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AN ANALYTICAL APPROACH TO HARMONIC ANALYSIS AND CONTROLLER DESIGN OF STATCOM

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Abstract: - The study of shunt connected FACTS devices is a connected field with the problem of reactive power compensation and better mitigation of transmission related problems in today's world. In this paper we study the shunt operation of FACTS controller, the STATCOM, and how it helps in the better utilization of a network operating under normal conditions. First we carry out a literature review of many papers related to FACTS and STATCOM, along with reactive power control. Then we look at the various devices being used for both series and shunt compensation. The study of STATCOM and its principles of operation and control, including phase angle control and PWM techniques, are carried out. We also delve into the load flow equations which are necessary for any power system solution and carry out a comprehensive study of the Newton Raphson method of load flow. Apart from this, we also carry out a study of the transient stability of power systems, and how it is useful in determining the behavior of the system under a fault. As an example, a six bus system is studied using the load flow equations and solving them. First this is done without the STATCOM and then the STATCOM is implemented and the characteristics of the rotor angle graph along with faults at various buses are seen. In this thesis, it is tried to show the application of STATCOM to a bus system and its effect on the voltage and angle of the buses. Next the graphs depicting the implemented STATCOM bus are analyzed and it is shown that the plots of the rotor angles show a changed characteristic under the influence of the STATCOM.

Keywords: Controller design, DC-link voltage, FACTS- statcom, Power factor.

I. INTRODUCTION

Power Generation and Transmission is a complex process, requiring the working of many components of the power system in tandem to maximize the output. One of the main components to form a major part is the reactive power in the system. It is required to maintain the voltage to deliver the active power through the lines. Loads like motor loads and other loads require reactive power for their operation. To improve the performance of ac power systems, we need to manage this reactive power in an efficient way and this is known as reactive power compensation. There are two aspects to the problem of reactive power compensation: load compensation and voltage support. Load compensation consists of improvement in power factor, balancing of real power drawn from the supply, better voltage regulation, etc. of large fluctuating loads.

Voltage support consists of reduction of voltage fluctuation at a given terminal of the transmission line. Two types of compensation can be used: series and shunt compensation. These modify the parameters of the system to give enhanced VAR compensation. In recent years, static VAR compensators like the STATCOM have been developed. These quite satisfactorily do the job of absorbing or generating reactive power with a faster time response and come under Flexible AC Transmission Systems (FACTS). This allows an increase in transfer of apparent power through a transmission line, and much better stability by the adjustment of parameters that govern the power system i.e. current, voltage, phase angle, frequency and impedance. The use of facts devices in a power system can potentially overcome limitations of the present mechanically controlled transmission systems. By facilitating bulk power transfers, these interconnected networks help minimize the need to enlarge power plants and enable neighboring utilities and regions to exchange power. The stature of FACTS devices within the bulk power system will continually increase as the industry moves toward a more competitive posture in which power is bought and sold as a commodity. As power wheeling becomes increasingly prevalent, power electronic devices will be utilized more frequently to insure system reliability and stability and to maximum power transmission along various transmission corridors.

The static synchronous compensator, or Statcom, is a shunt connected FACTS device. It generates a balanced set of three phase sinusoidal voltages at the fundamental frequency, with rapidly controllable amplitude and phase angle. This type of controller can be implemented using various topologies. A Static Compensator (Statcom) is a device that can provide reactive support to a bus. It consists of voltage sourced converters connected to an energy storage device on one side and to the power system on the other.

1.1 Objectives:

The study of shunt connected FACTS devices is a connected field with the problem of reactive power compensation and better mitigation of transmission related problems in today’s world. In this thesis deals the study of the shunt operation of FACTS controller, the STATCOM, and how it helps in the better utilization of a network operating under normal conditions. The main objectives of studying the STATCOM are described below.

1. A brief study about reactive power compensation using STATCOM.
2. Harmonic reduction by using STATCOM controller.
3. Studying the control techniques used for controlling the STATCOM.
4. Studying advantages of STATCOM over other Facts devices in reducing harmonics

1.2 Literature Survey:

A lot of literature has been presented to analyze and design a variety of controllers for the STATCOM. There are two control variables (phase angle and modulation index MI) as a sinusoidal pulse-width modulation (SPWM) technique is applied to generate the inverter output voltage of the STATCOM only the phase angle was employed as the control Variable.

The fast adjustment in inverter output voltage could not be achieved by this control scheme since the modulation index was held constant during the transient period. To achieve good dynamic response in inverter output voltage, a STATCOM control scheme with fixed and variable MI, a STATCOM controller with an adjustable modulation index during the transient period is designed by the pole assignment method to regulate ac system bus voltage in a very efficient manner. By comparing results obtained from the analytical approach, the computer simulations, and the experiments, it is concluded that the proposed analytical approach gives harmonic spectra which are very close to those from simulations and experiments.

