Improved Single Stage Grid Connected Solar PV System using Multilevel Inverter

Abanishwar Chakraborti[1], Mahua Chanda[2], Arnab Sarkar[3], Bikram Das[4], Prabir Kasari[5], Ardhendu Saha[6], Dilip Pandit[7], Amal C Sunny[8]

1,2,4,5,6,7,8 - Department of Electrical Engineering, NIT Agartala, Agartala, India
3 – Department of Electrical Engineering, Gargi Memorial Institute of Technology, Kolkata, India

Abstract— **A multilevel inverter based single stage grid connected solar PV system is proposed in this paper so as to reduce THD of the inverter voltage and reduce the size of filter circuit. A maximum power point tracking algorithm is implemented to obtain optimal performance of solar cell at different irradiance and temperature. Independent control of active and reactive power flow from inverter to the grid is obtained by implementing the control scheme in synchronously rotating reference frame. For interfacing the PV cell to the grid a 5kVA 3phase 3 level NPC Inverter is designed and fabricated. Space vector modulation scheme is used to generate the switching pulses for the inverter. Redundant switching states of a three level inverter are judiciously chosen to obtain capacitor voltage balancing. One of the most attractive features of a multilevel inverter is that it can generate output voltages with lower value of harmonic distortion and hence filter requirement is less. For hardware implementation the control scheme is implemented with a DSP. Complete scheme is simulated in MATLAB/ Simulink and verified in a 5kVA laboratory prototype.**

Keywords— Multi level inverter; MPPT, grid connected PV system; space vector

I. INTRODUCTION

The unlimited availability of renewable sources is one of the key factors for choosing them as a source for electric power generation. The Govt. of India has initiated National Solar Mission in 2010, aiming the installation of 100 GW of PV capacity by 2022, and the addition of more than 95 GW between now and later to achieve that goal [1]. The solar power generation has already crossed 19,000 megawatts (MW) in the just-concluded fiscal year 2015-16. Solar photovoltaic systems (PV) are very popular as they are clean, inexhaustible and require less maintenance. Solar PV systems can be used in isolation or in synchronization with grid. In this paper a grid connected system is proposed which requires interfacing power electronic converters from the photo voltaic arrays to the grid. Such power electronic converters are mainly meant for two objectives [2]. One is to ensure that the PV arrays are operated at the maximum power point (MPPT) and the other one is to inject a sinusoidal current into the grid. Conventionally, these two functions are realized in two stages of power conversion, one is a DC/DC converter with MPPT control and the other one is a DC/AC power converter which is required to inject sinusoidal current to the grid at grid frequency. A two stage power conversion results in more power loss than that of a single-stage conversion. Conventionally two-stage grid connected solar PV system are used, [3-4]. Some researchers have also proposed two stage grid connected solar PV system with additional features such as active filtering, reactive power compensation etc.[5-6]. Single-stage multifunctional grid interfaced solar photo-voltaic system is also proposed in which two level inverters are used. A two-level inverter can only create two different output voltages for the load. Usually to build sinusoidal output voltage these two voltages are switched with Sinusoidal Pulse Width Modulated (SPWM) signal. Though this method is effective, but it creates harmonic distortions in the output voltage, EMI and high dv/dt. With an expected target of 100 GW generation from solar PV system harmonic injection to the grid will be a great concern. Multi-level inverters are emerging as the new breed of power converter options for high power applications with an advantage of minimum harmonic distortion and lower dv/dt. Multilevel inverter is to synthesize a value nearer to sinusoidal voltage from several levels of dc voltages to obtain a smoother stepped waveform.

A single stage grid-connected PV systems is proposed in which both the control objective i.e. extracting maximum power from the solar panel at different temperature and insolation level and injecting sinusoidal current into the grid at desired power factor are realized simultaneously in one power conversion stage. Such configuration will reduce losses and simplify the system topology.

II. PV CELL AND MPPT ALGORITHM

A. Basic PV cell

Solar panel systems, also known as solar photovoltaic (PV), capture the sun's energy using photovoltaic cells (PV cells). A PV cell is made up of minimum two layers of semiconductors that is p-type and n-type semiconductors. When the cell is illuminated, the electrons of the n-type material acquire some energy from the light photons, which helps them to break free from their atoms. If the two terminals of the p-n junction are connected to a resistive load, the electrons move from the n-type material to the load and back to the p-type material rather than going through the depletion zone. When p-type material gains electrons, it becomes negatively charged and the n-type material positively charged. This potential difference causes the electron to move back to the n-type material to balance the charges. When the electron goes back to the n-type, it acquires new energy from the sunrays and the process is repeated. This flow of electrons constitutes current in the opposite direction [7]. This process is illustrated in Fig. 1.

