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A Novel Control Scheme for Buck-Boost DC to AC Converter for Variable Frequency Applications

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Abstract

This paper represents a novel control scheme for buck-boost DC to AC converter in variable frequency operation. Voltage controlled dual slope delta modulator is designed to reduce the harmonic distortion of the output voltage for variable frequency applications. The output of the buck-boost converter with the proposed control scheme produces near sinusoidal voltage of constant magnitude irrespective of the frequency. The total harmonic distortion of the proposed scheme is under 4% which within IEEE Std 519 Voltage Harmonic Limits.

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Keywords: *Switch Mode Power Supply, DC-AC Converter, Delta Modulator, Total Harmonic Distortion, And Voltage Controlled Resistor.*

1. Introduction

Voltage source inverters (VSI) used in photovoltaic (PV) systems, uninterruptible power supplies (UPS), drives and other applications usually operate at fixed frequency. Their characteristic is such that, the average output voltage is lower than the input DC voltage (Tsorng-Juu, Jueni-Lung, & Jiann-Fuh, 2002). But in applications like adjustable speed drives, induction heating etc., frequency needs to be controlled. With rising energy crisis throughout the world, the main focus is on the development of sustainable energy systems. Inverter design should add flexibility to control of both frequency and amplitude. The voltage waveform of an ideal inverter should be sinusoidal. However,

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the waveform of practical inverter are non-sinusoidal and contain undesirable harmonics. Appropriate switching pattern in the inverter can generate the sinusoidal shape. Though square, quasi-square or stepped voltages may be acceptable for low and medium power applications, but for high power applications, low distorted sinusoidal waveforms are required necessitating pulse width modulated switching control technique. In a voltage fed inverter the input DC voltage is essentially constant and independent of the load current drawn. The significance of the term constant voltage is to emphasize that, over the short duration of one cycle of output AC waveform, any change in DC source voltage is negligible. A voltage source inverter is best suited to loads which have a high impedance to harmonic currents such as a series tuned circuit or an induction motor. The series inductances of such loads may result in operation at a low power factor. Buck-boost and $C\hat{u}k$ inverters can produce an output voltage higher or lower than the input voltage (Almazan, Vazquez, Hernandez, Alvarez, & Arau, 2000; Vazquez, Almazan, Alvarez, Aguilar, & Arau, 1999). In these new generation of inverters, the necessity of frequency and amplitude variation can easily be addressed by switch mode inverter implementation. Also much emphasize is given to remove the transformer for AC-DC conversion adopting differentially connected load (Caceres & Barbi, 1999). To allow reduced inverter size, high efficiency and simpler control a multi-loop control strategy consists of inner current loop for regulating the inductor current and an outer voltage loop for regulating the output voltage is introduced (Tsorng-Juu, et al., 2002). The same control strategy is also reported (Sanchis, Ursaea, Gubia, & Marroyo, 2005; Sanchis, Ursua, Gubia, & Marroyo, 2004). But the proposed circuitry is complex. Two or more current sensors are necessary in order to implement the control strategies and it also increases the overall cost. The sliding mode control strategy although involves complex manipulation is reported (Almazan, et al., 2000). Similar control strategy is adopted for boost DC-AC converter (Caceres & Barbi, 1999). Discrete sliding mode control for buck-boost inverter is proposed (Matas, de Vicuna, Guerrero, Miret, & Lopez, 2002). The sliding mode control surfaces proposed in this paper are designed by imposing a dynamic behaviour on sliding mode controller which leads to discrete-time switching surfaces. Computationally complex mathematics is necessary to find the solution of the controller. The self-adjustable fuzzy sliding mode control for AC speed drive systems is reported (Li, Zou, Fu, Zhang, & Li, 2000). The sliding mode control is proposed to achieve robust performance against parameter variations and external disturbances. The analog implementation of this non-linear controller is not discussed. Instead of controlling each boost DC-DC converter separately a single controller is used to generate a sinusoidal voltage on the load regardless of the voltage in both capacitors. Current sensors are used for this non-linear control strategy, which makes the design simpler. The nonlinear control strategy is designed against the input dc perturbation and achieves good dynamic regulation and proper gating of the power switches and building resonance in the LC tank is proposed (Chien-Ming, 2004) for full-bridge buck-boost inverter. To achieve dynamic regulation and to properly gate the power switches, the sinusoidal PWM (SPWM) control strategy is proposed (Wang, 2007). A closed-loop sinusoidal pulse width modulation (SPWM) control for grid-connected single stage buck-boost inverters are proposed (Yaosuo & Liuchen, 2004). Two-stage inverters normally accomplish dc voltage boost in the first stage, and achieve buck dc-ac conversion in the second stage having a high frequency transformer to accomplish the voltage boost (Bing, Liuchen, & Yaosuo, 2008). Control of the boost DC-AC converter by energy shaping is reported (Albea & Gordillo, 2007). It is another non-linear control strategy. This implies cost and complex implementation. Adaptive control of the boost DC-AC converter is introduced (Albea, Canudas-de-Wit, & Gordillo, 2007). The adaptive control is accomplished by using a state observer to one side of the inverter and by measuring the state variables. Non-linear mathematical manipulation makes the method difficult to realize in practical applications. H^{∞} control strategy based controller is proposed (Naim, Weiss, & Ben-Yaakov, 1997), via the solution of two algebraic Riccati equations. This method also involves the solution of complex non-linear equation. New voltage mode control of single phase boost inverter is reported (Khan & Rahman, 2008).