II. FACTS CONTROLLERS AND REACTIVE POWER

2.1 Flexible AC transmission systems (FACTS) devices

Flexible AC transmission systems (FACTS) devices are installed in power systems to increase the power flow transfer capability of the transmission systems, to enhance continuous control over the voltage profile and/or to damp power system oscillations. The ability to control power rapidly can increase stability margins as well as the damping of the power system, to minimize losses, to work within the thermal limits range, etc. A power electronic-based system and other static equipment that provide control of one or more A C transmission system parameters.

2.2 Basic Types of Facts Controllers:

In general, FACTS Controllers can be divided into four categories:

- Series Controllers
- Shunt Controllers
- Combined series-series Controllers
- Combined series-shunt Controllers

STATCOM is used to connect in transmission system in shunt. All information about for the shut compensator.

III. STATCOM THEORY

3.1 Static Shunt Compensator: STATCOM

One of the many devices under the FACTS family, a STATCOM is a regulating device which can be used to regulate the flow of reactive power in the system independent of other system parameters. STATCOM has no long term energy support on the dc side and it cannot exchange real power with the ac system. In the transmission systems, STATCOMs primarily handle only fundamental reactive power exchange and provide voltage support to buses by modulating bus voltages during dynamic disturbances in order to provide better transient Characteristics, improve the transient stability margins and to damp out the system oscillations due to these disturbances.

A STATCOM consists of a three phase inverter (generally a PWM inverter) using SCRs, MOSFETs or IGBTs, a D.C capacitor which provides the D.C voltage for the inverter, a link reactor which links the inverter output to the ac supply side, filter components to filter out the high frequency components due to the PWM inverter. From the dc Side capacitor, a three phase voltage is generated by the inverter. This is synchronized with the ac supply. The link inductor links this voltage to the ac supply side. This is the basic principle of operation of STATCOM.

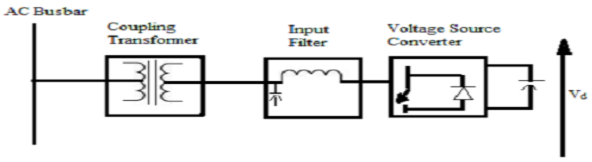


Fig.3.1 Block diagram of STATCOM

For two AC sources which have the same frequency and are connected through a series inductance, the active power flows from the leading source to the lagging source and the reactive Power flows from the higher voltage magnitude source to the lower voltage magnitude source. The phase angle difference between the sources determines the active power flow and the voltage magnitude difference between the sources determines the reactive power flow. Thus, a STATCOM can be used to regulate the reactive power flow by changing the magnitude of the VSC voltage with respect to source bus voltage.

3.2 Phase Angle Control:

In this case the quantity controlled is the phase angle δ. The modulation index "m" is kept Constant and the fundamental voltage component of the STATCOM is controlled by changing the DC link voltage. By further charging of the DC link capacitor, the DC voltage will be increased, which in turn increases the reactive power delivered or the reactive power absorbed by the STATCOM. On the other hand, by discharging the DC link capacitor, the reactive power delivered is decrease in capacitive operation mode or the reactive power absorbed by the STATCOM in inductive power mode increase.Forboth capacitive and inductive operations in steady-state, the STATCOM voltage lags behind AC line voltage ($\delta > 0$).

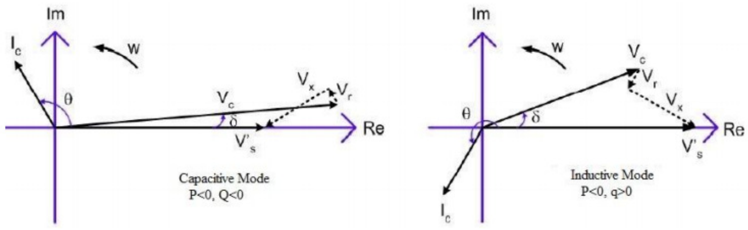


Fig.3.2 (a) Capacitive mode (b) Inductive mode

By making phase angle δ negative, power can be extracted from DC link. If the STATCOM becomes lesser than the extracted power, Pc in becomes negative and STATCOM starts to deliver active power to the source. During this transient state operation, V_d gradually decreases.

The phasor diagrams which illustrating power flow between the DC link in transient state and the ac supply is shown in above Fig.3.2 For a phase angle control system, the open loop response time is determined by the DC link capacitor and the input filter inductance. The inductance is applied to filter out converter harmonics and by using higher values of inductance; the STATCOM current harmonics is minimized. The reference reactive power (Q_{ref}) is compared with the measured reactive power (Q). The reactive power error is sent as the input to the PI controller and the output of the PI controller determines the phase angle of the STATCOM fundamental voltage with respect to the source voltage.