Large number of PV cells is connected in series to increase their voltage rating; this results in a PV module. Series or parallel

978-1-4673-8888-7/16/$31.00 ©2016 IEEE

combinations of PV modules form a solar panel and a group of PV panels result in a PV array.

B. Maximum Power Point Tracking (MPPT)

The voltage v/s current and voltage v/s power characteristics of a PV array are shown in Fig. 2. It can be observed that there is a distinctive operating point at which PV array provides maximum power. In other words, the current and voltage at which a PV array generates the maximum power is known as the Maximum Power Point (MPP). This point can be different for different environment conditions. So a dynamic tracking technique is important to ensure that maximum power is obtained from the photovoltaic arrays and this tracking algorithm is known as Maximum Power Point Tracking (MPPT) [8]. In this paper, perturb and observer method is implemented in hardware. A 24V, 5A boost converter is fabricated to experimentally validate the MPPT algorithm. A solar simulator is used to simulate the characteristics of a solar cell. Output of the solar cell is fed to the boost converter which is loaded with a variable resistive load. The output voltage and current of the PV simulator is sensed and fed to a DSP where MPPT algorithm is implemented. Output of the algorithm generates the reference voltage used to generate the switching pulses for DC-DC converter. Fig. 3(a) shows the switching pulses and Fig. 3(b) shows the input and output voltage of the DC-DC converter. A comparative study of the performance of MPPT Algorithm is tabulated in Table I.

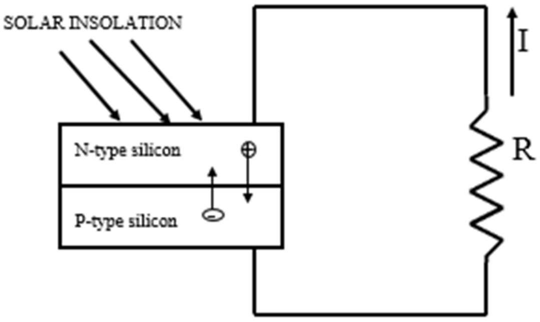

Fig. 1. Structure of solar cell

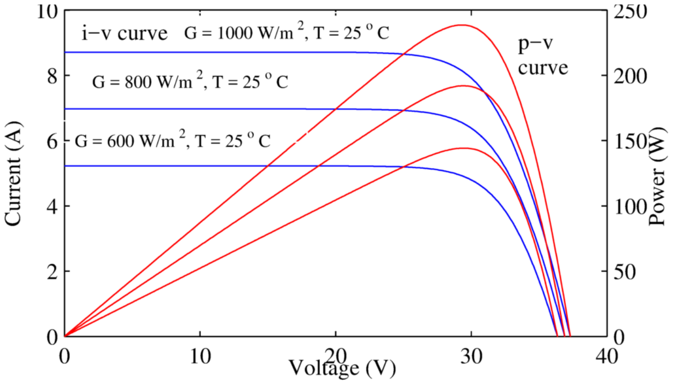

Fig. 2. Simulated i-v and p-v characteristics at different insolation and constant temperature

TABLE I. TABLE SHOWING EXPERIMENTAL RESULTS FOR VALIDATING MPPT ALGORITHM

Theoretical value		**Experimental Value**					
P_{max} (W)	**Duty ratio**	**Duty ratio**	**R_L (Ω)**	**R_{in} (Ω)**	**V_{pv} (V)**	**I_{pv} (A)**	**P_{max} (W)**
24	0.25	0.26	30.2	13.7	17.4	1.27	22.0
24	0.40	0.33	46.2	12.8	16.6	1.29	21.4
24	0.44	0.40	55.0	12.5	16.3	1.30	21.1
24	0.50	0.43	66.6	12.0	15.8	1.31	20.6
24	0.55	0.46	82.2	11.7	15.5	1.32	20.4
24	0.60	0.53	104	11.4	15.2	1.33	20.2

