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A Novel PV based STATCOM for Augmenting Real Power and Reactive Power for a Grid Connected Load

Ananthi Kaliyamoorthy* and S. Manoharan**

Abstract : STATCOM is a modern power conversion unit that belongs to the family of FACTS (Flexible AC Transmission System) devices. The STATCOM is basically meant for the compensation of reactive power to increase the power factor on the source side while the load is a low power factor system. In this application the STATCOM is used to integrate the DC power sourced by a Photo Voltaic Power Conversion (PVPC) system, Besides the applicability of the Sliding Mode Controller (SMC) for the Maximum Power Point Tracking and a PI based boost converter to maintain constant DC bus voltage is studied with the 2KW PVPC. The two controllers for active and reactive power management associated with the STATCOM are of the PI type each individually tuned by Particle Swarm Optimisation with the minimization of Integral Square error as the objective. The proposed idea of utilising the STATCOM capacity for real power injection, SMC for the PVPC and the PSO based tuning of the PI controllers have all been validated in the MATLAB SIMULINK environment.

Keywords : STATCOM, Integration of real power with STATCOM, Photo Voltaic Power Generation Using Solar Panels, Tuning of PI controllers, Particle Swarm optimisation

1. INTRODUCTION

With the fast depletion of fossil fuels and in the hazardous condition of global warming the photo voltaic power generation is encouraged globally. With the advent of modern power electronic devices and modern power electronic converters the FACTS devices are coming up and they promise to provide better manageability of power conversion and transmission with flexibility and with features that ultimately raise the usability of systems up to the thermal limits.

In this work, the STATCOM which is usually used for reactive power compensation in power systems is used to integrate the DC power from the solar PVPC system into the grid through the DC link of the STATCOM. Decoupled real and reactive power transaction control is carried out using two controllers that take care of the voltages at the point of common coupling and the maintenance of the DC link voltage. In this work the PVPC is equipped with an SMC for MPPT. During day time the STATCOM supports real power as derived from the PVPC system as well as reactive power compensation. During night the STATCOM is used for reactive power compensation only.

Extended use of the STATCOM during the day for real power integration and for reactive power compensation during day and night has been demonstrated in [1] and [2]. The development of power electronic power converters and their debut into the power transmission and distribution was first charted

* Assistant Professor, Department of Mechatronics Engineering, Sri Krishna College of Engineering and Technology, Coimbatore *anandhipilai@gmail.com*

** Professor and Head, Department of Electronics and Instrumentation Engineering, Karpagam College of Engineering, Coimbatore *manoish07@yahoo.co.in*

out by Hingorani in his FACTS specific famous treatise [3] in the year 1988. Since then a number of power electronic converters, their switching schemes, their cybernetic control systems and all these have been developed in many fold.

The advent of modern digital micro controllers and micro processors and the digital Signal processors and controllers have also developed into new dimensions and this has lead to the development of sophisticated control systems for the power electronics based power conversion systems into new heights. In [4] the authors have demonstrated how a Digital power factor control and reactive power regulation for grid-connected photovoltaic inverter can be designed and developed. In [5] the authors discussed about the modelling, analysis and design of a pulse width modulation voltage source inverter connected between a DC source, which is supplied from a photovoltaic (PV) array and the AC grid.

Maximum power point tracking for the energy source elements like the wind power generator and the solar PV panels have also become a very important issue and many developments have so far taken place in this area too. In [6] the authors have developed a micro controller based, photovoltaic maximum power point tracking system.

For Maximum Power Point Tracking the techniques differ slightly when used with DC to DC converters and in inverters where the manipulated variable becomes the duty cycle or the modulation index respectively. In [7] a study of maximum power tracking techniques and control of DC–DC converters for photovoltaic power system is presented. Grid integration of PVPC is also a popular technique where the PVPC directly drives an inverter that uploads power to the grid through a transformer. Transformer less power integration using inverters driven by solar PV panels has also been developed. In [8], a new control strategy for 2-stage grid connected photovoltaic power system for the gird integration of renewable Energy sources has been discussed.

In [9], the unified power flow controller has been presented as a novel system to overcome power flow bottle necks with flexible solutions. In [10] the authors have investigated the applicability of dynamic controllers for a unified power flow controller. Particle Swarm Optimization (PSO) based approach was demonstrated in [11] for the purpose of maintaining power system stability. The authors in [12] and [13] as well have demonstrated the synchronous reference frame based control system in FACTS devices.

.In [14] the authors have developed and demonstrated a microcontroller based, photovoltaic maximum power point tracking control system. In [15], the use of Adaptive Neural Network based fuzzy inference system ANFIS has been studied for the purpose of development of control systems in power conversion systems. In [16], the decoupled control of the flow of real and reactive power has been examined. In [17] and [18] clear studies of the FACTS devices have been presented that leads to the advanced analysis methodologies pertaining to the performance of the FACTS devices. The authors in [19] have studied the problem of determining maximum regulating capability of UPFC based on predicting feasibility limit of power systems. In the meantime, Soft computing based control techniques have also been developed in parallel [20]. The theory of fuzzy controllers has been exhaustively analysed. Further in [21] The Design and simplification of ANFIS for power plants have been analysed.

Since the operation of the STATCOM mainly depends upon the DC link capacitor and the voltage across it a though study of the same is made in [22] where specifically the Transient analysis of a unified power flow controller and its application to design of the dc-link capacitor has been made. Down the history any development that was done with regard to the UPFC was in parallel put into service with the STATCOM as well.

In this work the use of the STATCOM for uploading the solar Photo Voltaic power through the DC link of the STATCOM is studied. The Particle Swarm optimisation is used for tuning the two controllers used by the STATCOM. The paper has been arranged as follows. After this brief introduction a review of the STACOM and the decoupled control of STATCOM are discussed in chapter II. The principle of Particle Swarm optimisation is discussed in chapter III. The Sliding mode control for the MPPT of the solar panel and PI based boost converter for constant DC bus voltage are discussed in chapter IV. The development of the various subsystems in the MATLB environment is discussed in chapter V followed by the results and discussion and conclusion.

2. THE STATCOM

The STATCOM is a power electronic converter which means Static Synchronous Compensator. The three phases STATCOM is a bidirectional power conversion system that uses the Graetz Bridge structure. On the AC side of the STATCOM, it is connected to the point of common coupling through a set of three phase LC series filter. If necessary based on the voltage prevailing at the point of common coupling and the allowable AC side voltage of the STATCOM a three phase transformer may be used. The DC side of the STATCOM is terminated across a DC link capacitor. The STATCOM can simultaneously transact both real and reactive power in either direction. That is while the STATCOM is supplying reactive power to the point of common coupling it can draw active power to charge the DC link capacitor to maintain the required voltage across the DC link.

