Design and Analysis for High Performance Synchronized Inverter with PWM Power Control

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***Abstract*—This paper presents simulation results of a high performance single phase Sinusoidal PWM inverter compared to traditional SPWM type. The proposed inverter uses a suitable Voltage Controlled Oscillator (VCO) that to produce variable carrier frequency controlled by full rectified wave reference grid voltage. The reference grid voltage is compared with output triangular carrier wave of the VCO to generate variable frequency PWM pulses. An electronic controller is also designed to stabilize the fluctuation of the DC voltage supply that can occur in renewable energy sources such as solar or wind which is assumed to be an input to the power electronic circuit of the proposed inverter. The simulation results show reduction in the Total Harmonic Distribution (THD) when using variable carrier frequency compared with the traditional fixed carrier frequency SPWM. On the other hand the controller show effective range of Modulation Index (MI) controlling from 0.77 to 0.89 when the DC supply voltage is varying from 350V to 300V with capability to modify the controlling range of MI. satisfactory AC output specifications are obtained from the simulation results that may lead the proposed design to be considered for practical implementations using general purpose discrete components without the need of special DSP chip.**

***Index Terms*— Renewable Source, Voltage Controlled Oscillator, Sensing Circuit, Fluctuation Controller, Carrier Frequency, and Grid Synchronized Inverter.**

I. INTRODUCTION

The consideration of renewable energy as a valuable source of power that is more important for many reasons, first of all the availability of this source, cleaning merit, and then there are other merits related with the power specifications of this type. [1]. Beside of all mentioned reasons, in case increase using of renewable energy sources, this would be lead to minimize the rate of pollution in our environment, that may came because other types of energy sources such as fossil fuels, wood.

Solar cell is electronic components manufactured from a certain layers of semiconductors materials that transfer the incident light energy to direct current (DC) with a certain value of voltage that is mean the solar cell work as a voltage source. [2], the solar panel is an array of solar cells connected in parallel and serial to deliver the consumer with desired value of power which can be delivered from the panel depending on the number of included cells and the way of internal connection of these cells [3]. The interest from this type of power to alternating current (AC) loads obtained through a suitable inverter which is a power electronic equipment used to invert the direct current (DC) power to AC power with suitable specifications to supply AC loads. Fig. 1 represents H-Bridge Configuration using N – Channel MOSFETs inverter, There are four possible switch positions that can be used to obtain AC voltage across the load. These positions are outlined in Table 1. Note that all other possibilities are omitted, as they would short circuit power to ground. [4]

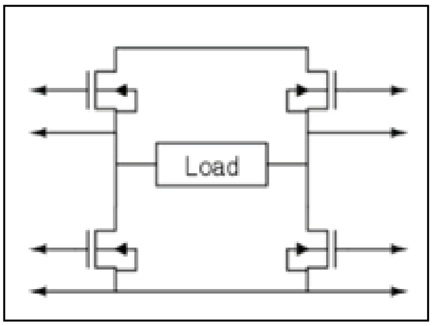

Fig.1. H-Bridge Configuration using N-Channel MOSFETs

TABLE I. VALID H-BRIDGE SWITCH STATES

High Side Left	High Side Right	Low Side Left	Low Side Right	Voltage Across Load
On	Off	Off	On	Positive
Off	On	On	Off	Negative
On	On	Off	Off	Zero Potential
Off	Off	On	On	Zero Potential

The shape of alternating output wave of inverter is depend on the technique used to produce switching pulses to the inverter switches, the square pulses with fundamental frequency without higher carrier frequency will lead to deliver output inverter voltage AC square wave to the connected loads, this square wave will produce high levels of harmonics, and consequently more losses in energy and negative effect on the response of the connected load. [5]. Pulse Width Modulation (PWM) have many techniques developed to achieve the following aims: wide linear modulation range, less switching loss, less total harmonic distribution in the spectrum of load voltage, easy implementation and less computation time. [6]. For the single phase full bridge inverter, there are two level PWM, three level PWM, and higher levels techniques that depending on the design of the generator of switching pulses, the technique of 2-level (Bipolar) PWM produce a much cleaner source of AC power than square or modified sine waves, there is relatively higher amount of higher level of harmonic.

