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Application of Shunt Active Power Filter for Dynamic Compensation of Reactive Power & Harmonics for 12-pulse Converter Power Supply of Tokamak Superconducting Coils

Paul D. Christian[1] , Mihir Chaudhari[2]

[1]*LDRP-ITR, Gandhinagar, INDIA / Institute for Plasma Research, Bhat, Gandhinagar.*
[2]*LDRP-ITR, Gandhinagar, INDIA*

Abstract—*AC/DC Converters Power Supplyof a Tokamak machine (for the Toroidal Field (TF) and Poloidal Field(PF) superconducting magnet coils) draws significant inductive reactive power from the AC supply system and also produces harmonics in the supply AC Currents. The quantum of reactive power demand and the current harmonics produced varies dynamically, depending on various system parameters, like load current of each magnet coil, quality of AC supply voltage, inductance of magnet coils etc.*
Fixed compensation solutions, e.g. passive filters, are not suitable for the subject application, as they may result in over/under compensation. Also, other solutions like SVC, FC-TCRs etc require passive components like capacitors or inductors, which have short service life. The Shunt Active Power Filter (SAPF) with comparatively smaller size capacitors & inductors can provide the same level of compensation and have a faster response to load changes.
In this paper, the modeling&simulation of AC/DC Converter Power Supply System of a typical Tokamak machine has been described, to determine the Reactive Power demand & Harmonics produced at the PCC. Then the modeling & simulation of Shunt Active Power Filter (SAPF), based on Instantaneous Reactive Power Theory(p-q Theory) has been described. The performance of the SAPF under unbalanced & distorted supply voltage conditions has also been evaluated.

Index Terms—*12-pulse AC-DC Converter; Extended Delta Transformer;Tokamak Superconducting Coils; Shunt Active Power Filter.*

I. INTRODUCTION

FOR fusion experiments using the Tokamak - with Toroidal magnetic confinement concept, superconducting magnet coils are used to produce magnetic field as per the physics requirements. Several magnet coils for Toroidal Field (TF) and Poloidal Field (PF) are used in specific arrangement. Superconducting type of coils are used for long duration operations, as an economical option. These superconducting coils have a typically near zero resistance and inductance values from 2mH to 1200mH. These coils produce high magnetic fields with profiled high DC currents. The experiment has two phases, a ramp phase and a flat top phase. In the ramp phase, direct current in the different TF & PF coils is raised up to certain pre-determined values. In the flat top phase, the currents are maintained nearly constant. The load current profile demands higher ramp phase voltage as compared to the hold phase voltageThe flat top phase may extend up to 1000s during which the coil current profile for different pulses range from 5 to 100%. Further, for accurate shaping and position control of the plasma, the DC current supplied to the superconducting magnet coils have to be precisely controlled.

The TF & PF coils require very high DC current (~10KA to 50KA) for the production of required magnetic field. The load current profile of each magnet coil can have different profiles, ranging from 5% to 100%, in terms of the physics requirements. The combined reactive power demand & harmonics produced by the converter system at the point of common connection (PCC) varies dynamically.

To meet the above power supply requirement of low voltage high current DC power supply of superconducting magnet coils, differentconfigurations of AC-DC converters are used. Amongst the different configurations available for the Power supply of the superconducting magnet coils, the choice is driven by factors such as high current with relatively low voltage dc output, high ramp voltage as against low hold voltage and converter device utilization. Theselection of a particular configuration is based onthe dynamic performance, harmonic generation, stability etc.

1.1 Method for Analysis:
The conversion of AC to DC supply injects harmonics in the AC supply system. The load profile, i.e. the DC load current requirement of the TF & PF coils is varying widely in view of the wide variations in plasma physics. The superconducting magnet coils have large inductance values and nearly zero resistance values. The coil current profile demands higher ramp phase voltage as compared to the hold phase voltage. In view of the above parameters and characteristics, the behavior of the AC/DC power conversion and supply system is very dynamic.

