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UTILITY INTERFACED PULSE-WIDTH MODULATION OF SOLAR FED VOLTAGE SOURCE INVERTER USING FIXED-BAND HYSTERESIS CURRENT CONTROLLER METHOD

C.U. Eya[a], **C.I. Odeh**, **D.B.N. Nnadi**, **M.U. Agu**, **S.E. Obe**

Department of Electrical Engineering University of Nigeria, Nsukka, Nigeria.

[a] ***Email:*** *ecandidus@yahoo.com*

Abstract

This paper describes a utility interfaced pulse-width modulation of solar-fed voltage source single phase full bridge inverter. The proposed system has to do with the conversion of solar energy into electrical energy; boosting the dc power; inversion of the dc to ac and then synchronization of the inverter output with the utility, and consequently, reduction of the total harmonics distortions in the supply. The proposed system will ensure steady state availability and sufficiency of power supply to its areas of applications .To achieve this, current sensor, fixed-band hysteresis current controller and filter were employed to ensure proper injection of power to utility side and vice versa. The computer simulations and spectral analysis of the system obtained from Simplorer Software were presented. This proposed system is designed for use in residential houses and industries.

Keywords: utility interface, single phase full bridge inverter, boost converter, pulse-width modulation, fixed-band hysteresis current controller, current sensor

1. Introduction

A utility interfaced Pulse-Width Modulation of solar-fed voltage source single phase full bridge inverter with current controlled operation could be considered as the connection as well as synchronization of the output of single-phase full bridge pulse-width modulated (PWM) voltage source inverter (VSI) with the single phase utility grid system. This is achieved by sensing the current passing through the inductor so that the current and the grid voltage will be at same frequency and in the same phase with each other [1]. It could also be called single phase gridconnected pulse width modulated solar fed voltage source inverter. The inverter is to be connected between two power sources (DC and AC sources) so that whenever there is shortage of load power from photovoltaic (PV) module, it will be supplemented by the utility. On the contrary, the excess power from PV module can be fed to utility [1]. The prime motives of the proposed system include reducing air pollution caused by the use of fossil fuel, minimization of global warming, reduction of damage to environment/ ecosystem and to respond to increase in electricity demand for the teeming population especially in Nigeria. Even though, this proposed system suffers from minor drawbacks such as high installation costs, low conversion efficiency, variable PV output power and weather conditions dependent, yet it is better than total dependency on fossil fuel.

The negative effects of the conventional sources of energy such as pollutions, oil spillage, high cost of fossil fuel products, depletion nature of fossil fuel and degradation level of ozone layer in the atmosphere caused by dependency on fossil fuel globally, have prompted the development of technologies required for the use of non polluted alternative energy sources such as solar energy and wind energy [2]. It is beyond doubt that especially the high establishment of the power electronics has made the energy produced by the above alternative sources accessible and at the same time at low cost [3]. Moreover, it has allowed the spreading of the distributed generation (DG) consisting of a great number of small and medium generation systems connected to the distribution grid to feed a dedicated consumer and then the excess to be supplied to the grid [4].

There are several ways through which power could be injected into grid utility supply that have been proposed and implemented by many people in the past. In [5] a single phase PV grid connected current source inverter topology with synchronized inverter current and voltage was presented but there was a high degree of current output fluctuations due to the losses incurred in DC link inductor used and the latching current losses of the thyristors hence reducing the efficiency and the power factor of the system. Moreover, [6] used asymmetrical sinusoidal pulse width modulated inverter in PV grid connected system to export excess power to the grid utility. Here, there is a very wide phase shift between the filtered inverter current and the grid voltage in the work. So the power factor of the system is far less than unity because of the presence of unwanted signals.

The author of [7] used a resonant pulse inverter and diode rectifier coupled with PWM inverter grid-connected system in injecting power to the grid. The circuit is shown as in Fig. 1.

The circuit above consists of solar cell, the controlled single phase full bridge resonant pulse inverter of high frequency carrier (input inverter), tank circuit, diode rectifier, and PMW current source inverter of low frequency (output inverter). It is used in injection of DC power to the grid utility from solar energy source. The PWM inverter (output inverter) synchronizes inductor current, iLF with the grid utility voltage under (k=2) discontinuous conduction mode. In this type of discontinuous conduction mode, the tank circuit rings for two complete half-cycles during each half-period of length Ts/2. After the two complete half-cycles, the rectifier diodes become reverse-biased. The graph of output inductor current and grid utility voltage synchronization of circuit topology of Fig. 1 is shown in Fig.2. It shows that the synchronization of output inductor current from the PWM inverter and grid utility voltage occurs in a discontinuous current mode. In discontinuous current mode, the inductor current grows from the zero axes throughout the operation. The current flowing into the grid utility is more than 100 amperes with a lot of harmonic distortions contents. The Fig.3 indicates the harmonic spectral display of the inductor current of unwanted signals affecting the current that are being injected into the utility. They contain some order of harmonics of high magnitudes; resulting in higher current distortions. This is because at resonance state, the ringing nature of the resonating components introduces a lot of noises in the whole circuit. One of the problems of this method is that it injects high polluted currents to the grid under discontinuous conduction mode. Secondly, it is very expensive to control. And finally, the circuit is very cumbersome.