In order to create a load signal closer to a true sine wave, a 3-level (Unipolar) PWM is a suitable choice. [7]. This paper proposed high performance design and simulation results during Multisim software to present a three levels single phase inverter adopts variable carrier frequency for each half cycle of fundamental AC signal compare with fixed carrier frequency in the traditional Sinusoidal Pulse Width Modulation (SPWM). The contain of section II shows the importance of grid synchronized inverter, while section III explains the proposed design and related merits as well as the manipulation process to cover the fluctuation of dc supplied voltage which assume happen in case using the renewable energy source of DC power which feed to the proposed inverter. Section IV covers the simulation results as well as analysis to the recorded data. The discussions and conclusions of presented design come in the section V.

II. THE IMPORTANCE OF GRID SYNCHRONIZED INVERTER

The function of synchronized inverter is produce alternated voltage synchronized to the grid that first important factor to connect inverter to grid.

The inverter called grid-tie inverter (GTI) when its able to connect with grid. GTIs are supplied from renewable energy sources, such as solar arrays or wind turbines with rectifiers, then invert the received DC power to an AC to have ability to export the produced AC power to the grid. The output waveform of GTI should be synchronized with the grid in terms of amplitude, frequency, and phase. [8]. In addition, GTI should be have capability to regulate the fluctuated DC power supply of renewable source that through included controller, a GTI ensures that the power supplied to the distribution panel of the house will be in phase and in a suitable slightly higher amplitude level compared to the grid waveform. This paper presents design with simulation results of inverter characterized by frequency and phase synchronization with grid electricity, and proposed a certain voltage controller to manipulate the fluctuation in the DC voltage which supplied the inverter from variable DC supply in simulation instead of renewable DC source. In addition, the voltage of the inverter output needs to be slightly higher the grid voltage to enable current to have excess power flow out to the utility and supply the loads in the house. [9].

III. THE PROPOSED SYSTEM

The most widespread single phase topology is the full-bridge one. This topology can be chosen to have bipolar or a unipolar PWM controlled switches. Using unipolar switching strategy the inverter pulses will have twice carrier frequency value that is in case of bipolar switching, therefore the output filter can be smaller, than in case of the bipolar. [10], for the mentioned difference the unipolar technique will have less harmonic distribution [7], the proposed system adopt the unipolar type with variable frequency range of carrier signal that determine through a certain selection of R, C values in VCO circuit while controlled by instantaneous value of full wave rectified of 50 Hz sine fundamental wave, the proposed simulation presents also a new controller designed to manipulate the fluctuation in the DC voltage which supply from variable DC power supply that used instead of renewable energy source, this supply feed the proposed inverter in simulation, Fig. 2, represents the block diagram of the presented design of grid synchronized inverter:

