A Modified PWM Scheme for Harmonic Reduction in Hybrid System without Filter

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Abstract: - The ever increasing demand for conventional energy sources drives society towards the research and development of alternative energy sources such as wind and solar energy. The integration of these energy sources form a hybrid system, is an excellent option for distributed energy applications. The successful implementation of such a hybrid energy system is greatly depend on the design of suitable power electronics and their control, which will help to improve the performance and reliability of the system. This research presents an important aspect of designing a voltage source inverter, using novel carrier PWM techniques. In this paper, a new UN shape Carrier Pulse Width Modulation (UNCPWM) technique has been suggested, which uses the conventional sinusoidal reference signal and an UN shape carrier for minimizing the Total Harmonic Distortion (THD) and to enhance the fundamental output voltage in hybrid system. The Simulation has been carried out in MATLAB Simulink to analyze the performance of the proposed technique by means of comparing the fundamental component of RMS output voltage and THD for different values of modulation index. This simulation results shows that the performance of the voltage source inverter, based on UNCPWM technique is considerably efficient than the existing pulse width modulation (PWM) techniques.

Key-Words: - PWM techniques, Voltage Source Inverter, Total harmonic distortion (THD), Wind-Photovoltaic systems.

1 Introduction

The tapping of conventional energy sources could become more challenging task in the future because of supply interruptions, environmental restrictions, and the depletion of known reserves. Renewable energy sources could be the right solution to solve energy crisis in the present age that has thrown many challenges to us in the field of industrial and economic development. Furthermore, these resources are ideal for remote locations, where the cost of extension of utility network would be prohibitively high. The design aspect of power electronic interface in hybrid energy systems plays more vital role to reduce voltage and current harmonics which are produced by a connected load. Hence, it is important to design a voltage source inverter to investigate the harmonic spectrum and fundamental RMS output voltage for analyzing the performance of hybrid system.

The delta modulation (DM) technique was proposed initially for smoothness of inverter, smooth transition between Voltage/frequency and constant voltage mode of operation with reduced circuit complexity and also improves the system reliability [1]. The Third Harmonic Injection PWM (THIPWM) method suitable for three-phase inverters was proposed, in which a modulating wave is obtained by adding the third harmonic component to fundamental sine in right proportion while the carrier was conventional triangular [2]. Later, the Triplen Harmonic Injection PWM (TRIPWM) technique was adopted with a variation of THIPWM, in which the modulation function was obtained by adding the harmonic components of integer multiples of three to the fundamental sine [3]. This technique requires a digital platform for its implementation and gives about 4% and 19% improvement in fundamental component while keeping alone and combining with THIPWM reference respectively.

All the previous attempts to achieve the same objectives are either regular sampled or mode-changing methods. However, in regular sampled PWM (digitally based controller), the generation of harmonics is dominated by quantization effects even with frequency ratios as low as 8:1 [4]. A comprehensive analysis was presented for AC-to-DC voltage source converter, using PWM with phase and amplitude control. A general mathematical model of the converter, which is discontinuous, time-variant, and nonlinear, was first established [5]. In the past three decades, Sinusoidal PWM (SPWM) inverter is effective in reducing lower order harmonics while varying the output voltage, many revisions has been made in this process through research [6-7]. The harmonic evaluation of three phase carrier-based two-level and three-level PWM methods was described, using harmonic distortion determining factor which represents the intrinsic spectral property of individual PWM methods [8].

The modified carrier PWM methods were proposed in which any two adjacent cycles of carrier triangular wave are grouped either as "W" Shape or "M" shape and then suitable "W" and "M" cycle group conversions are made [9]. A survey of eight different advanced Regular-Sampled PWM strategies were presented and compared, based on switching angles, performance of the Harmonic Elimination, Harmonic Minimization, and Space Vector Modulation (SVM), High-Frequency, and Hysteresis Band PWM strategies. The advantages and disadvantages of each were emphasized in terms of complexity and implementation [10]. A novel PWM technique was presented, using a trapezoidal modulator wave and a sinusoidal carrier signal with variable frequency. The proposed technique generates high-quality voltages with very few commutations per cycle, and it is particularly appropriate for reducing commutation loss [11]. The Inverted Sine Carrier PWM (ISCPWM) control scheme was proposed for controlling the output of a single phase full bridge inverter with improved fundamental component value, which eliminates some of the limitations of the conventional Sinusoidal pulse width modulation (SPWM) viz. poor spectral quality of the output voltage, poor performance with regard to output voltage [12].

A new control paradigm for integration of renewable energy sources with utility network was employed to increase interest in developing an appropriate control strategy to derive a current with less distortion from the inverter [13]. The implementation of a feedback controller model for obtaining constant amplitude and constant frequency supply from an integrated wind driven PM alternators and PV array has been developed [14]. An enhanced SPWM modulation scheme was developed in order to eliminate the high-ordered attenuated harmonics. The higher order harmonics are eliminated and the THD ratios are decreased owing to proposed SPWM scheme [15]. In this research, a new voltage source inverter utilizes UNCPWM technique has been proposed to investigate THD and fundamental RMS output voltage for analyzing the performance of hybrid system.

2 Investigations of PWM Techniques

Any PWM modulation techniques can be used to create constant voltage and constant frequency ac waveforms. PWM techniques are characterized by constant amplitude pulses and width of these pulses is however modulated to obtain inverter output voltage control and to reduce its harmonic content. This technique provides the sequences of width-modulated pulses to control power switches. The main aim of the modulation techniques is to attain the maximum voltage with the lowest Total Harmonic Distortion (THD) in the inverter output voltage.

