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* *Vol. 5, Special Issue 2, March 2016*

National Conference on Future Technologies in Power, Control and Communication Systems (NFTPCOS-16)

on 10, 11 and 12th March 2016

Organised by

Dept. of EEE, College of Engineering Perumon, Kollam, Kerala – 691601, India

# A New Delta Inverter System for Grid Integration of Large Scale Photovoltaic Power Plants

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**ABSTRACT**: This paper presents a new grid-connected delta inverter system (DIS) for large scale photovoltaic (PV) power systems. The delta inverter achieves DC to three phase AC inversion by using only three power semiconductor devices instead of six devices as in a conventional full bridge three phase inverter. This reduction in the number of switching devices contributes to higher power density for PV energy conversion systems and potentially, an increase in reliability and lifetime. Two configurations of the proposed DIS are discussed in the paper:

(a) A large scale PV field grouped into three DC voltage blocks, each block connected to a front end MPPT boost converter which is connected to a 3-switch DIS interfaced to the utility-grid;

(b) PV field connected to a flyback converter with high frequency isolation, followed by a DIS interfaced to utility grid. Advanced pulse width modulation (PWM) techniques are investigated for DIS for operation under unbalanced condition. A design example and simulation results of a 30 kW DIS based PV plant are presented to explore the feasibility of such a system. Experimental results on a scaled down laboratory delta inverter system are shown to demonstrate the operation of this topology.

**KEYWORDS:** delta inverter system, utility grid, photovoltaic power plants, sine pulse width modulation.

## I.INTRODUCTION

Less than 1% of the global electrical energy consumption comes from photon-to-electron conversion. But the installation of photovoltaic (PV) power stations has been increasing tremendously both on the residential scale and at the commercial / utility scale. Solar PV, at the time of publication, still has a long way to go in terms of financially competing successfully with conventional electricity. It has been established that reducing the inverter equipment and maintenance costs is essential to make solar energy more cost competitive. To achieve this goal, new methods to efficiently convert DC power to AC with low cost and high reliability are required. Different topologies and techniques to interface large scale PV plants to the utility grid have been studied in.

Reduced semiconductor devices and components count reduce failure rates and maintenance costs over the lifetime of a PV inverter. The architecture proposed in this paper is a delta inverter based system which utilizes three DC voltage sources and three semiconductor devices to produce a three phase output. The delta inverter was first introduced primarily for adjustable speed drives. Pulse width modulation (PWM) techniques for control of the delta inverter were developed. The delta inverter did not find acceptance in practice primarily due to the limitation of requiring three separate DC sources. But the need for more efficient PV topologies opens new possibilities for the delta inverter. The proposed delta inverter system (DIS) architectures for PV applications have the following advantages:

- DIS employs three switching devices which results in fewer components in the overall system (gate drive circuitry, heat sinks, busbars, fuses, etc.). This leads to higher reliability due to reduced number of power switching semiconductor devices which in turn results in higher lifetime of inverter and lower maintenance costs.
- Advanced PWM techniques proposed in this paper enable operation of DIS even while the insolation levels are unbalanced for the three PV sources.

However, the DIS suffers from some disadvantages such as the requirement for higher switch voltage ratings up to $3 \cdot V_{dc}$; and the requirement for three isolated DC voltage sources. This paper proposes two DIS architectures within the context of PV applications, since isolated PV arrays could produce isolated DC voltage sources, overcoming the latter of the above two disadvantages.

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## II.OPERATION OF DELTA INVERTER

The delta inverter as shown in Fig. 1, consists of three branches (a, b and c) connected in delta fashion and each branch consists of an isolated DC voltage source and a forward blocking semiconductor switch. The line-to-line output voltages are directly modulated by switches $S_{ab}$, $S_{bc}$ and $S_{ca}$. In order for the DIS to operate properly, two and only two switches must be closed at any time. In the case that only one switch is **ON** imbalances in the line currents occur and all three switches being **ON** results in a catastrophic short circuit through the DC voltage sources. If only two switches are closed at all times, there are 3 possible states, which are shown in Fig. 2.

The PWM line-to-line output voltages that are produced in each of the different states are given in Table I. It can be seen that in any given state, the sum of the three line-to-line voltages is zero, in other words, the output voltage is balanced. Because the negative voltages are twice the magnitude of the positive voltages, as seen from the table, in order to obtain a zero average value for one period, the modulation mark-to-space ratio must be set to 2:1.

The PWM switching strategy chosen was a single-edge modulation scheme. A positive slope sawtooth carrier and a negative slope sawtooth carrier are used to modulate three phase sinusoidal reference signals displaced by120°.When the modulating signal has a positive slope, the negative-slope carrier is used and when it has a negative slope, the positive-slope carrier is used.