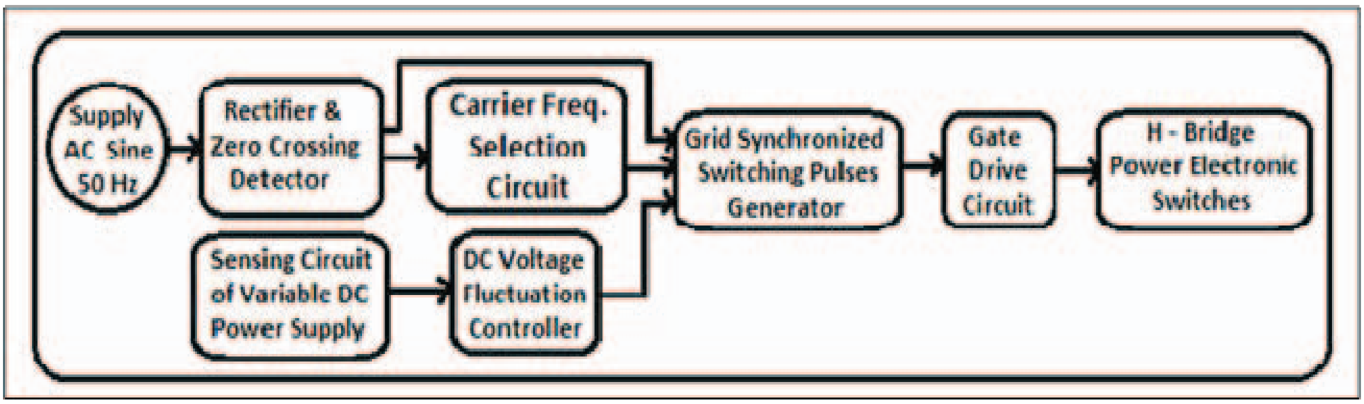

Fig. 2. Block Diagram of the Proposed Grid Synchronized Inverter

The proposed design took in account the work of [11], [12], [13], [14], [15] which wrote in close field of presented paper. The paper focus on, firstly, design and simulate a certain Voltage Controlled Oscillator (VCO) to produce one of two type of triangle waveform as a carrier signal then using this carrier with full rectifier of fundamental signal to produce PWM pulses which used later to drive the electronic switches in inverter bridge, first type of VCO output is variable frequency triangle carrier with frequency value proportional inversely with the instantaneous value of full wave rectifier of fundamental wave , while the second type of VCO output is fixed frequency triangle wave. VCO equation is given in (1).

$$f_{VCO} = f_o + K_{VCO} V_{ctrl} \quad (1)$$

In (1), f_o is the center frequency of the VCO, K_{VCO} is the gain of the VCO, V_{ctrl} is the input to the VCO that sets it to the desired frequency. [14]. Operational Amplifier used in simulation as a comparator to produce PWM pulses by comparing VCO output which triangle wave with variable carrier frequency with sine wave fundamental signal to produce Sinusoidal PWM, the proposed simulation able to compare the proposed improvement of the variable carrier frequency with traditional SPWM method, The SPWM pulses can be obtain by comparing fundamental sine wave r(t) with carrier wave c(t), and mathematically the binary PWM output can be written as

$$b_{pwm}(t) = \text{sgn}\,[r(t) - c(t)] \quad (2)$$

where 'sgn' is the sign function. [15], to maximize the AC voltages that can be produced from a given DC voltage source before the modulator saturates [16] for the purpose of developing general PWM models, the reference signal, r(t), assumed to consist of a DC and a single-frequency sinusoidal component in general:

$$r(t) = R0 + R1 \cos(2\pi f_1 t + \theta_1) \quad (3)$$

Each of the amplitudes *R*0 and *R*1 can be set to zero depending on the specific applications under study, f_1 is a reference frequency and θ_1 is a phase shift of fundamental signal.
In unipolar modulation, the carrier amplitude changes between 0 and a positive peak, the reference is always positive [15]; the ratio of reference or fundamental amplitude to the carrier amplitude named Modulation Index (MI). The ratio between carrier frequency (f_c) and reference frequency (f_1) named frequency ratio (FR) which is fixed value in the traditional SPWM,

$$FR = f_c / f_1 \quad (4)$$

While in the case of variable carrier frequency with in SPWM instead of fixed frequency, there are two new concepts which are minimum FR and maximum FR depending on the VCO output frequency range.

$$FR_{min} = f_{cmin} / f_1 \quad (5)$$

$$FR_{max} = f_{cmax} / f_1 \quad (6)$$

By using eq (1);

$$FR_{min} = f_{VCO(min)} / f_1 \quad (7)$$

$$FR_{max} = f_{VCO(max)} / f_1 \quad (8)$$

Figure 3. represents the block diagram of carrier frequency selection circuit which used to produce one of two types of triangle waveform, variable carrier frequency or fixed carrier frequency through VCO, Fig. 4. illustrate the resultant waveforms at MI (0.9), FR (14) for Unipolar Sinusoidal PWM with 2V/div & 2ms/div for upper waves and 5V/div & 2ms/div for lower waves, while Fig. 5 for proposed variable carrier frequency with FR_{min} (18), and FR_{max} (66).