Most of the circuit topology and the control discussed are designed for a particular frequency and works well for a fixed load. Moreover the control strategies involve non-linear control algorithm and include complex manipulation. But the true definition of inverter suggests the design of an inverter may have to operate under variable frequency and under variation of load. Therefore the ideal control scheme for such an inverter is yet to be found. This provides motivation for research of variable frequency inverter obtained by differential connection of SMPS. Further research efforts are to be made towards reducing inverter size, simpler control, minimizing loss and improving efficiency, reliability and robustness.

2. Proposed Control Scheme with Circuits

2.1. Differential Buck-Boost inverter

The operation analysis and control of buck-boost inverter was shown by (Caceres, Garcia, & Camacho, 1998) as shown in Fig. 1. Since the two converters of the inverter are 180^0 out of phase the voltage gain can be derived (Caceres, et al., 1998) and shown in equation (1),

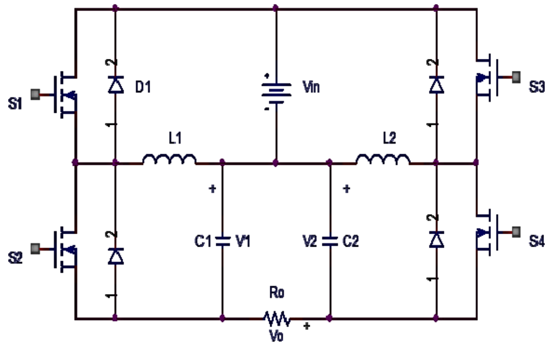


Fig.1 Differential DC– AC Buck-Boost converter.

$$\frac{V_o}{V_{in}} = \frac{2D-1}{D(1-D)} \tag{1}$$

Where,

$V_o =$ Output voltage,

$V_{in} =$ Input voltage,

$D =$ Duty cycle .

2.2. Proposed Voltage Controlled Dual Slope Delta Modulator

Delta modulation has been chosen in the present work to obtain the solution of the above problem because it is self-generating circuit which produces carrier signal (triangular wave) without any extra circuitry. Another advantage of the delta modulation is the ease to construct it with analog components. Fig. 2. shows the typical waveforms of the command signal v_{cmd} , carrier signal v_c and the modulator output signal v_m .