2. The Circuit Topology Of The Proposed System

The circuit of the proposed grid-connected inverter system of fig.4 used in the simulation consists of the PV cell for DC power production, the boost converter for stepping up the voltage, the insulated-gate bipolar transistors (IGBTs) and clamping diodes for conversion of DC power to AC power and for unidirectional flow of currents, reactor for filtering the unwanted signals or reduction of the harmonic contents, and the control circuits for triggering the switches as well as ensuring the high performance and protection of the power circuit. It is worthy to note that PV used in the proposed system was under a controller called maximum power point tracker (MPPT), this will ensure that only the peak values of both current (Impp) and voltage (Vmpp) were injected into the system.

3. A Brief Concept of Hysteresis

Hysteresis refers to systems that may exhibit path dependence or rate-independent memory [1]. It is not possible to predict the output of

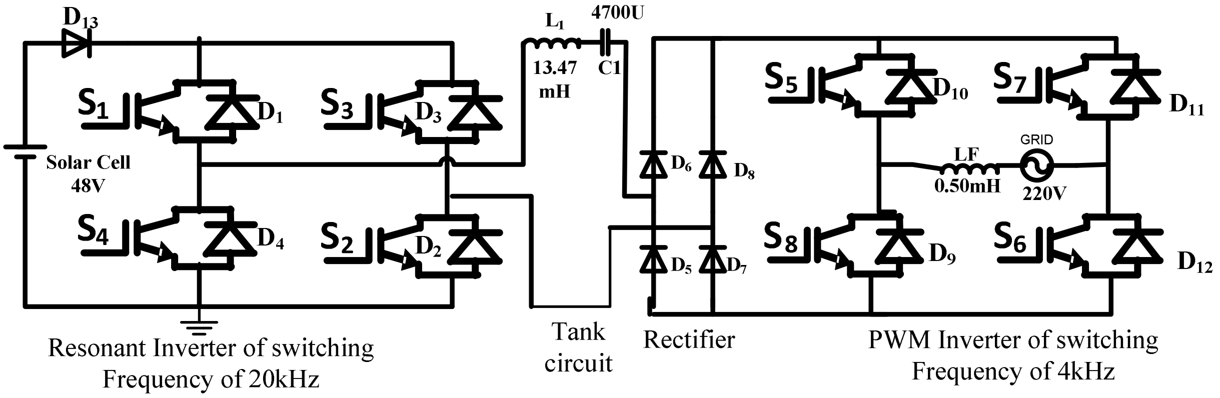


Figure 1: Resonant-pulse – DC-link PWM inverters coupled with grid utility supply.

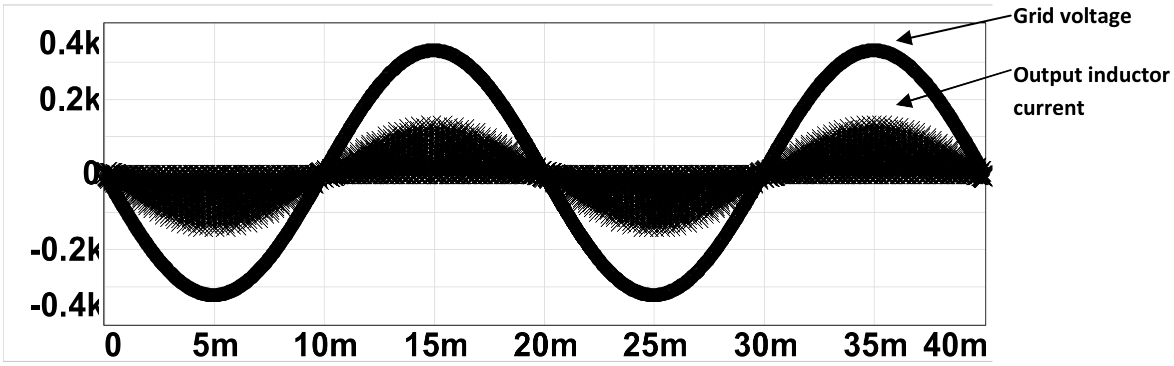


Figure 2: Output Inductor current of Resonant /PWM inverters and the grid utility voltage synchronization.