Second merit, there is a control and protection ability through a proposed Zero Crossing Detector to the reference wave by add a suitable switch Off period for all power switches in inverter bridge, Fig. 6, represent resultant full wave rectifier output and related zero crossing pulses of two different widths.

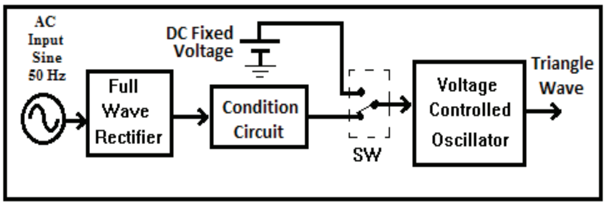

Fig. 3. Block diagram of carrier frequency selection circuit

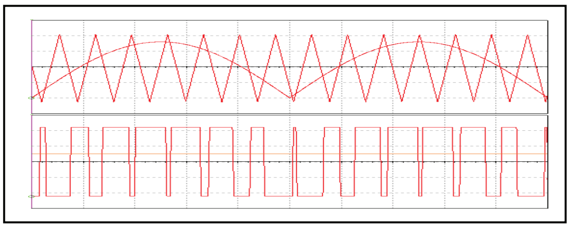

Fig.4. Procedure of fixed SPWM pulses generation at MI= 0.9

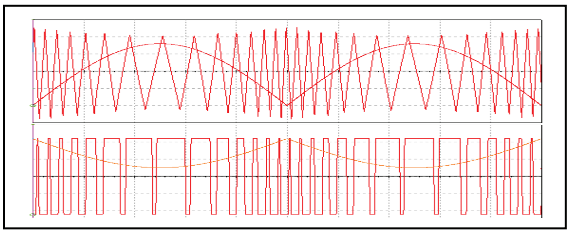

Fig.5. Procedure of variable carrier freq. SPWM pulses generation at MI= 0.9

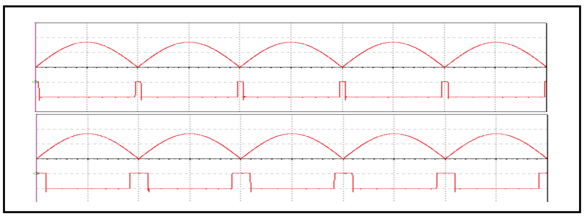

Fig. 6. Full rectified waves with related Zero Crossing Pulses

Third point in design took attention to manipulate the fluctuation problem in the voltage of dc power supply uses to feed proposed inverter, this paper present a certain design of controller work on covering the fluctuation in connected DC supply, the controller design include mixing of analog and digital sub circuits which started by sensing circuit deliver a low range of dc voltage linear proportional with the instantaneous level of dc supply, the sensing circuit include an insulation stage represented by a photo-coupler (4N25). A serial resistor connected with Light Emitting Diode (LED) which first part of photo coupler that to limit LED current, to calculate the practical value of serial resistor and its power value, here let supply voltage equal (500 V), the rated current of LED (12 mA), and the forward voltage (V_F) of LED (1.8 V) so the suitable value of serial resistor can be calculated from below equation:

$$R_s = (Vdc - V_F) / I_{LED} \quad (9)$$

So, R_s = (500-1.8)/0.012) = 41.5 kΩ, while the power value (P_{Rs}) of resistor can be obtained from the following equation:

$$P_{Rs} = I_{LED}^2 * R_s \quad (10)$$

So, the power of serial resistor (0.012*0.012*41500) = 6 Watt. Fig. 7. Represents the proposed sensing circuit of the dc supply level. The results explained in the following section (IV), sensing circuit adjusted with the range of changing in dc supply between (300 V – 350 V) within whole simulation.

