ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

(An ISO 3297: 2007 Certified Organization)

Website: www.ijareeie.com

Vol. 6, Issue 6, June 2017

Aalborg Grid-Tied Inverter for Photovoltaic Applications

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ABSTRACT: Renewable resources are gaining importance in our day today life because of ever growing demand for energy. In this scenario their is a need to integrate grid with the renewable sources also. This was made possible with the grid tie inverters which is gaining importance nowadays. But the output of these resources are variable in nature. To transfer this kind of dc energy into the grid, a two- or three-stage inverter may be required as the power interface, especially for the VSI-based system. If all the power stages work at high frequency, the efficiency of the inverter will be inevitably affected. In order to decrease the switching frequency, many interesting inverters have been proposed and the basic idea is to ensure that only one of the power stages of the system works at high frequency. In this paper a new type of dc/ac single phase transformer-less inverter topology has been investigated which is a buck and boost converter based inverter, where only one power stage work at high frequency and minimum voltage drop across the inductor is achieved their by improving both reliability and efficiency. In this thesis a novel inverter is investigated for photovoltaic applications. Which is abbreviated as Aalborg inverter. A simulation model of the inverter with photovoltaic source is developed in MATLAB SIMULINK and corresponding modes of operations and performance are verified and grid injected current THD was within the prescribed standards.

KEYWORDS: Renewable sources, transformer-less inverter , buck-boost, THD

I.INTRODUCTION

The number of distributed generation (DG) units connected to the power network has been continuously increasing during the last years[1]. Although this fact has provided significant economical benefits for both utility companies and customers, it has also led to more demands regarding the interconnection of DGs with the grid because they directly affect the stability of the power network. Therefore, the operation and control of grid-tied inverters, that link the DG units with the utility grid, are very important and should be maintained inside some given limits under both normal and abnormal conditions of the grid.The grid tied inverters can be classified into voltage-source inverters (VSI) and current-source inverters (CSI), where the VSI is the mostly used converter. One of the reasons is that the VSI does not need a large inductor as the energy storage element, while the CSI should adopt a higher inductor in order to keep the dc current constant for a proper modulation. The research related to CSI mainly focus on the control. So far, how to decrease the total dc-link inductance for CSI is a challenge, especially in the low voltage and three-phase application area.

As the VSI is a step-down inverter and the CSI is a kind of step-up inverter, the *Z*-source inverters (ZSI) [2]was proposed in order to fully utilize the normal character of VSI and CSI and the minimum semiconductors were used with the combined features of the step-down and the step-up converters. However, compared to the CSI or the VSI, the ZSI has two extra inductors in the power loop, which may cause effect to the efficiency. The control difficulty is also a disadvantage in the *Z*-source impedance.

In the renewable power generation system, the input dc voltage of the converter may vary greatly. For example, the output dc voltage of a solar panel will change a lot under different temperature conditions. To transfer this kind of dc energy into the grid, a two- or three-stage inverter may be required as the power interface, especially for the VSI-based system. If all power stages work at high frequency, the efficiency of the inverter will be badly affected. In order to decrease the switching frequency, many interesting inverters have been proposed and the basic idea is to ensure that

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Vol. 6, Issue 6, June 2017

only one of the power stages of the system works at high frequency. The main output filter of these inverters should be designed to satisfy the harmonic needs in the "buck" mode, especially when the dc input voltage is higher than the amplitude of the grid voltage. Thus, when they work in the "boost" mode, an over filtering may take place due to that the output filter is a *CL–CL* filter. Since the excessive inductance is in the power loop, extra conduction losses will be present and the grid current is not easy to control as well.

In this paper, a new type of "buck in buck, boost in boost" grid-tied inverter is investigated, which is abbreviated as Aalborg inverter[3] and the operating principle is illustrated through a half-bridge inverter with the equivalent circuits in the different working stages. Then,here the Aalborg inverter is investigated for solar application. Finally, simulations and experiments are given to verify the theoretical analysis and the principle of operation.

II.SYSTEM MODEL

The conventional three-stage inverter[4] was adopted in order to achieve higher efficiency with devices of MOSFET. One advantage of the inverter is that with the input *LC*-filter, the current ripple of dc input source is lesser than that of the conventional VSI. Note that due to the energy balance, a higher input smoothing capacitor should be inserted and its capacitance is mainly dependent on the ripple current at the double line frequency, so this *LC*-filter has small help to decrease the total input capacitance.