For the design of a Reactive Power & Harmonics Compensation solution, it is necessary to find out the quantum of instantaneous reactive power demand and the magnitude & order of different harmonics injected in the supply ac current, either by actual measurement or by simulation.

As the reactive power demand & harmonics production can have large variations in terms of the dynamics of the system, it is very difficult and cumbersome to analyze the behavior of the system through analytical methods. Further, as the behavior of the system is very dynamic under different operating conditions, practical measurement of the harmonics is not much useful to determine an optimum Harmonic Filter solution for the system.

Therefore, Simulation is the best suited method for analysis of such system, as different operating scenarios can be easily simulated and the behavior of the system can be easily analyzed by accurate modeling of the system.Also, the simulation method is convenient to assess the effectiveness of the compensation solution under different loading conditions as well as different conditions of the ac supply voltage.

1.2 Problems/assumptions & solution:
To meet the rated current requirement of about 10KA to 20KA of the magnet coils, multiple thyristors are connected in parallel configuration (Thyristor set) in actual systems. However, for simulation, a single thyristor has been used in each phase leg.

The Superconducting coils have resistance values in the range of nΩ. The connecting busbars, cables, terminal connections etc. are assumed to contribute resistance of about 1mΩ. Therefore, the superconducting magnet coils has been modeled as an RL load with resistance value of 1mΩ.

Desired load current profiles for three typical magnet coils have been simulated for verifying the performance of the model.

In practical systems, there are many linear and non-linear (AC/DC converter power supplies) load connected at the Point of Common Coupling(PCC) and the prospective Reactive Power & Harmonic Compensation solution has to be connected at the PCC. However, because of limitation in computer simulation, only three non-linear loads have been modeled & simulated.

II. BASIC SCHEMATIC

The basic schematic of the AC-DC converter power supply is shown in Fig.1 below. There are two converter transformers, one with extended delta D(+15^0) primary and two secondaries - one y0 and the other y6 connection. The other converter transformer is with extended delta D(-15^0) primary and two secondaries - one y0 and the other y6 connection. This configuration results in 12-phase secondary output voltage waveforms, with 30^0 phase displacement between the consecutive phases.

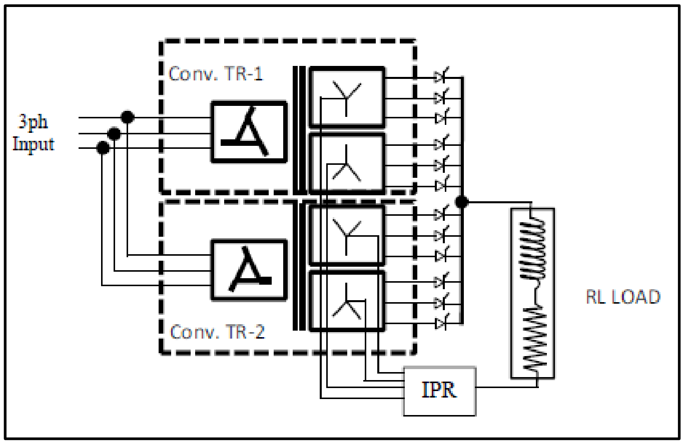

Fig.1. Basic Schematic of the 12-pulse AC-DC Converter Power Supply.

Each of the secondary line is connected with a thyristor set (multiple thyristors connected in parallel as required for rated capacity). The combined output voltage of one such secondary winding is connected in parallel with the secondary voltage of the other three windings. Thus there are 12 thyristor sets connected to phase shifted windings, resulting in a 12-pulse output DC voltage waveform.

The 12-pulse output DC voltage positive terminal is connected to the RL load (magnet coil), whereas the negative terminal is connected to the neutral terminals of the four secondaries through an Interphasing Reactor.

Load Current control is achieved by controlling the output DC Voltage through firing angle control of the thyristors.