The amplitude modulation index (M.I) can be defined as the ratio of reference signal of amplitude A_r to a triangular carrier wave of amplitude A_c. The RMS output voltage can be varied by varying the modulation index. The frequency of the reference signal determines the fundamental frequency of output voltage.

$$MI = \frac{A_r}{A_c} \tag{1}$$

The rms output voltage yields is shown in Eq. (2)

$$v_o = v_s \left(\sum_{m=1}^{2p} \frac{\delta_m}{\pi} \right)^{\frac{1}{2}} \tag{2}$$

Where δ_m width of the m^{th} pulses

The general form of a Fourier series for the instantaneous output voltage is shown in Eq. (3)

$$v_o(t) = \sum_{n=1,3,5}^{\infty} B_n \sin n\omega t \tag{3}$$

To determine the Fourier coefficient of output voltage as shown in Eq. (4)

$$B_n = \sum_{m=1}^{2p} \frac{4V_s}{n\pi} \sin \frac{n\delta_m}{4} \left[\sin n\left(\alpha_m + \frac{3\delta_m}{4}\right) - \sin n\left(\pi + \alpha_m + \frac{\delta_m}{4}\right) \right] \tag{4}$$

for n=1, 3, 5…

The performance analysis of voltage source inverter for hybrid system with four different carrier based sinusoidal modulating PWM technique has been analyzed and investigated. The evaluation is based on three existing techniques such as Triangular carrier with Sine wave reference (SPWM), Sine wave carrier with sine wave reference (SSPWM), Inverse Sine wave carrier with sine wave reference (ISCPWM) and the proposed technique named as UN carrier with sine wave reference (UNCPWM).The carrier based PWM techniques are preferred approach in most applications due to the low harmonic distortion waveform characteristics with well-defined harmonic spectrum, the fixed switching frequency and implementation simplicity. The different carrier based schemes are investigated in MATLAB environment and described in the following sections.

2.1 SPWM Technique:

The generation of Gating pulses to control power switches, using SPWM technique, is shown in the Fig. 1.

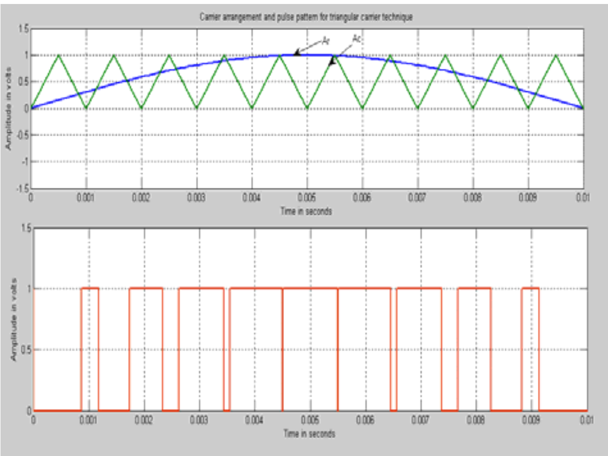


Fig.1.Gating pulse Generation using SPWM technique

In this SPWM technique, triggering pulse is generated by interaction of a inverter output frequency and its peak amplitude controls the modulation index MI, and Vrms output voltage. The number of pulses per half cycle depends on carrier frequency. In this scheme, the width, pulse number, and spacing of the pulses are optimized to keep low harmonic content in the harmonic spectrum of an inverter. The SPWM technique, however, inhibits poor performance with regard to maximum attainable voltage and power and also susceptible to EMI (electromagnetic interference), and production of audible noises.

2.2 SSPWM Technique

The Fig.2. Shows the way of generating pulse pattern, using SSPWM technique

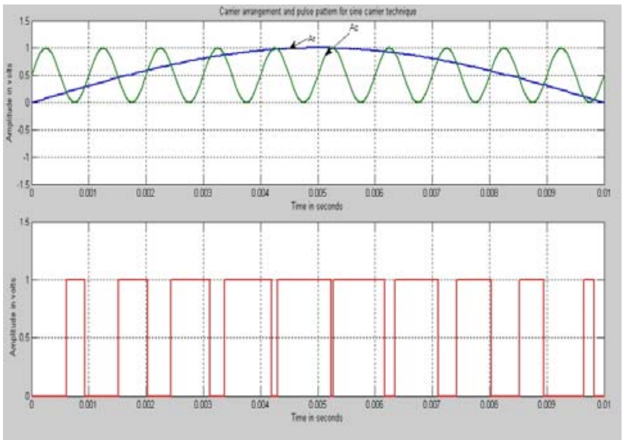


Fig.2. Gating pulse Generation using SSPWM technique

In SSPWM scheme, gating signal is generated by intersection of sine wave carrier with sinusoidal modulating signal. This technique produces inadvertent harmonics with reduced fundamental output voltage, compared to the conventional SPWM technique.

2.3 ISCPWM Technique

The pulse pattern, using ISCPWM technique, is shown in the Fig. 3.