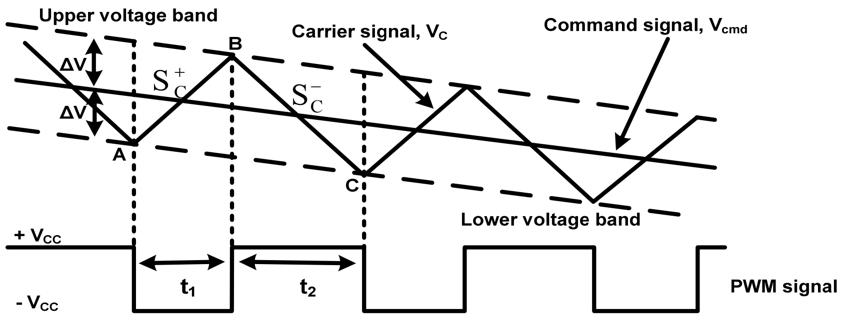


Fig 2. Typical waveforms of control signal v_{cmd} , carrier signal v_c and the output PWM signal of the delta modulation controller.

The period T and duty ratio D of the delta modulation controller can be derived as,

$$T = \frac{2\Delta V\left(S_C^+ - S_C^-\right)}{\left(S_C^+ - S_{cmd}\right)\left(S_{cmd} - S_C^-\right)} \tag{2}$$

$$D = \frac{\left(S_C^+ - S_{cmd}\right)}{\left(S_C^+ - S_C^-\right)} \tag{3}$$

Where,
$T =$ Period,
$S_C^+ =$ Positive slope of the carrier,
$S_C^- =$ Negative slope of the carrier,
$\Delta V =$ Window width and
$S_{cmd} =$ Slope of the control signal.

The investigation on the delta modulation indicates the necessity to change both the amplitude and the frequency of the command signal for variable frequency operation of the inverter. In delta modulation there is nothing called modulation index since the carrier signal is an internal property of the delta modulator. Thus the change in the carrier signal is done by changing the time constant or the slope of the integrator of the delta modulator. This demands a change in the delta modulator circuit. Dual slope delta modulation scheme was proposed by Rahman (Rahman, Choudhury, Rezwan Khan, & Rahman, 1997) which includes either a capacitor or resistor to control the gain of the inverter by changing the slope of the integrator. The circuit with additional resistor is better to change the gain of the inverter as it is easier to change the resistance instead of capacitor.

The resistance of the dual slope needs to be changed or controlled with change in the control voltage. This requires change in the model of the modulator proposed in the reference (Rahman, et al., 1997). A voltage controlled resistor can solve the problem of change in frequency of operation of the inverter. Hence voltage controlled dual slope delta modulator is designed. The proposed modulator is shown in Fig. 3.

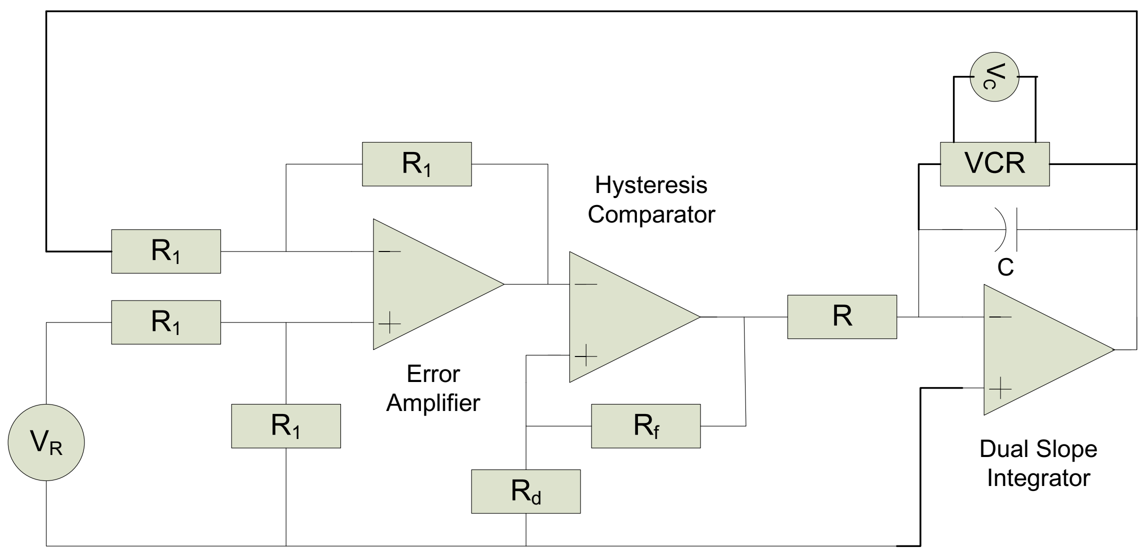


Fig. 3. Proposed voltage controlled dual slope delta modulator.