As for the control of the STATCOM, with the advent of modern power electronic converters and advanced PWM techniques it is possible to control real and reactive power transactions independently by controlling the Phase angle and the Modulation Index (MI) of the three phase reference to be used for PWM at the inverter. For this purpose the Park Transformation or the DQ transformation is inevitable. Park transformation transforms the three phase quantities into a rotating frame for which the speed of rotation is equal to the frequency of the three phase quantities being transformed.

1. Flow control of Real Power through STATCOM

In the conventional application of the STATCOM, which is reactive power compensation, the DC link voltage across the DC link capacitor is to be maintained at the appropriate level. For this purpose to start with the DC link capacitor has to draw real power from the point of common coupling. Even as the STATCOM is in action the DC link capacitor may exhibit gradual fall of voltage and this has to be topped up by drawing real power from the point of common coupling.

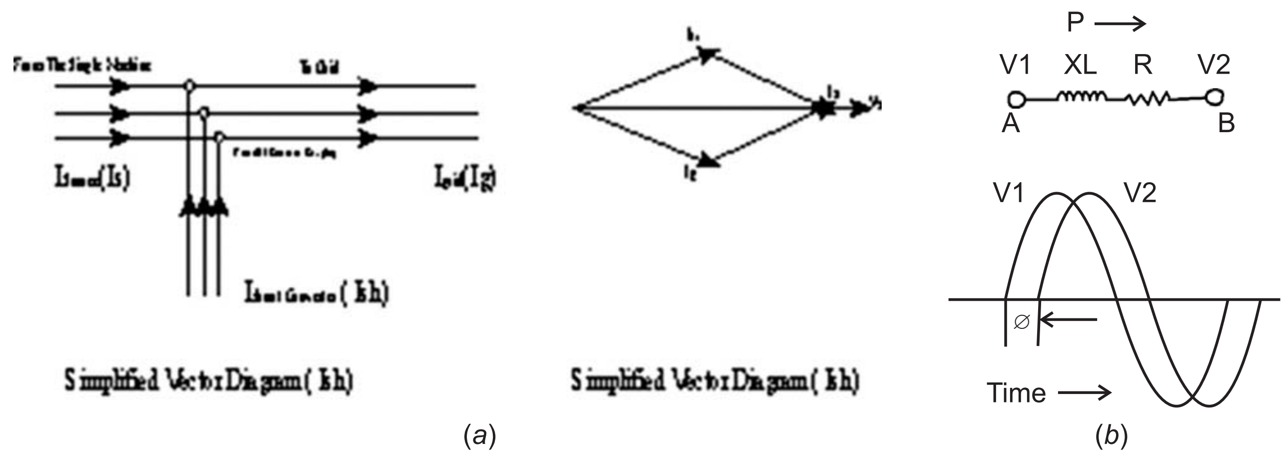

Figure 1: (*a*) The Currents Associated with the STATCOM (*b*) The voltage relationship for real power transfer

In the proposed work, during the day time and whenever the solar insolation is sufficient the STATCOM will get the real from the Solar PV unit and this power will be pumped into the point of common coupling. During this period the STATCOM transacts real power from the DC link to the point of common coupling. But during night or during the day time when the solar insolation is significantly poor the STATCOM will draw real power from the point of common coupling. Thus the STATCOM is capable of transacting real power in either direction. The real power flow is electrically accomplished by maintaining the phase angle of the three phase voltage across the STATCOM to be lagging or leading with respect to the phase angle of the three phase voltages at the point of common coupling. The amount of real power transacted over two nodes connected through an inductor can be given by the equation (1).

$$P = (V1 * V2 \sin(\theta))/(X) \quad (1)$$

With reference to the given equation if there are two nodes A and B and if they are connected through an inductive reactor of reactance X then there must some value for θ that makes possible for the flow of real power. Even if the two nodes are at different potentials, if the value for θ is zero then real power transaction will be zero. However, even if the two voltages V1 and V2 are equal then real power can be transacted between the nodes A and B by keeping the phase difference θ.

In practice, this angular shift is appropriately introduced for three phase AC voltage at AC side of the STATCOM by using this angle θ as phase angle for the three phase reference signal with respect to three phase voltages prevailing at the point of common coupling.

2. Flow control of Reactive Power through STATCOM

In conventional application of the STATCOM, which is reactive power compensation required reactive power demand is to be supplied by the STATCOM so that no reactive power is drawn from main source and thus power factor at the source side is held high.

In the proposed work, during the day time and the night time depending upon the reactive power demand of the load STACOM will have to supply reactive power. The reactive power flow is electrically accomplished by maintaining the amplitude of voltage at the point of common coupling to be at a higher level than voltage at the terminals of the STATCOM. The amount of reactive power transacted over two nodes connected through an inductor can be given by the equation (2).

$$P = (V1* (V1–V2) \cos(\theta))/(X) \quad (2)$$

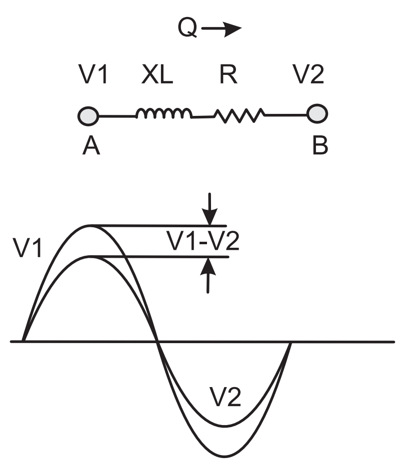

Figure 2: The voltage relationship betweenVpcc and Vstatcom for reactive power

With reference to the given equation if there are two nodes 1 and 2 and if they are connected through an inductive reactor of reactance X then there must some value for V1 -V2 that makes possible for the flow of reactive power. Even if the two nodes are at the same phase angle, with zero degree difference, with no lagging or leading, different potentials for V1 and V2 will cause reactive power transaction. However, even if the two voltages V1 and V2 are equal then reactive power transacted between the nodes 1 and 2 will be zero.

