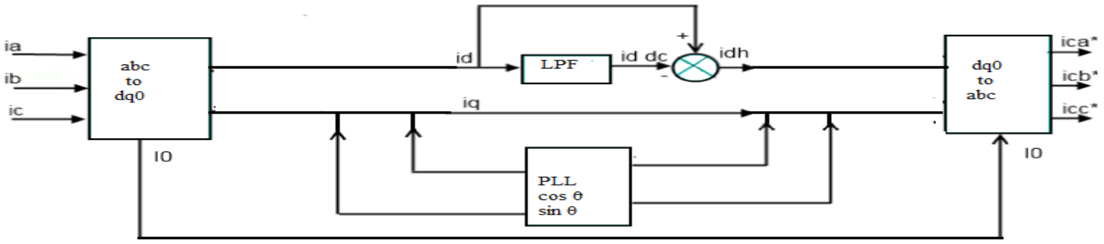

Figure 3.Block diagram of SRF theory

This algorithm makes use of park transformation. This transformation is used to convert three phase current or voltages into synchronously rotating d-q reference frame. It is done as follows:

$$\begin{bmatrix} i_q \\ i_d \\ i_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta-120) & \cos(\theta+120) \\ \sin\theta & \sin(\theta-120) & \sin(\theta+120) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

This transformation is done because in synchronous reference frame the fundamental component becomes a constant which can then be low pass filtered to leave behind the high frequency components which can easily be extracted. Also, Low pass filtering of a DC component does not cause any phase error in the signal which might be an issue if a High Pass filter was used. In this method, the load current is first converted from three phase to the d-q synchronous reference frame. The d-q currents thus obtained comprises of AC and DC parts. The fundamental component of current is represented by the fixed DC part and the AC part represents the harmonic component. The d component is passed through low pass filter (LPF).This component comprises of fundamental and harmonic component. LPF is second order butter-worth filter, whose cut-off frequency is selected as 50Hz so that higher order frequency harmonics are eliminated. Therefore fundamental frequency is the output of low pass filter [4]. This is subtracted from original d component to obtain the high frequency components. The q component represents the part of harmonic component. Hence is directly used. Inverse park transformation is then performed to obtain three phase harmonic signals.

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta-120) & \sin(\theta-120) & 1 \\ \cos(\theta+120) & \sin(\theta+120) & 1 \end{bmatrix}\begin{bmatrix} i_q \\ i_d \\ i_0 \end{bmatrix}$$

The PLL circuit provides the rotation speed (rad/sec) of the rotating reference frame, where t is set as fundamental frequency component [3].

6.2 Control Circuit

The control circuit produces pulses in order to drive the active filter inverter in such a way so as to generate the compensating current which is same as the reference obtained by reference current generator. There are numerous methods for active filter configurations such as Fuzzy logic current controller, artificial neural network current controller, etc. But hysteresis current control method is proven to be efficient because it's easy for implementation, quick current controllability can be achieved, its robust, provides fastest control with minimum hardware.

6.2.1 Hysteresis Current Controller

It consists of a hysteresis band surrounding the generated error current. The current error is obtained by subtracting the actual filter current from the reference current. The reference current is obtained by the SRF method which is represented as Iabc*. The actual filter current is represented as Ifabc. The error signal is then fed to the relay with the desired hysteresis band to obtain the switching pulses for the inverter [4].

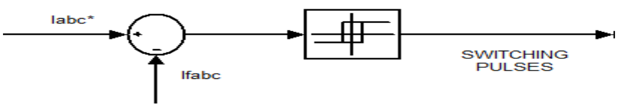

Figure 4: Hysteresis band current controller.

The operation of APF depends on the sequence of pulse generated by the controller. The operation of APF depends on the sequence of pulse generated by the controller. A band is set above and below the generated error signal. Whenever this signal crosses the upper band, the output voltage changes so as to decrease the input current and whenever the signal crosses the lower band, the output voltage changes to increase the input current. Accordingly switching signals are generated. According to the operating principle of the inverter, the output voltages of each phase are significant to the switching pulses of the switches in each leg. As a result, the switching gates for the active power filter can be obtained. The ripple of the generated current is dependent on different factors such as: instantaneous supply voltage, dc bus voltage, coupling inductor, and the switching time. The only controlled variable from these factors is the switching time. The switching time can be controlled by changing the hysteresis band.

6.3 Voltage source inverter

Most of the active power filter topologies use voltage source converters, which have a voltage source at the dc bus, usually a capacitor, as an energy storage device. By appropriately gating the power semiconductor switches it converts DC voltage into AC voltage. The pulses which are obtained by hysteresis controller are used as gating signals for the inverter. The inverter used is a 6 leg inverter which consists of IGBTS [5].