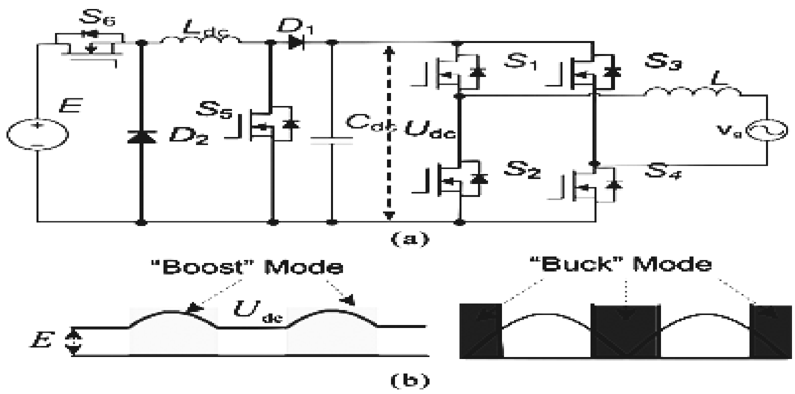

Fig.1 Proposed "full-bridge" aalborg inverter: (a) topology and (b) operating principle.

Since the input dc *LC*-filter of the conventional three-stage dual-mode time-sharing inverter may not be so necessary, a new family "boost in boost, buck in buck" inverter is proposed and abbreviated as the Aalborg Inverter. A "full-bridge" three- stage inverter is proposed and shown in Fig. 1. Liken the conventional three-stage dual-mode time-sharing inverter, only one power stage works at high frequency and the output power stage works at the line frequency. Compared with the conventional inverter topology, the main difference is that the physical position of "boost" stage and "buck" stage has been interchanged and one inductor can be saved. So, in theory, the related conduction power loss is also reduced and a higher efficiency can be obtained.

Here in this paper half bridge Aalborg inverter is taken into investigation. Circuit diagram of the half bridge Aalborg inverter is given in fig.2. Basic operation of aalborg inverter is based on the comparison between the instantaneous grid voltage and the input voltage. Based on that a buck and buck boost modes are selected.

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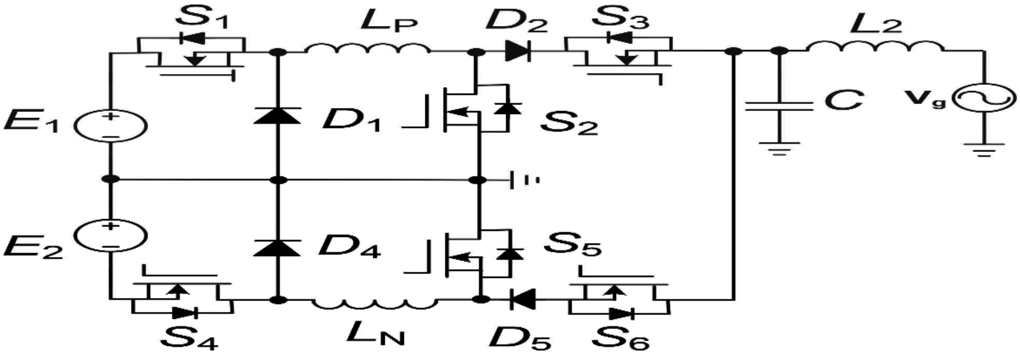

Fig 2. Aalborg "half-bridge" inverter**.**

III.OPERATING MODES OF AALBORG INVERTER

Half bridge inverter consist of two input sources E_1 and E_2 , which are currently taken as pure voltage sources in order to explain the working of the system. Vg stands for the grid voltage. Two modes of operations are there , a buck mode and a buck boost mode.