The next process of controlling produce invers changing with respect to the output of sensing circuit. The output voltage of sensing circuit in the whole simulation equal (7.90 V) at 300 Volt of dc supply while 9.26 V at 350 V), the next inverse range of voltage designed to be 9.90V at 300 V, and 8.56V at 350V , this low range of DC voltage converted to digital form (8-bits) during Analog to Digital Converter (ADC) then by a new proposed design of Analog / Digital Multiplier works on multiply the digital form (8-bits) with other input in analog form represented by full wave rectified of fundamental sine wave which used to control the value of modulation index starting with MI equal 0.9. The proposed design of Analog / Digital Multiplier include the following sub circuits: Voltage Divider, Voltage Follower Array, Analog Control Switch Array, and Analog Adder Circuit, the controller produce an analog form output signal with the same shape of input analog waveform but with other voltage level represents multiplying result. The function of Analog / Digital Multiplier explained in the following equation:

$$Vo = V_{in1} * (V_{in2} / 2^{n-1}) \quad (11)$$

Where, V_{in1} is first input voltage in analog form, V_{in2} is second input voltage in binary form, n is number of bits which is equal 8-bits in the design, and Vo the output voltage of Analog Adder Circuit that in analog form. Fig. 8. Shows the block diagram of the controller. The output power controlled by selecting the desired value of modulation index, while Fig. 9. hows the range of changing in the amplitude of full rectified sine wave which will be control the value of modulation index in the desired range.

The proposed inverter include PWM pulses generator, used to produce two groups pulses complement each other, and synchronized with the grid voltage, the pulses used to switch the MOSFETs in the H-bridge during insulation stage represented by four photo-couplers, Fig. 10. illustrate the resultant PWM pulses at 0.9 of the traditional fixed carrier frequency SPWM inverter, while and Fig. 11. show pulses at the variable carrier frequency.