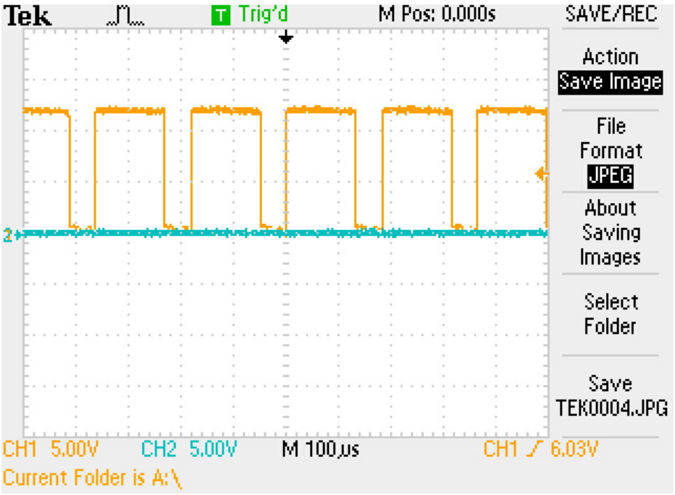

Fig. 3(a). Switching pulses obtained from dSPACE

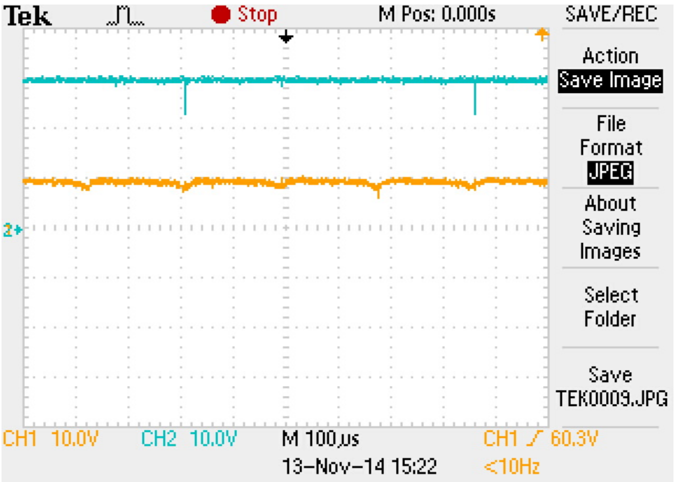

Fig. 3(b). Input and output voltage of DC-DC converter

To validate the performance of MPPT algorithms, load resistance is varied from 30Ω to 104Ω. Even though the output load resistance is varied from 30 Ω to 104 Ω the input resistance of boost converter is approximately constant. It can be concluded that the solar array simulator is providing the maximum power irrespective of the load changes.

III. GRID CONNECTED INVERTER

A. Neutral Point Clamped Inverter

The neutral point clamped three-level inverter topology [9] is proposed in this paper. This class of inverters can generate an output voltage which is closer to a sinusoidal and hence an improved Total Harmonic Distortion (THD) profile of its output voltage waveform is obtained. A simplified power circuit of three-level NPC inverter is shown in Fig. 4. Each of the three phases of the inverter shares a common dc bus, which has been subdivided by two capacitors into three levels. The voltage across each capacitor is V_s, and hence the voltage stress across each switching device is limited to V_s whereas the total DC bus voltage is $2V_s$ [10]. Three output voltage levels are possible for one phase of the inverter with respect to the midpoint of the capacitor. Each phase has two complementary switch pairs such that switching on one of the switches of the pair demands the other complementary switch to be switched off. The complementary switch pairs for phase A are (Sa1, Sa3) and (Sa2, Sa4).

Carrier based PWM has a major limitation that it requires N-1 number of isolated DC sources. The solar array can be divided into two individual DC sources but which does not ensure that they will produce equal voltage all the time. If the voltages of individual DC sources are not same, then THD will be high and the performances of the system will reduce. Space vector modulation scheme is used in this paper to split one single DC source into two equal DC Bus.

B. Space Vector Modulation

In a three phase three level NPC inverter there are $3^3 = 27$ switching states of the inverter as indicated in the space vector diagram shown in Fig.5. The hexagon is divided into 6 sectors identified by A, B, C, D, E and F and each of the sectors is subdivided into four regions identified by 1, 2, 3 and 4. The principle of SVPWM method states that the reference voltage V_{ref} is approximately calculated by the combination of three adjacent vectors during a sampling period T_s. It is seen from the vector diagram of a three-level inverter that there are redundant states for all regions. These redundant states are appropriately chosen to control the direction of current through the capacitor and thus voltage across each capacitor is controlled [11].