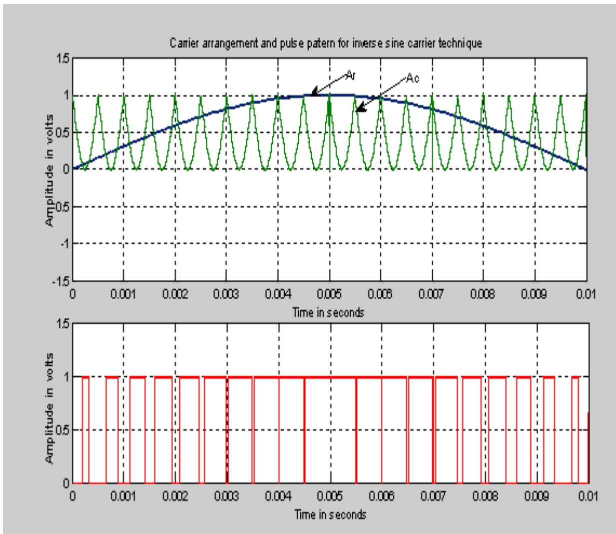


Fig.3. Gating pulse Generation using ISCPWM Technique

In ISCPWM scheme, pulse pattern is generated by intersection of unidirectional inverted sine wave carrier with sinusoidal modulating signal. The drawbacks of the ISCPWM scheme are marginal boost in the lower harmonics and non-linearity in fundamental component for various modulation index (MI) values.

2.4 Proposed UNCPWM Technique

To overcome the drawbacks of the existing techniques, a new UNCPWM technique has been developed, using the conventional sinusoidal reference signal and an UN carrier. This technique is used to minimize the Total Harmonic Distortion (THD) and to enhance the fundamental output voltage in hybrid generation system. The development of proposed PWM technique has been discussed in the subsequent section 3.4.

3 Modelling of Proposed UNCPWM Technique for Hybrid System

The hybrid wind/PV system with controlled UNCPWM technique is shown in Fig. 4.

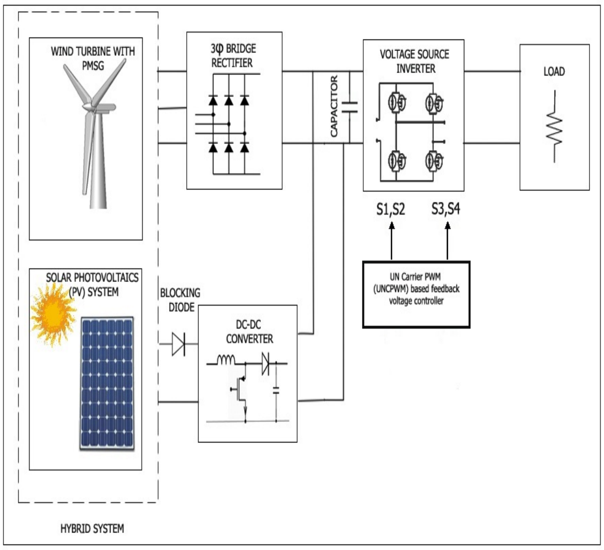


Fig. 4: Proposed model of UNCPWM technique for hybrid system

The PV array is connected in parallel to the three-phase bridge-rectifier output of the PMSG. The PM alternator is directly driven by the wind-turbine and hence the frequency and the amplitude of the stator voltage of the alternator vary with the wind-speed. The varying stator voltage is fed to an uncontrolled bridge rectifier and the PV array is connected in parallel through a blocking diode to the output of the rectifier, which forms the DC bus of the hybrid system. Hence, the operating voltage of the hybrid system varies with the wind-speed and irradiation.

A single phase full bridge voltage source inverter, consisting of four IGBTs, is connected across the DC bus. In general, inverters receive power from a fixed voltage dc source and supply it to a load at a controllable voltage. However, in the present application, the input dc voltage to the inverter itself varies with irradiation and wind-speed. As the DC bus voltage varies, a controller which automatically varies the width of the pulses is necessary to obtain a constant amplitude AC supply. In this proposed model, a UNCPWM based feedback controller is implemented to vary the pulse-widths of the inverter-output-voltage waveform until actual rms value and set rms value of the inverter output voltage are in conformity. The nature and the quality of output voltage of the inverter have been improved by employing proposed UNCPWM technique.

3.1 Configuration of UNCPWM Based Voltage Controller

The Fig.5 shows the block diagram of UNCPWM based voltage controller.

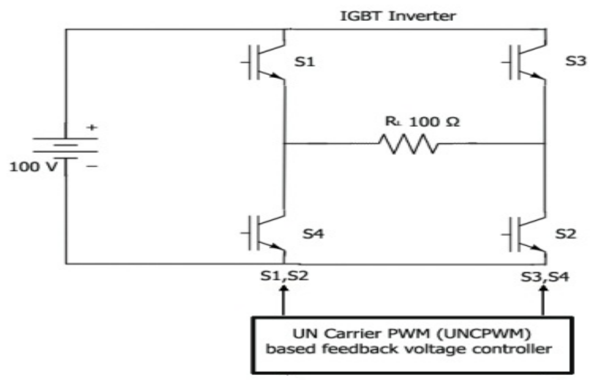


***Fig.* 5(a) Power circuit of single phase VSI**

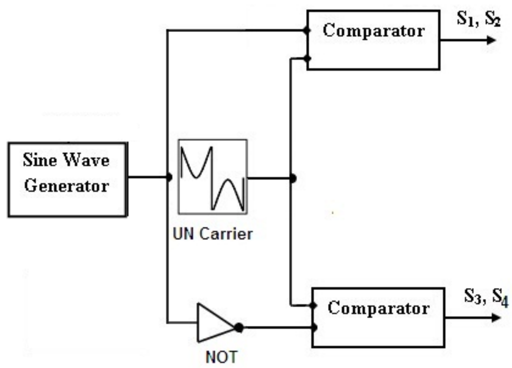


Fig. 5(b): Configuration of UNCPWM voltage controller

The deviation from the set-value is given to the Proportional – Integral (PI) controller and the output of the PI block in turn varies the amplitude of the reference sine wave of the UNCPWM controller. The inverter output voltage is varied by varying the modulation index by means of controlling the modulating signal (*Ac*). The control voltage $v_C(t)$ is then modulated with a UN carrier wave to generate the appropriate pulses for the inverter to attain the maximum voltage with insignificant harmonics spectrum in the output voltages.

