https://doi.org/10.31436/iiumej.v20i2.1142

DESIGN AND IMPLEMENTATION OF TWO-PHASE INTERLEAVED VOLTAGE SOURCE INVERTER FOR PV APPLICATIONS

HARIKA SRIDHARAN, SEYEZHAI RAMALINGAM

Department of Electrical and Electronics Engineering,
SSN College of Engineering, Chennai, India.

Corresponding author: sriharkal@gmail.com

(Received: 10th March 2018; Accepted: 29th June 2019; Published on-line:2nd December 2019)

ABSTRACT: The design of a voltage source inverter is challenging for PV-grid connected systems due to power quality issues. To improve the power quality,a two-phase interleaved voltage source inverter (IVSI) is proposed in this paper. IVSI phase shifts two voltage source inerters connected in parallel. The inverter topology is interfaced with a 40W PV panel employing a multiple maxima search (MMS) MPPT algorithm. This algorithm results in higher tracking efficiency compared to existing methods. Modelling of the PV with MPPT and the circuit configuration of the interleaved inverter is simulated in MATLAB/SIMULINK. The switches in the IVSI is controlled by employing a unipolar PWM technique. The performance of the IVSI is investigated in terms of weighted total harmonic distortion (WTHD), distortion factor (DF), harmonic spread factor (HSF), and inductor current ripple and compared with classical VSI. From the analysis, it is inferred that the proposed inverter results in reduced total harmonic distortion(THD) and decreased inductor current ripple thereby producing a high-quality output. The hardware model of the two-phase IVSI is developed and interfaced with PV where gating pulses are generated in FPGA. The simulation results are validated experimentally.

***ABSTRAK*:** Rekaan pembalik sumber voltan adalah mencabar pada sistem gabungan grid-PV disebabkan isu kualiti tenaga. Bagi memperbaharui kualiti tenaga, pembalik sumber voltan antara lembar dua-fasa (IVSI) telah dicadangkan dalam kajian ini. Anjakan fasa IVSI pembalik sumber voltan dua-fasa telah dihubungkan secara selari. Topologi pembalik telah diantaramukakan dengan 40W panel PV dengan mengunakan carian maksima berganda (MMS) algoritma MPPT. Hasil algoritma menunjukkan lebih tinggi keberkesanan dibandingkan dengan kaedah sedia ada. PV model dengan MPPT dan konfigurasi litar pembalik antaramuka telah disimulasi menggunakan MATLAB/SIMULINK. Suis dalam IVSI dikawal dengan menggunakan teknik PWM unipolar. Dapatan kajian ke atas IVSI adalah berdasarkan berat pengherotan total harmoni (WTHD), faktor pengherotan (DF), faktor sebaran harmoni (HSF), getaran arus pembalik dan dibandingkan dengan kaedah klasik VSI. Analisis menunjukkan kesimpulan dapatan kajian ke atas pembalik yang dicadangkan telah berkurang jumlah pengherotan harmoni (THD) dan getaran arus pembalik telah berkurang, oleh itu menghasilkan hasil akhir yang berkualiti tinggi. Model perkakasan IVSI dua-fasa telah dibangunkan dan diantaramukakan dengan PV di mana signal pengegetan dihasilkan dalam FPGA. Dapatan hasil simulasi telah disahkan secara eksperimen.

KEYWORDS: *IVSI; total harmonic distortion(THD);ripple; MPPT*

1. INTRODUCTION

Nowadays, renewable energy has been employed for various applications in order to meet the electricity demand and in particular, solar PV power generation is mostly used due to its eco-friendly nature and abundant availability [1]. The difficulty with this power generation is tracking peak power. To obtain maximum power from PV, various maximum power point algorithms have been investigated in the research work. [2]. The traditional MPPT algorithms are perturb-and-observe (P&O), incremental conductance (INC), fractional open circuit voltage, fractional short circuit current, and current sweep. The P&O and INC suffer from the drawback that they lose the MPP tracking if the solar irradiation varies rapidly. Existing fractional open circuit voltage and fractional short circuit current have the same drawback as their MPP tracking is not real, leaving the computation based on approximation. The sweep waveform of the PV array current is used in the case of the current sweep tracking method, which obtains MPP if the sweep is instantaneous but is difficult to apply in practical situations. Thus the traditional algorithms fail to find global MPP under variable irradiation conditions [3]. Thus, this research work proposes a MMS algorithm that follows the direct search technique (DST) to track a maximum operating point that overcomes the cons of the traditional MPPT algorithms. DST samples the sampling interval by assuming one point to be the center, dividing that intotwo intervals, and proceeding in the same way for the other intervals[4, 5]. In this way, an optimum operating point is obtained. With this MMS algorithm, high tracking efficiency can be achieved even in a partially shaded condition. Tracking efficiency of 97% is achieved with DST, based on the dividing rectangle algorithm. It is also possible to achieve a tracking efficiency of 99 % if this direct search algorithm is employed to get a globalpoint alongwith the traditional algorithm. Thus, the MMS MPPT algorithm is implemented, as itis suited for PV [6, 7].

A voltage source inverter is the most commonly used interface circuit for PV [8] but it suffers from various issues like high THD and high inductor current ripple content. Thus, this research work focuses on interleaving two voltage source inverters, known as the two-phase interleaved voltage source inverter (IVSI) [9]. IVSI is defined as a parallel operation of two voltage source inverters with an interleaving angle (κ) that is chosen based on the equation given by,

$$\kappa = \frac{360}{N} \qquad (1)$$

where, N = number of the inverter connected in parallel.

The paper deals with twoinverters connected in parallel ($N = 2$). From equation (1), it is found that the interleaving angle is 180 degrees. The performance of the VSI depends upon the control strategy [10]. So, the proposed topology is investigated with different modulation strategies such as fundamental frequency switching, unipolar sine PWM, and space vector modulation. The performances of IVSI with different modulation strategies are compared and unipolar SPWM was found to have low THD and reduced inductor current ripple [11]. Thus, to improve the powerquality of the waveform, IVSI with unipolar SPWM technique is studied in MATLAB/SIMULINK. Finally, a prototype model of the two-phase interleaved voltage source inverter is built and interfaced with a 40W solar panel. The schematic block diagram of the overall work is depicted in Fig.1.

The performance parameters computedfor comparisonare total harmonic distortion (THD_v) and inductor current ripple. From the results, it is found that the two-phase IVSI has less THD and reduced inductor current ripple compared to traditional VSI.

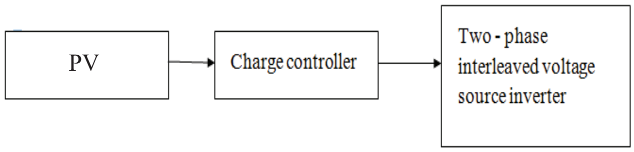


Fig.1: Block diagram of the proposed work.