3.3 Pwm Techniques Used In Statcom:

Sinusoidal PWM technique: We use sinusoidal PWM technique to control the fundamental line to-line converter voltage. By comparing the three sinusoidal voltage waveforms with the triangular voltage waveform, the three phase converter voltages can be obtained. The fundamental frequency of the converter voltage i.e. fm, modulation frequency, is determined by the frequency of the control voltages, whereas the converter switching frequency is determined by the frequency of the triangular voltage i.e. fs, carrier frequency. Thus, the modulating frequency f1 is equal to the supply frequency in STATCOM. The Amplitude modulation ratio, m_a is defined as:

$$m_a = \frac{V_{control}}{V_{tri}}$$

Where $V_{control}$ is the peak amplitude of the control voltage waveform and V_{tri} is the peak amplitude of the triangular voltage waveform. The magnitude of triangular voltage is maintained constant and the $V_{control}$ is allowed to vary. The range of SPWM is defined for $0 \leq m \leq 1$ and over modulation is defied for $m > 1$.

The frequency modulation ratio m_f is defined as:

$$m_f = \frac{f_s}{f_i}$$

The frequency modulation ratio, m_f, should have odd integer values for the formation of odd and half wave symmetric converter line-to-neutral voltage (VA0). Thus, even harmonics are eliminated from the VA_0 waveform. Also, to eliminate the harmonics we choose odd multiples of m.The converter output harmonic frequencies can be given as:

$$f = (jm \pm k) f$$

The relation between the fundamental component of the line-to-line voltage (VA0) and the amplitude modulation ratio m_a can be gives as:

$$V_{A0} = m_a \frac{V_d}{2}, m_a \le 1$$

From which, we can see that Vao varies linearly with respect to m irrespective of m.

The fundamental component converter line-to-line voltage can be expressed as:

$$V_{LL1} = \frac{\sqrt{3}}{2\sqrt{2}} m_a V_d ; m_a \le 1$$

In this type of PWM technique, we observe switching harmonics in the high frequency range around the switching frequency and its multiples in the linear range. From above equation, we can see that the amplitude of the fundamental component of the converter line-to-line voltage is 0.612m V. But for square wave operation, we know the amplitude to be 0.78V. Thus, in the linear range the maximum amplitude of fundamental frequency component is reduced. This can be solved by over modulation of the converter voltage waveform, which can increase the harmonics in the sidebands of the converter voltage waveform. Also, the amplitude of VLL1 varies nonlinearly with m and also varies with m in over modulation as given In a Constant DC Link Voltage Scheme the STATCOM regulates the DC link voltage value to a fixed one in all modes of operation. This fixed value is determined by the peak STATCOM fundamental voltage from the full inductive mode of operation to full capacitive mode at minimum and maximum voltage supply. Therefore, for $0 \le ma \le 1$; the fundamental voltage is varied by varying ma in the linear range.

3.4 Shunt Compensation:

It has long been recognized that the steady-state transmittable power can be increased and the voltage profile along the line controlled by appropriate reactive shunt compensation. The purpose of this reactive compensation is to change the natural electrical characteristics of the transmission line to make it more compatible with the prevailing load demand. Thus, shunt connected, fixed or mechanically switched reactors are applied to minimize line overvoltage under light load conditions, and shunt connected, fixed or mechanically switched capacitors are applied to maintain voltage levels under heavy load conditions.

In this Report, basic considerations to increase the transmittable power by ideal Shunt-connected var compensation will be reviewed in order to provide a foundation for power electronics-based compensation and control techniques to meet specific compensation objectives. The ultimate objective of applying reactive shunt compensation in a transmission system is to increase the transmittable power. This may be required to improve the steady-state transmission characteristics as well as the stability of the system. Var compensation is thus used for voltage regulation at the midpoint (or some intermediate) to segment the transmission line and at the end of the (radial) line to prevent voltage instability, as well as for dynamic voltage control to increase transient stability and "damp power oscillations”

3.5 STATCOM Operating Principle at Fundamental Frequency:

As shown in Fig. 3.4 two impedance loads (one is fixed and the other is connected to the point of common coupling (PCC) through a switch) are supplied power from a distribution substation with source voltage V_S through a distribution feeder with the impedance R_S+JWL_S. To regulate the PCC bus voltage, a STATCOM, which is composed of a VSI and a dc capacitor, is included. The STATCOM is connected to the PCC through a coupling transformer and a filtering inductor which can be represented by the series impedance R_S+JWL_f.

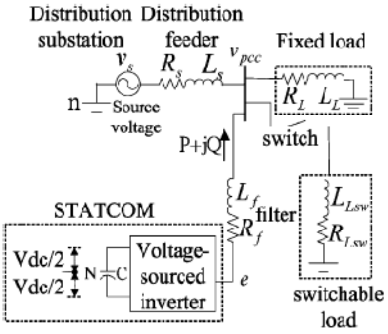


Fig. 3.3 Single-line diagram of a STATCOM connected to a power system

3.6. STATCOM Output Power:

Under balanced three-phase conditions, it is convenient to use the per-phase equivalent circuit as shown in Fig.3.5(a) to explain how the STATCOM output reactive power can be modulated by a VSI using the pulse-width modulation (PWM) technique. For simplicity, the resistances of the coupling transformer and filtering inductor are neglected. The complex power supplied by the STATCOM to the ac power system is given by the following equations:

$$P = \frac{|E_{an1}||V_{pcca}|}{X_f}\sin\alpha$$

$$Q = -\frac{|V_{pcca}|^2}{X_f} + \frac{|E_{an1}||V_{pcca}|}{X_f}\cos\alpha. \qquad \text{................(3)\&(4)}$$