3.2 Wind Power Generation System

The generated power of the wind turbine generator depends upon the wind speed. The wind speed is considered to be the algebraic sum of base wind speed (V_{WB}), gust wind speed (V_{WG}), ramp wind speed (V_{WR}) and noise wind speed V_{WN} [16]. Hence speed is given by Eq. (5)

$$V_w = V_{WB} + V_{WG} + V_{WR} + V_{WN} \tag{5}$$

The detailed mathematical modeling of these wind speed components are considered from the reference [17].

The typical approximate output characteristic of the wind turbine [16] is given by Eq. (6)

$$P_w = 0.5 C_P \rho A_r V_w^{\ 3} \tag{6}$$

where ρ (kg/m^3) is the air density and A_r (m^2) – is the swept area of turbine blades and V_w (m/s) is the wind velocity. C_P, a dimensionless power coefficient which is a function of tip speed ratio (λ) and blade pitch angle (β). The transfer function of WTGs is given by a simple linear first order lag by neglecting all the non-linearities are given by Eq.(7).

$$G_{WTG_k}(s) = \frac{K_{WTG}}{1 + sT_{WTG}} = \frac{\Delta P_{WTG_K}}{\Delta P_W} \tag{7}$$

for k = 1, 2, 3 and with K_{WTG} – the gain constant and T_{WTG} – the time constant.

3.3 Solar Generation System

A solar system consists of PV array with many cells connected in series and parallel to provide the desired voltage and current. The voltage and current relationship is non-linear in nature. The maximum power output of the PV array varies according to solar radiation or load current. Therefore control strategy is required to use solar radiation effectively in order to obtain maximum power. The output power of the PV system can be expressed as [18], [19], [20].This equation is given as Eq. (8)

$$P_{PVPG} = \eta S \varphi [1 - 0.005(T_a + 25)] \tag{8}$$

where, η – the conversion efficiency of the PV array, S – the measured area of PV array (m^2), φ – the Solar radiation (kW/m^2) and T_a – the ambient temperature (Celsius degree). The transfer function of PV can be given by a simple linear first order lag

$$G_{PV}(s) = \frac{K_{PV}}{1 + sT_{PV}} = \frac{\Delta P_{PVPG}}{\Delta \phi} \tag{9}$$

with K_{PV} – the gain constant and T_{PV} – the time constant.

3.4 Gating pulse generation using UNCPWM technique

The Fig.6 shows the MATLAB-Simulink model for generating pulse pattern using proposed UNCPWM technique.

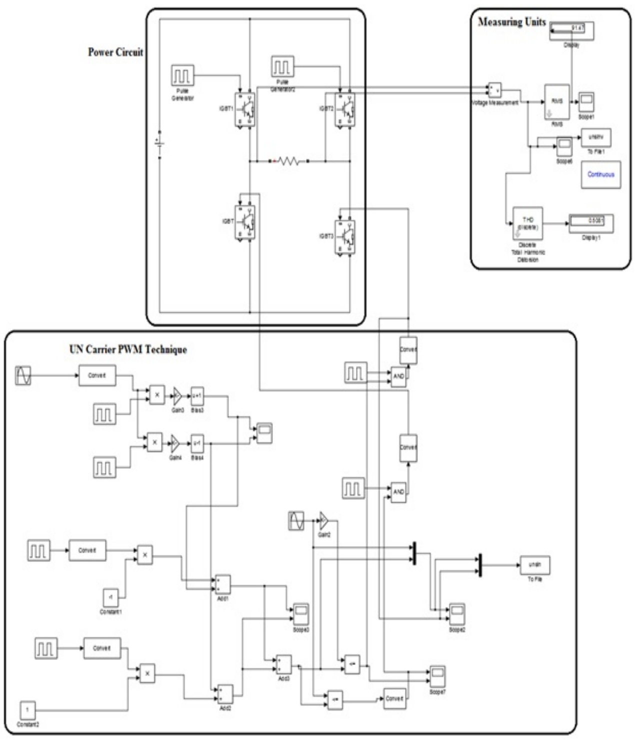


Fig.6. Simulink model of UN carrier based SPWM Technique

The simulation parameters used in the UNCPWM technique are Fundamental frequency of 50 Hz, Switching frequency of 1 kHz, inverter input voltage of 100 Volt, resistive load of 100Ω and Solver ode23tb. The IGBT based full bridge voltage source inverter is modeled using simpower system block set. The firing pulses to the inverter are generated by proposed carrier, based on sinusoidal modulating technique. The output voltage waveform generated by the UN carrier based PWM inverter is observed on the scope block. Once the simulation is completed, powergui is opened and the Fast Fourier Transform (FFT) analysis is selected to display the spectrum of harmonic signal with the range of 2500 Hz. The resulted Gating pulse Generation, using UNCPWM Technique in MATLAB-Simulink model, is shown in the Fig. 7.