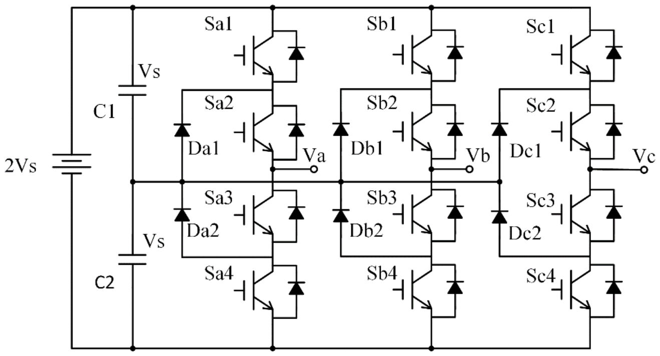

Fig. 4. Topology of a three-phase three-level NPC MLI

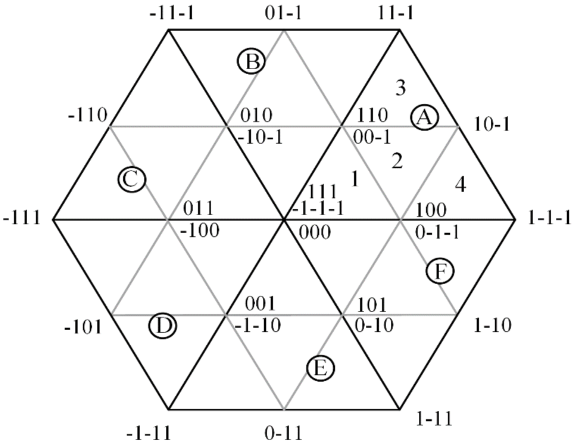

Fig. 5. Space vector diagram of 3 level inverter

Fig. 6(a). shows that the waveform of the voltage across capacitors in a three- level neutral point clamped inverter using carrier based PWM scheme. Results show that there is a variation of ±15% in the capacitor voltage. In space vector modulation scheme switching patterns are chosen such that current through the capacitor are alternated. Hence, the capacitor voltage fluctuation is less. Fig. 6(b). shows that variation is reduced to approximately ±1.5% by implementing proper switching patterns using space vector modulation technique.

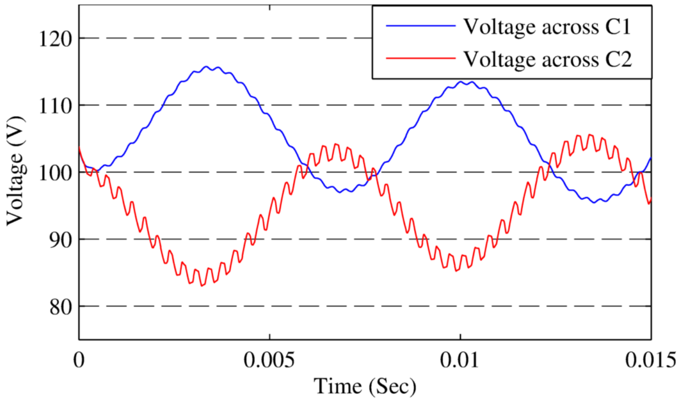

Fig. 6(a). Capacitor voltage variation for three level NPC inverter: Carrier based modulation

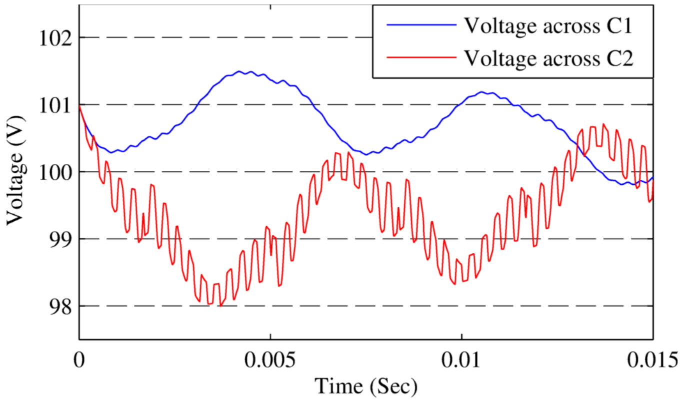

Fig. 6(b). Capacitor voltage variation for three level NPC inverter: space vector modulation