In practice, magnitude of three phase terminal voltage across the AC terminals of the STACOM can be adjusted in such a manner that enables flow of reactive power in the desired direction by controlling the modulation index of the PWM carried out at switching of the STATCOM converter. Thus by controlling phase angle of the reference three phase signal real power transaction is controlled. The reactive power transaction is controlled by the control of the Modulation Index used at the STATCOM and this quantity in reality is the magnitude of three phase reference signal that is used with an explicit carrier for sinusoidal PWM or without an explicit carrier in case of Space Vector PWM.

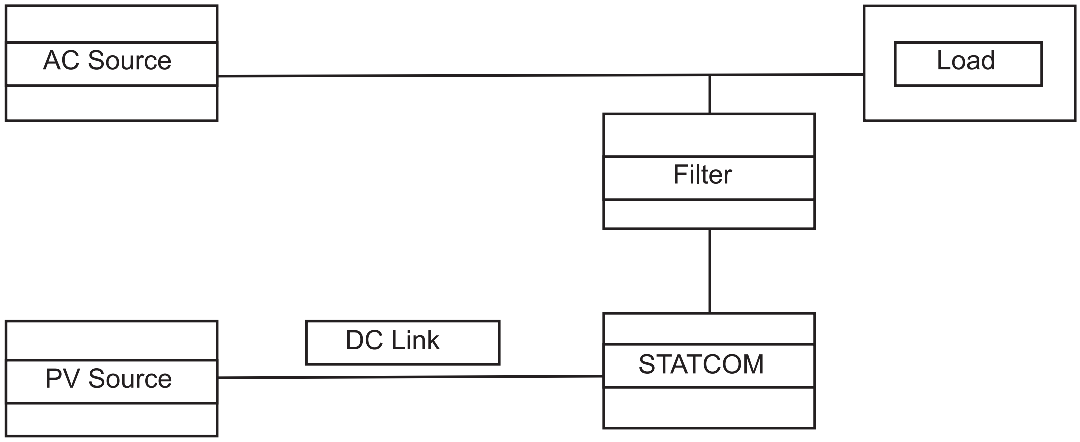

Figure 3: Block schematic of STATCOM system with provision to integrate PV

3. PARTICLE SWARM OPTIMIZATION

The particle swarm optimisation is a heuristic search system capable of arriving at the optimal solution vector in a multi dimensional search space. A number of particles initialised with values in the appropriate range venture into the search operation and after a certain number of iterations all the particles attain almost the same vector values with admissible errors, and thus they all point the same location in the search space as the final optimal solution. All the particles, engaged in the search operation, which were randomly initialised, change their position by adding a velocity to the existing position. The velocity added to each particle is different and is derived for each particle individually based on the performance of all the particles in the swarm and the past performance of the individual particle. Two parameters are considered in the estimation of the velocity for each particle and these two particles are known as the personal best and the global best. The personal best of a particle is that vector pertaining to that particle assumed in any one of the past iterations that gave the best results in terms of the objective function. The global best far at the end of an iteration is that vector of any of the particles among all the particles in any of the past iterations that gave the best results in respect of the objective function. Therefore, it is possible that any particle, during the course of iteration become the globally best particle at the end of an iteration and that vector perhaps is the best one for that particle itself considering its own past performance. During the course of iterations the quality of the solutions of the individual particles improve and at the end of the process all the particles will show up the same vector, that is the solution vectors of all the particles will be almost equal. The termination if iterations can be done by either considering the error that becomes less than the allowable threshold value or the number of iterations. At the end of each iteration, an individual velocity vector is used to change the current position of the particle. For each particle the velocity vector will be much different for each of the particles and this difference narrows down as the solution is approached.

In this work we have two *pi* controllers. Each of them should be tuned with appropriate K*p* and K*i* values. For each of the *pi* controller the minimisation of the integral square error is the objective and the minimisation of the sum of integral square error of both the PI controllers is the objective function for PSO tuning. The two *pi* controllers are simultaneously tuned and their K*p* and K*i* values are simultaneously estimated in single session of running the PSO program with 10 particles and 5 iterations. The final values for the K*p* and K*i* values for the two *pi* controllers as derived using the PSO program are as follows.

Table 1

K*p* and K*i* value for the PI control of real power

Method	*Kp1*	*Ki1*
Trial and Error Method	0.25	0.025
PSO based Tuning	.34	0.037

Table 2
K*p* and K*i* value for the PI control of reactive power

Method	*Kp2*	*Ki2*
Trial and Error Method	0.0625	0.00625
PSO based Tuning	0.078	0.0069

4. MATLAB SIMULINK BASED SIMULATION

The system parameters are Source side Vline = 380V, *f* = 50 Hz. The short circuit capacity of the source is 100MVA. The nominal load on the load side is 20KVA.The load operates at 380V, 50 Hz. The STATCOM used in this research can handle a real power of 5 KW and it can support 5 KVAR reactive power and thus its capacity is selected for a nominal 10 KVA rating. The PWM technique employed is sinusoidal PWM and the *dc* link voltage is 1200V. The value of the dc link capacitor is 2000 MFD.

The main MATLAB system including Main Source, load STATCOM and the PV sub System as shown in Fig. 4

Fig.5*a*. shows the sub system consisting of the controllers. One of the two controllers takes care of the real power and the other controller takes care of the reactive power. For the first controller that takes care of the real power the set point is the dc link voltage of 1200 volts. The difference between set point and actual dc link voltage is applied to the PI controller. The output of this controller is used as the phase angle for the three phase reference signal to be used for the sinusoidal PWM section.

In the case of the second controller, the set point is 1 and it refers to the per unit value of the D component of the park transformed three phase voltage at the point of common coupling.