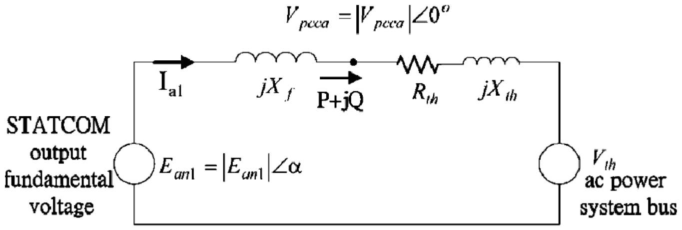


Fig. 3.4(a)

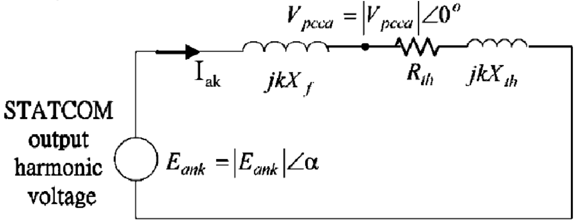


Fig3.4 (b) Single-phase equivalent circuit of a STATCOM connected to a power system. (a) At fundamental frequency. (b) For harmonic analysis.

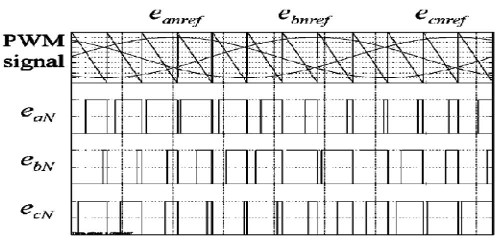


Fig3.5. PWM modulation process with a trailing-edge saw-toothed waveform and the STATCOM output voltage to the neutral N of the dc capacitor.

It is obvious from (3) and (4) that the STATCOM real power output and reactive power output can be controlled by either its output voltage magnitude or its phase angle or both. In the design of a STATCOM controller, the reactive power output is of major concern to us since the negative of simply gives us the real power that must be supplied by the ac bus to the STATCOM in order to cover the converter loss and transformer and filter loss.

IV. SIMULATION RESULTS

To examine the effectiveness of the proposed analytical approach to the analysis of the line to neutral harmonic voltage and the proposed STATCOM controller with the steady state modulation-index regulator and transient modulation index controller, the system in Fig. 4.1 was simulated using MATLAB /Simulink. In addition, a prototype STATCOM for the simple power distribution system in Fig. 4.1 has been set up in the laboratory. The simulation and experimental results of the proposed STATCOM controller at steady state. The harmonic spectra of the STATCOM output voltage and current from the analytical harmonic analysis method, computer simulations and experiments. Note that the system parameters used in the simulations were the same as those used in the experiments as described in Table I. Both steady-state performance and dynamic responses were investigated. The main purpose for the simulations and the experiments is to show that the proposed analytical approach to the analysis of line to neutral harmonic voltage can perfectly describe the behavior of the STATCOM harmonics, and the proposed STATCOM controller can generate lower harmonic voltages and currents than the STATCOM controller with fixed and variable MI at steady state.

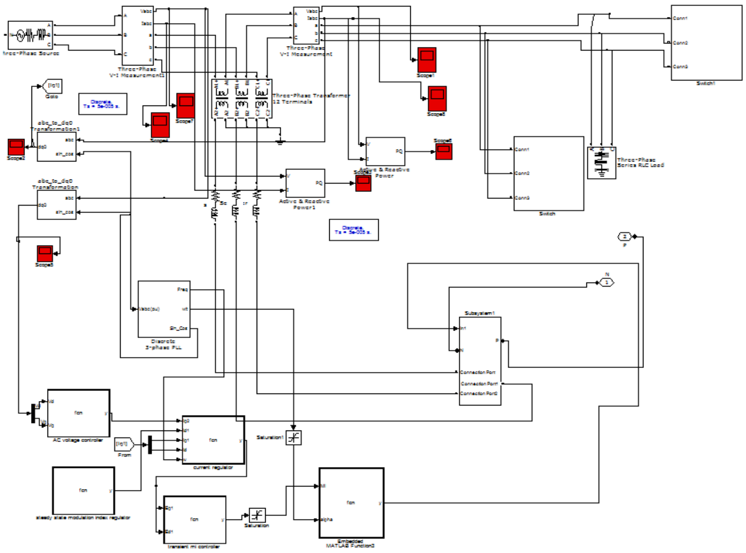
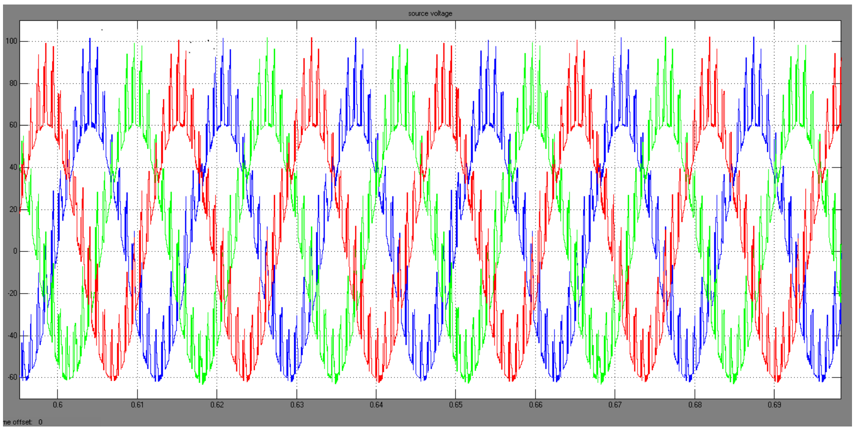