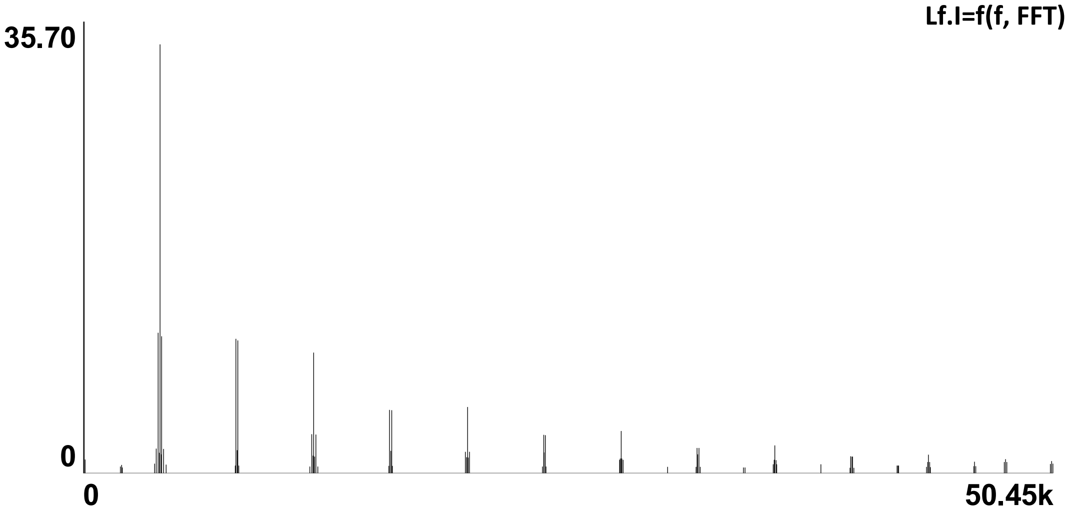


Figure 3: Spectral analysis of inductor current of output PWM inverter (THD of 3.061%; Power factor of 0.574 calculated using Fast Fourier Transform, FFT).

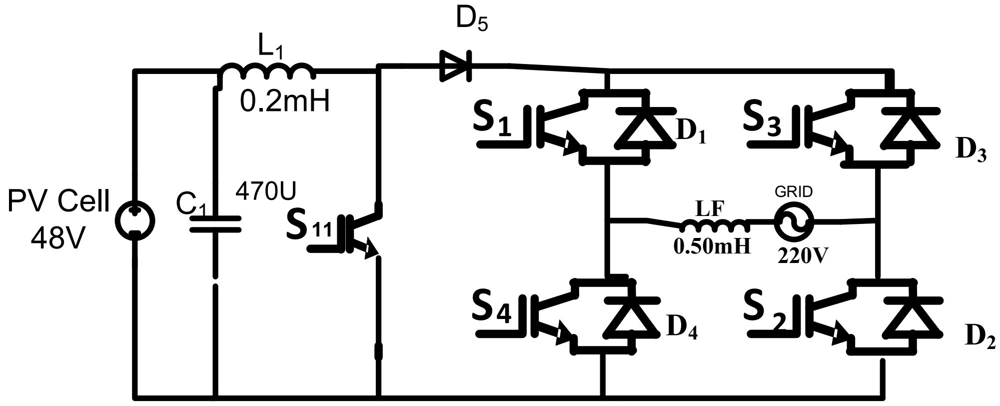


Figure 4: The circuit diagram of the proposed Grid-connected Pulse-width modulated solar-fed voltage source inverter system.

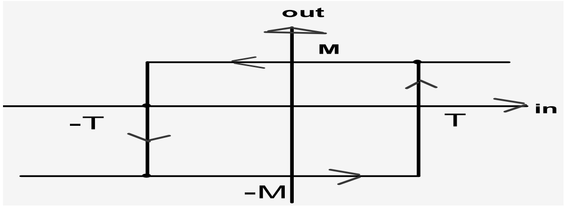


Figure 5: Sharp hysteresis loop of a Schmitt trigger.

a system with hysteresis at an instant in time by mere taking into consideration only its input at that time. This means that its output solely depends on the internal state of the system and its input parameters. There are many areas where hysteresis can be applied such as in engineering control, ferromagnetic materials, ferroelectric materials, elastic materials, e.t.c. For instance, Schmitt triggers are examples of electronic circuits that exhibit hysteresis [2]. A sharp hysteresis loop of a Schmitt trigger is shown in fig.5. The letters M,-M, T and -T (boundaries) are used to indicate the pathway (loop) of the hysteresis of the Schmitt trigger.