2.3. Modified Voltage Controlled Oscillator

The command signals required for different frequencies of inverter operation are generated by voltage controlled oscillator. Dual output quadrature oscillator has been used for this purpose. The control voltage of this open loop control strategy will determine the frequency of the reference sine wave.

A voltage controlled oscillator is a circuit that provides a variable output signal whose frequency can be adjusted over a range by a dc control voltage. The output of VCO can be square wave, triangular wave or sine wave. Voltage controlled oscillator is also known as voltage to frequency converter. The quadrature oscillator generates two signals that are in quadrature that is, out of phase by 90^0. The design of the voltage controlled quadrature oscillator is available in the datasheet of AD633 analog multiplier which is shown in Fig. 4.

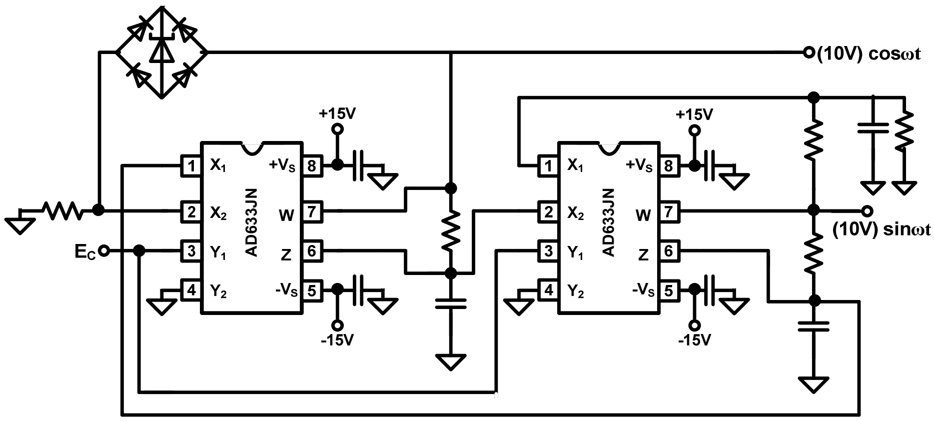


Fig. 4. Voltage controlled quadrature oscillator from datasheet of AD633.

The circuit provides a sine and cosine wave of amplitude of 10V. Expected output was not obtained from the circuit of Fig. 4. An analog amplifier with a filter was added to obtain desired output. The modified circuit is shown in Fig. 5.

