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# LMS Adaptive FIR Filter-Predictive Controller Based On D-Q Control Theory for Grid-Connected Solar PV System

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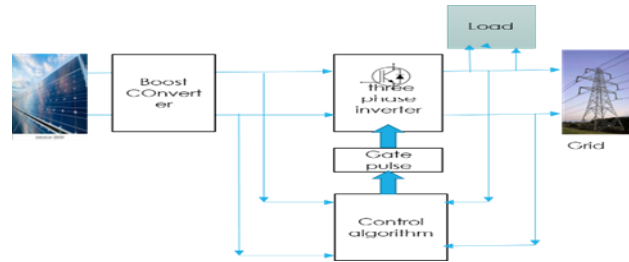
**Abstract.** A Least Mean Square (LMS) adaptive Finite Impulse Response (FIR) filter-predictive controller is presented for the control of a grid-connected solar PV energy system. The objective of the work is to reduce total harmonic distortion (THD) in the grid and load current. It follows the systematic development and analysis of the implementation of an adaptive LMS control based on the direct-quadrature control theory. The analysis is done for the proposed adaptive control technique for grid-connected solar photovoltaic systems under the variation of solar irradiation and load. In this proposed work, the reference current is estimated by developing the LMS control technique. The proposed system is modeled in d-q frame form and simulated on the MATLAB Simulink platform. Developing an LMS control algorithm using the p-q theory reduces computational hard work. The reduction in load current harmonics is improved. The simulation results are used to discuss the convergence rate, harmonics reduction, and advantages of the adaptive LMS algorithm d-q control theory.

**Keywords:** Adaptive LMS algorithm, Converter, Controller, Solar PV panel, D-Q theory

## 1. Introduction

Solar photovoltaic systems (SPV) have become popular to generate electrical energy. It is also an alternate solution for the modern power system to meet electrical energy demand. The major advantage of this SPV is that there is no rotating part, availability of sunlight energy and conversion of photon energy into electrical energy is possible using a semiconductor diode. The interconnection of the SPV system to the grid causes many power-quality issues like voltage-current waveform distortion, harmonics introduction, flickers, and many more with load conditions. The synchronization of a PV system to the grid is enabled through power electronics devices like a converter. These power electronics switches introduce harmonics in the grid. The control of grid-connected PV systems has become more important to face technical challenges. This has created motivation and interest for the researcher. Effective control is required to solve these power problems to ensure the system's smooth operation. Conventional control techniques like Proportional Integral (PI) controller are well-practiced in the control of a solar PV system. They have certain disadvantages of improper tuning of controller gains. Many soft computing control techniques are developed based on fuzzy logic, particle optimization techniques, etc to tune the parameters of the PI controller. These techniques need more computation time. Sometimes they fail due to the slow convergence. The adaptive algorithms are simple, easy and require less computational time. The adaptive algorithm for PV inverters can result in great accuracy and faster dynamic response. These algorithms can be implemented on hardware using a DSP processor.





**Figure 1.** Block diagram of a Solar PV system

Control techniques based on adaptive algorithms are becoming more popular. Their performance is effective in the real-time operation of the system with dynamic load conditions. The proposed setup is assisting in reducing harmonics and maintaining the shape of AC voltage and current.

An adaptive finite impulse response filter is a self-learn filter, As the signal into the filter continues, the adaptive filter coefficients regulate themselves to achieve the desired result. An adaptive algorithm is an algorithm that changes its behavior at the time it is run, based on information available [1-2].

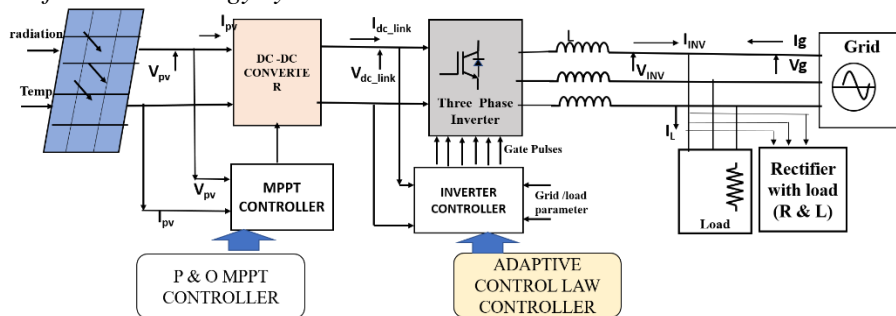
This paper discusses system formation, control technique, implementation of an adaptive algorithm for the grid-connected solar PV system, simulation results, discussion, and conclusion. The involvement of this paper is as given below

- The double-stage grid-connected solar panel energy system using the dc booster and voltage source inverter
- The reference dc current is obtained from reference dc voltage and dc bus voltage at maximum power extraction from the Solar PV system.
- An Adaptive LMS control is developed to extract the active weight component of load current.
- The d-q theory is considered to develop an LMS control scheme for this system.