The power supply for such superconducting magnet coil have been modeled using MATLAB®& simulated using Simulink®, for a 12-pulse AC-DC Converter with extended delta D($\pm 15^0$)y0-y6 converter transformer, H3 bridge (i.e. Half Bridge configuration having Three Thyristors connected in bridge configuration in a three phase system) and an Interphasing Reactor, which has been described in this paper. This choice is driven by the requirements which include,

- High current output at low voltage.
- High ramp up phase voltage as compared to hold phase voltage.
- Dynamic current balance between transformer windings.

The no load output DC voltage of Thyristor converter is given by,

$$E_d = E_{do} + E_\alpha + E_x \qquad (1)$$

Where, E_d = Output DC Voltage.
E_{do} = No load output DC Voltage.
E_α = Voltage drop due to phase control
E_x = Reactive Voltage drop.

For a 12-pulse converter, the no load output DC Voltage is give by [1],

$$E_{\mathrm{do}} = 0.989\, E_{\mathrm{m}} \qquad (2)$$

Where, E_m = Peak Value of the Converter Transformer Secondary Voltage.
Depending on winding connections, the line-to-line voltage of the transformer secondary winding may lead or lag its primary voltage by a phase angle δ.

The transformer can produce a phase shifting angle δ, defined by,

$$\delta = \angle V_{ab} - \angle V_{AB} \qquad (3)$$

Where, V_{AB} and V_{ab} are the phasors for the primary and secondary line-to-line voltages V_{AB} and V_{ab}, respectively.
The winding connection diagram for the extended delta D($+15^0$)y0y6 connection is shown in Fig. 2.As shown in Fig. 2, the primary winding is composed of two sets of coils having N1 and N2 turns per phase. The N2 coils are connected in delta and

then in series with the N1 coils. The secondary winding is connected in wye with N3 turns per phase. Such an arrangement is known as extended-delta connection [2]. The winding connection diagram for extended deltaD(-15^0)y0y6 connection is shown in Fig. 3.

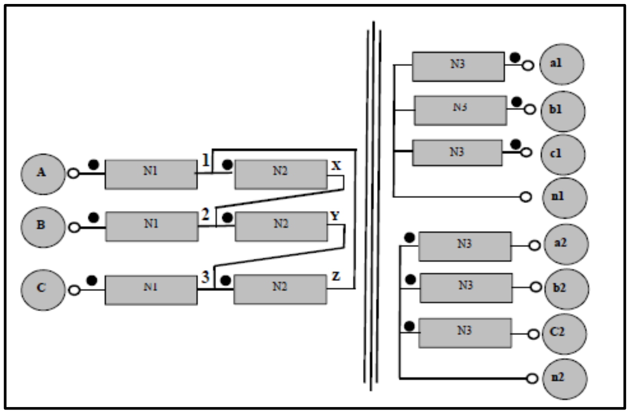

Fig. 2. Connection Diagram for Extended Delta Transformer (D+150 y0 y6)

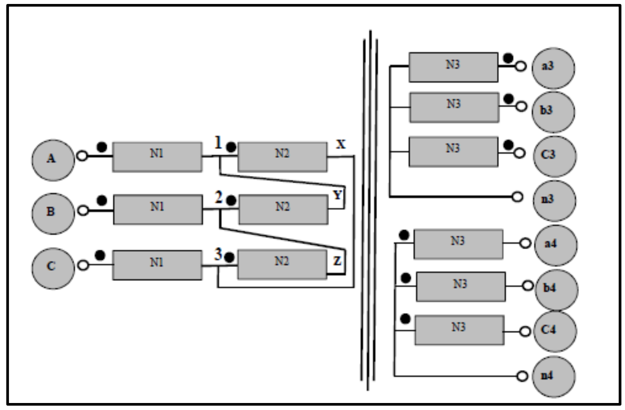

Fig. 3. Connection Diagram for Extended Delta Transformer (D-150 y0 y6)

For the particular Converter Transformer with extended delta primary and two secondaries, there is no suitable block readily available in the Simulink® library which can be used directly. Therefore, for the modeling of the converter transformer, the multi-winding transformer block available in Simulink® library has been used and configured as the extended delta converter transformer. The secondary voltage waveforms (with unity transformation ratio) for each of the four secondaries and their combined output, together with the primary supply voltage waveform are shown in Fig. 4 and Fig. 5, which shows that these converter transformer pair results in 12-phase secondary waveforms.