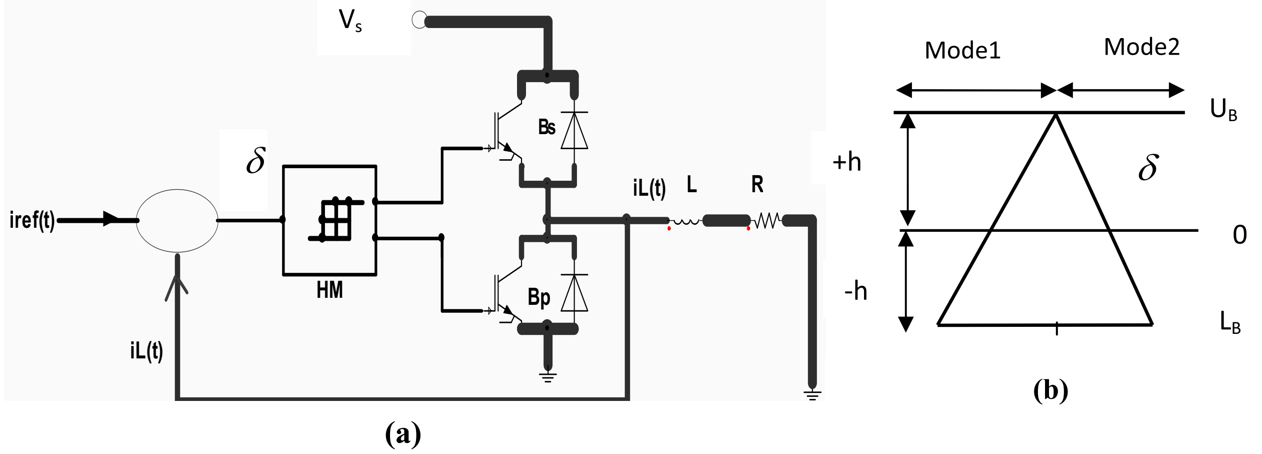
It is also used in controlling the switching mode of AC chopper for minimization of errors and fast recovery from disturbances that may exist in the system in which it is controlling.

4. The Fundamental Concepts of Hysteresis Current Control in Voltage Source Chopper (VSC) (FEEDBACK Control)

The fundamental structure of a single-phase current hysteresis control loop of a voltage source chopper containing R-L load, is shown in fig.5a. The load current $i_L(t)$ of the AC chopper is fed back to be compared with the reference current $i_{ref}(t)$ in the hysteresis modulator (HM), the current error δ is compared with the hysteresis band as shown in fig.5b. When the current error δ crosses the upper boundary U_B, the lower chopper switch Bp is turned ON and upper chopper switch Bs is turned OFF (here the delays and dead times are neglected) while the opposite process happens at the crossing of the lower boundary L_B [2]. As a result, the output voltage is transitioned from $V_s \sin \omega t$ to 0 and where, V_s is the input chopper voltage. The actual current is thus forced to track the sine reference wave to desired hysteresis. Another important area application of hysteresis control is in regulation of current into the grid utility supply which could be applied either in a fixed-band hysteresis current controller or sinusoidal current controller.

5. Theoretical Analysis of the Control of Current in Proposed Grid Connected PWM Voltage Source Inverter Using Fixed-Band Hysteresis Current Controller Approach

In fixed band hysteresis current controller, the reference current, upper band and lower band limits are created so that the filtered inverter output current is forced to track the reference current within the hysteresis bands for the near unity power factor actualization. In the hysteresis current controller used in this proposed system, the inductor current is compared with the sine wave



(a) (b)

Figure 6: (a) Fundamental scheme of VSC hysteresis current control. (b) current error over one switching cycle.

reference current, and the error signal is passed through the hysteresis band to generate the firing signal pulses, which is operated to produce output voltage in manner to reduce the current error signal. In fixed hysteresis band, the hysteresis bands are fixed throughout the fundamental period [8]. It gives good performance in controlling current in the course of injecting power to the grid. The algorithm for this scheme is given by the following:

$$i_{ref}(t) = I_{max}\sin\omega t \qquad (1)$$

$$\begin{aligned} \textit{upper band},\ i_{up} &= i_{ref}(t) + h \\ \textit{lower band},\ i_{low} &= i_{ref}(t) - h \end{aligned} \qquad (2)$$

Where h is hysteresis band limit; i_{ref} is reference current; I_{max} is the peak current of the reference current

If $i_L > i_{up}$; turn OFF S_1 and S_2; turn ON S_3 and S_4

If $i_L < i_{low}$; turn OFF S_3 and S_4; turn ON S_1 and S_2

6. Maximum Switching Frequency of Inverter

The maximum switching frequency (MSF) of inverter [9] is defined as

$$\text{MSF} = \frac{1}{T_1 + T_2}(\text{Hz}) \qquad (3)$$

Where T_1 and T_2 are minimum ON and OFF periods available to the device to switch from previous OFF and ON states.

The maximum switching frequency of inverter using fixed-band current controller is analyzed considering a section drawn in Fig. 7 as shown below [8].

Considering when S_1 and S_2 are turned ON in Fig.7 [3], the inductor current will reach P from A in time T_1 = AB. The slope of the reference current at $t = \frac{T}{2}$ is expressed as:

$$m = \frac{di}{dt_{t=T/2}} = 2\pi f_m M \qquad (4)$$

Assuming the line PD to be in parallel to the tangent drawn on the reference current at $T/2$ and PQ a line parallel to AB, the geometry of Fig. 7

$AD = AQ + QD = 2h$, with the identities of the following

$$AQ = PB = AB\tan\alpha = T_1\tan\alpha$$

And $QD = PQ\tan(DPQ) = T_1(2\pi f_m M)$ T_1 is approximately given by:

$$T_1 = \frac{2h}{2\pi f_m M + m}(\text{sec}) \qquad (5)$$

M = I_{max} = Peak value of the reference current (amps.); f_m = frequency of the reference current m Slope of the reference current (di/dt) h Hysteresis band (amps). α - angle between the inductor current and T1 in Fig. 7. f_m - frequency