## 2. System Formulation

The proposed system is a grid-connected solar PV system. It has different interconnected subsystems like solar PV array, DC-DC converter, three-phase DC-AC converter, inverter filter, grid, and load as shown in figure 1.

### 2.1. Formation of Solar PV energy system



**Figure 2.** Block Diagram of LMS Adaptive FIR Filter-Predictive Controller Based On D-Q Control Theory for Grid-Connected Solar PV System

The expected electrical energy generation from the PV system is 51kW. The selection of parallel and series modules is decided as per the given equation (1).

The number of series modules in the panel (1)  $n_s$ ,

$$n_s = \frac{V_{dc}}{V_{mp}} = \frac{400}{29.5} = 14 \quad (1)$$

The number of parallel modules in the panel (2),  $n_p$

$$n_p = \frac{P_{\max}/V_{dc}}{I_{mp}} = \frac{51kW/406}{7.4} = 17 \quad (2)$$

Where  $V_{dc}$  is the total dc voltage of the PV panel,  $V_{mp}$  is the voltage at the maximum power point (29.5 V),  $P_{\max}$  is the total output power from the PV panel, and  $I_{mp}$  is the current at the maximum PowerPoint (7.4 A). Therefore, the solar PV array with a peak power capacity of 51kW is modeled with 14 modules connected in series and 17 modules connected in parallel [8].

### 2.2 DC bus voltage selection

The selection of DC bus voltage is done by calculating the minimum value of dc bus voltage for the Voltage source inverter which has to be maintained at the common interconnection point or grid. The dc bus voltage is in (3).

$$V_{dc} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}m} = 620.537 \quad (3)$$

$V_{LL}$  is grid line voltage (380V), and  $m$  is the modulation index ( $m=1$ ). The selected value of DC bus voltage is 700 V.

### 2.3 Formulation of DC-link capacitor and inductor

The  $L_{boost}$  and  $C_{boost}$  are an inductor and a capacitor of the boost converter. They are estimated by given equations (4) and (5). There  $V_o$  is the DC converter output voltage (700 V) and  $V_{in}$  is the input DC voltage of the DC converter is 406 V.  $F_{sw}$  is the switching frequency of the IGBT switch used in the DC-DC converter.  $\Delta I$  is the current ripple factor and  $\Delta V$  is the voltage ripple factor in dc converter current and voltage respectively.

$$L_{boost} = \frac{V_{in}(V_o - V_{in})}{F_{sw} * \Delta I * V_o} \quad (4)$$

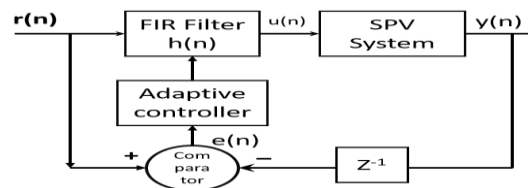
$$C_{boost} = \frac{I_o(V_o - V_{in})}{F_{sw} * \Delta V * V_o} \quad (5)$$

### 2.4 Inverter filter inductance formulation

The inverter output filter inductance is evaluated by (6)

$$L_f = \frac{0.1 * U^2}{2 * \pi * f * P/3} \quad (6)$$

$$R_{Lf} = L_f * 25$$



**Figure 3.** Adaptive control system using LMS algorithm

where  $P$ =Power capacity of inverter in kW,  $f$ = grid frequency in Hz,  $U$ = inverter output line voltage in Volt. The basic schematic of the three-phase grid-connected solar PV system in d-q form is shown in figure 2.