Interphase Reactors are used to support ac voltage differences existing between converter outputs and allows the converters to act as if they are operating alone. However, they cannot help balance the steady state differences in DC voltage. The windings carry both dc and ac currents. Connections are made such that dc currents, flowing to the load, cause opposing ampere-turns on the core [3].

I. G. Park and S. I. Kim [4], have described in detail the analysis of Multi-Interphase Transformers for connecting power converters in parallel.Also, R.S.Bhide and S.V. Kulkarni [5], have described in detail the Modeling & Analysis of two three pulse controlled converters with Interphase Transformer.

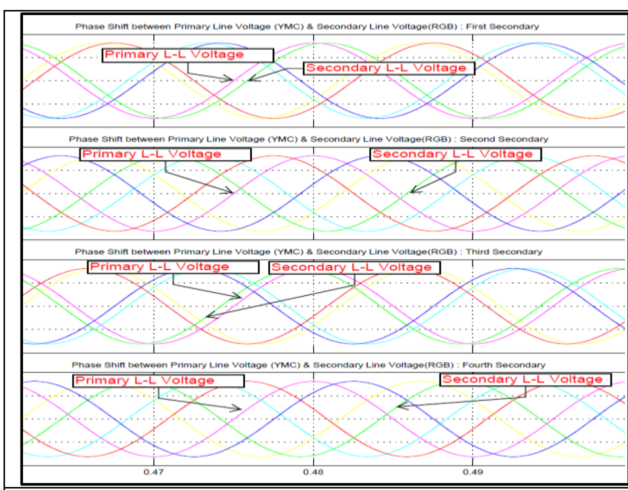

Fig. 4. Phase Shift between Primary Line Voltage and Secondary Line Voltage.

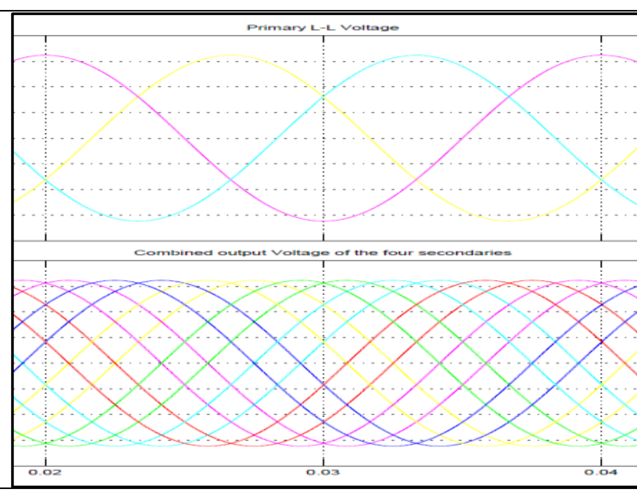

Fig. 5. Primary Line Voltage and Combined Secondary Voltage Waveform of the four secondaries.

III. System Description

The AC/DC converter power supply system is fed through a 415V Main LT Panel as shown in Fig.6. The Shunt Active Power Filter (SAPF) is to be connected at the Point of Common Coupling (PCC), so that the consolidated reactive power demand & Harmonics produced by all the AC/DC converter power supplies, is compensated by a common SAPF.