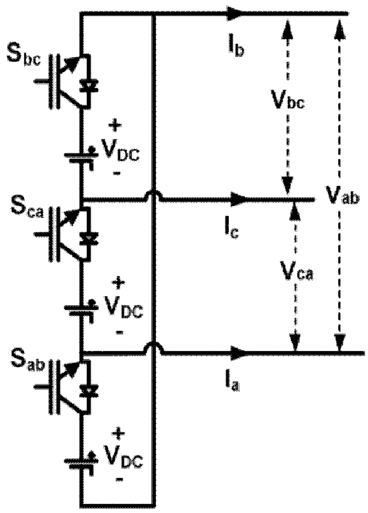


Fig. 1: Three phase delta inverter, first proposed in [9].

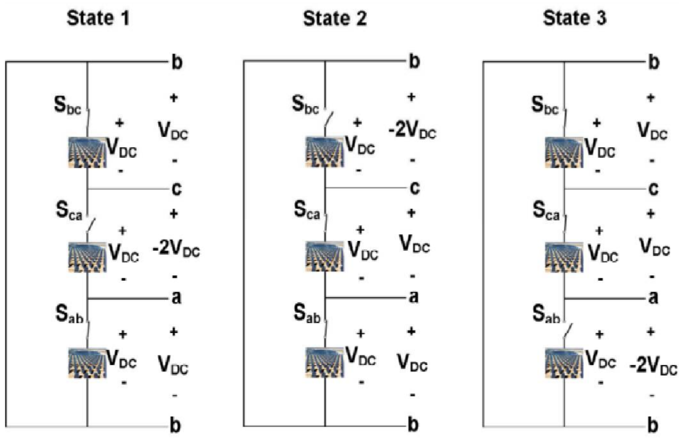


Fig. 2: Three possible states of switch combinations in a delta inverter for PV application. At any time, two switches of the inverter are **ON**. It is ensured that the sum of the three switching functions $S_{ab}+S_{bc}+S_{ca} = 2$ at all times.

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TABLE I: PWM LINE-TO-LINE OUTPUT VOLTAGES FOR THREE SWITCHING STATES IN A DIS

| State | $V_{ab}$ | $V_{bc}$ | $V_{ca}$ |
|---|---|---|---|
| 1 | $V_{DC}$ | $V_{DC}$ | -2 $V_{DC}$ |
| 2 | $V_{DC}$ | -2 $V_{DC}$ | $V_{DC}$ |
| 3 | -2 $V_{DC}$ | $V_{DC}$ | $V_{DC}$ |

The generated PWM signal is applied to the gate drive circuitry only for the most-positive 240° of the modulating signal. For the remaining 120°, the switch is simply turned

**ON** to satisfy $S_{ab}+S_{bc}+S_{ca}$ = 2, akin to a freewheeling function. Fig. 3 shows the carrier control scheme for $S_{ab}$. With this control scheme the line-to-line output voltages form a three phase balanced set. Fig. 4 shows the instantaneous line-toline voltage $V_{ab}$ produced by a delta inverter and its fundamental component.

*A.Advanced PWM Technique under Unbalanced Operation*

When the insolation levels of the three PV arrays connected to a delta inverter change and become asymmetric, the controller uses advanced PWM techniques to produce balanced three phase output voltages from thee unequal DC voltage sources during the transition period. The line-to-line instantaneous PWM output voltages of the DIS under unbalanced operation are given by:

$$-\left|V_{DC,bc}\right|-\left|V_{DC,ca}\right|\le V_{ab}\le V_{DC,ab} \quad (1)$$

$$-\left|V_{DC,ab}\right|-\left|V_{DC,ca}\right|\le V_{bc}\le V_{DC,bc} \quad (2)$$

$$-\left|V_{DC,ab}\right|-\left|V_{DC,bc}\right|\le V_{ca}\le V_{DC,ca} \quad (3)$$

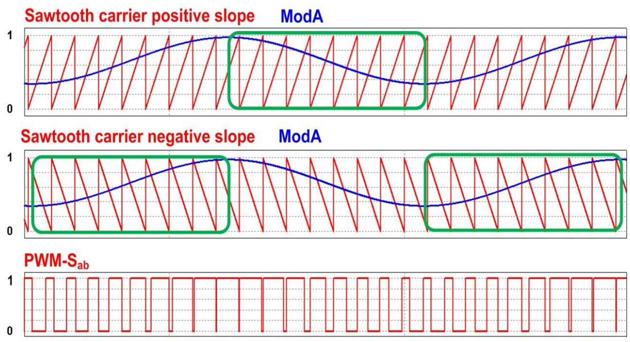


Fig. 3: Positiveslope sawtooth Carrier chosenduringnegative

slope of modulating the sum of ModA-produced-PWM and the NAND logic of PWMs produced by ModB and ModC. unction and vice-versa. PWM-$S_{ab}$ is This is done to ensure that only two switches are **ON** at any time.