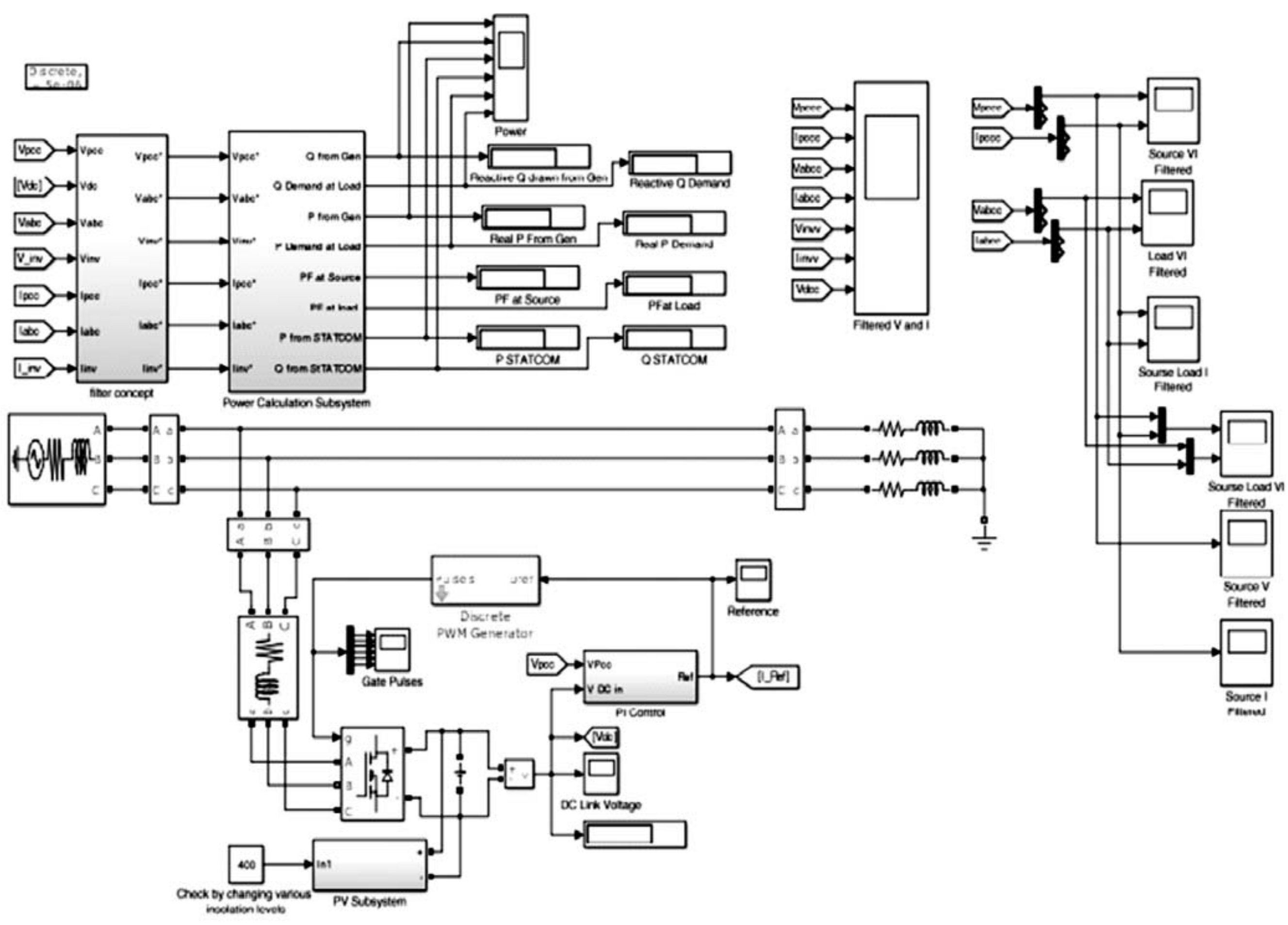

Figure 4: The main MATLAB system including the Main Source, the load, the STATCOM and the PV sub System

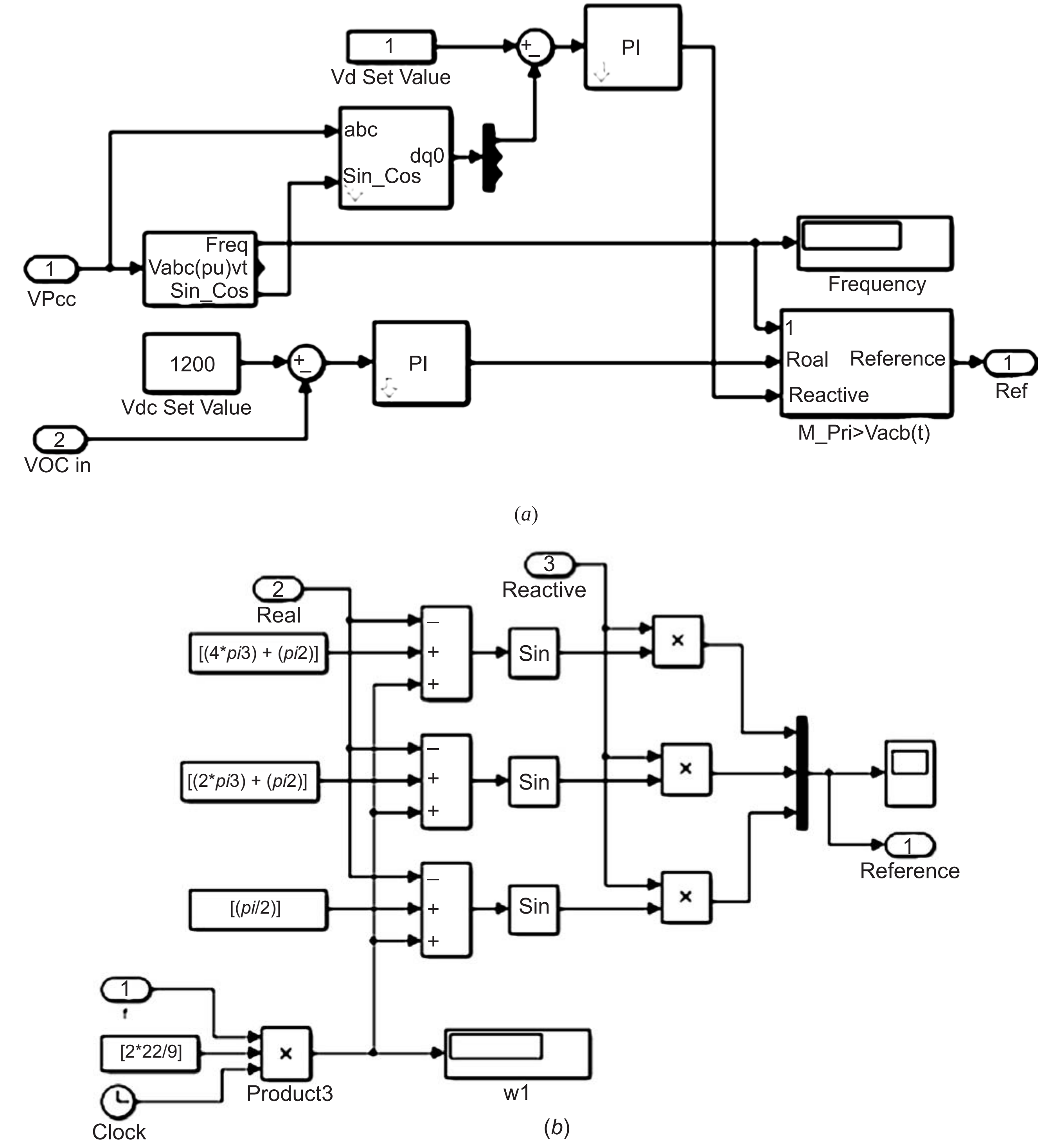

Figure 5: (*a*) The sub system containing the two PI controllers (*b*) Three phase reference for Sinusoidal PWM