### 3. Control Theory

#### 3.1 Adaptive Control theory

An Adaptive control system using the LMS algorithm is proposed in this paper based on the Finite Impulse Response (FIR) filter concept as shown in Figure.3. The output signal  $u$  is the control input to the inverter control circuit. The control input is given by the convolution of the reference input  $r(n)$  and filter function  $h(n)$ . The step size  $\mu$  (8) is selected between the range 0 to 1, which is any real number. The advantage of the adaptive LMS algorithm is easy and simple to calculate. The output signal  $y(n)$  is delayed and used as a feedback signal, later it is compared to the reference signal  $r(n)$  to determine the error signal  $e(n)$ . The weight function  $h(n+1)$  is updated by using the LMS algorithm in (8).  $u(n)$  is the output signal of the FIR filter which is the result of convolution between weight function  $h(n)$  and  $r(n)$ . The following steps are used to implement the LMS Adaptive FIR Filter as a controller.

- Sense the output signal  $y(n)$
- Calculate the error,  $[r(n)-y(n-1)]$
- Determine the  $h(n+1)$  using eq. (8)
- Repeat the process for a given number of iterations

$$u(n) = \sum_{i=0}^N h_i r(n-i) \quad (7)$$

$$h(n+1) = h(n) + \mu e(n)r(n) \quad (8)$$

#### 3.2 Overview of d-q theory (d-q-0)

The d-q theory is the product of Clarke and Park transforms. This can be used to rotate the reference frames of AC waveforms so that they get converted into dc signals. The three-phase quantities and transformed into DC frame quantities. Simplified calculations can be done on dc quantities before performing the inverse transform. It is mostly used for the analysis of the three-phase system. In this work, the sensed three-phase system parameters are transformed into d-q components by using the d-q frame control theory.

### 4. Proposed Control Scheme

The proposed algorithm's schematic is expressed in Figure 3. In a Solar PV System, the Perturb and observe MPPT controller is applied to track the maximum power point and the developed adaptive LMS control technique in sub-section 4.2.3 is implemented with a three-phase inverter. The MPPT algorithm is to extract maximum power from the solar panel array at all conditions. Due to simplicity and ease, the MPPT algorithm Perturb and observe is selected. On the other side, the control scheme of the voltage source converter (VSC) emphasizes generating gating signals for the appropriate switching of the Converter's IGBTs under different conditions [8].

#### 4.1 MPPT Control

The maximum power point tracking (MPPT) method is used in the Solar PV DC-DC converter. It continuously adjusts the impedance of the converter circuit by looking into the solar array to track the PV system operating at the peak power point of the SPV panel under changing solar irradiance, temperature, and load. The P-O algorithm is based on finding the maximum power point by taking the derivative of power with respect to voltage [1-9].

#### 4.2 Control method for switching of VSC

##### 4.2.1. D-Q component estimation

The control structure is divided into sub-section as shown in figure.3. The grid voltage is sensed at the interconnection point of the grid, load and inverter. This voltage is converted into the  $\alpha$ - $\beta$  phase system.

The phase angle  $\rho$  is found by (9) and (10).  $V_\alpha$  and  $V_\beta$  are alpha-beta components of grid voltage. The d-q components of load current and grid current with respect to phase angle  $\rho$  are found by eq. (9).

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} V_a - \frac{V_b}{2} - \frac{V_c}{2} \\ \frac{\sqrt{3}V_b}{2} - \frac{\sqrt{3}V_c}{2} \end{bmatrix} \quad (9)$$

$$\rho = \omega t = \cos^{-1} \left( \frac{V_a - \frac{V_b}{2} - \frac{V_c}{2}}{\frac{\sqrt{3}V_b}{2} - \frac{\sqrt{3}V_c}{2}} \right) \quad (10)$$

The q component and q component are determined by applying Clarke's -park transformation theory (11). Determine  $I_{gd}$  and  $I_{gq}$  which are the d-q component of grid current by (11).