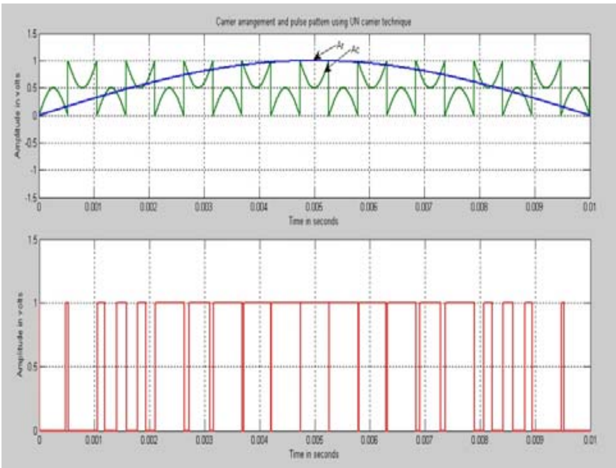
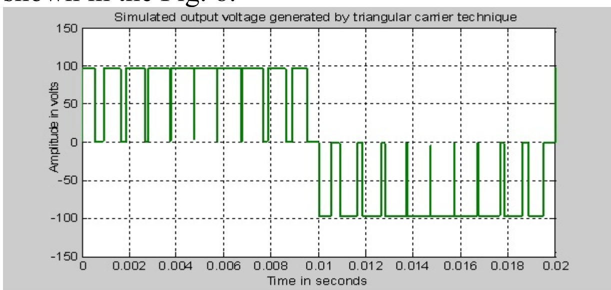


Fig.7. Gating pulse Generation using UNCPWM Technique

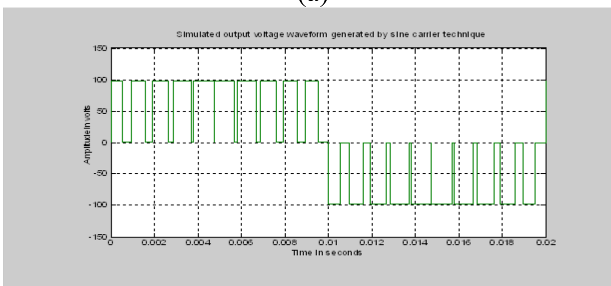
The generated gating pulse pattern, using UNCPWM technique, involves the conventional sinusoidal reference signal and an inverted sine carrier as above and below the zero reference. The modulating waveform has peak to peak amplitude (Am), a frequency (fm), and its zero centered in the middle of the UN carrier set. The sinusoidal signal is continuously compared with each of the UN carrier signal. The intersection defines the switching instants of the gating signal. If the modulating signal is greater than that of a carrier signal, then the active device corresponding to that carrier is switched on, and if the modulating signal is less than that of a carrier signal, then the active device corresponding to that carrier is switched off. The proposed technique implemented in the hybrid system results in the less insignificant harmonics with more fundamental output voltage compared to the existing techniques.

4 Performance Analysis

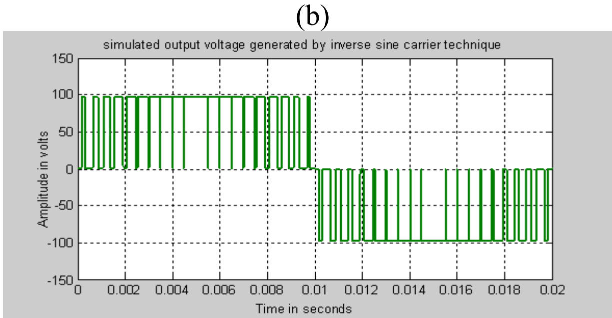
The performance analysis mainly focuses on the fundamental RMS output voltage of the inverter and the Total Harmonics Distortion (THD). For revealing the advantages of the proposed UNCPWM technique, it is necessary to compare and validate the output voltages and FFT spectrums of harmonic Distortion values attained, using existing SPWM, SSPWM and ISCPWM techniques. The main aim of any modulation technique is to obtain variable output, having maximum fundamental component with reduction of Total harmonic distortion. The output voltages of different PWM techniques are shown in the Fig. 8.



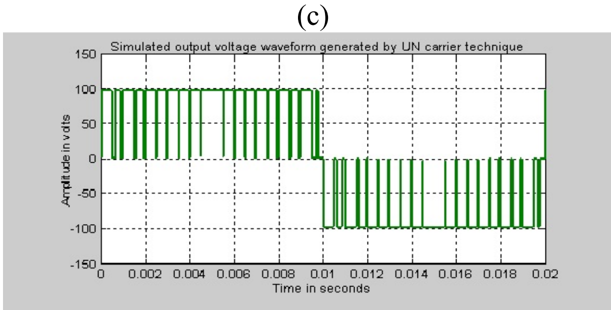
(a)



(b)



(c)

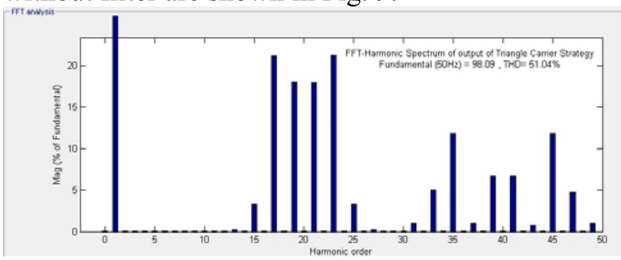


(d)

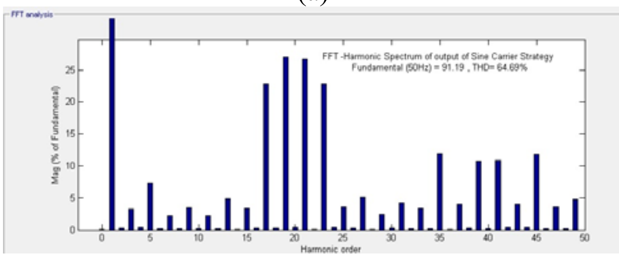
Fig.8. Output voltage of different Carrier based PWM inverter *(a) SPWM scheme (b) SSPWM) (c) ISCPWM (d) UNCPWM*

The observation from the voltage waveform in each scheme produces different switching instant for the same modulation index.