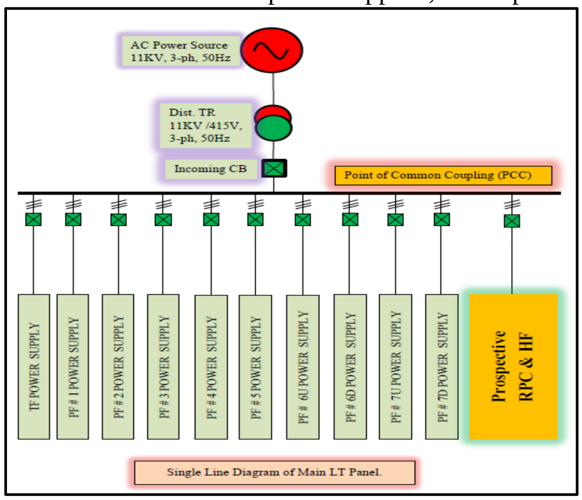

Fig.6. SLD of Converter Power Supply

IV. Shunt Active Power Filter

The concept of Shunt Active Filters (SAFs) was introduced by Gyugyi and Strycula in 1976. Nowadays, many SAFs are in commercial operation all over the world. For dynamic compensation of the Instantaneous Reactive Power and ac Supply Current Harmonics, VSC based PWM Inverter is used as a Shunt Active Power Filter(SAPF). The 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 a control algorithm for active filtering. The Instantaneous Reactive Power Theory (*p-q* theory) introduced by H. Akagi et al [6]in 1984 forms a very efficient basis for designing active filter controllers.

E. Watanabe, H. Akagi and M. Aredes[7] discussed some problems and solutions for Active Filter Control based on the PQ theory.

Joao Afonso et al. [8] have presented the Active Filters with control based on the P-Q Theory. This paper also discusses the control strategy for the constant instantaneous supply power and the control strategy for sinusoidal supply current.

A comprehensive review of the Active Filters for power quality improvement have been provided by Bhim Singh et al. [9]referring to more than 200 research publication on the subject.

Juan Dixon et al. [10] have presented a detailed overview of the state of the art in reactive power compensation technologies. The paper presents the principle of operation; design characteristics and application examples of VAR compensators implemented with thyristors and self-commuted converters.

Hysteresis Band PWM technique has been used for the SAPF current control. The SAPF has been configured for full dynamic compensation of reactive power &ac supply current harmonics.

The circuit diagram of the SAPF is shown in Fig. 7.

The power system model with SAPF is shown in Fig. 8.

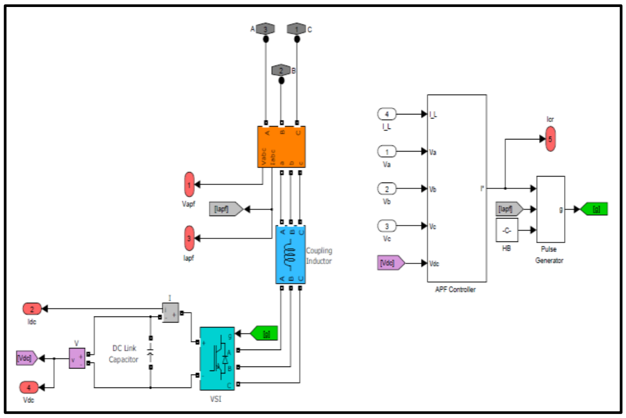

Fig. 7. Circuit Diagram of SAPF

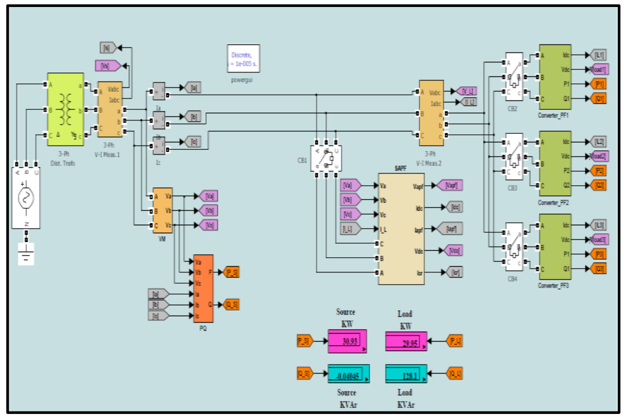

Fig. 8. Power System Model with SAPF

V. Unbalanced & Distorted AC Supply Voltage

In practical situations, the utility supply voltage is often unbalanced and/or is distorted due to harmonics. For assessing the performance of the system under such abnormal ac supply voltage conditions, the following unbalance & voltage harmonics has been simulated for the ac supply voltage.