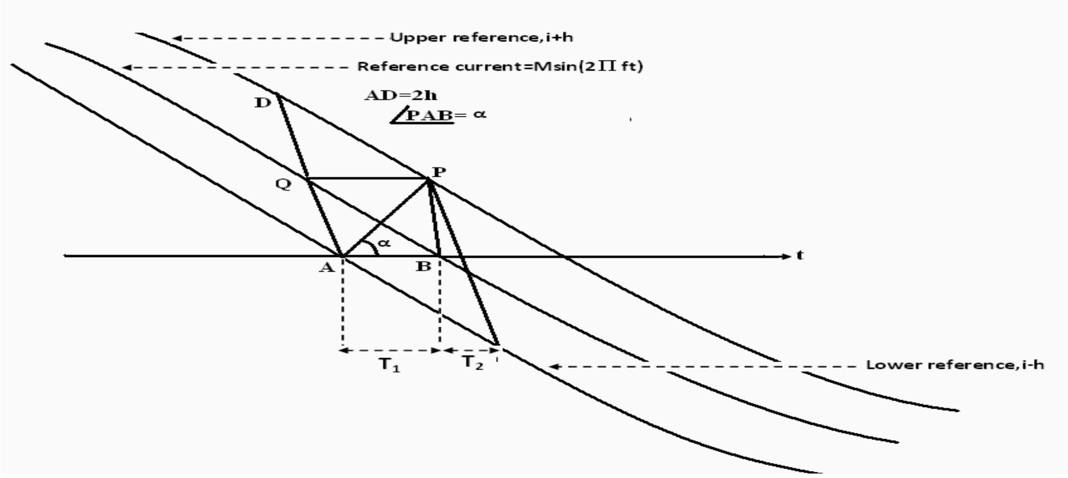


Figure 7: Determination of MSF of fixed-band Current Controller.

of the reference current(Hertz). T - fundamental period.

Then assuming that $T_2 = T_1$, the maximum switching frequency (MSF) is given by:

$$MSF = \frac{2\pi f_m M + m}{4h} (\text{Hz}) \tag{6}$$

Considering a sampling rate of "N" per cycles, current increment of S in the sampling interval, the current slope, m, can be written as:

$$m = \frac{S}{1/f_m N} = S f_m N \quad (\text{A/sec}) \tag{7}$$

The Maximum switching frequency of fixed hysteresis band is:

$$(MSF)_{fixed} = \frac{f_m (SN + 2\pi M)}{4h} \tag{8}$$

Where N-number of sampling rate per cycle; S-current increment in the Sampling interval. The Average Switching Frequency of inverter (ASF) is defined as:

$$ASF = \frac{N_s}{T} (\text{Hz}) \tag{9}$$

Where N_s - number of switching in one fundamental period, T - fundamental period.

7. Modeling And Simulation Of Grid-Connected PWM Of Solar-Fed VSI Near Unity Power Factor

The parameters used for the simulation of the system are shown in table 1.

Table 1: Simulation parameters of utility interfaced PWM of solar-fed voltage source Single phase full bridge inverter.

Name of the parameters	**Values of parameters**
PV module Voltage	48.00V
Frequency of Grid (Utility)	50Hz
Grid (Utility) Voltage	(220 - 230)V
Duty Cycle	0.500
Filter inductor(reactor)	0.500mH
Input Capacitor	470μF
Input Inductor	0.200mH
IGBT	6000V
Clamping diode (thermal Voltage)	32.00mV
Time duration	40ms
Carrier Frequency	20k(Hz)
Power factor got in fixed band controller	0.975

7.1. Operation of the grid-connected pulse-width modulated voltage source inverter system

As far as the input DC voltage and current are not at their maximum values, the inverter will be set to idle state to save energy. But immediately the maximum current and voltage (maximum power) are detected, the signals are passed to the analog-digital (A/D) converter which digitizes them and transmits them to the signal processing part of the control unit. This control unit sets the switch of boost converter into operation to step-up the voltage and produce current which is proportional to (1-D), (that is boosted DC power) after matching the impedance of PV and that of the boost converter; and then delivers it to the inverter, where D, is the PWM duty cycle of the DC- DC converter. The inverter will still be functionless until it receives triggering signals. When it receives positive incoming signals from control unit through the gate drive terminals of the IGBT (S_1, S_2), it produces a gating signal to emitter voltage, $\mathrm{V_{GE}}$ greater than the threshold voltage $\mathrm{V_{GE(TH)}}$ to open up the IGBT channel, then the already established voltage between collector and the emitter, pumps the majority carriers (electrons) from the emitter to collector terminals through the inversion layers which convert the available DC currents to negative half cycle of non-sinusoidal alternating current.