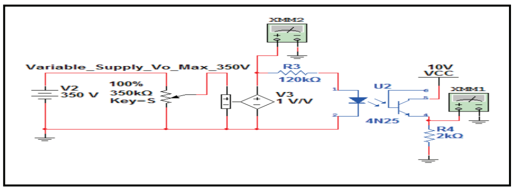

Fig.7. Sensing circuit of dc voltage supply level

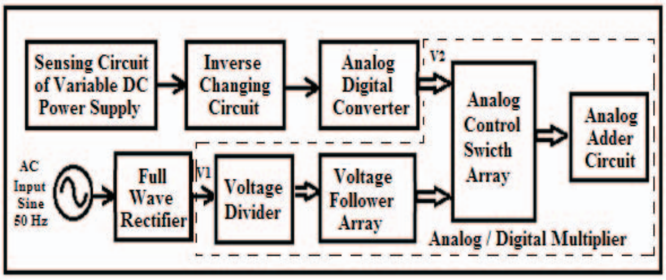

Fig.8. DC voltage supply fluctuation controller

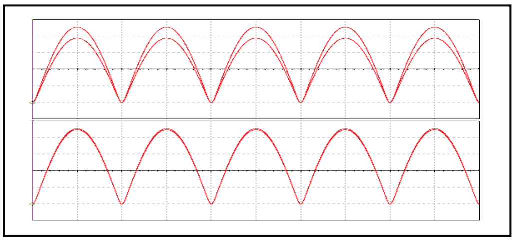

Fig.9. Simulation resultant of fluctuation voltage controller

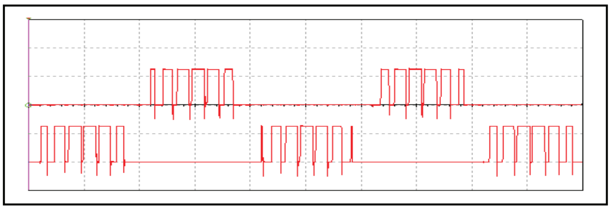

Fig.10. Fix carrier frequency pulses of SPWM at MI = 0.9

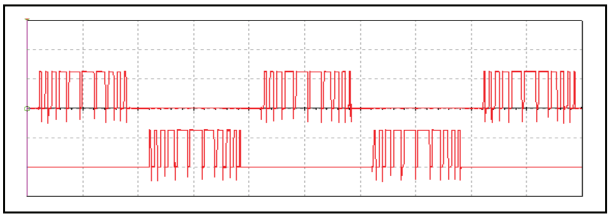

Fig.11. Proposed variable carrier frequency pulses of SPWM at MI = 0.9

Figure 12. Shows the photo-coupler (4N25) insulation, and full H-bridge MOSFET (IRF840) with specifications 500V/8A:

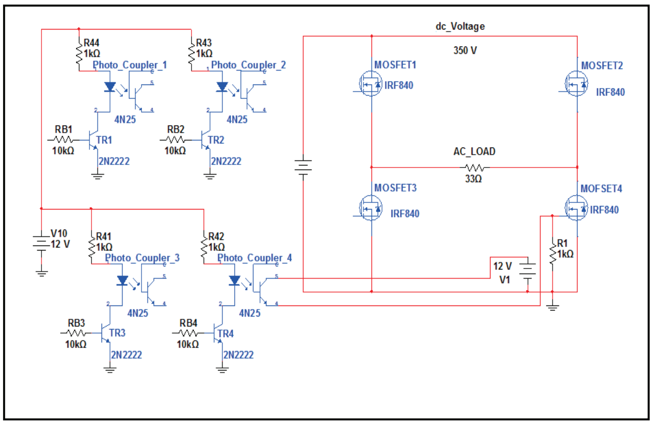

Fig. 12. Photo-Couplers and H- Bridge stages

A conventional way of describing the harmonic content of a signal is by its THD, defined in equation (12), V1 is the fundamental frequency content and $V_2 - V_n$ are the harmonics contents. [13].

$$THD = [(V_2^2 + V_3^2 + V_4^2 + \ldots V_n^2)^{0.5}] \;/\; V_1 \qquad (12)$$

The selected software program of presented simulation results that is Multisim program which have ability to measure THD directly by display one value of THD, for this reason, a simple averaging operation during equation (13) for an enough number of THD readings to inverter output voltage that required to explain and show the reduction in the THD records as well as indicate that more stable behavior at the proposed variable carrier frequency technique for SPWM compared to traditional SPWM that explained in section IV.

$$\text{THD (Average)} = \frac{\sum_{m=1}^{m=k} THD_m}{k} \qquad (13)$$

IV. Simulation Results

Part of the resultant waveforms explained in the previous section while this section focus on the output voltage of designed inverter through plot the waveforms and calculate average value of THDs of the load voltage for the proposed and traditional SPWM techniques. The simulated responses of sensing circuit and the fluctuation DC supply controller are also presented.

Figure 13. shows the response of sensing circuit for full varying of DC supply voltage, the simulated results reflect accurate linear response for varying range starting 50V to 350V. Fig.14. illustrates the response of the designed controller which work on manipulate the fluctuation in the DC voltage of variable power supply which assume replaced by a counter part of a DC renewable power source, the controlling function adopt produce inverse changing in the modulation index with a suitable range to cover the fluctuation in the voltage range ± 25 Volt around 325 Volt and the controlling voltage in the range 300V to 350V this leads to control the reference wave peak then the Modulation Index (MI) will be effected, AC output voltage of the designed inverter will be under controlling effect through width changing of PWM pulses.

Figure 15. shows the output AC load voltage 200V/div, 5ms/div at MI equal 0.9 of the grid synchronized SPWM inverter. Fig. 16. shows output of traditional SPWM inverter. The resultant waveforms indicate full synchronization with grid electricity reference sine waveform 5V/div, 5ms/div. Fig. 17. illustrate the reduction in the average of THD values as well as stable behavior in the proposed variable carrier frequency compared with fixed carrier frequency SPWM.