Fig5.1 simulink model of proposed STATCOM

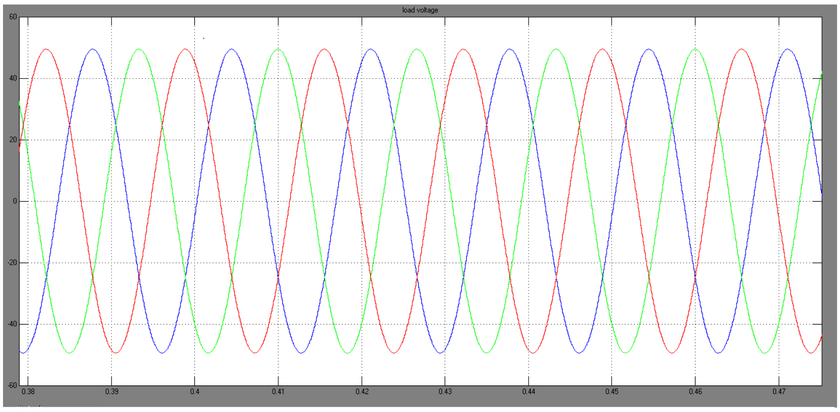
5.2 Load voltage with harmonic waveform:

The following fig, load voltage with harmonic waveform shows DSTATCOM is connected at PCC, due to satisfactory operation of STATCOM harmonic are present in load voltage. To suppress the voltage STATCOM injects the voltage at PCC with controller.



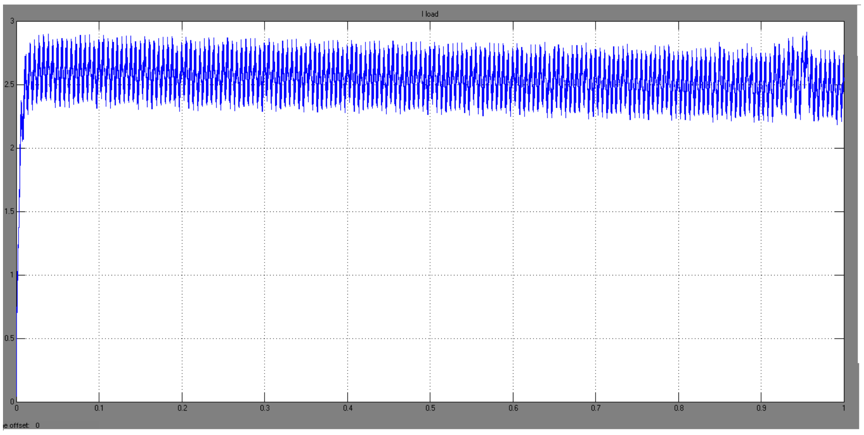
5.3 Harmonic free waveform:

To suppress the harmonic STATCOM is connected at PCC because of shunt connected STATCOM harmonics are injected from load voltage as shown in following fig. which is harmonic free wave form.



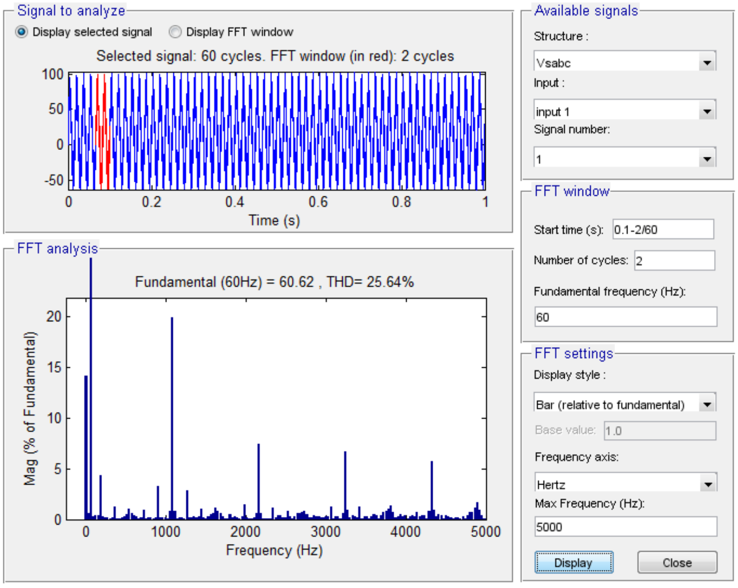
5.4 STATCOM output current:

Following figure shows the output current of the STATCOM also fig shows the harmonic Contained current at PCC.