When the incoming terminal signal is negative to trigger gates of S_3 and S_4, a positive half cycle of non-sinusoidal alternating current appears at the collector terminals of the IGBTs; hence a complete non-sinusoidal alternating current cycle is formed. The continuously turning ON and OFF of the switches of the S_1 and S_2; with S_3 and S_4 produces many cycles of non-sinusoidal AC waveforms as the output of the inverter. The output of the inverter in most cases is a square wave. Then the output of the inverter is allowed to pass through an inductor which filters the ripples and eliminates majority of the harmonics (higher order ones) to generate a triangular- sinusoidal waveform which is the signal output of inductor. The control unit has a feedback loop such that the switching mode is determined by comparison of the actual current and sinusoidal reference current, or the actual current oscillates in a fixed band hysteresis (FBH). This implies that the error current applied to a hysteresis element, gives the PWM pattern for proper controlling of the injection of DC power to the grid utility.

Another function of the output inductor of 0.5mH, in Fig. 4 is that it is the point of common coupling component between the inverter and the utility grid. As soon as the output of the inductor is formed, the controller forces it to track the reference current in-between the upper and lower band limits accordingly in order to be delivered to the grid closed a unity power factor.

The instantaneous voltage across the inverter output for (n=1) is expressed as follow:

$$v_{inv} = V_l + v_{grid} \tag{10}$$

$$V_{inv} = \frac{Ldi_l(t)}{dt} + V_{01}\sin\omega t \tag{11}$$

$$i_L(t) = \frac{1}{L}\int_o^T (v_{inv} - V_{01}\sin\omega t)dt \tag{12}$$

Where v_{in} is the instantaneous inverter output voltage, L - inductance, V_{01} is the maximum grid voltage, ω - angular frequency, i_l - instantaneous output inductor current (filtered inverter current), T - fundamental period.

8. Fixed-band Current Controller for Synchronization of Filtered Inverter Current and Grid Utility Voltage at near Unity Power Factor

The algorithm of the fixed-band current controller is stated as follows: Considering the alternating current from the utility supply as the reference current at (n=1), that is, the fundamental component and is expressed as:

$$i_{ref}(t) = I_{max}\sin\omega t \tag{13}$$

The upper current band of waveform is given by:

$$i_{UP} = i_{ref} + h \tag{14}$$

For the lower current band of the waveform, we have:

$$i_{LOW} = i_{ref} - h \tag{15}$$

If $i_L > i_{UP}$; Turn OFF S_1 and S_2; turn ON S_3 and S_4; $V_{inv} = \frac{-V_{mpp}}{2}$

If $i_L < i_{LOW}$; Turn OFF S_3 and S_4 ; turn ON S_1 and S_2; $V_{inv} = \frac{+V_{mpp}}{2}$

When the current sensor detects the inductor current flowing, it sends the information to the hysteresis comparator for comparison, if the inductor current is greater than upper current band limit, the comparator sends out the error current signal to activate the power switches by turning OFF S_1 and S_2; and turning ON S_3 and S_4 thereby decreasing the current gradient to force the inductor current to track the reference current. Besides, the voltage output of the inverter would be equal to half of the boosted maximum DC voltage with negative sign. But if the filtered inverter current is less than the lower current band limit, the comparator produces current error signal which turns OFF S_3 and S_4; and turns ON S_1 and S_2 for pulling up the current gradient so that the inductor current is confined within the hysteresis band limits. Under this condition the voltage output across the inverter is equal to $+V_{mpp}/2$.

Therefore the continuously decreasing and pulling up of current gradient as the inductor current is flowing makes proper synchronization of the filtered inverter current to have the same frequency and in phase with the grid utility voltage. Hence, it makes the power factor of the circuit close to a unity factor. The graphical representation of the fixed-band hysteresis current controller for controlling the injection of current into the utility grid is shown in Fig.8.

The synchronization of inverter current and grid utility voltage near a unity power factor waveforms is shown in Fig. 9. But as far as the inductor current is within the normal range, the controller continues on its normal switching operation. And once it traces it well, the current flowing through inductor and the grid utility voltage simultaneously start from the same origin, rise at their minimum points of different amplitudes at angles of 90° and 270°, fall back to zero at angles 180° and 360° to complete a cycle. Hence they are said to be synchronized and at an approximately unity power factor.

Fig.4 shows the circuit representation of grid-connected PWM voltage source inverter system in which the maximum DC input power is transferred to the inverter circuit when there is uniform matching of PV impedance and the impedance of the boost converter. The input bank of capacitor bank assists in making the input power fluctuations ripple free.

Fig.9 shows that the maximum synchronized voltage amplitude is 311(volts) and peak synchronized current of 98A is flowing into the grid utility near a unity power factor. The current distortion is drastically reduced to minimal level but not completely eliminated because of existence of irregular frequencies associated with the fixed-band hysteresis current controller on the course of regulating the flow of current into the grid. The harmonic order of the output inductor current is analyzed by Fast Fourier Transform (FFT) and is shown in Fig. 10. The total harmonic distortion is about 1.8146% and the power factor is 0.975.

9. Simulation Results

The solar module we used is BP SX 160S PV module of amorphous type. The module is made of 82 multi-crystalline silicon solar cells in series and provides 160W of nominal maximum power. Table 2 shows its electrical specification.