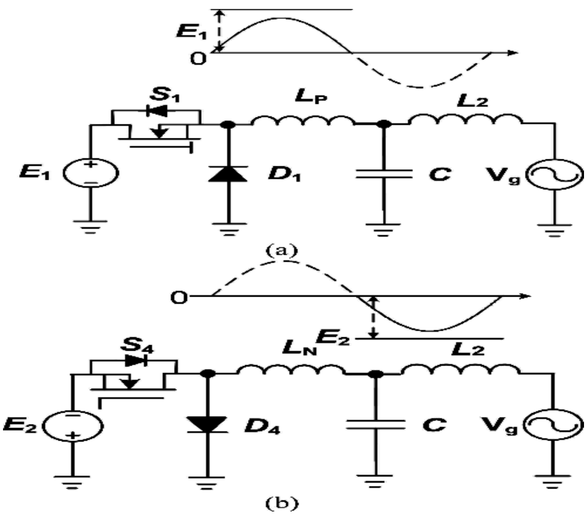

Fig.3 Equivalent circuits when E_1 or $E_2 \geq Vg_A$

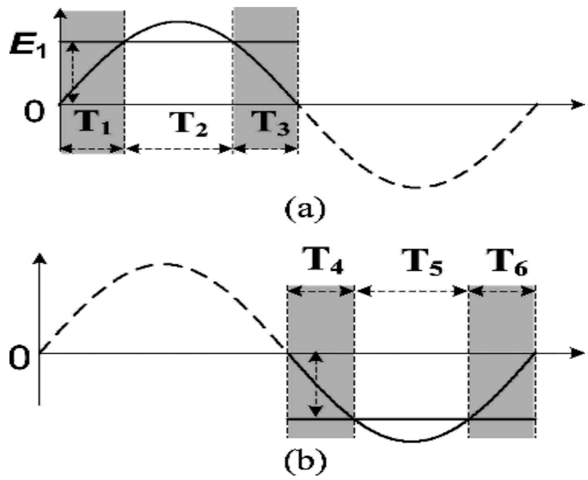

Fig. 4 Sequence when E1 < Vg_A

1) $|E_1|$ or $|E_2| \geq V_{g_A}$ *:* When the input dc voltage (E_1 , E_2) is larger than V_g , the amplitude value of grid voltage, the equiv-alent circuits are as shown in Fig. 3. As shown in Fig. 3(a), during the positive period of the grid voltage, S_3 is ON, S_2 is OFF, S_1 works at high frequency in order to achieve a sinusoidal grid-injected current, and E_1 provides the total energy. In the same way, as shown in Fig. 3(b), during the negative period of V_g, S_6 is ON, S_5 is OFF, S_4 works in the high frequency mode in order to keep the grid-injected current sinusoidal, and E_2 delivers the total energy. The inverter works as a VSI connected to the grid through an *LCL*-filter.

2) $|E_1|$ and $|E_2| < V_g$ *:* When the input dc voltage (E_1 , E_2) is lower than the amplitude of grid voltage (V_{g_A}), the control becomes a little bit more complicated. Fig. 4 shows the working sequence of the proposed "half-bridge" inverter, when the amplitude of the input dc voltage is lower than the ac grid voltage, where the sequence can be separated into

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six parts during a full line frequency period. During T_2 and T_5 boost operation carried out and during other period buck operation similar to first mode happens.

During T_2, S_1 and S_3 are ON, S_2 works with high frequency, and the rest of the switches are OFF.It can be seen that it works like a pure boost converter with a *CL*-filter connected to the grid. If the current of the boost inductor can be fully controlled, this equivalent circuit can be seen as a CSI. Similar operations carried out during T_5 .Fig.5 shows the simplified control diagram. Control equations where derived from the indirect current control method [5]. Then, the parameter design is similar to the conventional VSI with the *LCL*-filter [6]. Parameter for the 1000 W system are listed in the table. 1.