7. SimulationandResults

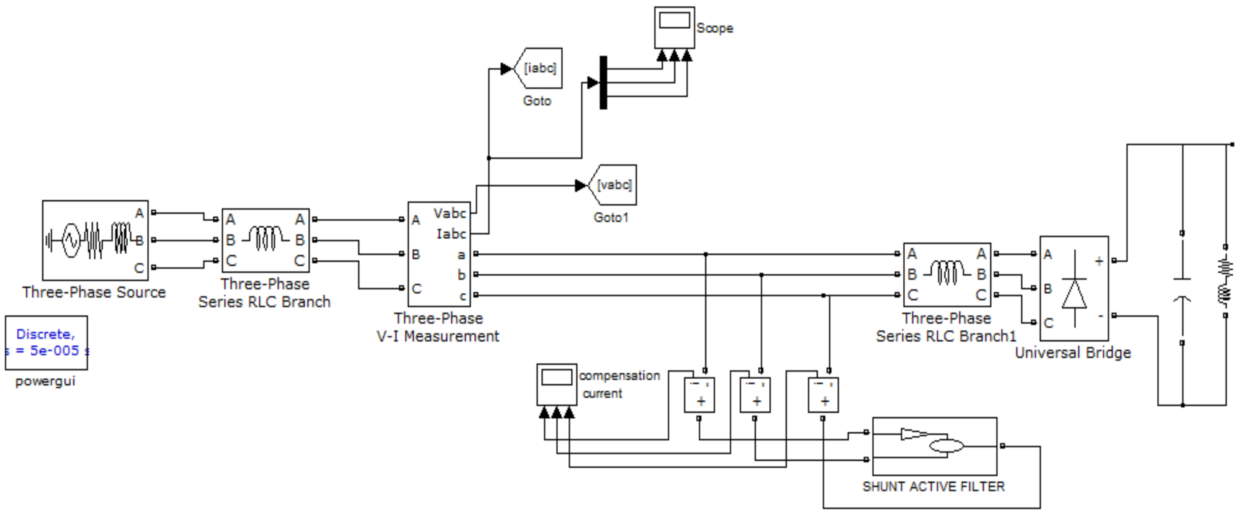

Figure 6: simulation of complete circuit

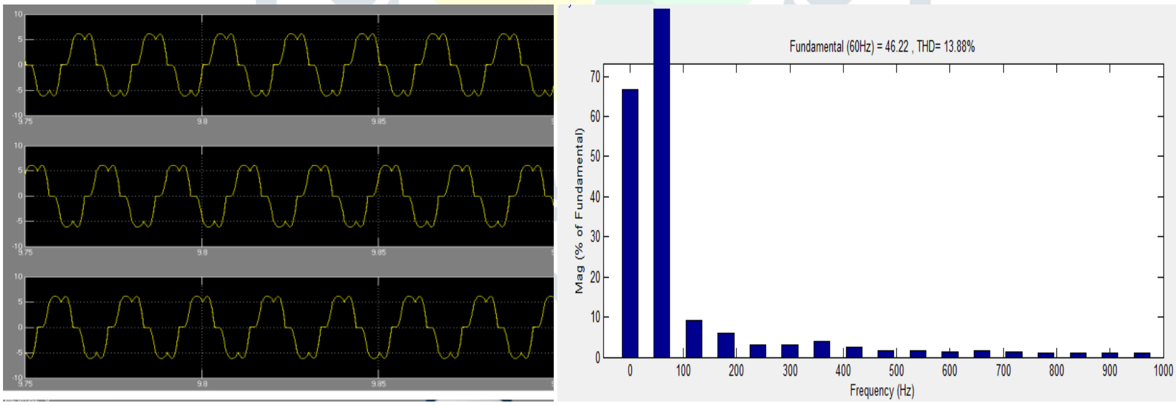

Figure 6: Current waveforms before connecting the filter showing harmonics

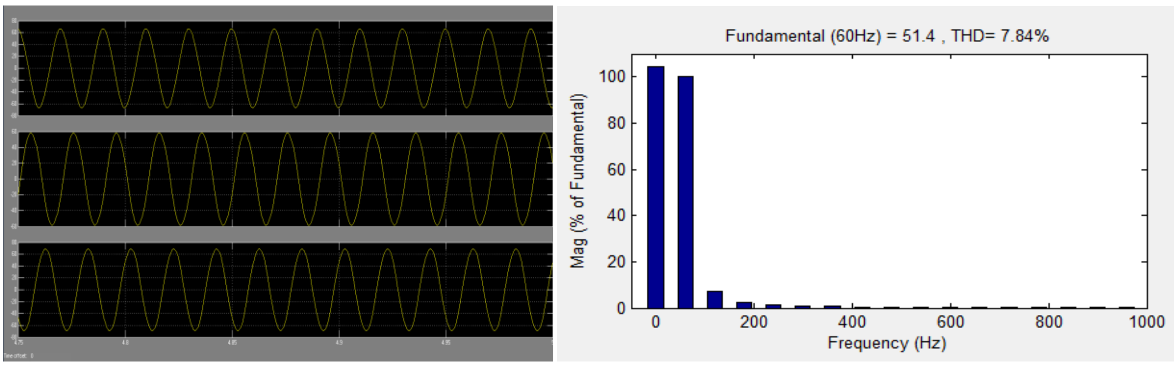

Figure 7: Current waveforms after connecting the filter

Table1. THD analysis

THD % Before connecting filter.	THD % After connecting filter
13.88	7.84

8. Conclusion

The circuit was implemented in mat-lab /Simulink. The harmonic compensation was achieved successfully using shunt active filter connected in parallel. The synchronous reference theory was used and was implemented for the estimation of reference currents. Hysteresis controller is efficient in producing the switching pulses to the IGBT's of the inverter such that it produces the compensating current to cancel out the harmonics produced by non-linear load.

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