10. Analysis of the Results

Figures 2 and 3 show synchronization of current and grid utility voltage and the spectral current analysis of injected current of resonant pulse-DC-link PWM inverter coupled to the grid utility. The size of the amplitude current is 125A (0.125kA) and peak grid voltage is 311V. Fig.8 clearly shows the waveforms of how the output inductor current traced and tracked the reference current in the control unit of the proposed system. In Figs. 9 and 10, the synchronized filtered inverter current and utility voltage waveform and its spectral current display of the grid-connected inverter system near a unity power factor under fixed-band hysteresis current controller were graphically represented. The size of peak current and maximum grid voltage are 98A and 311V.

Table 3 shows clear distinctions between the two methods of injection of current into the grid utility. For instance, the peak value of current, power factor and THD in resonant pulse-DC-link PWM inverter coupled with grid utility are 125A, 0.574 and 3.061% while in the proposed system, the maximum value of current, power factor and THD are 98A, 0.975 and 1.8141%. Moreover, the size of the proposed circuit is smaller than the resonant-pulse-DC-link PWM grid connected inverter.

Therefore due to high current injection into the grid and tremendous size of the circuit in resonant pulse-DC-link PWM inverter coupled with grid utility as result of resonance in the system, there is a lot of power losses in the circuit and high cost of execution and maintenance of the system. This is the contrary in the proposed system. The power factor in the proposed system is high and this brings about the reduction in power loss and in the cost of maintenance. Due to the above reasons, the proposed system is highly recommended for utility interface connections.

Table 2: Electrical Characteristics of BP SX 160S PV Module from Manufacturer Data Sheet.

Max. Power (P_{max})	**Voltage at** P_{max} (V_{mp})	**Current at Pmax** (I_{mp})	**Open-circuit voltage** (V_{oc})	**Short-circuit current** (I_{sh})	**Temp. coefficient of** I_{sh}	**Temp. coeffi. of** V_{oc}
160W	36.45V	4.40A	44.5	4.85	0.065 ± 0.015	-160 ± 20mV/oC

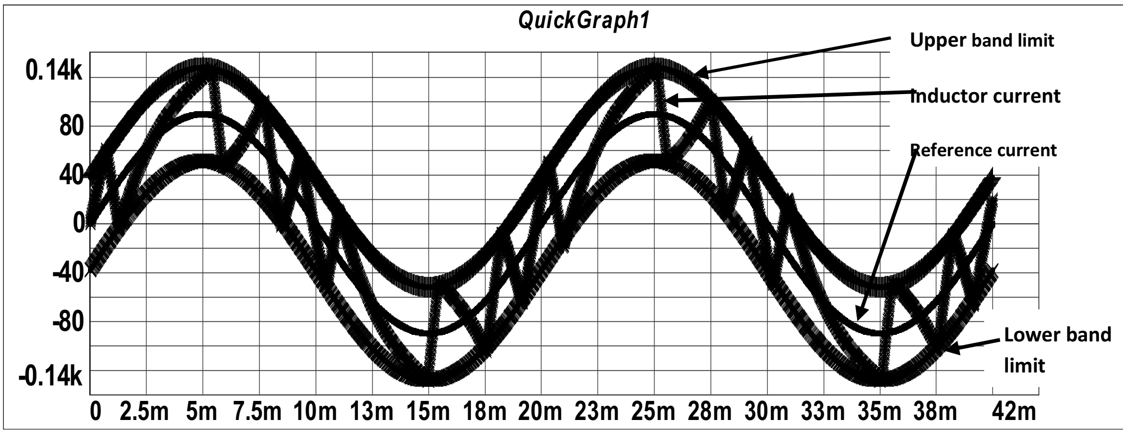


Figure 8: Behavioral pattern of output inductor current (triangular-like waveform), reference current (ac current in middle); upper current band limit and lower current band limit at control unit using fixed- band current controller Approach or (current waveforms in hysteresis current control technique).

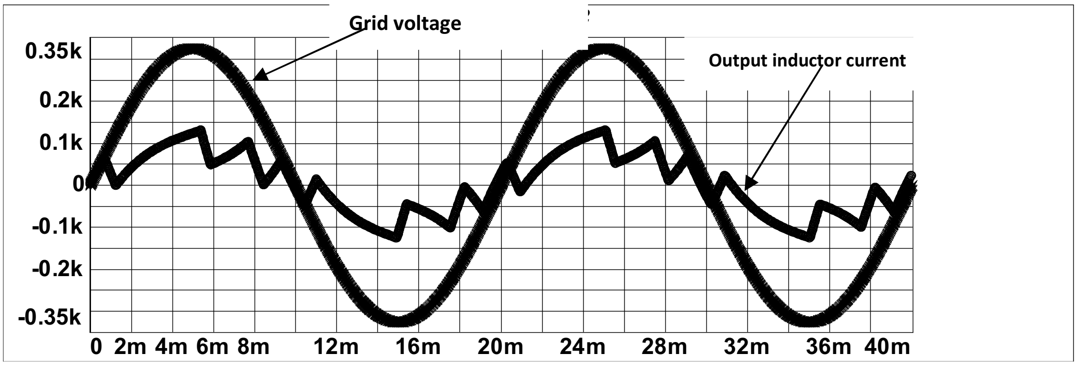


Figure 9: The synchronized filtered inverter current (red -tooth waveform) and utility voltage waveform (dark red wave) of the grid-connected inverter system near a unity power factor under fixed-band hysteresis current controller.