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} \cos \rho & \sin \rho \\ -\sin \rho & \cos \rho \end{bmatrix} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (11)$$

#### 4.2.2 DC component estimation

$I_d^*$  set point dictates the current that is being pumped into the grid. It indicates the total space current vector that is fed into the grid as the grid voltage is fixed. The control point of view  $I_q^*$  is made zero.  $I_d^*$  is the  $I_{dc\_ref}$  dc current which is obtained from dc bus voltage and reference voltage eq (12) or the output of the MPPT algorithm [13].

$$I_d^* = V_{dce} \cdot K_p + K_I \int V_{dce} dt \quad (12)$$

Where  $V_{dce} = V_{dc\_bus} - V_{dc\_busref}$

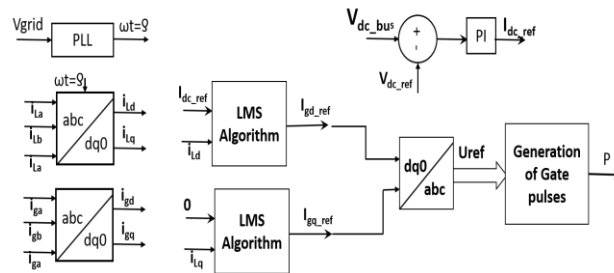
#### 4.2.3 Extraction of the reference current

The instantaneous error at  $k^{th}$  instant is determined from sensed grid current and weighted current for the d-q component by applying the FIR filter concept in section 3. The weighted component of the load current has been evaluated.

$$e_g(n) = I_d - \varphi(n)I_{dc\_ref}(n) \quad (13)$$

$$\varphi(n) = \varphi(n-1) + \eta e(n)I_{dc\_ref}(n) \quad (14)$$

The reference compensator current component is found by (15)



**Figure 4.** An Adaptive Control Algorithm for SPV System

$$I_d(n) = \varphi(n)I_d^*(n) \quad (15)$$

$$e_{qg}(n) = I_q - \varphi(n)I_q^*(n) \quad (16)$$

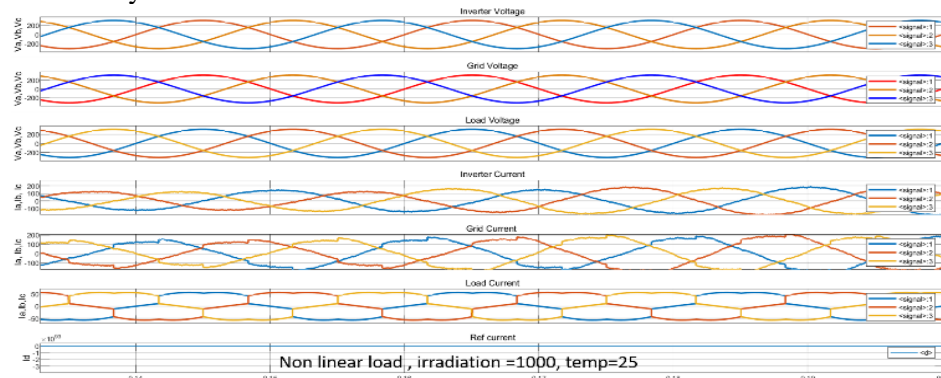
$$\varphi(n) = \varphi(n-1) + \eta e(n) I_q^*(n) \quad (17)$$

$$I_q(n) = \varphi(n) I_q^*(n) \quad (18)$$

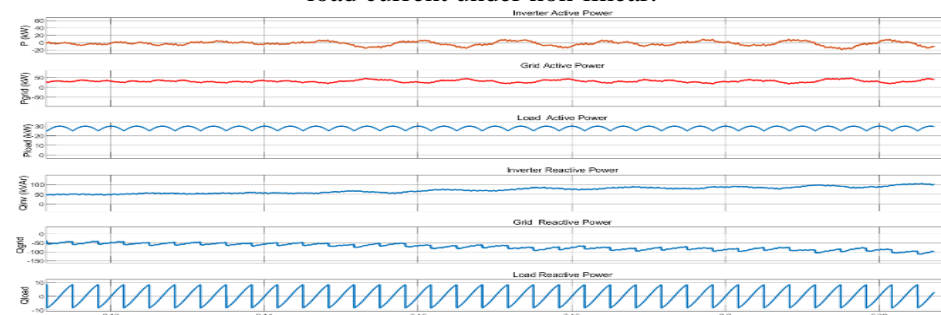
Where,  $\varphi(n)$  is the weight value at the  $n^{\text{th}}$  instant,  $\eta$  is increment size in the weight function. The reference quadrature component is made zero. The q-component ( $I_q^*$ ) of the reference compensator component is calculated by (16), (17), and (18). The generated reference components are transformed into a-b-c three-phase form. There are used to generate gate pulses for the multifunctional inverter [11].