Time variation of amplitude in R-Phase Voltage was applied as per Table-1 and Harmonics in the supply voltage was applied as per Table-2.

Table 1: Amplitude Variation of R Phase Supply Voltage.

Amplitude, in pu	1	0.8	1.2	1.15	1.0	0.85	1	1.2	1.0
Time, in Sec	0	0.07	0.10	0.15	0.20	0.25	0.30	0.35	0.40

Table 2: Supply Voltage Distortion

Particulars	**Order (n)**	**Amplitude (pu)**	**Phase (degrees)**	**Sequence (0, 1 or 2)**
Harmonic A	5	0.05	-10	2
Harmonic B	7	0.10	25	1
Time in Sec	**Start**		**End**	
	0.100		0.450	

The simulation results for the achieved load current profiles, waveform of the source voltage, load currents, source currents etc. are shown in following sections.

VI. Reactive Power Demand and Current Harmonics

The converter power supply system shown in Fig. 8 has been simulated for different supply voltage conditions as mentioned in Table-1 & Table-2 for compensation of only the Harmonics as also for compensating both, Harmonics & Reactive Power.

The simulation results for the Un-balanced & Distorted Supply voltage conditions, for the compensation of both Harmonics & Reactive power, are shown in the following figures. The DC Load Current profiles for the three magnet coils, PF-1, PF-2 and PF-3 are shown in Fig. 9.

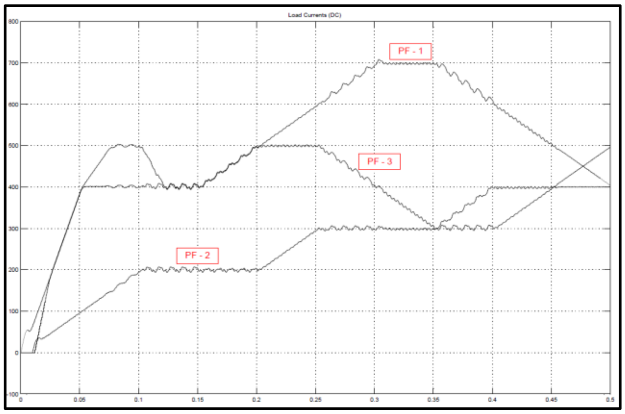

Fig. 9. DC Load Currents for PF-1, PF-2 and PF-3

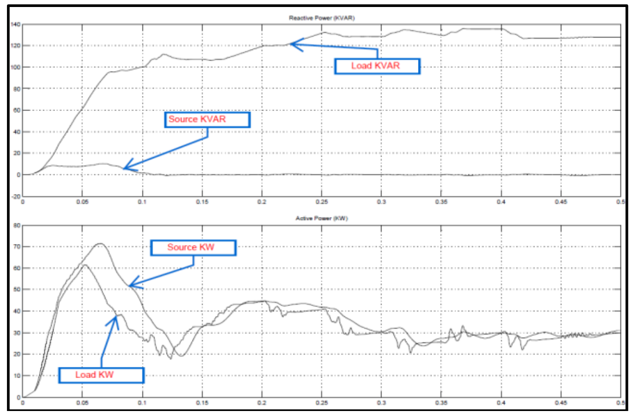

Fig. 10. Instantaneous Reactive Power & Active Power Demand

For the DC load current profiles shown in Fig. **9.** DC Load Currents for PF-1, PF-2 and PF-3Fig. **9**above, the resultant Instantaneous Reactive Power & Active Power Demand are as shown in Fig. **10**.

The SAPF Current for compensation of only the Harmonics is shown in Fig. 11 and that for compensation of both, Harmonics & Reactive Power, is shown in Fig. 12.