2. TWO-PHASE INTERLEAVED VOLTAGE SOURCE INVERTER

The main feature of the two-stage IVSI is that it eliminates the zero voltage level, which is present in conventional voltage source inverters [12,13]. With the single-level inverter, the voltage levels are $+V_{dc}/3$, 0, $-V_{dc}/3$ but with a two-levelinverter, the voltage levels are $+V_{dc}/2$ and $-V_{dc}/2$. This shows that IVSI suits the PV application [14]. The circuit diagram of the proposed parallel connected voltage source inverter is shown in Fig.2.

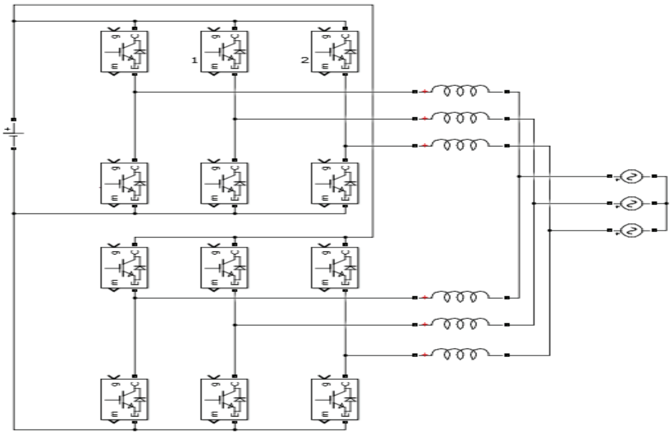
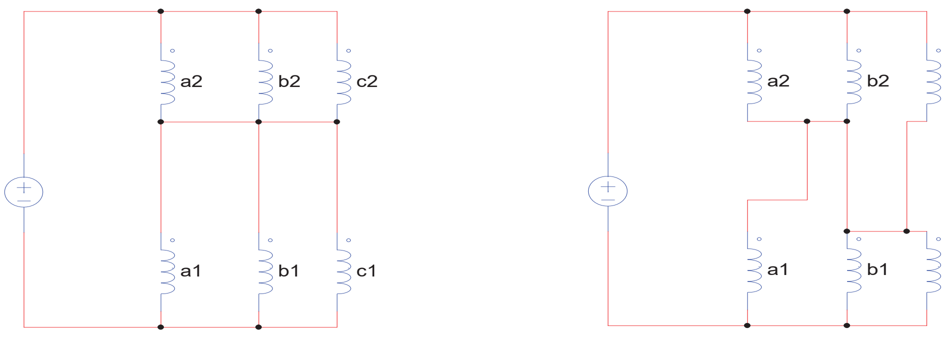


Fig.2: Circuit diagram of the parallel connected voltage source inverter.

Figure 2 shows that the two voltage source inverters are parallel through the filter inductance and connected to the grid. The operation of the IVSI is elaborated into six periods, T_1 to T_6. The switching states are different for different intervals [15, 16]. During T_1, the inductor voltage is zero if a single inverter is employed whereas, with two parallel connected inverters, the voltage across the inductor is $V_{dc/2}$. Similarly, during T_2, if a single inverter is employed, the inductor voltage will be $-V_{dc/3}$ whereas for interleaved inverter the voltage level will be - $V_{dc/2}$. Thus, the zero voltage level is eliminated in the interleaving operation of the VSI. The circuit diagram of the interleaved VSI during T_1 and T_2 is depicted in Fig.3.

3. MODULATION STRATEGIES

The proposed two-stage IVSI is analyzed with different modulation strategies such as fundamental frequency switching, unipolar SPWM, and space vector modulation [17]. The results of the different modulation strategies are compared in terms of current THD (total harmonic distortion) and inductor current ripple content [18]. From the comparison, the unipolar SPWM is chosen since it has low THD_i and reduced ripple content. Then, the outputs of the interleaved inverter and conventional voltage source inverter are compared to prove that the proposed inverter topology has low THD, has low filter requirements, and operates at a high switching frequency.



(a) (b)

Fig.3: Operation of the proposed inverter (a) during T_1 and (b) during T_2.

The unipolar PWM requires one sinusoidal reference waveform and one triangular carrier waveform. The switches in the same leg are triggered in a complementary manner with one switch turned on and other switch turned off [19]. Thus, only the gating pattern of the upper switch is considered. The three sinusoidal waveforms with 120-degree phase shift are compared with the triangular carrier waveform for VSI_1 as depicted in Fig. 4, whereas for VSI_2 , the three reference sinusoidal waveform is compared with the 180 degree phase shifted carrier waveform. The pulse pattern for two-stage interleaved VSI is shown in Fig.5. S_1, S_2, and S_3 denote pulse output for VSI_1 and S_1',S_2',and S_3' denote pulse output for VSI_2.

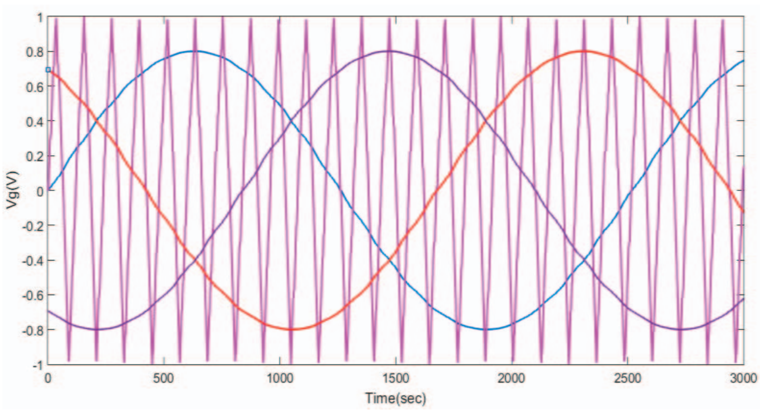


Fig.4: Reference and carrier waveforms for Unipolar PWM.

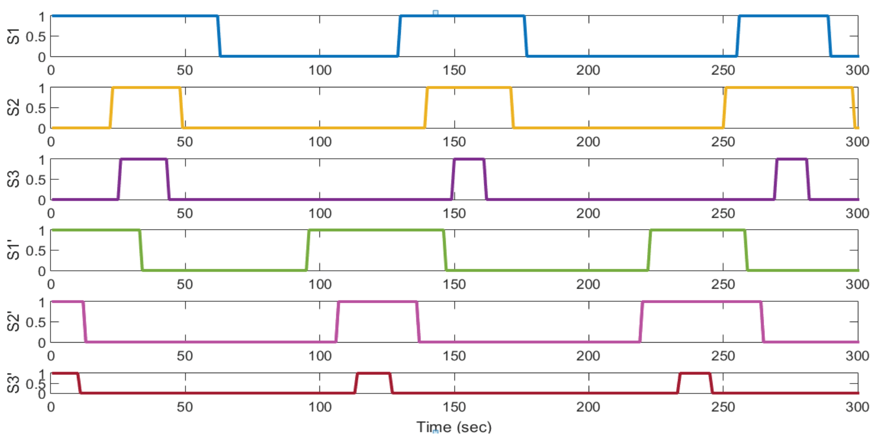


Fig.5: Gating pattern of IVSI.