The actual value to be compared with the set point is the per unit value of park transformed three phase voltage prevailing at the point of common coupling. The error between these two quantities is calculated and this error is fed to the second PI controller. The output of this PI controller is the amplitude of the reference signal to be used for PWM. The amplitude and phase of the three phase reference signal is generated and its frequency is determined by a PLL unit.

Fig. 6 shows the photo voltaic power conversion system along with the PV panel and the associated sliding mode controller for MPPT and boost converter for constant DC bus voltage. Fig. 7 shows the PI control subsystem used for PSO based tuning.

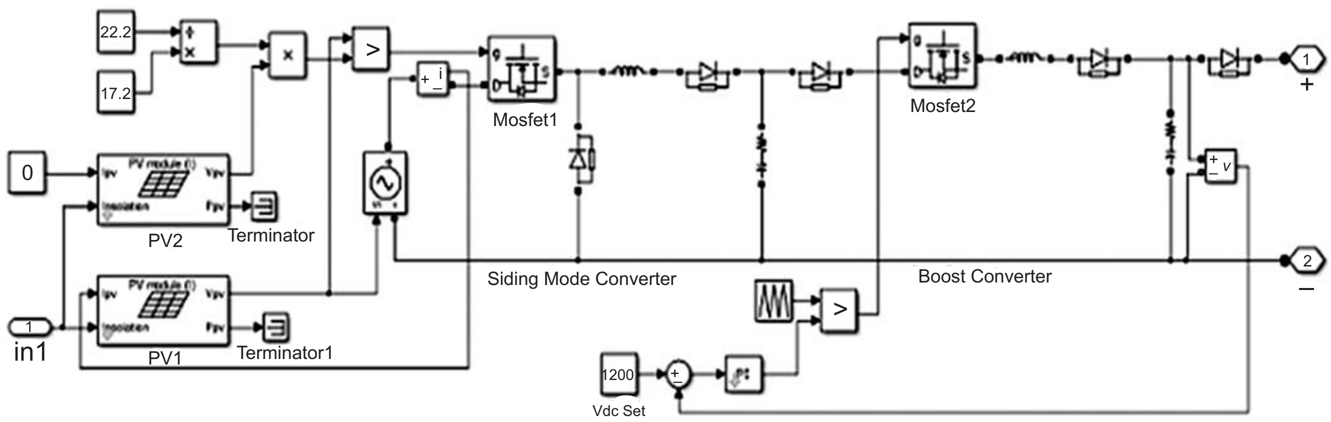

Figure 6: Photo Voltaic Power Conversion sub system consisting of the PV panel with MPPT and Boost Converter

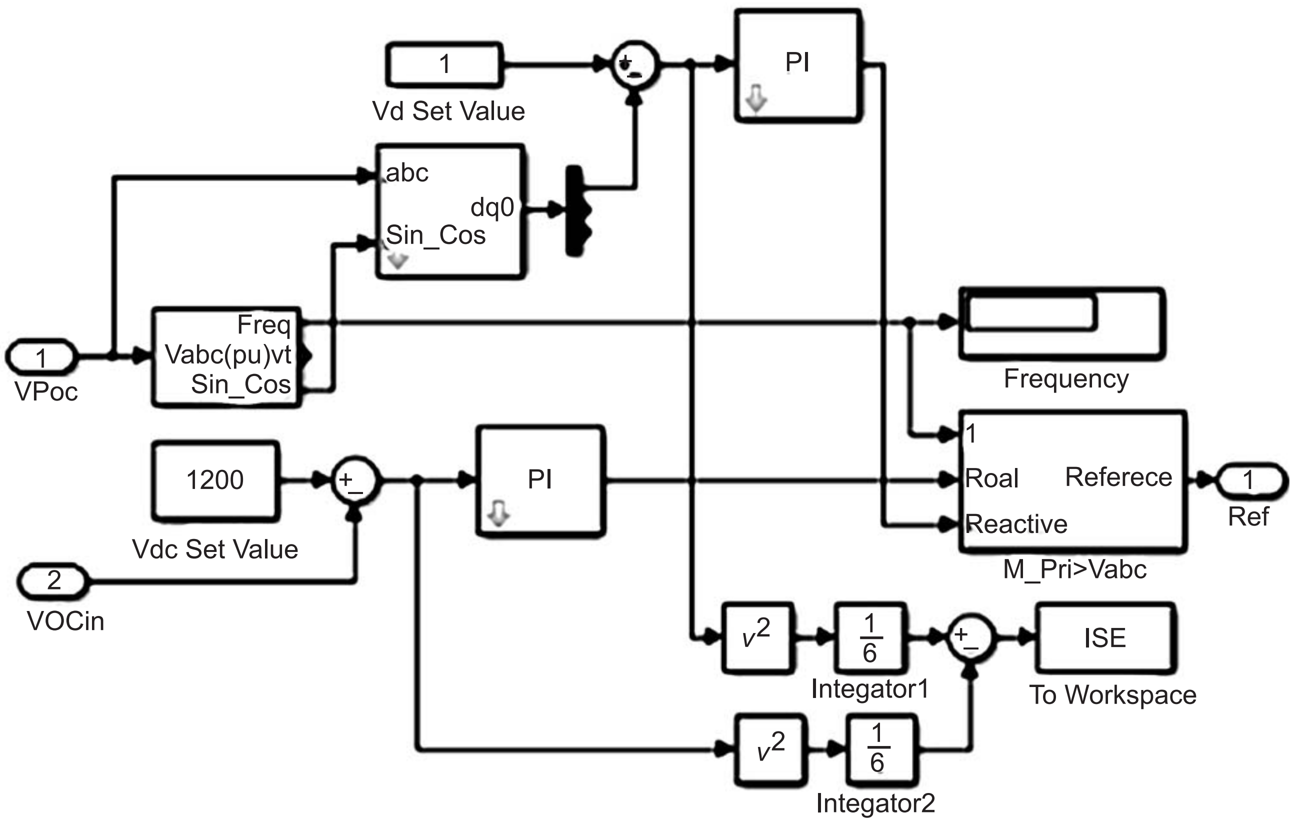

Figure 7: PI controller Section used for PSO tuning

The program segment used for invoking the SIMULINK model through the PSO based optimization program is as follows.