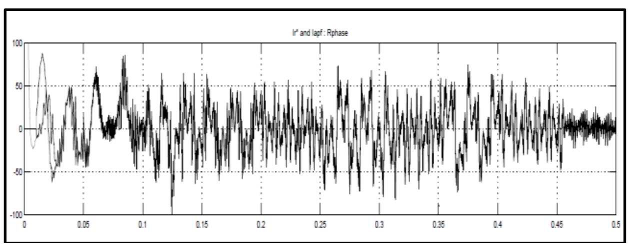

Fig. 11. SAPF Current for compensation of Harmonics

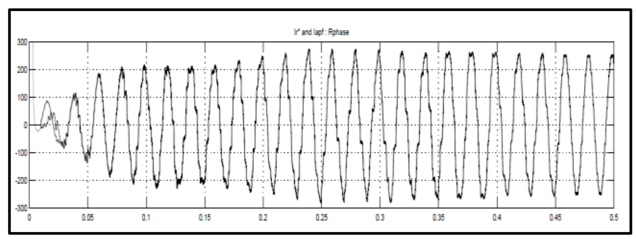

Fig. 12. SAPF Current for compensation of Harmonics & Reactive Power.

The AC Supply voltage, supply current and load current waveforms are shown in Fig. 13. The simulated unbalance and distortion in the supply voltage can be seen from the waveform of the AC Supply Voltage in Fig. 13.

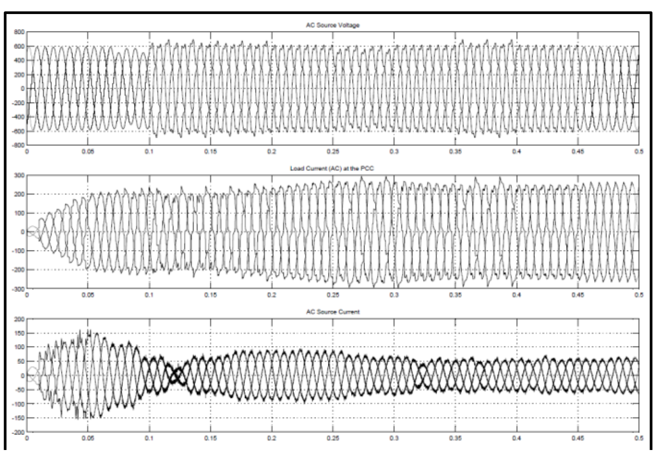

Fig. 13. AC Supply Voltage, Supply Current and Load Current

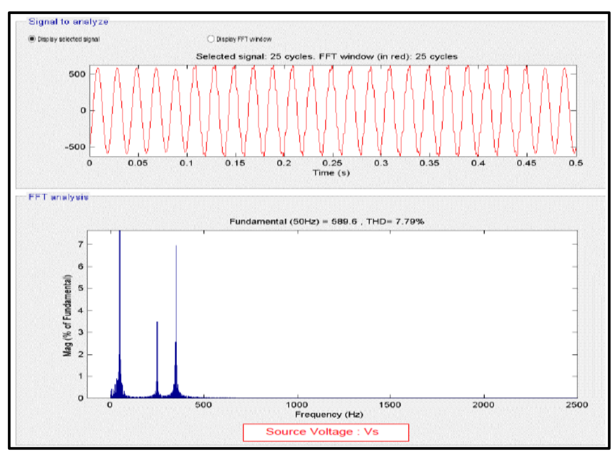

Fig. 14. H&RPC : Harmonics in Source Voltage for Un-balanced and Distorted Supply Voltage

The FFT analysis of the ac supply voltage, load current and source current is shown in Fig. 14 to Fig. 16.

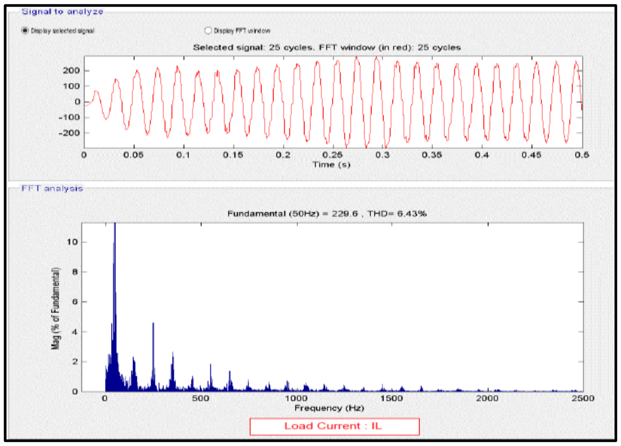

Fig. 15. H&RPC : Harmonics in Load Current for Un-balanced and Distorted Supply Voltage.