5.5 Harmonic analysis in FFT source side (phase 1):

Following fig. shows analysis of harmonics in FFT of Vsabc at phase 1. Also fig shows total harmonic distortion at fundamental frequency (60Hz)



● Display selected signal ○ Display FFT window

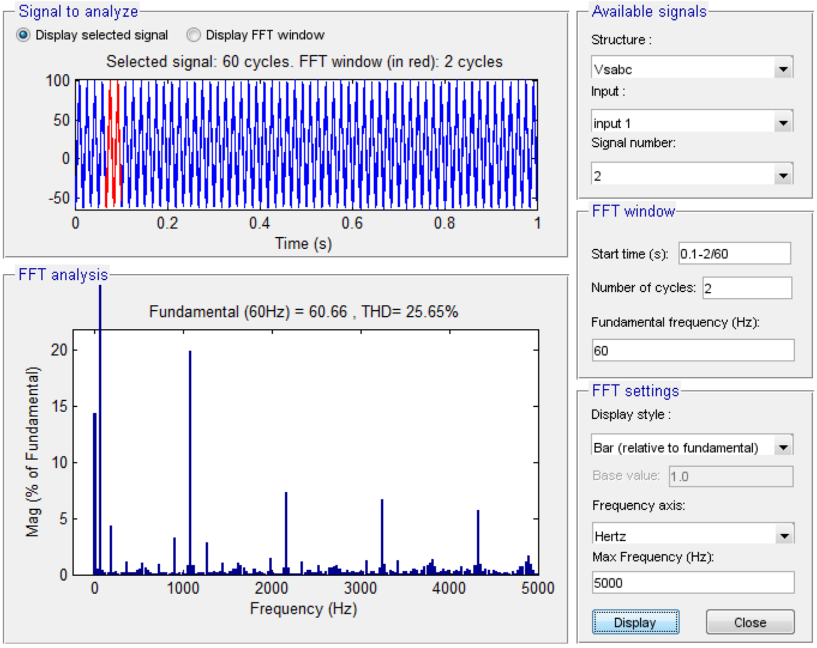
Selected signal: 60 cycles. FFT window (in red): 2 cycles

Fundamental (60Hz) = 60.62 , THD= 25.64%

Structure : Vsabc
Input : input 1
Signal number: 1
Start time (s): 0.1-2/60
Number of cycles: 2
Fundamental frequency (Hz): 60
Display style : Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz
Max Frequency (Hz): 5000

5.6 Harmonic analysis in FFT source side (phase 2):

Following fig. shows analysis of harmonics in FFT of Vsabc at phase 2. Also fig shows total harmonic distortion at fundamental frequency (60Hz)



● Display selected signal ○ Display FFT window

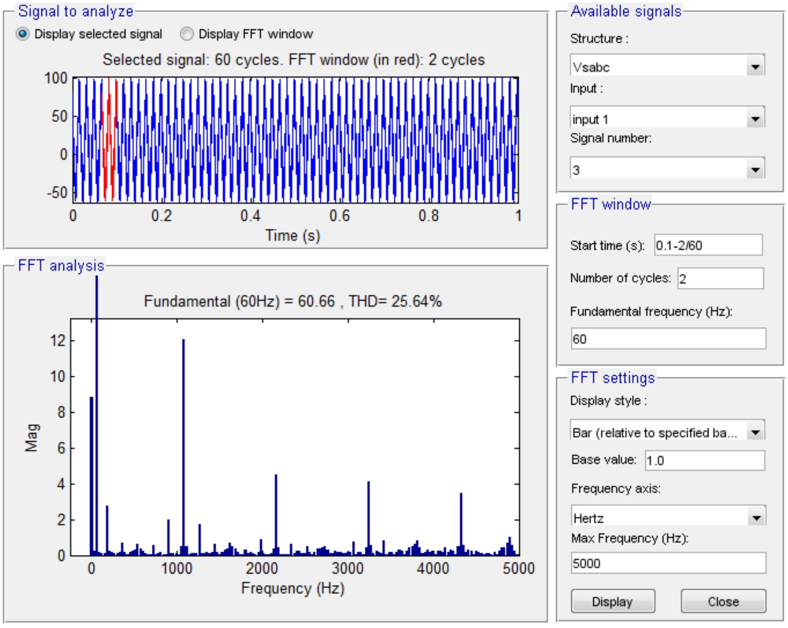
Selected signal: 60 cycles. FFT window (in red): 2 cycles