## 5. Simulation Results and Discussion

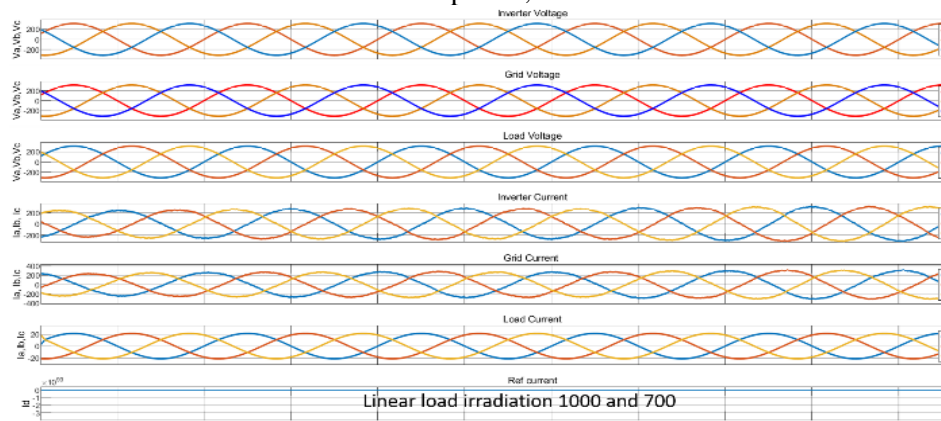
The proposed work is modeled, simulated, and verified on the MATLAB Simulink platform. The LMS Adaptive FIR Filter-Predictive Controller is tested under linear and nonlinear conditions and variations in solar irradiation. The system details are given in appendix A. The total harmonics distortion (THD) analysis is obtained by the FFT tool.



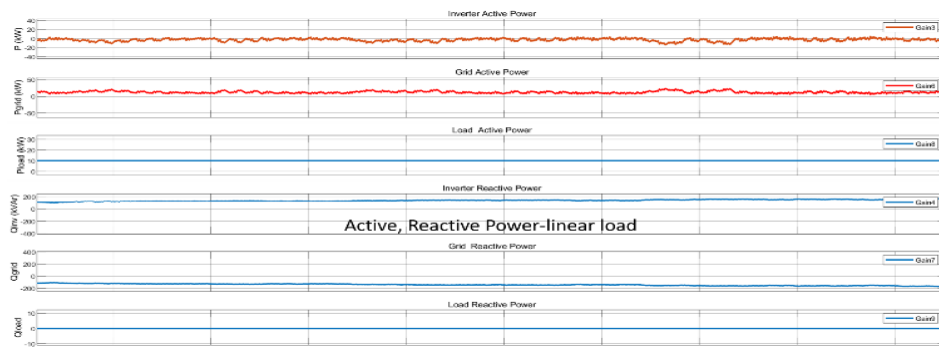
**Figure 5.** Performance of inverter voltage, grid voltage, load voltage, inverter current, grid current, load current under non-linear.



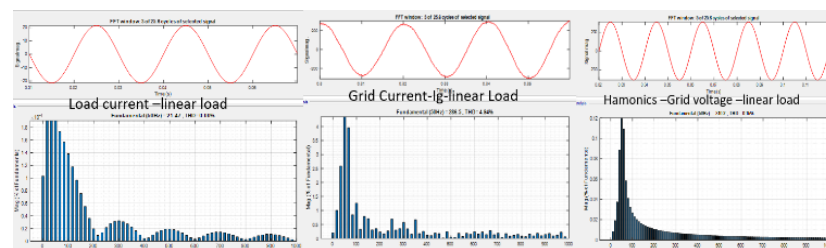
**Figure 6.** Performance of inverter active and reactive power, grid active and reactive power, load active and reactive power, under non-linear.



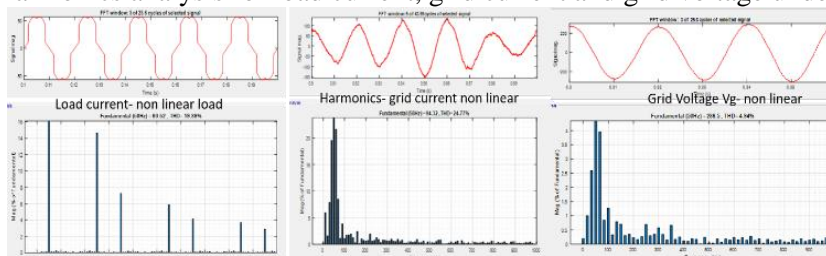
**Figure 7.** Performance of inverter voltage, grid voltage, load voltage, inverter current, grid current, load current under linear load



**Figure 8.** Performance of inverter active and reactive power, grid active and reactive power, load active and reactive power, under linear.