4. SIMULATION RESULTS

The interleaved voltage source inverter has been simulated in MATLAB/Simulink and the various PWM strategies have been implemented. The simulation model is depicted in Fig.6 and the simulation parameters are shown in Table. 1. The output voltage of the interleaved inverter is shown in Fig.7.

Table 1: Simulation Parameters

PARAMETER	VALUES
DC voltage(V_{dc})	400 V
Inductor(L)	50mH
Modulation Index (m_a)	0.8
Switching Frequency	1050 Hz
Interleaving Angle	180 Degree

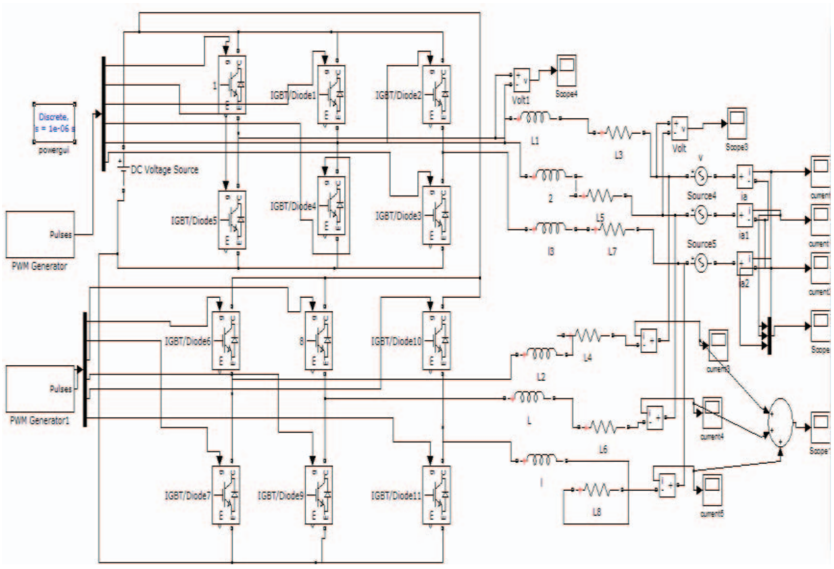


Fig.6: Simulink model of the proposed two-stage IVSI.

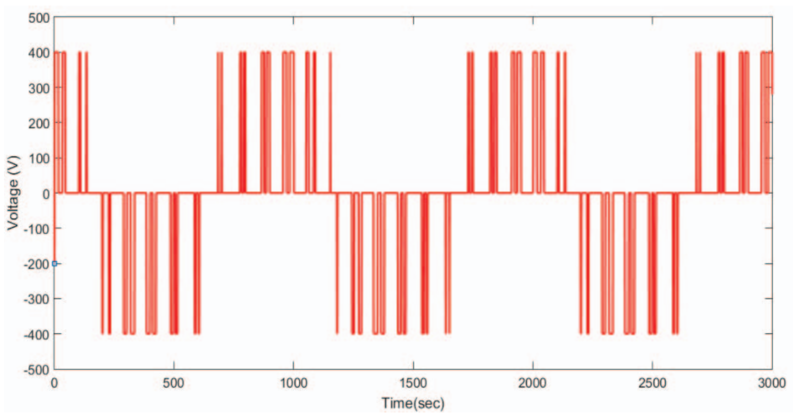


Fig. 7: Output Voltage of the parallel connected VSI.

Table 2: Comparison of different modulation strategies for the interleaved inverter

Modulation techniques	**THDi%**	**I_{Lr}**
Unipolar SPWM	0.97	L_{ia}=0.82, L_{ib}=0.82, L_{ic} = 0.82
Fundamental frequency switching	1.07	L_{ia} = 1.46, L_{ib} = 1.38, L_{ic} = 1.20
Space vector PWM	2.92	L_{ia} = 2.59, L_{ib} = 2.60, L_{ic} = 2.59

Table 3: Comparison of interleaved inverter and conventional VSI

Modulation techniques	**THDi%**	**I_{Lr}**
Conventional single-stage voltage source inverter	2.33	L_{ia} = 2.33, L_{ib} = 2.33, L_{ic} = 2.32
Unipolar SPWM	0.97	L_{ia} = 0.82, L_{ib} = 0.82, L_{ic} = 0.82

The comparison of the simulation results are depicted in Table 2 and Table3, showing that the two-stage IVSI with unipolar PWM has low THD and reduced ripple content compared to single-stage VSI. Thus, the performance of the proposed topology with unipolar SPWM is analysed for different modulation indexes. The performance parameters are total harmonic distortion(THD), weighted total harmonic distortion(WTHD), distortion factor(DF), and harmonic spread factor(HSF).

4.1 Total Harmonic Distortion (THD)

A deviation in the shape of an obtained waveform from its fundamental component is called total harmonic distortion, the expression for THD is

$$\text{THD} = \frac{1}{(V_o)_1}\sqrt{\sum_{3,5,7}^{\infty}(V_o)_n^2} \qquad (2)$$

where $(V_0)_n$ = RMS value of the harmonic component, $(V_0)_1$= RMS value of the fundamental component.

4.2 Weighted Total Harmonic Distortion (WTHD)

Evaluating the quality of pulse width modulation (PWM) inverter waveforms is commonly called a weighted total harmonic distortion (WTHD). The frequency and the measured voltage harmonics are inversely proportional to each other.

$$WTHD = \frac{\sqrt{\sum_{n=2}^{\infty}(\frac{V_n}{n})^2}}{V_1} \qquad (3)$$

4.3 Distortion Factor (DF)

The distortion factor is a measure of the intensity of the deviations of the measured waveform from its fundamental waveform and the mathematical expression of the DF is

$$\text{DF} = \frac{\sqrt{\sum_{n=2,3}^{\infty}(\frac{V_n}{n^2})^2}}{V_1} \qquad (4)$$

where V_1 = Fundamental voltage, V_n = total harmonics voltage, n = order of the harmonics.

4.4 Harmonic Spread Factor(HSF)

Harmonic Spread Factor defines the noise generation level in the motor and measures the voltage spectrum quality of the inverters.

$$\text{HSF} = \sqrt{\frac{\sum_{j=2}^{N}(H_j - H_0)^2}{N}} \quad (5)$$

where H_j= value of j^{th} harmonic, H_0 = average value of all N harmonics.