Fundamental (60Hz) = 60.66 , THD= 25.65%

Structure : Vsabc
Input : input 1
Signal number: 2
Start time (s): 0.1-2/60
Number of cycles: 2
Fundamental frequency (Hz): 60
Display style : Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz
Max Frequency (Hz): 5000

5.7 Harmonic analysis in FFT source side (phase 3):

Following fig. shows analysis of harmonics in FFT of Vsabc at phase 3. Also fig shows total harmonic distortion at fundamental frequency (60Hz)



Signal to analyze
● Display selected signal ○ Display FFT window
Selected signal: 60 cycles. FFT window (in red): 2 cycles

FFT analysis
Fundamental (60Hz) = 60.66 , THD= 25.64%

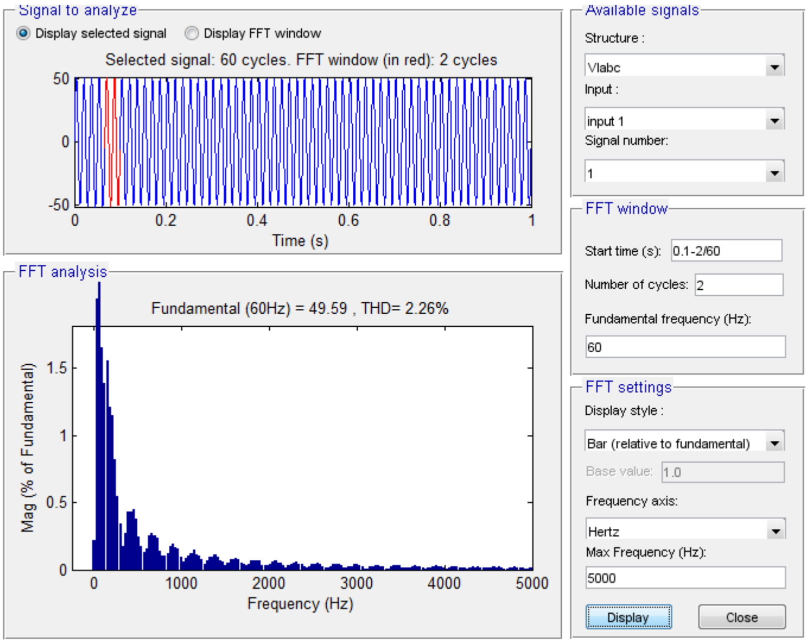
Available signals
Structure : Vsabc
Input : input 1
Signal number: 3

FFT window
Start time (s): 0.1-2/60
Number of cycles: 2
Fundamental frequency (Hz): 60

FFT settings
Display style : Bar (relative to specified ba...
Base value: 1.0
Frequency axis: Hertz
Max Frequency (Hz): 5000

5.8 Harmonic analysis in FFT at load side (phase 1):

Following fig. shows analysis of harmonics in FFT of Vlabc at phase 1.also fig. shows Total harmonic distortion of load voltage after injected by the STATCOM.



Signal to analyze
● Display selected signal ○ Display FFT window
Selected signal: 60 cycles. FFT window (in red): 2 cycles

FFT analysis
Fundamental (60Hz) = 49.59 , THD= 2.26%

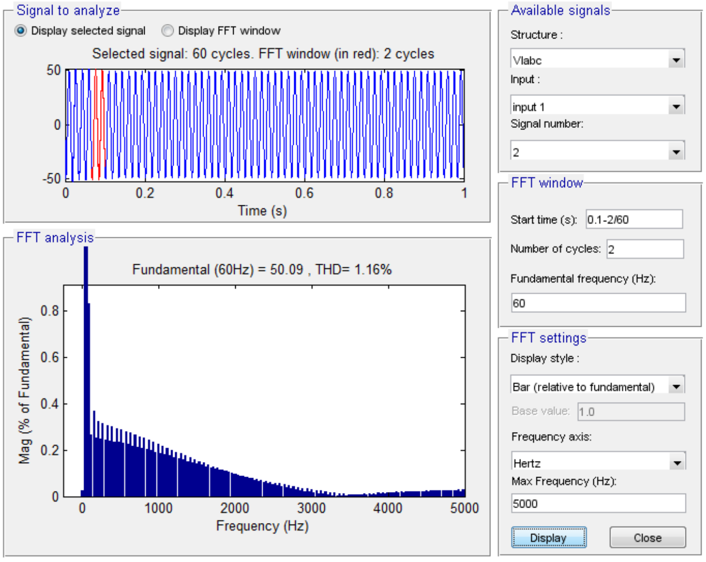
Available signals
Structure : Vlabc
Input : input 1
Signal number: 1

FFT window
Start time (s): 0.1-2/60
Number of cycles: 2
Fundamental frequency (Hz): 60

FFT settings
Display style : Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz
Max Frequency (Hz): 5000

5.9 Harmonic analysis in FFT at load side (phase 2):

Following fig. shows analysis of harmonics in FFT of Vlabc at phase 2.also fig. shows Total harmonic distortion of load voltage after injected by the STATCOM.