function [ISE] = Objfun_*pi*(*x*) global Kp1 Ki1 Kp2 Ki2 iter warning off

for *i* = 1:length(x)

Kp1 = *x*(*i*,1);

Ki1 = *x*(i,2);

Kp2 = *x*(i,3);

Ki2 = *x*(i,4);

sim('PV_Statcom_PSO_PI_Tune')

F(*i*) = sum((ISE));

end

ISE = F;

5. RESULTS AND DISCUSSIONS

The two *pi* controllers of the STATCOM were first tuned by the trial and error method. The results if the trial and error method is tabulated in Table 1. As for the reactive power compensation the trial and error method worked fine but not optimal. The PSO tuned PI controllers offered better results. The results of operation with the PSO tuned pi controllers are tabulated in Table 2.

The source current is smaller in magnitude as compared to the load current, as it is subsided by the STATCOM. It has been observed that quality of the source power has improved when used with PSO tuned pi controllers as compared to the trial and error tuned pi controllers. The FFT and THD for both the cases are also shown in Fig. 11 and 12. The performance of the STATCOM has been studied with the worst case load of P = 5 KW and Q = 5 KVAR. At this loading condition the real and reactive demands are equal and the load power factor is as low as 0.707.

On the load side there is phase lagging of the current from the voltage however on the source side voltage and current are in phase.

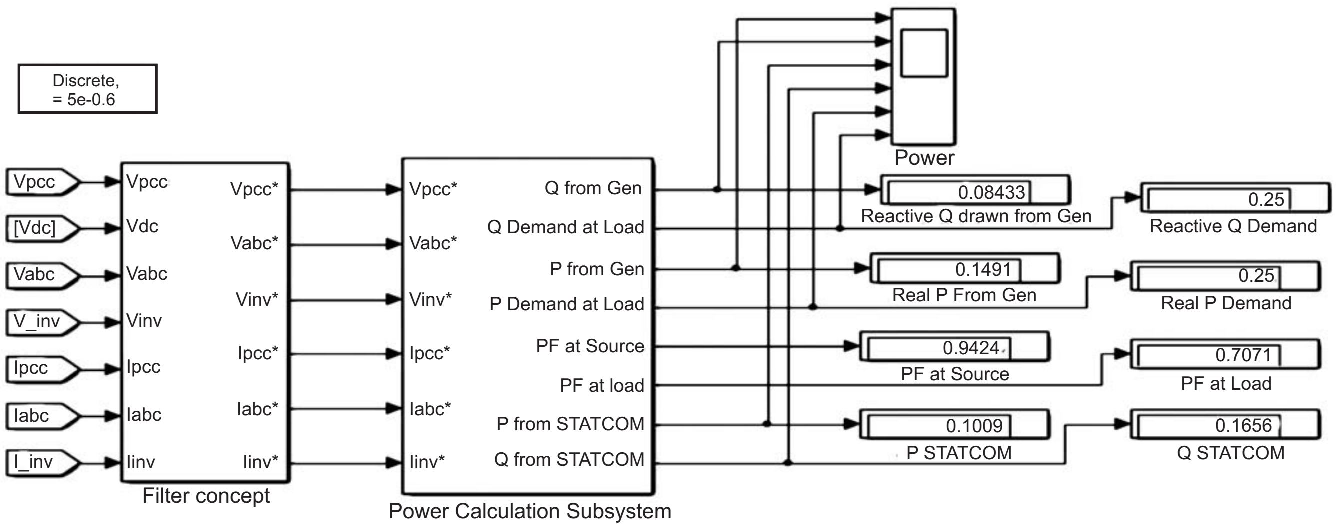

Figure 8: The MATLAB SIMULINK display section showing the power factor on the source and load sides the various real and reactive power transactions.

Table 3
The power transaction metrics, the THD the source and the load side power factors. (PI with Trial and Error)

Demand	*Main AC source*	*STATCOM*	*PF source*	*PF Load*	*THD Source Current*
P = 5KW	3.8 KW	1.2 KW	0.935	0.707	4.39
Q = 5KVAR	0.2 KVAR	4.8 KVAR	....	....	

Table 4
The power transaction metrics, the THD the source and the load side power factors. (PI with PSO tuning)

Demand	*Main AC source*	*STATCOM*	*PF source*	*PF Load*	*THD Source Current*
P = 5KW	3.6 KW	1.4 KW	0.965	0.707	1.61
Q = 5KW	0.18 KVAR	4.9 KVAR	....	....	