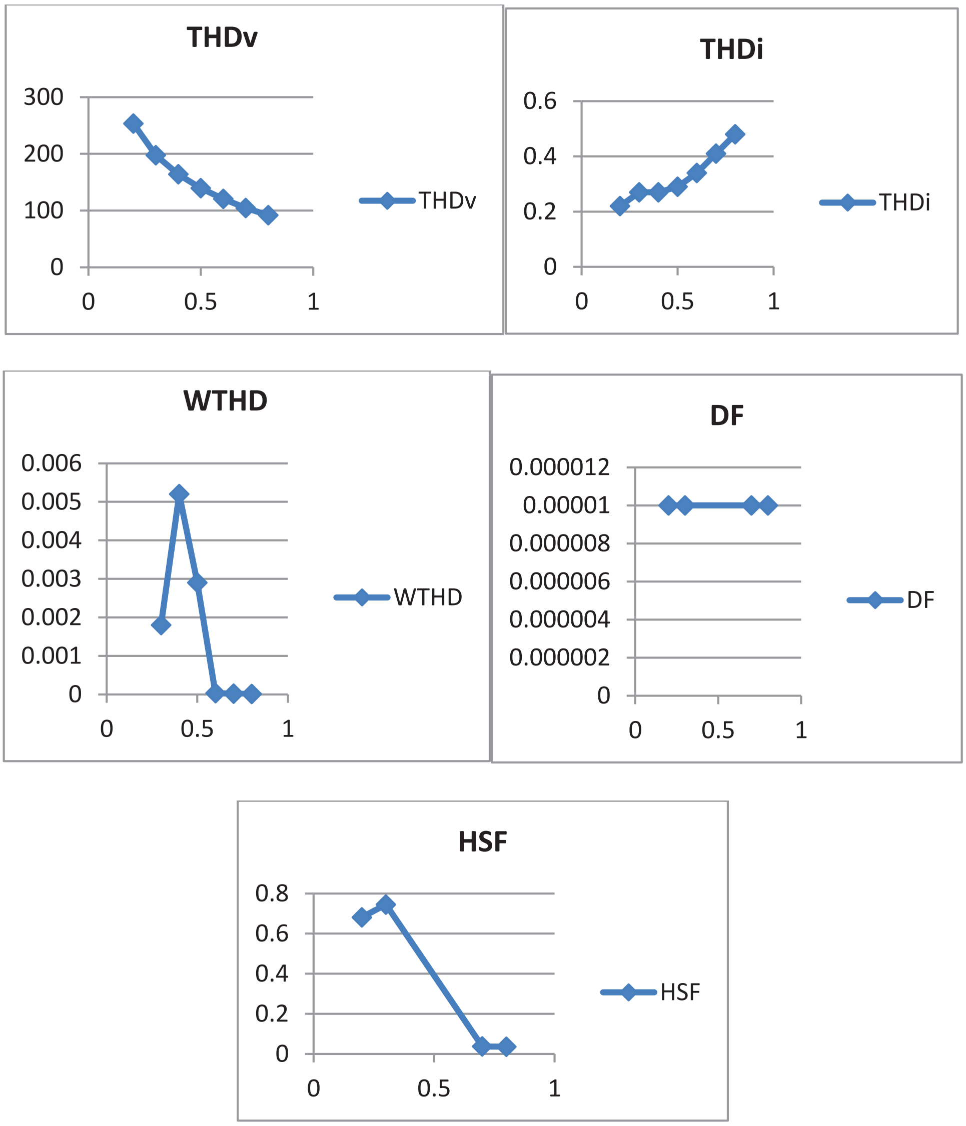


Fig. 8: Performance analysis of the interleaved VSI.

From Fig. 8, it is proven that the total harmonic distortion(THD), weighted total harmonic distortion(WTHD), distortion factor(DF), and harmonic spread factor(HSF) are low at a modulation index of 0.8. Hence, 0.8 is chosen as the modulation index for the proposed topology.

5. INTERFACE OF INTERLEAVED VSI WITH PV

A PV panel is modeled in MATLAB/SIMULINK. The parameters are obtained from the PV panel datasheet and the important electrical parameters need to be considered to get electrical characteristics of the PV panel for the open-circuit voltage and the short-circuit current [20]. Practically, V-I and P-V characteristics are observed for a 40W solar panel as shown in Fig.9.

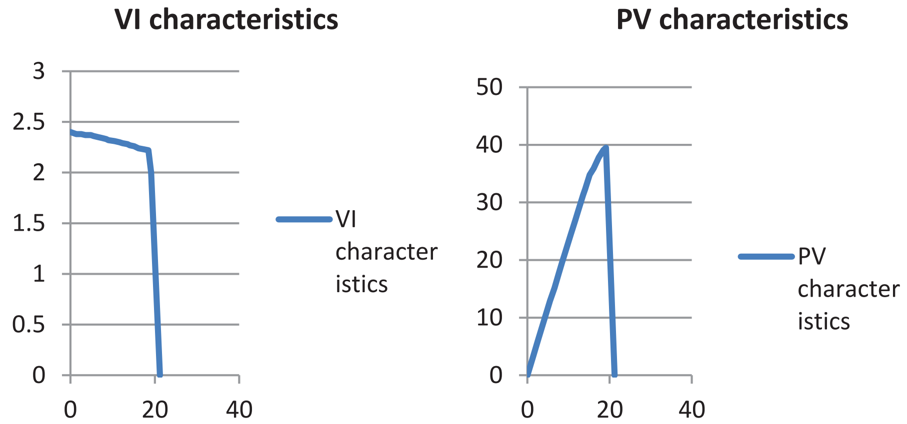


Fig. 9: V-I and P-V characteristics of PV model for 40W panel.

To track the maximum power from the PV, a MMS MPPT algorithm is used. The direct search technique based on the dividing rectangle strategy is clearly explained in Fig.10.

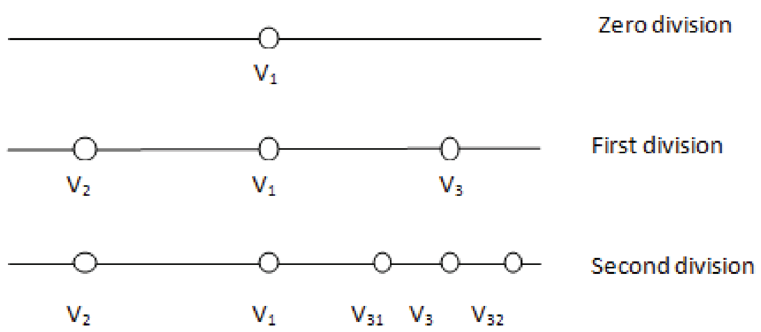


Fig.10: Dividing rule.