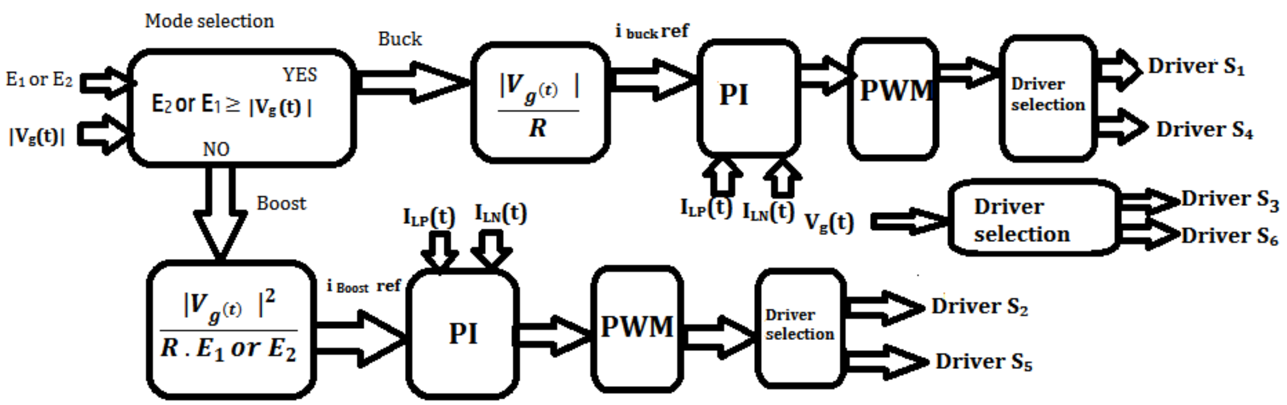

Fig. 5 simplified control diagram of Aalborg inverter.

parameters	L_2	C	L_p & L_n	F_{s}(switching frequency)
unit	600 µH	2 µF	600 µH	40 kHz

Table 1. designed parameters for 1 kW inverter

IV.MODELLING OF PV ARRAY

A. PV Array Model

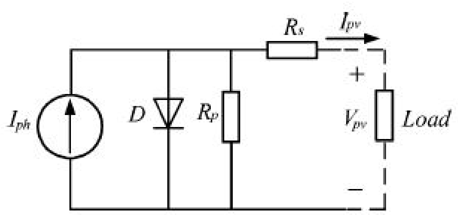

Fig 6. Equivalent circuit of solar cell

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Fig. 6 shows the equivalent circuit of a PV panel with a load.The PV module is modeling is done by considering it as a current source in parallel with an antiparallel diode. Taking into account the internal losses series and shunt resistances are also added. The modeling is done as per the equations in [6]. Table. 2 shows the designed PV array parameters.The relevant equations are given below.

By applying Kirchhoff's law,

$$I = I_{ph} - I_d - I_p \qquad (1)$$

Where I_{ph} is the photocurrent
I_d is the diode current and
$I_p$is the current leak in the parallel resistor

But $$I_d = I_0 \left[\exp \left(\frac{V + IR_s}{a} \right) \right] \qquad (2)$$

Where $I_{0\ is}$ the reverse saturation current
R_s is the series resistance
a is the modified ideality factor given by

$$a = \frac{AkT_c N_s}{q} \qquad (3)$$

Where A is the diode ideality factor (0.3 for Si)
k is the Boltzmann constant (1.381×10^{-23}J/K)
N_s is the number of series connected cells
T_c is is the cell temperature
q is the electron charge (1.602×10^{-19}C)
R_p is the parallel resistance

$$I_p = \frac{V + IR_s}{R_p} \qquad (4)$$

Cells per module (Ncell)	60
Open circuit voltage of one module	42
Short-circuit current	9.19
Voltage at maximum power point	36
Current at maximum power point	7.96
No. of parallel strings in array	1
Series-connected modules per string	5

Table 2. designed parameters for 1 kW PV array

V. SIMULATION AND DISCUSSION

In the simulation model two voltage sources were replaced by PV array. Simulation model is shown in fig.7. Here two PV array of same ratings are needed for the proper working of inverter. Simulations were done for different irradiations and sinusoidal grid voltage and sinusoidal grid injected voltage were obtained. PV array with constant MPPT is done. Different operating modes were selected based on the instantaneous grid voltage and PV panel output. Two operating modes are a buck and buck-boost mode. Six switches are there only one operates at high frequency at a time.

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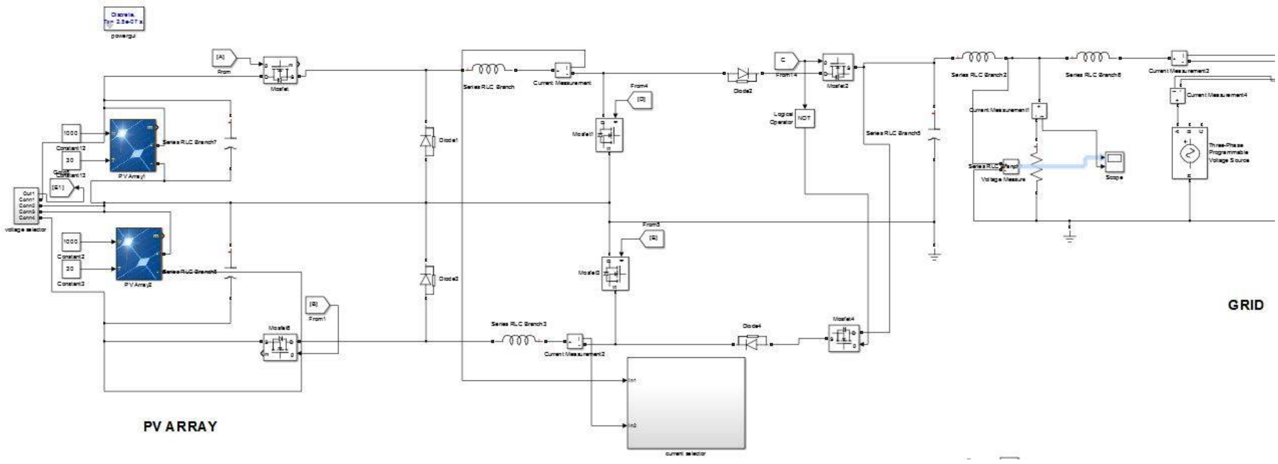