**Figure 9.** Harmonics analysis for load current, grid current and grid voltage under linear load.



**Figure 10.** Harmonics analysis for load current, grid current and grid voltage under nonlinear load.

### 5.1 Performance under linear and nonlinear load

The performance of LMS Adaptive FIR Filter-Predictive Controller for a grid-connected PV system under linear and non-linear load is observed from results shown in figure 5 to figure 10. It is observed that the waveform of voltage and current are maintained in sinusoidal form with a change in linear to nonlinear load.

**Table 1.** Harmonics results obtained under linear and nonlinear load

Load Condition	Grid voltage (THD) in %	Grid current (THD) in %	Load current (THD) in %	Convergence rate	P Power	Q power
Linear load	310.5, 0.15%	107.19A, 4.9%	21.47, 0%	0.05 sec	$P_g=10$ kW $P_{inv}=0$ $P_L=$	$Q_g=0$ $Q_{inv}=0$
Non-linear load	310.5, 0.00	133.5A, 4.70%	60.52, 19.89%	0.1sec	$P_g=20-40$ kW $P_{inv}=10$ kW $P_L=25-30$ kW	$Q_g=50-80$ $Q_{inv}=50-80$ $Q_L=10$ VAR

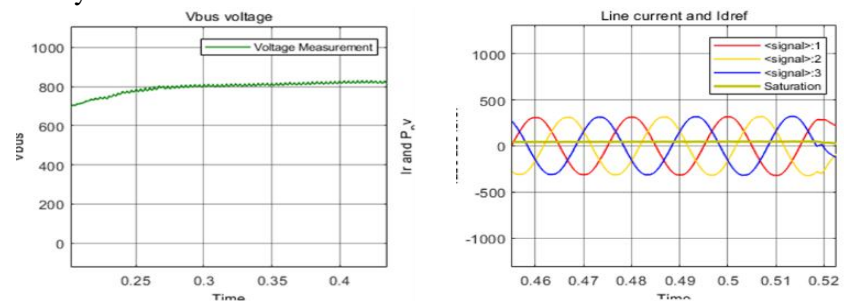
Under linear load, the grid supplies the active power to the load. Whereas the reactive power is supplied from the inverter to the grid. The THD measured in grid current,  $I_g$  is 4.9%, grid voltage ( $V_g$ ) is 0.15%, and load current,  $I_L$  is 0% under linear load. Similarly, THD in grid voltage  $V_g$  is 0%, grid current THD  $I_g$  is 4.70%, and load current THD is 19.89% under nonlinear, as mentioned in table 1. Grid voltage



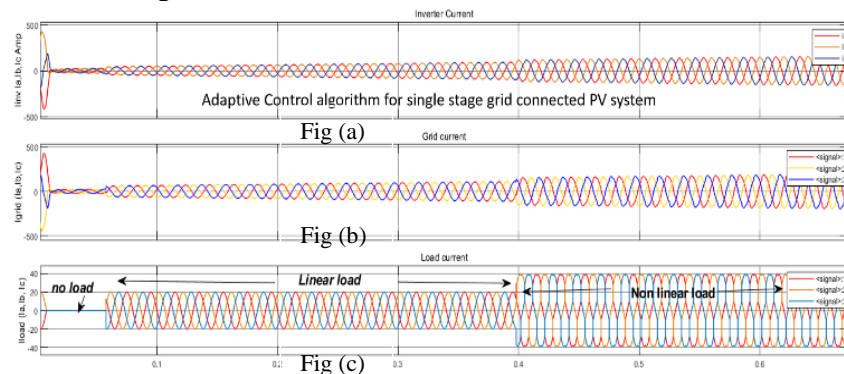
harmonics have been reduced drastically. It is observed that the efficiency of the LMS adaptive control algorithm is better for the nonlinear load. The simulation is started with the non-linear load. So, this control algorithm has proved that it works systematically under a change in load. It has a fast convergence rate of less than 0.01 sec. Under the nonlinear condition, the grid supplies active power as well as reactive power. This reactive power is compensated by inverter reactive power. During a change in load conditions from linear to nonlinear, the convergence rate of the adaptive controller is quite fast.