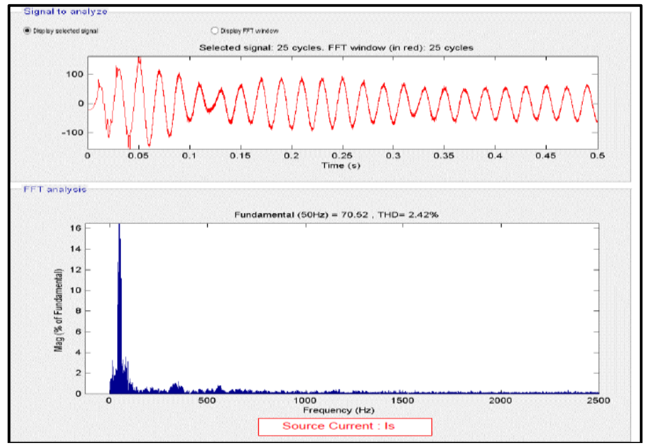

Fig. 16. H&RPC : Harmonics in Source Current for Un-balanced and Distorted Supply Voltage:

VII. Results and Discussions

The Shunt Active Power Filter performance has been evaluated by simulating different supply voltage conditions. It can be observed from the above figures that the Reactive Power Demand is compensated dynamically and instantaneously by the SAPF. The response time of the SAPF to load changes is less than a cycle.

The results for THD are summarized in Table 3. It can be seen that the THD in the Load Current is within the specified limits as per IEEE519 when the supply voltage is sinusoidal. However, in practical applications, the supply voltage may not always be sinusoidal. The simulation for distorted supply voltage condition shows that under such distorted supply voltage conditions, the THD is above the values specified in the standards. For both, Harmonic Compensation, as well as Harmonic & Reactive Power Compensation, the application of SAPF reduces the THD in source current, to well within the limits specified in IEEE519.

Table 3: THD in Source Current after Compensation

Supply Voltage Condition		Harmonic Compensation		Reactive Power Compensation	
		THD (%) in		THD (%) in	
Condition	THD(%)	Load Current IL	Source Current Is	Load Current IL	Source Current Is
Balanced & Sinusoidal	0.00	4.38	1.58	4.38	2.88
Un-Balanced but Sinusoidal	0.06	3.92	0.98	3.92	2.44
Balanced But Distorted	7.83	7.96	1.54	7.97	3.04
Un-Balanced And Distorted	7.79	6.36	0.99	6.43	2.42

VIII. Conclusion

Modeling & Simulation 12-pulse AC-DC Converter with extended delta D($\pm15^0$)y0-y6 converter transformer with H3 Thyristors and an Interphasing Reactor has been modeled and simulated. The simulation results for the phase shift achieved in the converter transformer have been represented.

The MATLAB® modeling of the Converter Power Supplies of Tokamak has been carried out. Different operating conditions have been simulated. The MATLAB® modeling of Shunt Active Power Filter has also been carried out, as per the Instantaneous Reactive Power Theory (*p-q* Theory). The simulation of SAPF shows that the Shunt Active Power Filter based on the *p-q* Theory is suitable for Harmonic & Reactive Power Compensation. The simulation results shows that the SAPF can fully compensate the Reactive power demand and at the same time, also reduce the load current harmonics from 6.43% to 2.42% even when the supply voltage is unbalanced & distorted. Therefore, the SAPF, based on the Instantaneous Reactive Power Theory (*p-q* theory), can be applied to achieve full dynamic reactive power compensation and to reduce the THD in source currents to less than the limits specified in IEEE519.

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