IV. CONTROL SCHEME

The control scheme is implemented in synchronously rotating reference frame [12]. In the synchronous rotating frame, the active and reactive powers of a three-phase grid-connected VSI are given by

$$p = \frac{3}{2}\left(v_d i_d + v_q i_q\right) \qquad (1)$$

$$q = \frac{3}{2}\left(v_d i_q - v_q i_d\right) \qquad (2)$$

Fig. 7 shows the control scheme for decouple control of active and reactive power [13]. The grid voltages and line currents are transformed into $dq0$ reference frame and are used as feedback variables for the controller. The MPPT scheme will set the voltage reference for the outer loop (voltage control loop). In order to adjust the DC voltage at a fixed value, the error $e = (V_{dc}^{*} - V_{dc})$ is is passed through a PI-type compensator. The output of the compensator sets the reference for the quadrature axis current (i_q) and hence the active power. It is desirable to operate the converter at unity power factor and hence i_d reference is set to zero, if the reactive power control is not required. These references i_d and i_q are compared with measured value of i_d and i_q and the error is passed through a PI compensator to generate V_d and V_q. Decoupling terms are added to obtain decoupled control. V_d and V_q are transformed back into abc co-ordinates and these are used as reference waveforms in the PWM generator block. The PWM generator block provides pulses to the three-level NPC inverter. The total system is simulated in MATLAB Simulink and implemented in a hardware using dSPACE 1104 board. The experimental setup is shown in Fig. 8.

Fig. 9 shows the flow of 1550 W of active power and 470 VAR of reactive power from the system to the grid (simulation results). In Fig. 10 the active power is kept constant and reactive power is changed to 920 VAR. It is seen that changing the reactive power does not change the active power flow and hence independent control of active and reactive power is obtained. This result has been obtained for a solar insolation of 800 W/m^2.