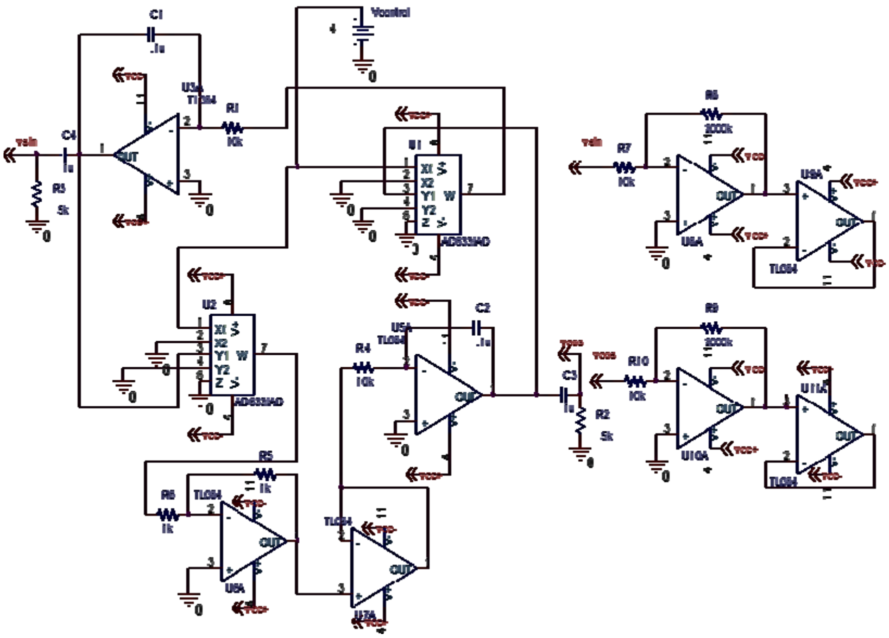


Fig. 5. Modified voltage controlled quadrature oscillator.

3. Analyses and Results

Dual slope delta modulator can solve the problem of the waveshape distortion, but the amplitude of the inverter output is variable. It was observed that the change in the additional resistor of the dual slope delta modulator allows a means of changing the gain of the inverter. Thus two separate control parameters are needed for the variable frequency constant amplitude output. One of them is the control voltage and the other one is the additional resistor. To come up with a single control parameter it was needed to design a voltage controlled resistor. The variation of the additional resistor for different values of the control voltage V_{con} is shown in Fig. 6.

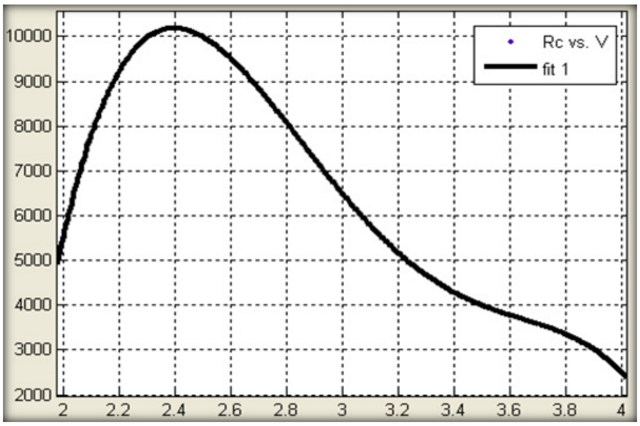


Fig. 6. Required characteristic of the voltage controlled resistor.

A voltage controlled dual slope delta modulator (VCDSDM) was designed incorporating the voltage controlled resistor of desired characteristics. The schematic diagram of the VCDSDM is shown in Fig. 7. The voltage controlled resistor was designed using built-in voltage controlled voltage source block of PSPICE. In practice it can be designed using FET since FET also provides similar transconductance characteristics. In the reference (Baiying, Scott, Gupta, Sridharan, & Black, 1998; Smith, Dimitrijev, & Harrison, 2000) FET was used as voltage controlled resistor. The simulation results for different frequency with proposed control scheme are shown in Fig. 8 and the result are tabulated in Table 1.