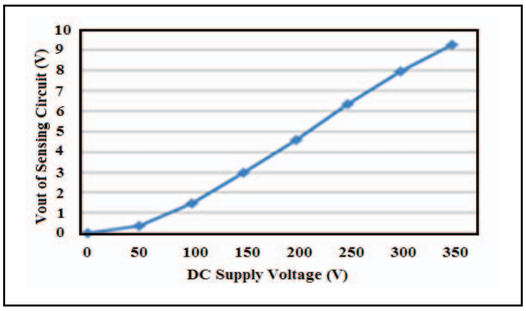

Fig.13. Sensing Circuit Response

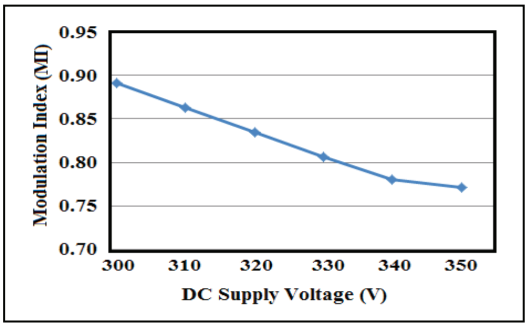

Fig.14. DC Supply Voltage Fluctuation Controller Response

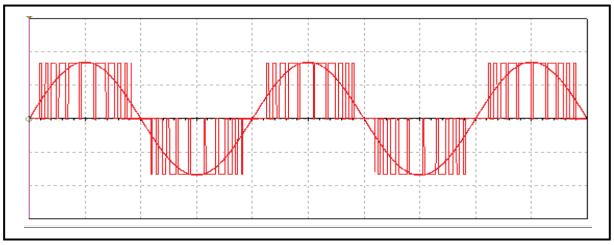

Fig. 15. Output waveform of proposed synchronized inverter at MI = 0.9

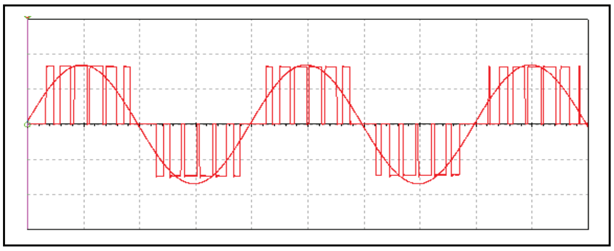

Fig. 16. Output waveform of traditional synchronized inverter at MI = 0.9

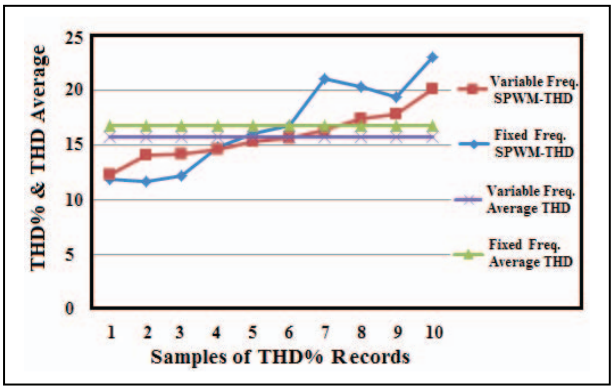

Fig. 17. THD % with average values at MI = 0.9

V. CONCLUSION

From the simulation results and its analysis, the conclusion summary as follow:

- The simulation results give good indication for promising practical prototype.
- The design able to test other type of control waves as input to the VCO, as example, triangle wave instead of full rectified fundamental sine wave, and trying upper carrier frequency ranges to check total harmonic distribution.
- The proposed design acceptable to construct by general purpose discrete components without needs to any special integrates circuit.
- The controller design is flexible to modify or change the range of controlling voltage of the applied DC supply.
- The design presents a new idea of multiplying analog voltages with digital forms to cover a certain defect.

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