From the proposed UNCPWM technique, the behaviour of generating pulse pattern shape varies inverse sinusoidal in nature during OFF period and the shape varies sinusoidal in nature during ON period. This kind of variation which leads to improvement in the fundamental output voltage with reduced harmonics in the harmonic spectrum. The harmonic spectrums of different PWM techniques without filter are shown in Fig. 9.



(a)



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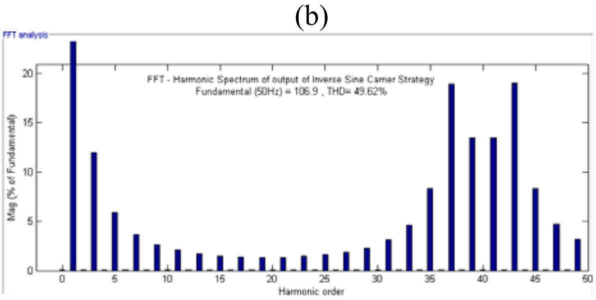
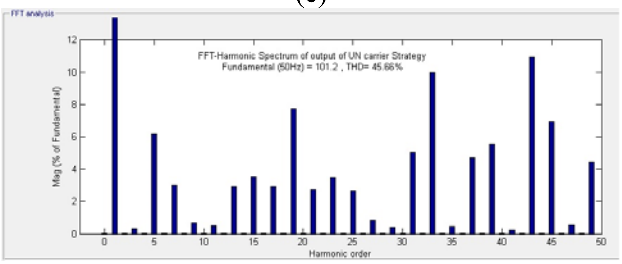


(c)



(d)

Fig.9. Harmonic spectrum of different Carrier based PWM inverter without filter (Modulation Index is 1) (a)SPWM scheme (b) SSPWM) (c) ISCPWM (d) UNCPWM

The observation from the spectrum each technique yields variation in the different THD values for the same value of modulation index.

From the above result, the conventional SPWM technique has more 3rd order harmonics rather than SSPWM & ISCPWM techniques. Even though the shapes of the SPWM and SSPWM have resemblance in nature, the magnitude of harmonic content in the SSPWM technique is reduced when compared to SPWM technique. Similarly, the shape of the ISCPWM harmonic spectrum has the same resemblance of proposed UNCPWM harmonic spectrum in nature. However, the magnitude of harmonic content in the UNCPWM technique is reduced with more fundamental output voltage than other existing techniques.

In the case of SSPWM scheme, the lower order and higher order harmonics are more predominant at side band frequencies. In the case of ISCPWM scheme, the harmonic component is less at switching frequency and high at side band frequencies. The ISCPWM works better than the conventional SPWM in the over modulation; its performance cannot be appreciated to the extent as in linear region. The above said drawback is eliminated, using the proposed UNCPWM technique in which harmonic in the side band frequencies are less and the lower order harmonics are slightly higher than that of ISCPWM technique.

The four different PWM techniques are investigated in the linear region and the result of fundamental output voltage for various modulation index values are plotted as curve in the Fig. 10.

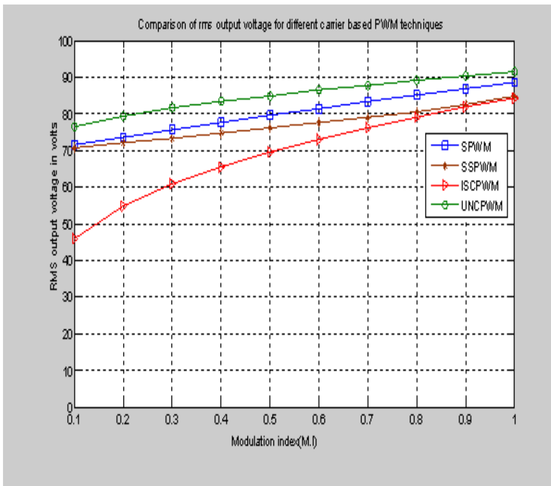


Fig.10. Variation of Modulation Index Vs RMS output Voltage for Carrier based PWM schemes

The techniques have been validated by the means of varying modulation index in the linear region of 0 to 1. The inference from the result shows that, the proposed UNCPWM technique has more fundamental RMS output voltage for various modulation index, compared to other techniques. The limitation of the proposed technique is providing high value of RMS output voltage even at low value of modulation index rather than existing techniques.

The four different PWM techniques are investigated in the linear region and the results of Total Harmonic Distortion (THD) for various modulation index values are plotted as curve in the Fig. 11. The techniques have been validated by means of varying modulation index in the linear region of 0 to 1.

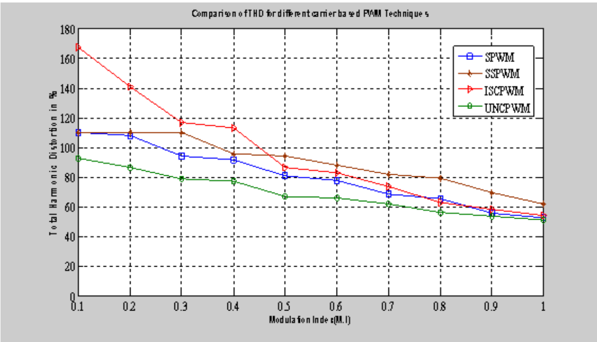


Fig.11. Variation of Modulation Index Vs Total Harmonic Distortion of Carrier based PWM scheme

As per the observation made from the Fig.10 & 11, the UNCPWM technique provides less in THD than other techniques. Finally, the performances of different PWM techniques have been compared and investigated with the obtained solution and the proposed UNCPWM technique has the features of increase in fundamental output voltage along with reduced harmonic content rather than existing techniques.