Fig. 7 Simulation model of Aalborg inverter with PV array

Fig. 8 shows the control diagram of the inverter based on which each switches are switched. Separate boost and buck control are there which have different PI controller. Pulses are generated at 40kHz frequency based on the comparison between the instantaneous grid voltage and solar voltage. From this control signal gate pulses are given to the inverter.

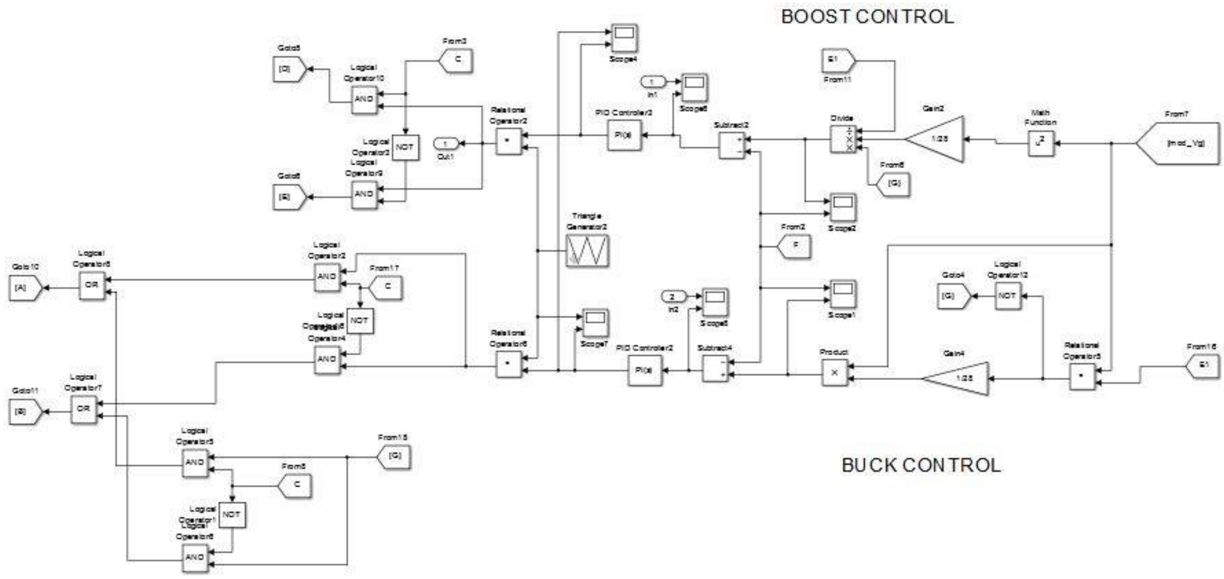

Fig. 8 Control diagram of the inverter

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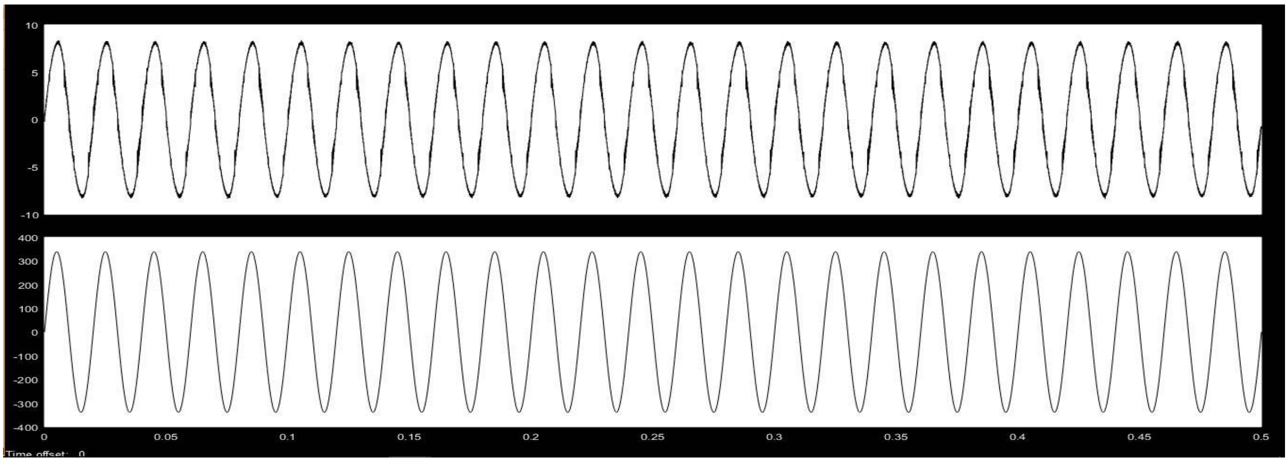

Fig .9 Output current and voltage waveform of the proposed system operating at irradiation=1000 W/m^2 & Temp erature=30^0

Fig.9 shows the grid injected current and voltage waveforms when the irradiation was 1000 W/m^2,that is at maximum output power. Here THD was also below 5% , so the IEEE standards[8] for grid injections were satisfied. Similarly Fig.10 shows the grid injected current and voltage waveforms when the irradiation was 500 W/m^2 .During this operation also THD was within the prescribed limit. So system with PV array was working perfectly and good output current quality is obtained when integrating with grid.