Figure 10 shows that V_1 is taken as a sample and assumed as its centerpoint. When compared to V_1 and V_2, V_3 has the maximum peak and it is further divided into three samples as V_{31}, V_3,and V_{32}. By doing so, the MMS MPPT algorithm tracks the maximum power, even under the partially shaded condition, and reaches a high tracking efficiency of 97%. The results are compared with the traditional perturb-and-observe method. Both MMS and P&O algorithms are modelled in MATLAB/SIMULINK and results are shown in Fig. 11.

From Fig.11,tracking efficiency is calculated:

With multiple maxima search MPPT,

$$\text{Tracking Efficiency} = \frac{48}{52} = 92\%$$

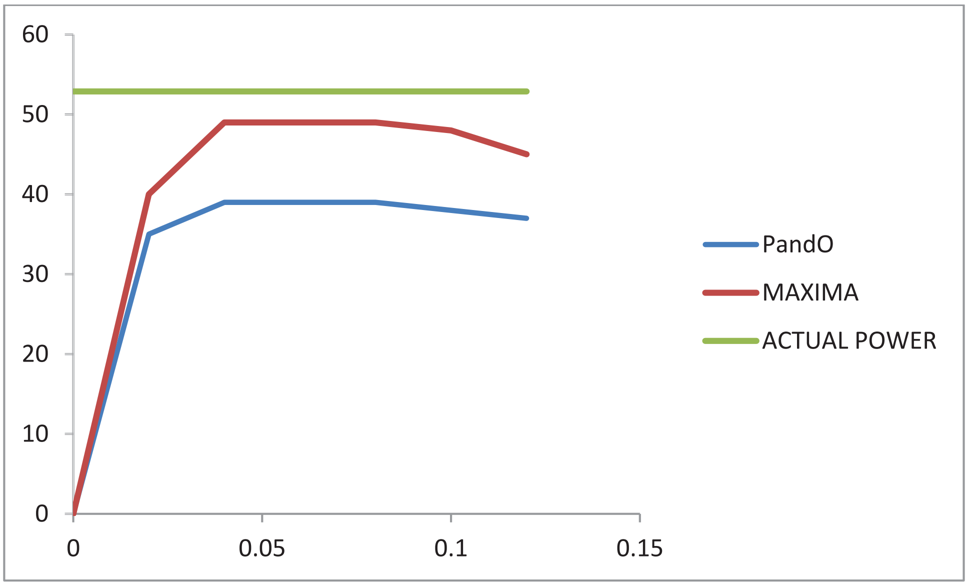


Fig.11: Actual power and tracked power.

With perturb-and-observe,

$$\text{Tracking Efficiency} = \frac{39}{52} = 75\%$$

Thus, it is proven that the multiple maxima search MPPT has high tracking efficiency compared to a traditional algorithm. The overall circuit diagram of the proposed interleaved inverter interfaced with PV panel and output is shown in Fig.12 and Fig.13.

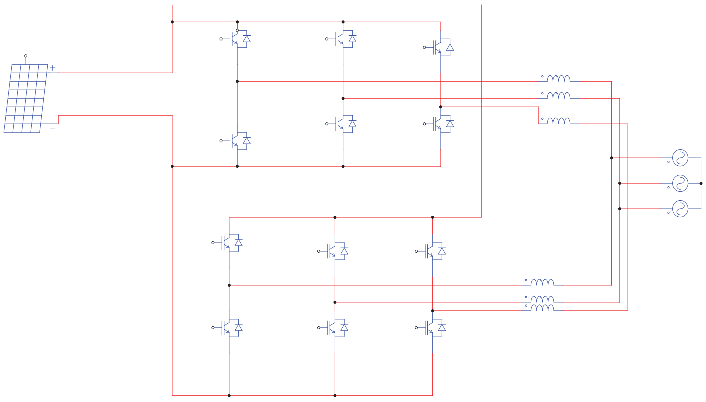


Fig.12: PV interfaced with IVSI.

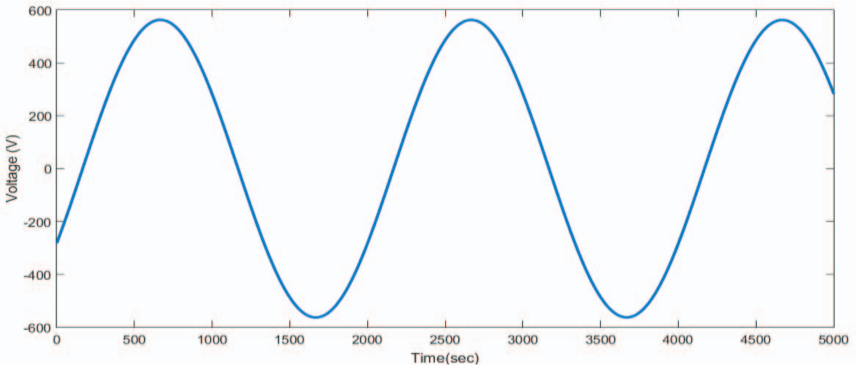


Fig.13: Output Voltage (filtered output) of inverter interfaced with PV.

https://doi.org/10.31436/iiumej.v20i2.1142

6. HARDWARE RESULTS

The two-stage IVSI with unipolar SPWM is implemented in hardware, which includes a gating circuit, pulse generation using FPGA-SPARTAN 3E, and design and development of a three phase two-stage interleaved voltage source inverter. The gating for the two-stage interleaved voltage source inverter is generated using Xilinx Spartan 3E FPGA. The generated pulse is given to the switch (MOSFET IRF 840) using an optocoupler IC (TLP 350). The gating circuit is important for providing gate pulses to switches used in the inverter in order to isolate the low power control circuit and the high power inverter circuit. The pulse generated by FPGA is given through the gating circuit. The logic for pulse generation of the proposed inverter is shown in Figs.14 - 16.

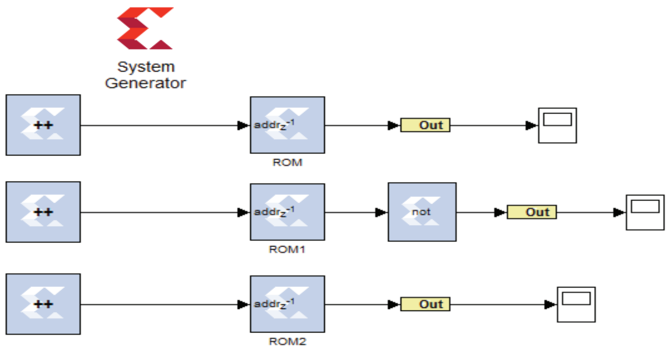


Fig.14: Sine wave generation.