5 Time Domain Simulation of Isolated Hybrid System

In this section, time domain simulated responses of the hybrid wind-PV system, under various operating points and different disturbance conditions are carried out.

The response of the scheme for varying irradiation (assuming constant wind speed) is simulated and plotted as a graph shown in Fig.12.

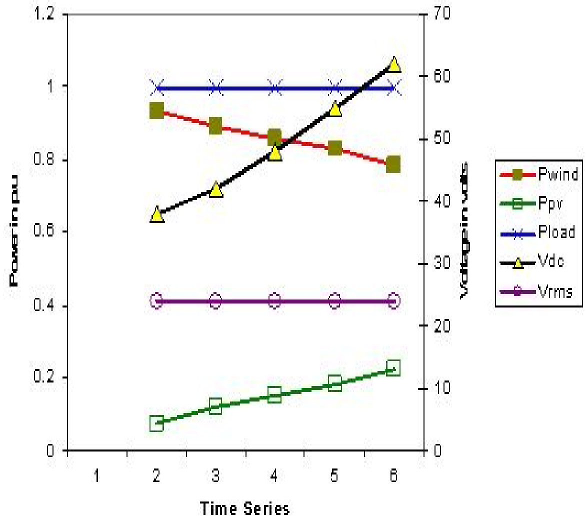
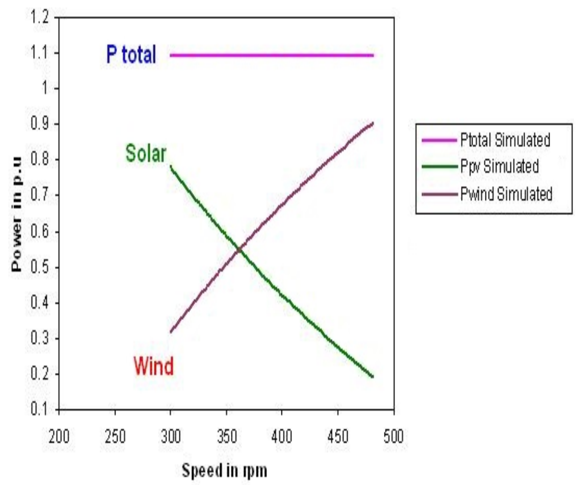
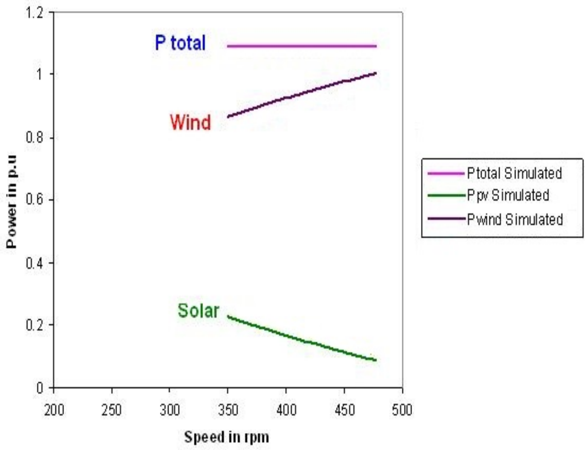


Fig.12. Performance characteristics of the proposed scheme (Increase in Irradiation)

It is observed that inverter output (AC RMS load voltage) is found to be constant. Similarly, the response of the controller for varying wind-speed at different irradiation was simulated and plotted as a graph shown in Figure 13 (a, b)



(a)Performance of Hybrid System when Isc 4.1A (Q=900 Wm^{-2})



(b) Performance of Hybrid System when Isc 1.25A (Q=300 Wm^{-2})

Fig.13. (a) & (b) Performance of Hybrid Scheme

Fig.13 (a) and (b) shows the sharing of power between the wind-generator and PV array at different irradiation conditions. For a given irradiation, the power supplied by the PV array is maximum only when the wind-speed is low. As the speed of the wind-generator increases, the power supplied by the PV array decreases, thus confirming our analysis. Fig.14 presents the variation of the modulation index with varying irradiation and torque.

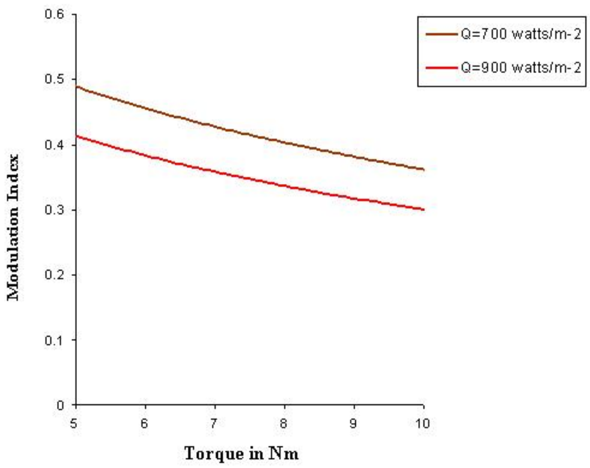


Fig.14. Variation of modulation index with irradiation and torque

The controller automatically varies the modulation index with variation in the DC bus voltage to maintain the load voltage constant. It can be observed from this Fig.14 the ON time of the firing pulses automatically decreases (decreases in modulation index) with increasing V_{dc} or vice-versa in order to maintain the load voltage constant.