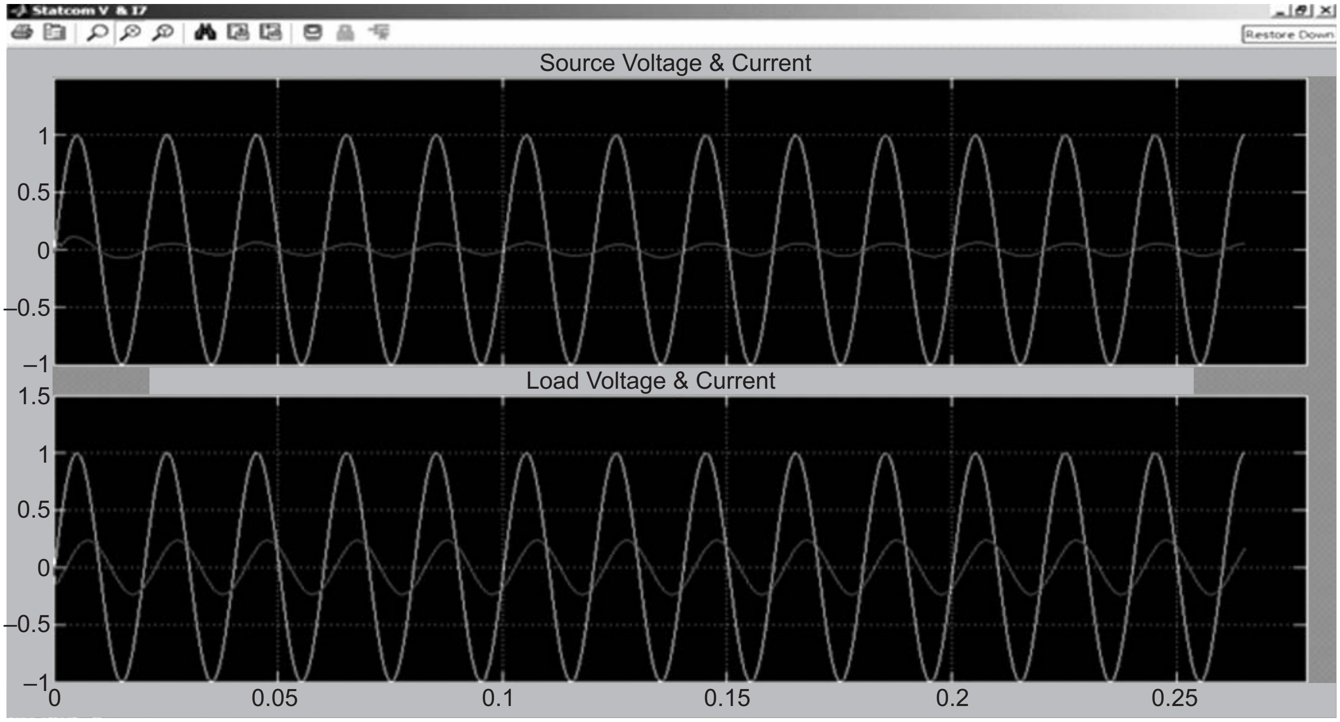

Figure 9: The source voltage, source current, the load voltage, the load current, STATCOM voltage and current

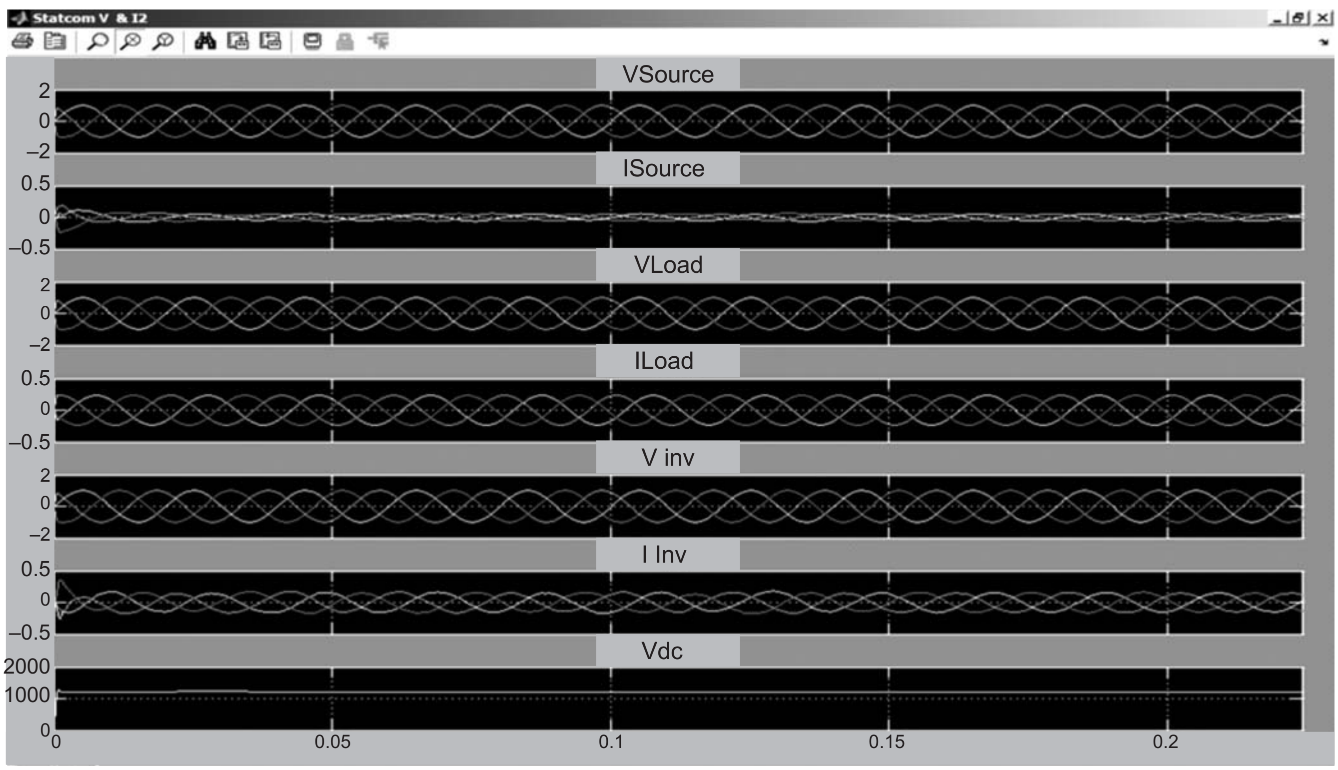

Figure 10: Source voltage, and source current; Load voltage and load current

6. CONCLUSION

A novel STATCOM based augmentation of the DC power from the Photo Voltaic Power conversion system is presented in this paper. The proposed idea uses sliding mode controller for the MPPT of the solar PVPC system and PSO based tuning technique for the tuning of the two PI controllers of the STATCOM The proposed idea has been tested in the MATLAB environment and the results validated the proposed idea.

There is ample scope for further research; Validation of the proposed idea by an experimental validation has to be carried out in the immediate future.