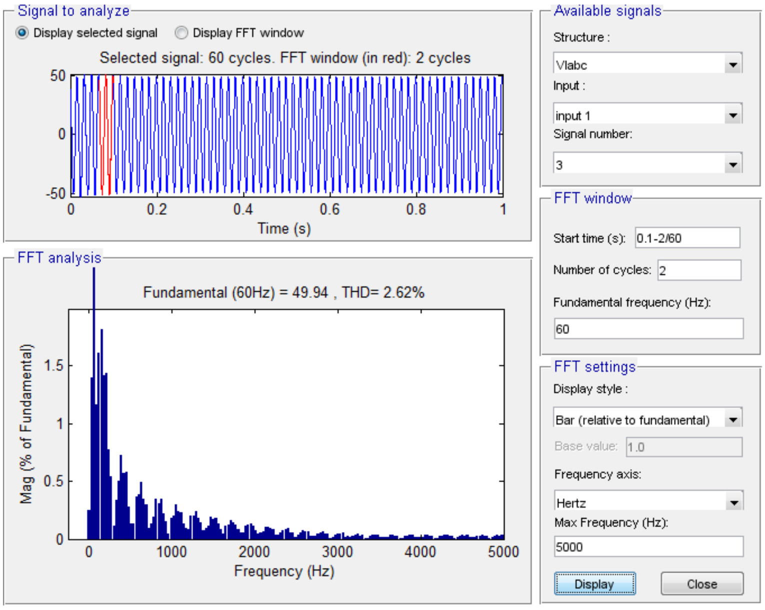
Selected signal: 60 cycles. FFT window (in red): 2 cycles

Fundamental (60Hz) = 50.09 , THD= 1.16%

Structure : Vlabc
Input : input 1
Signal number: 2
Start time (s): 0.1-2/60
Number of cycles: 2
Fundamental frequency (Hz): 60
Display style : Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz
Max Frequency (Hz): 5000

5.9 Harmonic analysis in FFT at load side(phase 3):

Following fig. shows analysis of harmonics in FFT of Vlabc at phase 3.also fig. shows Total harmonic distortion of load voltage after injected by the STATCOM.



Selected signal: 60 cycles. FFT window (in red): 2 cycles

Fundamental (60Hz) = 49.94 , THD= 2.62%

Structure : Vlabc
Input : input 1
Signal number: 3
Start time (s): 0.1-2/60
Number of cycles: 2
Fundamental frequency (Hz): 60
Display style : Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz
Max Frequency (Hz): 5000

Table I] System Parameters Used In Simulations and Experiments

Fundamental frequency	f=60 hz
Source voltage	V_s=78v $_{peak}$(110VLL_{rms})
Source resistance	R_s= 0.7 ohm
Source inductance	L_s=1.6mH
Filter inductance	L_f=0.01H
Filter resistance	R_f=0.4

Switching frequency	f_c=1920hz
DC capacitor capacitance	C=2200microf
Estimated inverter loss	R_p=5000ohm
Reactance of fixed RL load	L_L=40mH
Resistance of fixed RL load	R_L=8.4 ohm
Reactance of switched RL	L_{LSW}=35.5mH
Resistance of switched RL	R_{LSW}=7ohm
Sampling frequency	F_s=15360Hz

Table ii] System Eigen Values at Full Load:

System with STATCOM but without controller	System with STATCOM and with AC voltage controller(K_1=15, K_2= 15,K_3=10,K_4=50 ,K_5=-1.23,and K_6=-60)
-227±j377	-216±j377
-85±j377	-2070,-420
-0.187	-7.94
	-9.06±j9.06
	-1,-1

V. CONCLUSION

This project focuses on harmonic reduction in ac system with the use of STATCOM controller. Here we used simulation to see different parameters related to harmonic spectra. A STATCOM controller, which comprises an ac voltage controller, a current regulator, a steady-state modulation-index regulator, and a transient modulation-index controller, has been proposed in this work. Through the fast adjustment of the modulation index during the transient period, the ac bus voltage can be regulated in a very efficient manner since the STATCOM reactive power output can be modulated rapidly. The steady-state harmonics generated by the STATCOM can be kept minimal as the modulation index is held constant at the reference value (MI^*=1 in this work) at steady state by the steady-state modulation-index regulator. By comparing the harmonic spectra for the proposed STATCOM controller and those for the STATCOM controller with fixed V_{dc}^* and variable MI, it has been concluded that the proposed STATCOM controller generates lower harmonic contents than the STATCOM controller with fixed V_{dc}^* and variable MI.

VI. FUTURE SCOPE

We can implement this project in hardware by using IGBT driving circuit.

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