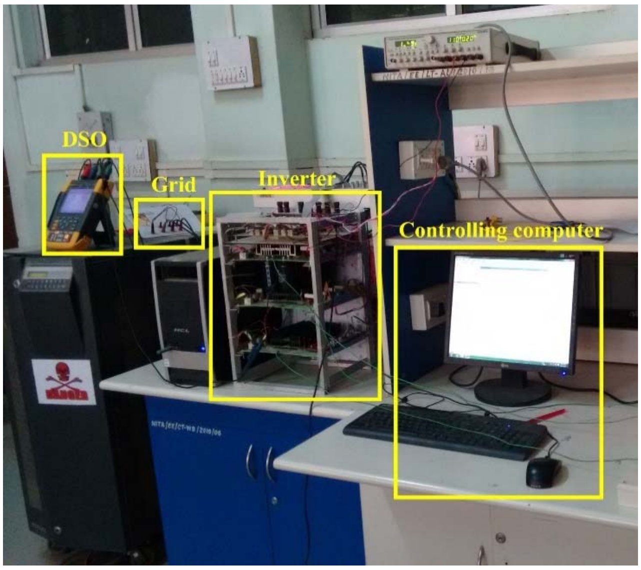

Fig. 8. Photograph of experimental setup

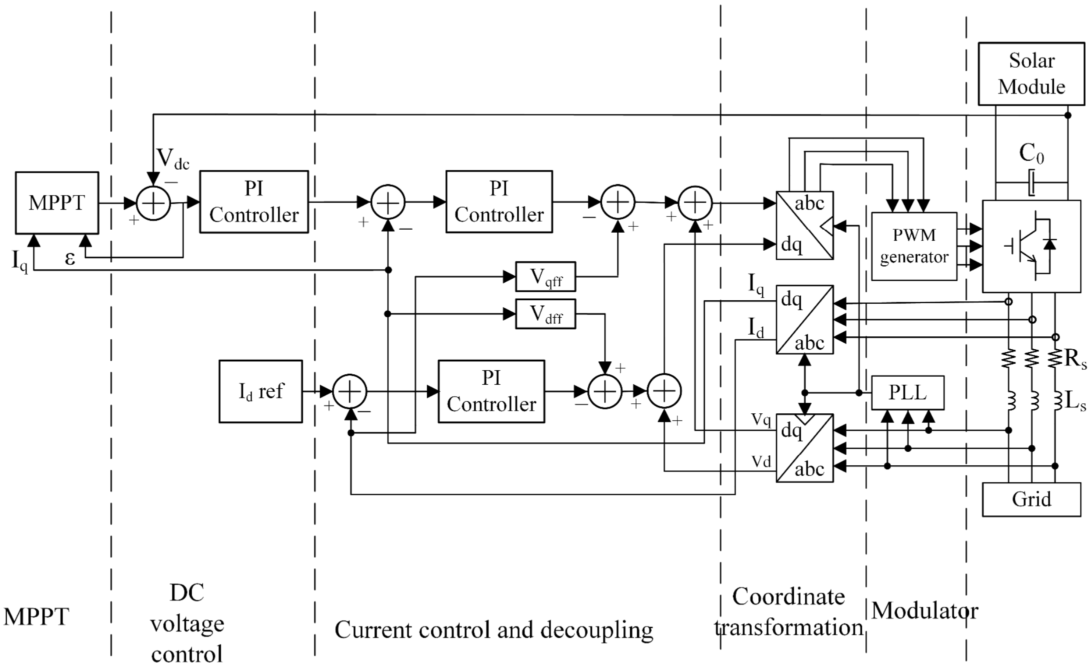

Fig. 7. Control Scheme

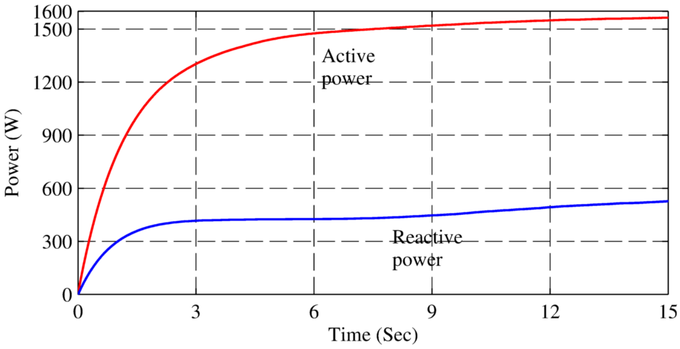

Fig. 9. Flow of active and reactive power from inverter to grid

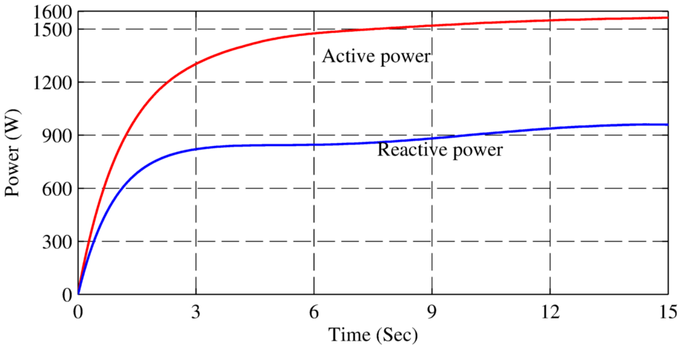

Fig. 10. Flow of active and reactive power from inverter to grid

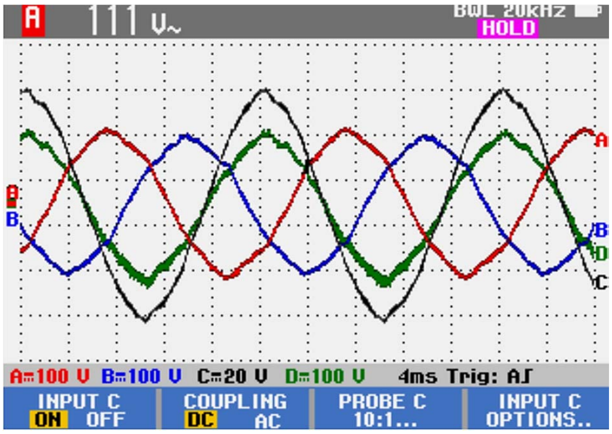

Fig. 11. 3 phase inverter voltage (Red Blue Green) Synchronized with grid voltage (Black)

V. EXPERIMENTAL RESULTS

A dSPACE 1104 board is used to implement the proposed scheme in hardware. The dSAPCE board supplied from the manufacturer cannot generate 6 independent PWM signal. The firmware of dSPACE is modified to generate 6 independent PWM signals. Complementary signals with a dead time of 4µsec is generated using an external circuit. Grid voltage is stepped down using a transformer and is fed into the DSP. DC link voltage is sensed using an isolated voltage sensor. Current is sensed using a bipolar Hall Effect current sensor. A PLL is designed and implemented in dSPACE where three phase quantities are converted to synchronously rotating reference frame. Control scheme as discussed previously is used to obtain independent control of active and reactive power. Output voltage thus generated is synchronized with the grid. Fig. 11. shows the three phase voltages (red, blue and green). In Fig. 11 it is also seen that grid voltage (black) is synchronized with the inverter voltage (green).