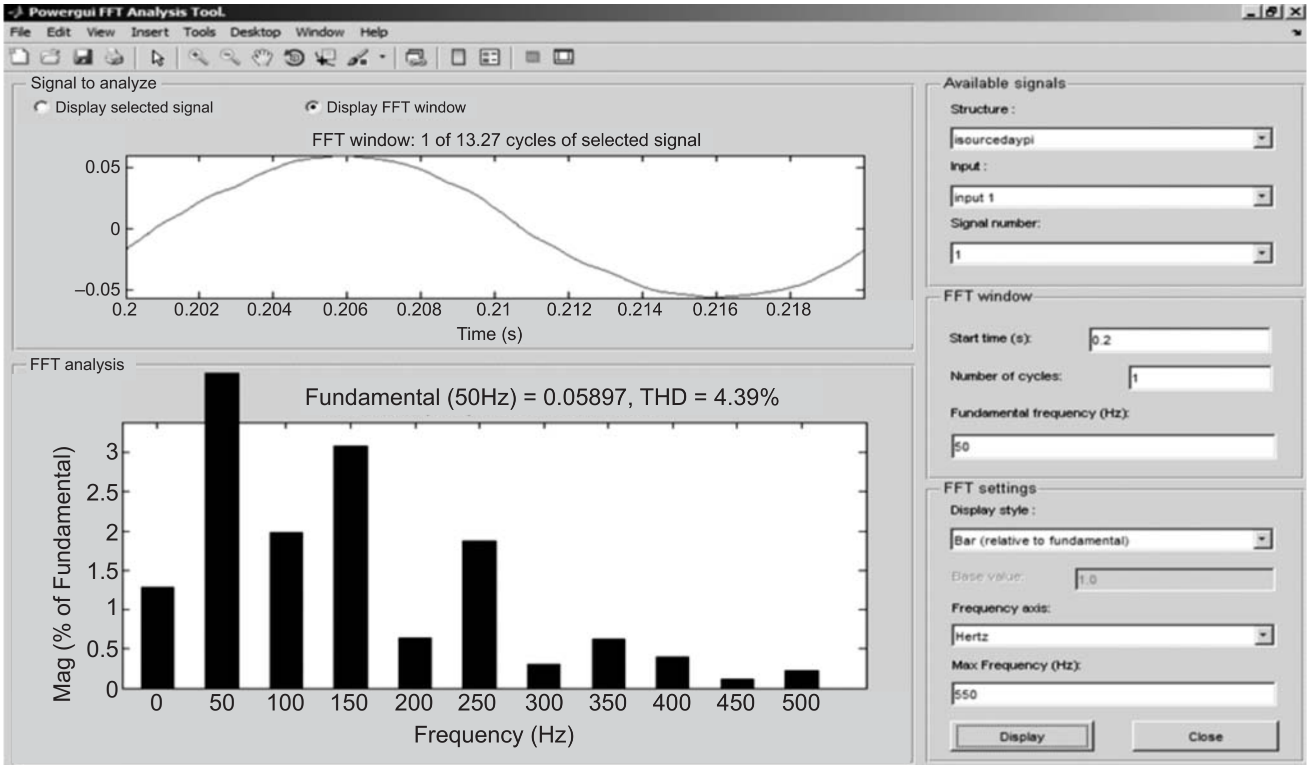

Figure 11: The FFT of the source curretn with the manually tuned (Trial and Error) PI controller in action

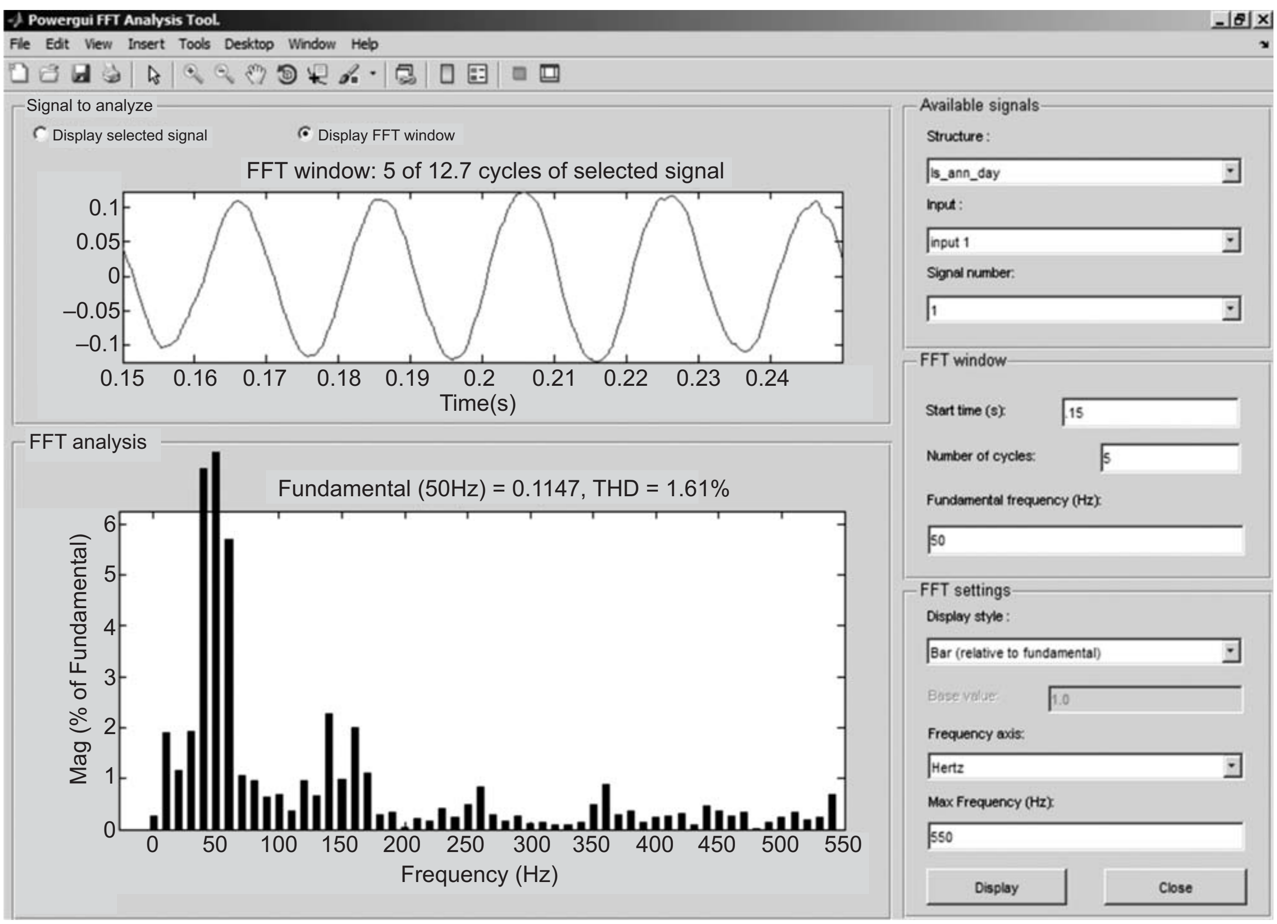

Figure 12: FFT of the source current with the PSO tuned PI controller in action

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