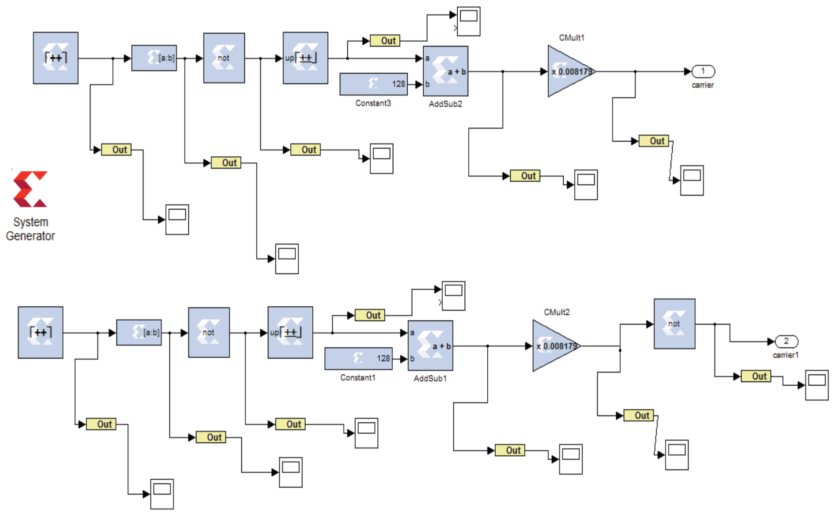
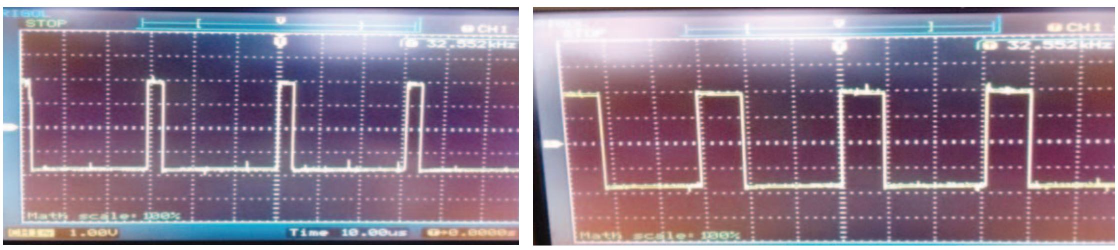


Fig.15: Triangular wave generation.



(a) Switch S1 (b) Switch S2

Fig.16: Gating pulse for interleaved VSI.

Figure 17 shows the prototype model of a two-stage interleaved voltage source inverter with gating circuit. The line-to-line voltage of the IVSI has a THD of 6.576% and its bar graph representation is shown in Fig.18.The phase voltage of the interleaved VSI has a THD of 6.58% and its bar graph representation is shown in Fig.19.

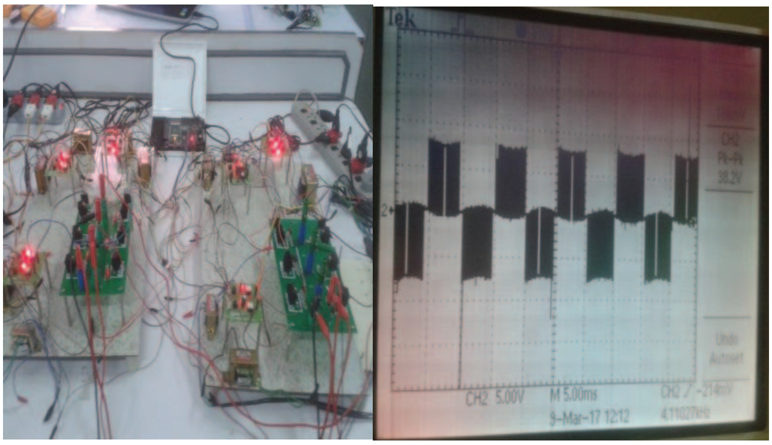


Fig.17: A prototype model of a two-stage IVSI.