### 5.2 Performance under solar irradiance variation

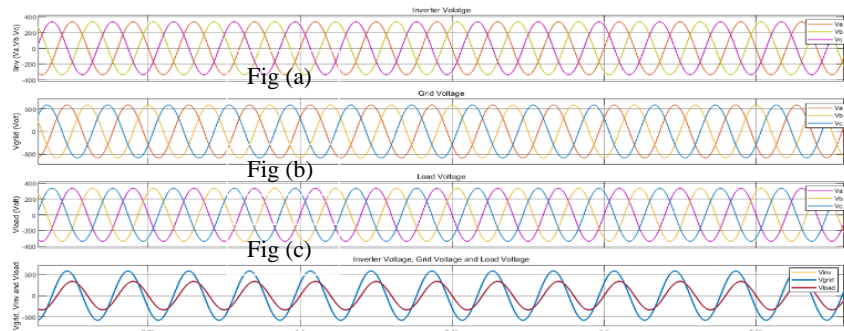
The entire system with LMS Adaptive FIR Filter-Predictive Controller is tested for various solar irradiation 600 to 1000 W/m<sup>2</sup>. The DC bus is retained at a constant value Figure 11 (a). The same adaptive algorithm is implemented for single-stage grid-connected PV systems. The results are shown in Figures 12 and 13. The control algorithm works satisfactorily for both single and two-stage grid-connected solar PV systems.



**Figure 11.** (a) DC bus voltage, (b) dc reference current and inverter line current –irradiation 1000w/m<sup>2</sup>



**Figure 12.** Performance of Adaptive control algorithm for single stage grid-connected PV system, (b) Inverter current, (c) grid current and (d) load current



**Figure 13.** Performance of Adaptive control algorithm for Single Stage grid-connected PV system, (a) inverter voltage, (b) grid voltage (c) load voltage.

**Table 2.** Steady-state and dynamic comparison of other LMS family controllers and LMS d-q control

Control algorithms	Steady-state	Amplitude of oscillation	Convergence rate
LMS d-q	Less	Less	Fast
Sign Error- LMS [5]	Less	Less	Slower
Sign Data-LMS	Medium	More	Medium
Sign Sign-LMS	Medium	Less	Medium

### 5.3 Summary

The number of equations derived to build the control scheme are less in number. The convergence time is less. If the sampling time is more than 30 microseconds and the hardware processor is of high speed, convergence time reduces. LMS Adaptive FIR Filter-Predictive Controller is a better substitute for the PI controller. This controller does not require tuning the parameters. The selection of step size is a difficult task.

### 5.4 Future Scope

Implementation of LMS Adaptive FIR Filter-Predictive Control on DSP Processor can experiment. The effect on parameters of change in step size of LMS algorithm can be observed,

## 6. Conclusion

The objective of the work was to develop LMS Adaptive FIR Filter-Predictive Controller to control a Solar PV system. Performance was analyzed by implementing LMS Adaptive FIR Filter-Predictive Controller with a Solar PV system. The development of the LMS Adaptive FIR Filter-Predictive Controller was based on the d-q theory for a grid-connected PV system observed under linear, nonlinear load and variation in solar irradiation. It was found that the system operation was more efficient for nonlinear load and change in solar irradiation from 600 to 1000 W/m<sup>2</sup>. This control algorithm was a good solution for the conventional controller. Building an LMS control algorithm based on p-q theory has reduced computational cost and the results obtained were satisfactory. The load current THD was 19.89 % which was less than 25% and grid current THD was 4.70 % also less than 5 % as per IEEE 519 standards. The waveform of grid current and inverter current was retained in sinusoidal.

## Appendix A

*PV system parameters:* nominal power:51 kW, DC Output voltage:406 V, nominal current:150 A

Interfacing inductor:0.027 H, resistor:0.0676 ohm

*DC- DC converter:* Inductor (Henry):00.0014e-4, Capacitor (farad):8.73690x10<sup>-4</sup>

Input voltage=406V, Output voltage=700V

*DC-AC converter:* 51kVA, 380 V, DC input voltage:700V

Linear load:10 kW, Nonlinear Load: rectifier with load (P=10 kW, Q=100 VAR)

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