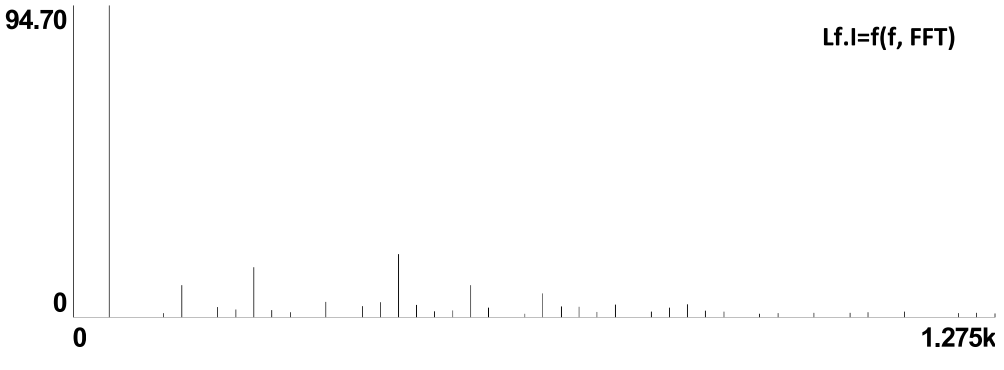


Figure 10: Spectral analysis of filtered Inverter output current under fixed band current controller (THD of 1.8146% and power factor is 0.975 calculated using Fast Fourier Transform FFT).

Table 3: Comparison of the Resonant-Pulse DC-Link PWM Inverters coupled with Grid Utility Supply and the utility interfaced pulse-width modulation of solar-fed voltage source single phase full bridge inverter.

Name	**Resonant pulse-DC-link PWM inverter coupled with grid utility**	**The proposed system**
Numbers of inverter used	Two inverters (input inverter of carrier frequency of 20kHz and output inverter of carrier frequency of 4kHz)	One inverter of carrier frequency of 20kHz
Method of injected current control	Resonant method	Fixed band hysteresis current approach
Size of Injected current	125A (0.125kA)	98A
Total harmonic distortion(THD)(%)	3.061%	1.8141%
Power factor	0.574	0.975
Size of circuit	Very large	Small
Mode of current	Discontinuous current mode injection	Continuous current mode injection

11. Conclusion

This paper presented the utility interfaced Pulse-Width Modulation of solar-fed voltage source single phase full bridge inverter with current controlled operation at near unity power factor using fixed band hysteresis current controller's approach. The simulation results have demonstrated the feasibility of the proposed system in scaled-down grid-connected condition. Moreover, due to the simplicity and fastness in the control method, low cost of production due to miniature nature of the circuit, high power factor and low cost of maintenance, the proposed system can be massively produced with little power loss in operations.

References

1. N.Mohan, T.M undeland,and W.P Robbins, *Power Electronics-Converters Applications and Design*, 2nd; John Wiley & Sons, Inc.1995.
2. Muhammad H.Rashid , *Power Electronics-Circuits, Devices, and Applications,3rd Edition*, Dorling Kindersley (India) Pvt.Ltd.2006
3. D.K Mohamed, A.Midoun, F.Safia, Optimisation of Photovoltaic generator Supplying an Induction motor using fuzzy logic technique, *JNVER 99* Tlemeen 1999.
4. Kjaer,S.B; Pedersen, J.K ; Blaabjer .F, A review of single-phase grid-connected Inverter for Photovoltaic modules, *IEEE Transactions on Industry Applications*, vol.41, no.5, pp.1292-1306, September-October, 2005
5. Calais,M; Myrzik, J. Spooner,T.Agellids,V.G, Inverters for single-phase grid-connected Photovoltaic System-an overview, *IEEE Power Electronics Specialists Conference*, vol.4, pp.1995-2000, 2002
6. Hassaine, E.Olias, M.Haddidi and A.Malek, Asymmetric SPWM used in inverter grid-Connected, *Revue Des Energies Renouis velables* vol.10 No3 (2007), pp421-429.
7. L.Malesani and D.M Divian, A Synchronized resonant dc link converter for soft-switched PWM, in *IEEE Ann. conf. Rec*, 1989, pp 1037-1044.
8. A.Tripathi, P.C Sen, Comparative analysis of fixed and sinusoidal hysteresis current Controller for voltage source inverters, *IEEE Trans.on Industrial Electronics*, Feb-1992, Vol.39, No.1, pp.63-73