Reference value of reactive component is set at zero. Maximum power point tracking algorithm sets the reference value of DC link voltage and the voltage control loop sets the reference for the active component of current. Experimental results as obtained from dSPACE control desk is shown in Fig. 12. Active power transfer between two sinusoidal voltage sources takes place when there is phase shift be two voltage source. Power flows from the leading source to the lagging source. Fig. 13 shows the grid voltage (red) and inverter voltage (green). It can be seen that grid voltage is lagging the inverter voltage and hence it can be concluded that power is flowing from inverter to the grid.

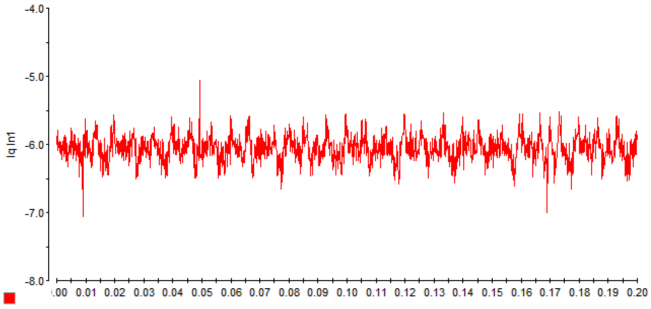

Fig. 12(a). Iq as obtained in dSPACE control desk

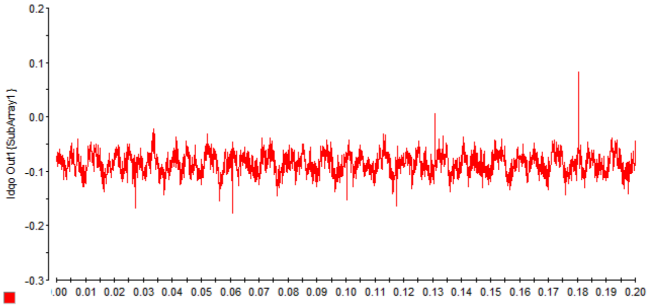

Fig. 12(b). Id as obtained in dSPACE control desk

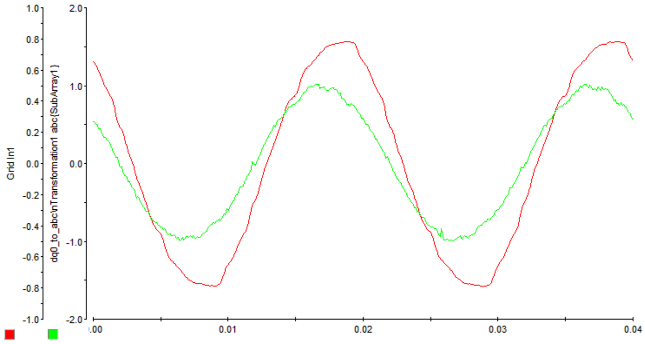

Fig. 13. Grid voltage (red) and Inverter voltage (green) in dSPACE control desk

A 5KVA 400V, 3 phase 3 level NPC inverter is fabricated. Space vector modulation scheme as discussed in section III (B) is used to generate the gate signal for the reference voltage signal obtained above. Output of the inverter is filtered by a 10% inductive filter. Experimental results of voltage and current wave form is shown in Fig. 14.

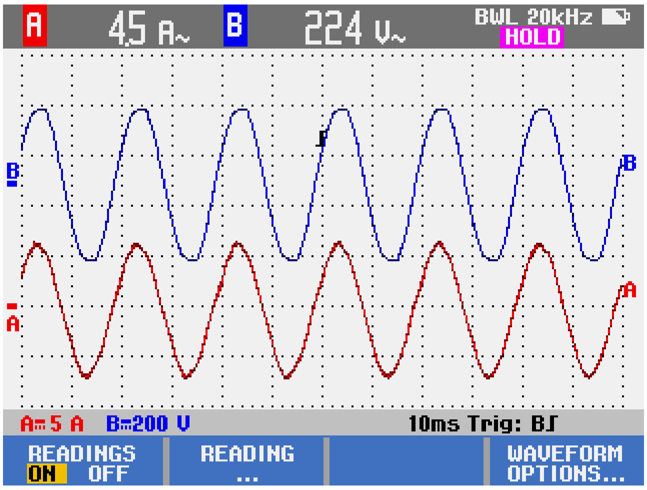

Fig. 14. Voltage (blue) and Current (red) waveforms.