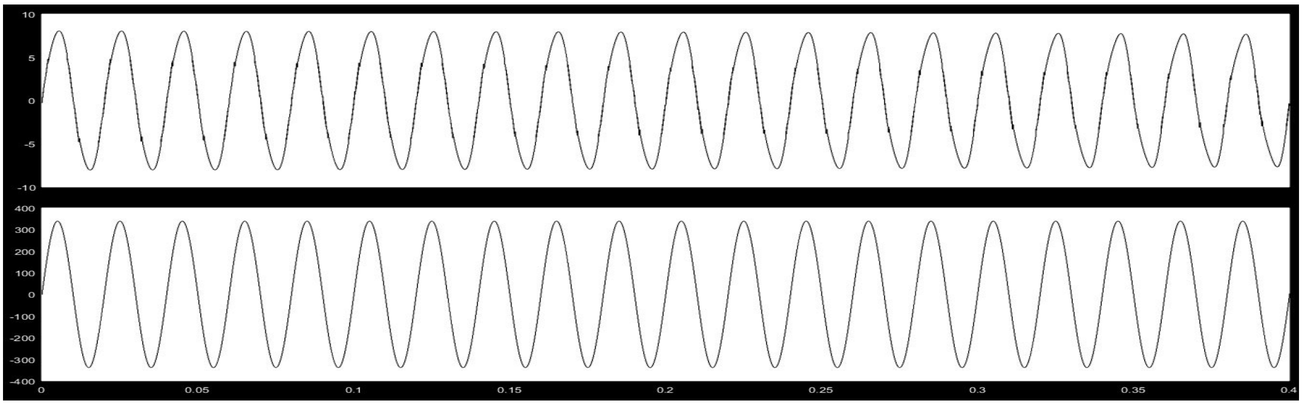

Fig .10 Output current and voltage waveform of the proposed system operating at irradiation=500 W/m^2 & Temperature=30^0

VI.CONCLUSION

In this paper Aalborg inverter, which is a novel ”buck in buck, boost in boost” inverter is investigated. This inverter works based on the comparison between instantaneous grid voltage and varying input dc voltage. Based on the comparison buck and boost modes were operated. A 1000 W PV array integrated with the inverter and its performance during grid tied application were analyzed for different irradiation. Inverter shows good control and performance during the operation. THD level of the grid injected current were below 5%. Still the Aalborg inverter lacks better

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isolation and need two PV array of same rating for positive and negative half cycle. Which can be considered as drawbacks , which need attention.

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