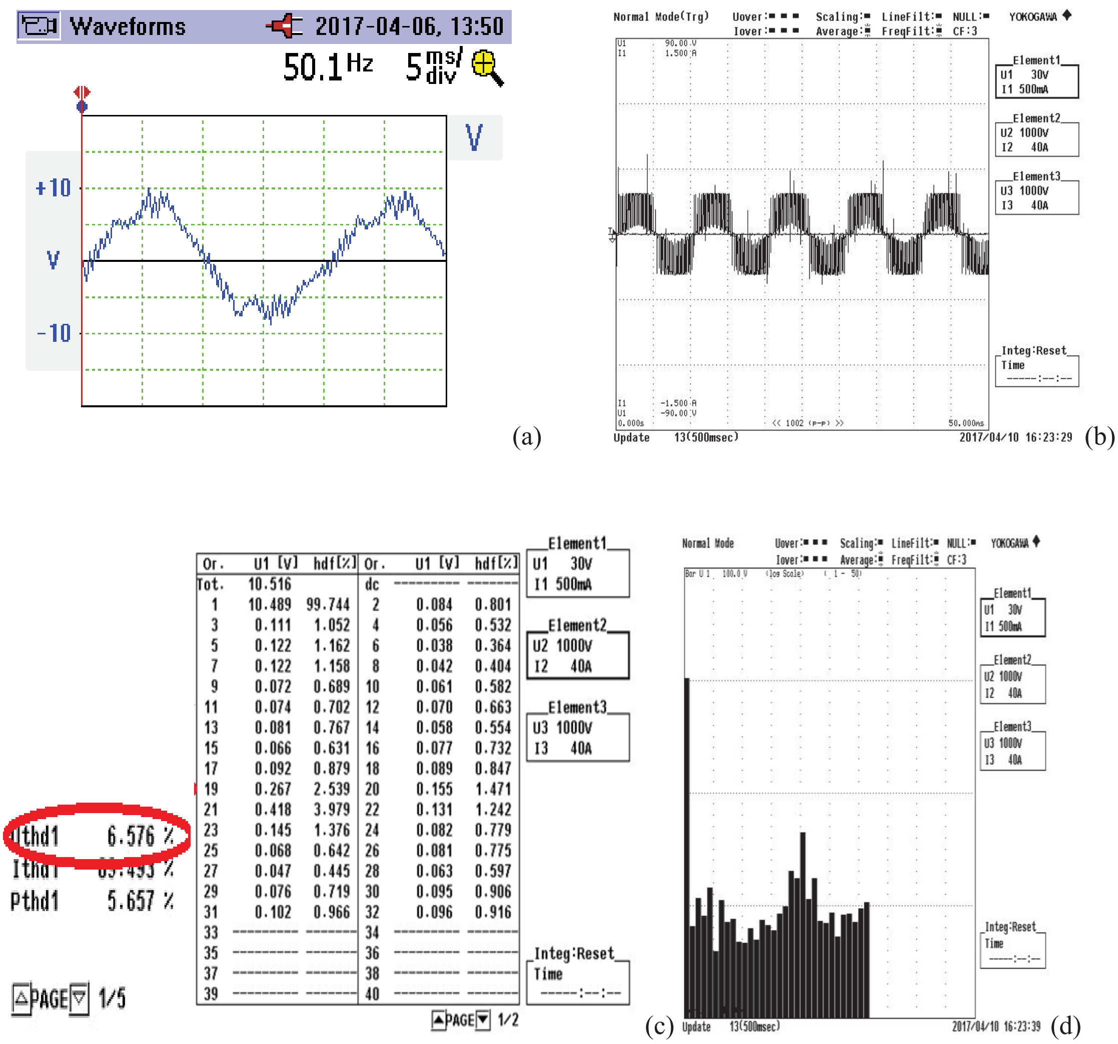
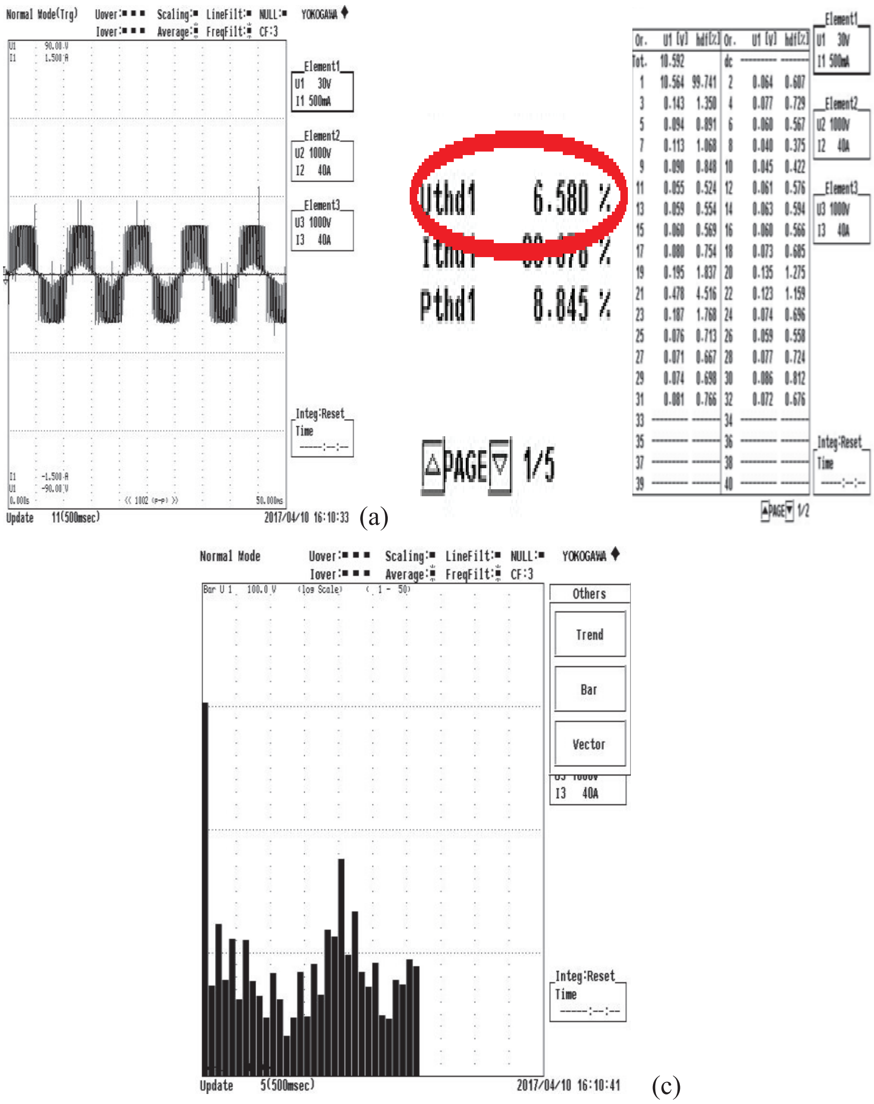


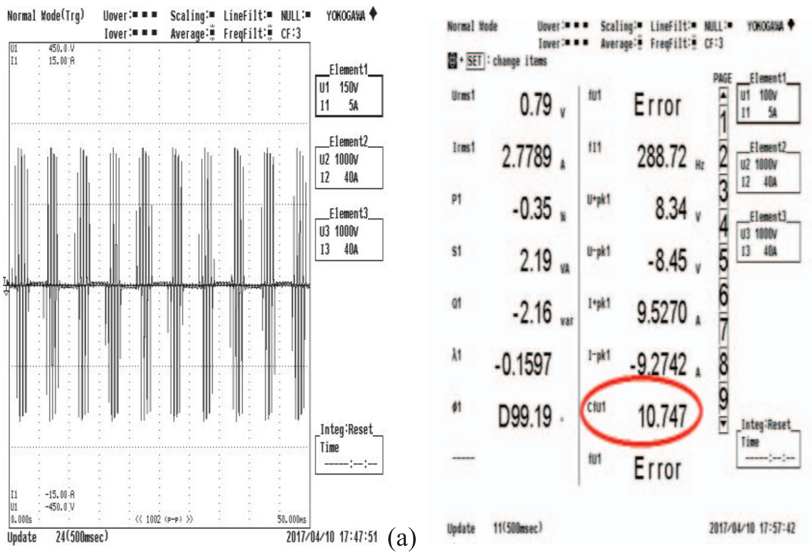
Fig.18: (a) The output voltage of proposed inverter with filter (b) Line-to-Line Voltage of Interleaved Voltage Source Inverter (c) Line-to-Line Voltage THD (d) Bar graph representation of voltage THD.

https://doi.org/10.31436/iiumej.v20i2.1142



(a) (b) (c)

Fig.19: (a) phase Voltage of Interleaved Voltage Source Inverter (b) Phase Voltage THD (c) Bar graph representation of voltage THD.



(a) (b)

Fig.20: (a) Inductor current (b) Inductor current ripple.

From Fig.20, it is clear that the proposed interleaved VSI has a lower filter inductor current ripple of 10.747%.

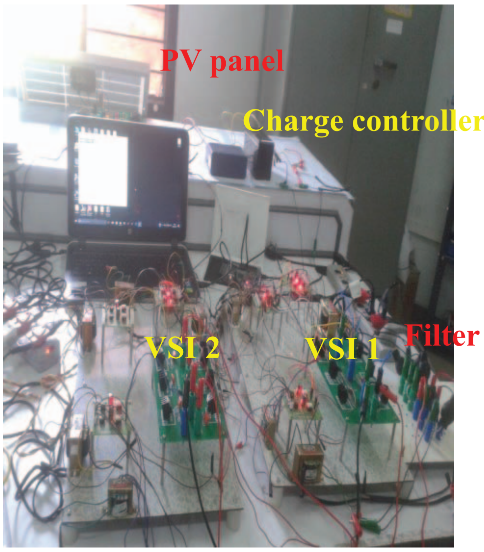


Fig.21: Two-stage VSI is interfaced with PV panel

Figures 18 - 20 prove that the proposed two-phase interleaved voltage source inverter has low THD and reduced inductor current ripple content compared to the conventional voltage source inverter. A prototype model of the interleaved inverter interfaced with PV is shown in Fig.21.The comparison of simulation results and hardware results is listed in Table 4.