VI. CONCLUSION

A single stage grid connected solar PV system is proposed in this paper. Three-level 5 kVA NPC inverter is used to transfer the power generated by the PV cell to the grid. Since a multilevel topology is used the filter requirement is greatly reduced. A 10% inductor in series with the inverter is used as a filter circuit. At a switching frequency of 10 kHz the THD of the current waveform is found to be 1.8% which is as par IEEE Std. 519 [14]. The control scheme is implemented in a synchronously rotating reference frame. For implementation of the scheme in hardware a dSPACE 1104 board is used. Experimental results of grid synchronization and independent control of active and reactive power are presented in this paper. The scheme is successfully implemented and the results are found to be satisfactory.

VII. AKNOWLEDGEMENT

This paper is a part of the project titled “Multilevel Inverter based Single Stage Grid Connected Solar PV system” funded by the Department of Electronics and Information Technology (DeitY) under NaMPET II project. Authors would like to thank the sponsoring authority for supporting the research.

VIII. REFERENCES

[1] “India unveils annual solar goals towards 2022 target”, [Online]. Available: http://www.pv-magazine.com/news/details/beitrag/india-unveils-annual-solar-goals-towards-2022-target_100020619/#ixzz4C6KHlMtQ [Accessed 17th Aug 2015].

[2] Marcelo G. Molina, and Luis E. Juanico, “Dynamic modeling and control design of advanced photovoltaic solar system for distributed generation”, Journal of Electrical Engineering: Theory and Applications, Vol.1, Issue. 3, pp. 141-150, 2010.

[3] "Power Sector at a Glance ALL India | Welcome to Ministry of Power," [Online]. Available: http://powermin.nic.in/power-sector-glance-all-india. [Accessed 5 April 2016].

[4] Lin Chen; Amirahmadi, A.; Qian Zhang; Kutkut, N.; Batarseh, I., "Design and Implementation of Three-Phase Two-Stage Grid-Connected Module Integrated Converter," in Power Electronics, IEEE Transactions on , vol.29, no.8, pp.3881-3892, Aug. 2014.

[5] Singh, B.; Jain, C.; Goel, S., "A UVT based control for single-stage grid interfaced SPV system with improved power quality," in Power India International Conference (PIICON), 2014 6th IEEE , vol., no., pp.1-6, 5-7 Dec. 2014.

[6] Jain, S.; Agarwal, V., "A Single-Stage Grid Connected Inverter Topology for Solar PV Systems With Maximum Power Point Tracking," in Power Electronics, IEEE Trans.,vol.22, no.5, pp.1928-1940, Sept. 2007

[7] “Photovoltaics”, [Online], Available : http://www.engineering.com/SustainableEngineering/RenewableEnergyEngineering/SolarEnergyEngineering/Photovoltaics/tabid/3890/Default.aspx

[8] Y. Chen and K. Ma-Smedley, “A cost-effective single-stage inverter with maximum power point tracking,” IEEE Trans. Power Electron., vol. 19, no. 5, pp. 1289–1294, Sep. 2004

[9] H. -P. Krug, T. Kume, M. Swamy,“Neutral-point clamped three-level general purpose inverter - features, benefits and applications”, in Power Electronics Specialists Conference, 2004. PESC 04.2004 IEEE 35th Annual (Volume:1), doi: 10.1109/PESC.2004.1355764.

[10] Maske Ashadeep M, Mrs. Bachwad Manjusha.R, “Implementation of MOSFET based diode clamped 3-level inverter”, in International Journal of Innovations in Engineering Research and Technology [IJIERT], ISSN: 2394-3696, VOLUME 3, ISSUE2, Feb.-2016.

[11] George Alin RADUCU, “Control of Grid Side Inverter in a B2B Configuration for WT Applications”, Master Thesis, Department of Power Electronics and Drives , Institute of Energy Technology, Aalborg University, 2008.

[12] IEEE Recommended Practices and requirement for Harmonic Control on Electric Power System, IEEE Std. 519, 1992.

[13] A.C.Sunny,B.Das,P.R.Kasari,A.Sarkar,S.Bhattacharya,A.Chakrabarty, “SVPWM based decouple control of active and reactive power for single stage grid connected solar PV system”, IEEE Power India international conference (PIICON) ,November,2016.