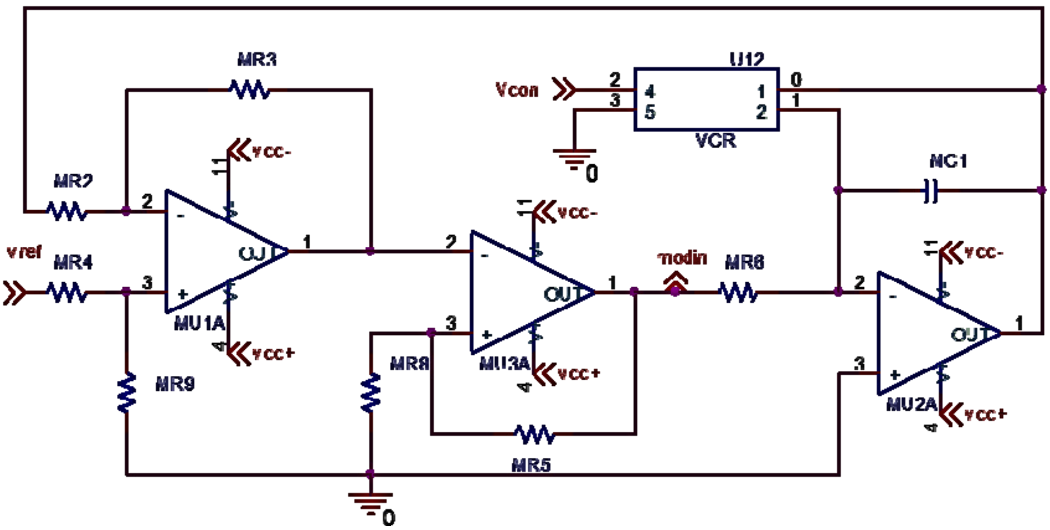
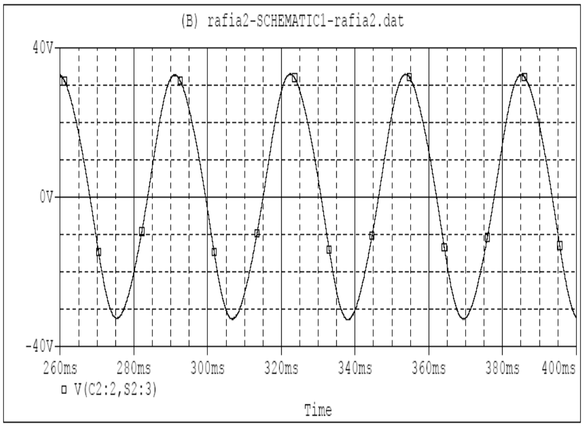
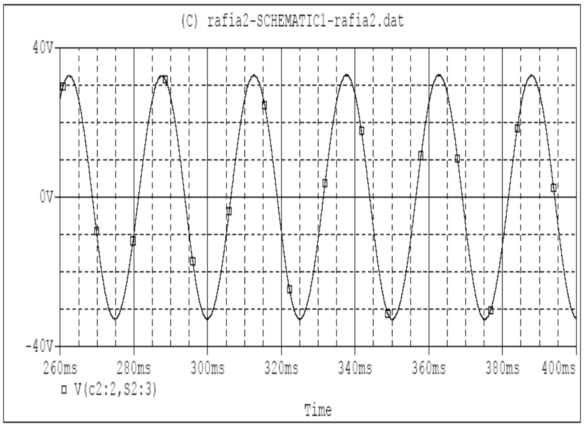


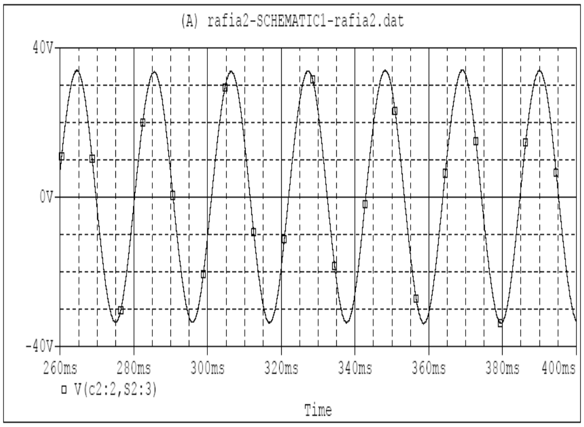
Fig. 7. Schematic diagram of the VCDSDM.



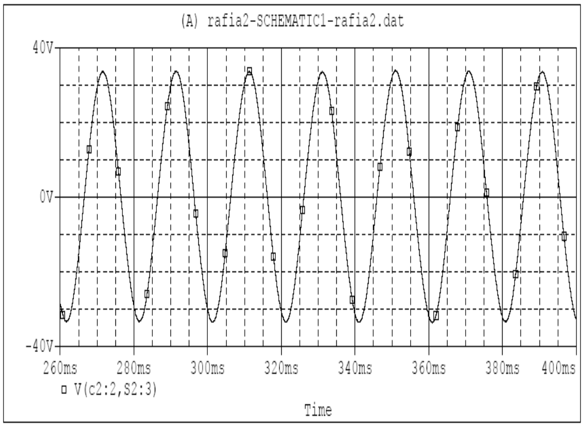
(a)