Table 4: Simulation andhardware results

PARAMETERS	SIMULATION RESULTS	HARDWARE RESULTS
THD (%)	4.1	6.58
Inductor current ripple (%)	0.82	10.47

From Table 4, it is found that the proposed two-phase interleaved VSI has reduced THD (6.58%) and lower inductor current ripple (10.47%). Thus the simulation results are validated through a prototype model.

7. CONCLUSION

A two-stage interleaved VSI is studied and analyzed with different modulation strategies. The results of different modulation strategies are compared and it is concluded that the unipolar PWM has lower THD and reduced ripple content in comparison to the other techniques. Then, the two-stage VSI and traditional VSI are analyzed and it is proven that the interleaved technique had better performance. A prototype model of the two-phase interleaved voltage source inverter is built and interfaced with PV through a charge controller. The simulation results are validated experimentally. Hence, the proposed two-phase interleaved voltage source inverter topology is an appropriate choice for a PV grid connected system.

ACKNOWLEDGMENT

Authors thank the SSN Institution for providing the financial support in carrying out this research work.

REFERENCES

[1] Kenneth J. Sauer, Thomas Roessler, and Clifford W. Hansen. (2015) Modelling the Irradiance and Temperature Dependence of Photovoltaic Modules in PV syst. IEEE Journal of Photovoltaic, 5(1):152-158.

[2] T. Esram, P.L. Chapman. (2007) Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques. IEEE Transactions on Energy Conversion, 22 (2): 439-449.

[3] L. Piegari, R. Rizzo. (2010) Adaptive perturb and observe algorithm for photovoltaic maximum power point tracking. IET Renewable Power Generation, 4 (4): 317-328.

[4] Weidong Xiao, Fonkwe Fongang Edwin, Giovanni Spagnuolo, JuriJatskevich. (2013) Efficient Approaches for Modelling and Simulating Photovoltaic Power Systems. IEEE Journal of Photovoltaics, 3 (1):500 - 508.

[5] Bader N. Alajmi, Khaled H. Ahmed, Stephen J. Finney, and Barry W. Williams. (2013) A Maximum Power Point Tracking Technique for Partially Shaded Photovoltaic Systems in Microgrids. IEEE Transactions on Industrial Electronics, 60 (4): 1596 - 1606.

[6] Francesco Adamo, Filippo Attivissimo, Attilio Di Nisio, and Maurizio Spadavecchia. (2011) Characterization and Testing of a Tool for Photovoltaic Panel Modelling. IEEE Transactions on Instrumentation and Measurement, 60 (5): 1613 - 1622.

[7] Shibin Qin, Stanton T. Cady, Alejandro D. Dominguez -Garcia, and Robert Carl Nikolai Pilawa-Podgurski. (2015) A Distributed Approach to Maximum Power Point Tracking for Photovoltaic Sub module Differential Power Processing. IEEE Transactions on Power Electronics, 30 (4): 2778-2785.

[8] Feng Yang, Xu Zhao, Cong Wang, ZhiFei Sun. (2013) Research on Parallel Interleaved Inverters with Discontinuous Space-Vector Modulation. Energy and Power Engineering, 5(4): 219-225. https://doi.org/ 10.4236/epe.2013.54B043

[9] Abusara. Mohammad A and Sharkh. Suleiman M. (2013) Design and Control of a Grid-Connected Interleaved Inverter. IEEE Transactions on Power Electronics, 28 (2), 748-764.

[10] G. Shen, D. Xu, L. Cao, and X. Zhu. (2008) An improved control Strategy for grid-connected voltage source inverters with an LCL filter. IEEE Transaction on Power Electronics,23 (4):1899–1906.

[11] S.Harika, Dr.R.Seyezhai. (2016) Analysis of Modulation Strategies for Two-Stage Interleaved Voltage Source Inverter Employed for PV Applications. International Journal of Advanced Research in Basic Engineering Sciences and Technology (IJARBEST), 2 (11):1-12

[12] Jonq-Chin Hwang, Po-Cheng Chen and Chuan-Sheng Liu. (2014) A novel Single-Phase Interleaved Bi-directional Inverter for Grid-Connection Control. IEEE 23rd International Symposium on Industrial Electronics (ISIE):375-379. https://doi.org/ 10.1109/ISIE.2014.6864642

[13] Christian Nemec, Jörg Roth-Stielow. (2011) Ripple current minimization of an interleaved-switched multi-phase PWM inverter for three-phase machine emulation. 14th European Conference on Power Electronics and Applications (EPE):1-8.

[14] Abusara. M. A, Jamil. M, Sharkh. M.S. (2012) Repetitive Current Control of an Interleaved Grid Connected Inverter. 3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG):558-563. https://doi.org/ 10.1109/PEDG.2012.6254057

[15] Miss. Sangita R Nandurkar, Mrs. Mini Rajeev. (2012) Design and Simulation of three-phase Inverter for grid-connected Photovoltaic systems. Proceedings of Third Biennial National Conference, NCNTE:80-83

[16] Daniel Glose and Ralph Kennel. (2016) Continuous Space Vector Modulation for Symmetrical Six-Phase Drives. IEEE Transactions on Power Electronics, 31 (5):3837 - 3848.

[17] Siva Prasad. J .S and Narayanan. G. (2014) Minimization of Grid Current Distortion in Parallel-Connected Converters Through Carrier Interleaving. IEEE Transactions on Industrial Electronics, 61 (1), 76 - 91.
[18] Brenna. M, Chiumeo.R, and Gandolfi. C. (2011) Harmonic analysis: comparison between different modulation strategies for three-phase inverter connecting Distributed Generation. IEEE International conference on clean Electric power(ICCEP):231-236. https://doi.org/ 10.1109/ICCEP.2011.6036261
[19] Rixin Lai, Lei Wang, Juan Sabate. (2011) A High-Efficiency Two-Phase Interleaved Inverter for Wide Range Output Waveform Generation. IEEE Energy Conversion Congress and Exposition (ECCE):4533-4537. https://doi.org/ 10.1109/ECCE.2012.6342204
[20] Marcelo GradellaVillalva, Jonas Rafael Gazoli, and Ernesto RuppertFilho. (2009) Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays. IEEE Transactions on Power Electronics, 24 (5).