6 CONCLUSION

Power production from renewable energy sources such as solar cell array and wind turbines have been increased significantly since last decade. In this paper, a new UNCPWM technique based voltage source inverter is connected between hybrid energy generation system and a load for increasing the reliable power supply. The optimal level in quality of power is obtained when Total Harmonic Distortion is reduced and fundamental RMS output voltage is increased and this technique is compared with existing techniques such as SPWM, SSPWM and ISCPWM. Based on the investigation, it is observed that the performance of the voltage source inverter, using proposed technique, is considerably maintains good voltage regulation with lower harmonic content. Furthermore, the investigation can be extended by implementing Selective Harmonic Elimination (SHE) technique for the significant amount of THD reduction.

References:

[1] Phoivos D. Ziogas, “The Delta Modulation Technique in Static PWM Inverters”, IEEE Transactions on Industry Application, Vol. 1 A-17, March/April 1981,pp. 199-203.

[2] J.A. Houldsworth, D.A. Grant “The Use Harmonic Distortion to Increase the Output Voltage of Three-Phase PWM Inverter”, IEEE Transaction on Industry Application, Vol. 1 IA-20, Sept./Oct. 1984.pp.1224-1228.

[3] K. Taniguchi, Y. Ogino, H. Irie “PWM Technique for Power MOSFET Inverter”, IEEE Transactions on Power Electronics, Vol. 3, No. 2, July 1988,p.p. 328-334.

[4] W.G. Dunford, J.D. Van Wyk “The Calculation of Sub-Harmonics in an Asynchronous PWM Induction Motor Drive”, Proceedings of IEEE PESC Conference Record, 1990pp. 672-677.

[5] R. Wu, S.B. Dewan, and G.R. Slemon, “Analysis of an AC-to-DC voltage source converter using PWM with phase and amplitude control,” IEEE Trans. on Industry Applications, vol.27, no.2, Mar/Apr 1991pp.355-364.

[6] Joachim Holtz, “Pulse width Modulation-A Survey”, IEEE Transaction Industrial Electronics, Vol. 39, No. 5, Dec. 1992,pp. 410-420.

[7] Michael A. Boost, Phoivos D. Ziogas “State-of-the-Art–CarrierPWM Techniques:

A Critical Evaluation", IEEE Transactions Industry Applications, Vol. 24, No. 2, March/April 1998,pp. 271- 280.

[8] S. Fukuda and K. Suzuki, "Harmonic evaluation of two-level carrier-based PWM methods" in Proc. EPE, Trondheim, Norway, 1997,pp. 331–336.

[9] S. Jeevananthan, P. Dananjayan, S. Venkatesan "A Novel Modified Carrier PWM Switching Strategy for Single-Phase Full-Bridge Inverter", Iranian Journal of Electrical and Computer Engineering, Summer Fall - Special Section on Power Engineering, Vol. 4, No. 2, 2005,pp. 101-108, Tehran, Iran.

[10] S. R. Bowes and D. Holliday, "Optimal regular sampled PWM inverter control techniques," IEEE Trans. Ind. Electron., vol. 54, no. 3, Jun. 2007.pp. 1547–1559.

[11] F. Vargas-Merino, M.J. Meco-Gutierrez, J.R. Heredia-Larrubia, and A.Ruiz-Gonzalez "Low Switching PWM Strategy Using a Carrier Wave Regulated by the Slope of a Trapezoidal Modulator Wave," IEEE Trans. on Industrial Electronics, vol.56, no.6, June 2009,pp.2270-2274.

[12] S. Jeevananthan, R. Nandhakumar, P. Dananjayan "Inverted Sine Carrier for Fundamental Fortification in PWM Inverters and FPGA Based Implementations", Serbian Journal of Electrical Engineering, Vol. 4, No. 2, Nov. 2007pp. 171 – 187.

[13] H. Habeebullah Sait and S. Arul Daniel "Modulation index control of a SPWM inverter fed from an Autonomous Hybrid Wind-driven PM alternator and Photovoltaic Array", Australian Journal of Electrical and Electronics Engineering, Vol.6 No.2. 2009, pp 191-203. (Institution of Engineers, Australia).

[14] H. Habeebullah Sait and S. Arul Daniel "A New Control Paradigm for Integration of Photovoltaic Energy Sources with utility network", International Journal of Electrical power and Energy Systems(Elsevier), Volume 33, Issue 1, 2011,pp. 86-93.

[15] Colak Ilhami, et al "Developing a novel sinusoidal pulse width modulation (SPWM) technique to eliminate side band harmonics", Electric Power and Energy Systems Vol. 44, 2013, pp. 861–71.

[16] Anderson, P. M.Bose, "A Stability simulation of wind turbine system", IEEE Transaction Power Apparatus System Vol. 12, 1983.pp.3791–3795.

[17] Lee, D. J. and Wang, L.: Analysis of a novel autonomous marine hybrid power generation/energy storage system with a high-voltage direct current link, Journal of Power Sources 185, No. 2, Dec. 20081284–1292.

[18]. H.Matsuo and F.kurokawa, "Novel solar cell power supply system using bidirectional dc-dc converter" in proc. IEEE power electron. spec. conf. (PESC), Cambridge, MA, June 1982, pp. 14-19.

[19] T.Shimizu, M.Hirakata, T.Kamezawa and H.Watanabe, "Generation control circuit for photovoltaic modules" in IEEE Trans. Power Electron. vol. 16, no.3, March 2001pp.293-300.

[20] Dong-jing Lee and Li Wang, "Small-signal stability analysis of an autonomous hybrid renewable energy power generation/energy storage system Part I: Time-Domain Simulations", IEEE Transactions on Energy conversion, vol.23, March 2008,pp.311-320.