(b)



(c)



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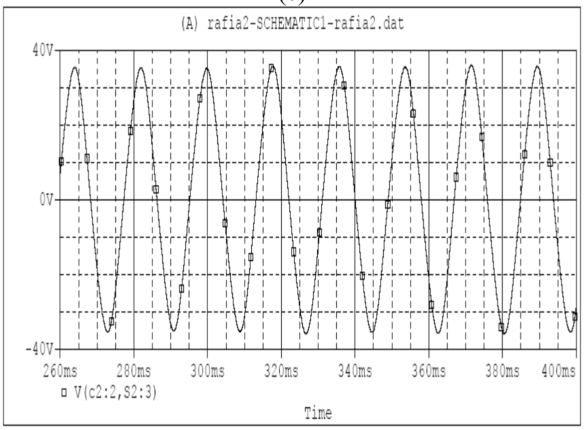
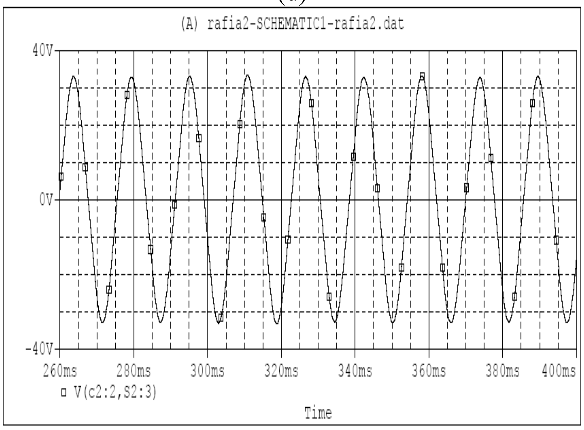


(e)



(f)

Fig. 8. The output of the proposed scheme for (a) Vcon = 2.0V corresponding to 32Hz (b) Vcon = 2.5V corresponding to 40Hz (c) Vcon = 3.0V corresponding to 48Hz (d) Vcon = 3.16V corresponding to 50Hz (e) Vcon = 3.5V corresponding to 55Hz (f) Vcon = 4.0V corresponding to 63Hz.

Table 1. The results of variable frequency operation for buck-boost inverter with proposed VCDSDM.

Control Voltage (V)	Frequency of Operation (Hz)	Fundamental Component (V)	% THD
2.00	32	32.01	3.26
2.50	40	32.54	0.89
3.00	48	33.42	1.05
3.16	50	33.12	1.37
3.50	55	34.53	3.15
4.00	63	31.78	3.95

4. Conclusion

A simplified control scheme to regulate the output voltage for different frequency of inverter operation is found in this paper. To avoid the complexity of the existing controllers, hysteresis band delta modulator is chosen, since it is easy to construct with analog components. In the proposed control scheme the command signal of desired amplitude and frequency is generated by voltage controlled quadrature oscillator. Dual slope delta modulator was introduced in the proposed control scheme. As a result the inverter output voltage became sinusoidal for different operating frequency but the amplitude of the output voltage remained variable. Regulated output voltage over a range of frequency was obtained by changing the duty cycle as well as the carrier frequency of the delta modulator. At this point, gain adjustment allows two control parameters for smooth operation over a range of frequency with a regulated output. A voltage controlled resistor was designed of desired characteristics using the built-in voltage controlled voltage source of the PSPICE. In practice such a VCR can be designed using FET since FET also provides similar trans-conductance characteristics. From the proposed control scheme regulated inverter output (approximately 33V) is obtained over a frequency range for an input of 12V dc. Variable output voltage can be obtained as per requirement if the VCR is replace by a variable resistor. The output wave-shapes of the proposed control scheme for buck-boost inverter confirm the performance of the inverter. It was found that each output voltage wave-shape is almost purely sinusoidal in nature. The THD is always within IEEE Std 519 Voltage Harmonic Limits. THD of output voltage was under 4% for different frequency of operation.

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