## III.PROPOSED NEW DIS FOR PV ENERGY SYSTEMS

### *A. DIS with Front End Boost Converter*

The first DIS configuration proposed for PV grid integration utilizes a front-end boost converter for each phase which performs maximum power point tracking (MPPT). The proposed architecture, shown in Fig. 6, employs three DC voltage sources which consist of a series-parallel combination of solar PV modules. The three power semiconductor devices ($S_{ab}$, $S_{bc}$, $S_{ca}$) are controlled by sinusoidal PWM as discussed in [10]. The output of the boost converters serve as the DC voltage sources for the delta inverter. The inverter output is connected to an LC filter tuned at half of the switching frequency. The filtered output of the delta inverter is then interfaced to a three phase utility grid.

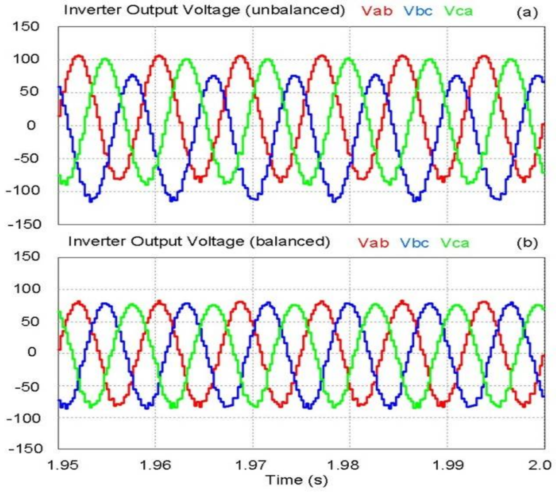


Fig. 5: 5(a) Operation of DIS with unbalanced DC sources ($V_{DC,ab}$ = 110 V, $V_{DC,bc}$ = 105 V, $V_{DC,ca}$ = 80 V) without corrected modulation indices. The outputs are unbalanced and have a DC average.

### *B.DIS with Front End Flyback Converter*

The second DIS configuration proposed in this paper for power harvest from a PV array is shown in Fig. 7. A multikW PV array is interfaced via a three phase interleaved DCDC flyback converter (high frequency isolation), the outputs of which form the DC voltage sources in a DIS. The flyback converter serves as the MPPT stage, the transformer turns ratio also contributing to the voltage gain of the converter. The inverter switches are controlled using the same SPWM technique as discussed in section II. The inverter output is also connected to an LC filter tuned at half the switching frequency. The interleaved structure provides the following advantages: (a) Since the carriers of the three semiconductor devices are phase shifted by 120°, the PV current is continuous (b) Since the 60 Hz currents flowing out of the DC bus capacitors are phase shifted by 120°, the PV array current harmonics do not have a 60 Hz component.

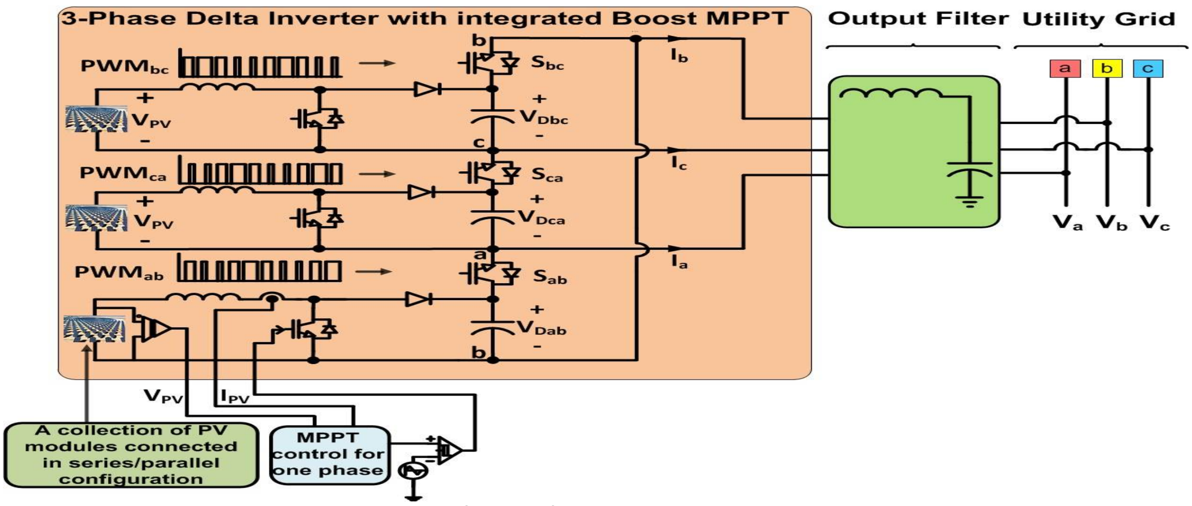


Fig. 6: Proposed Delta Inverter System (DIS) for interfacing large scale Solar PV to utility grid. The DIS system uses reduced number of switches, compared to a conventional 3-phase full bridge inverter. MPPT is performed by individual boost converters for each phase.

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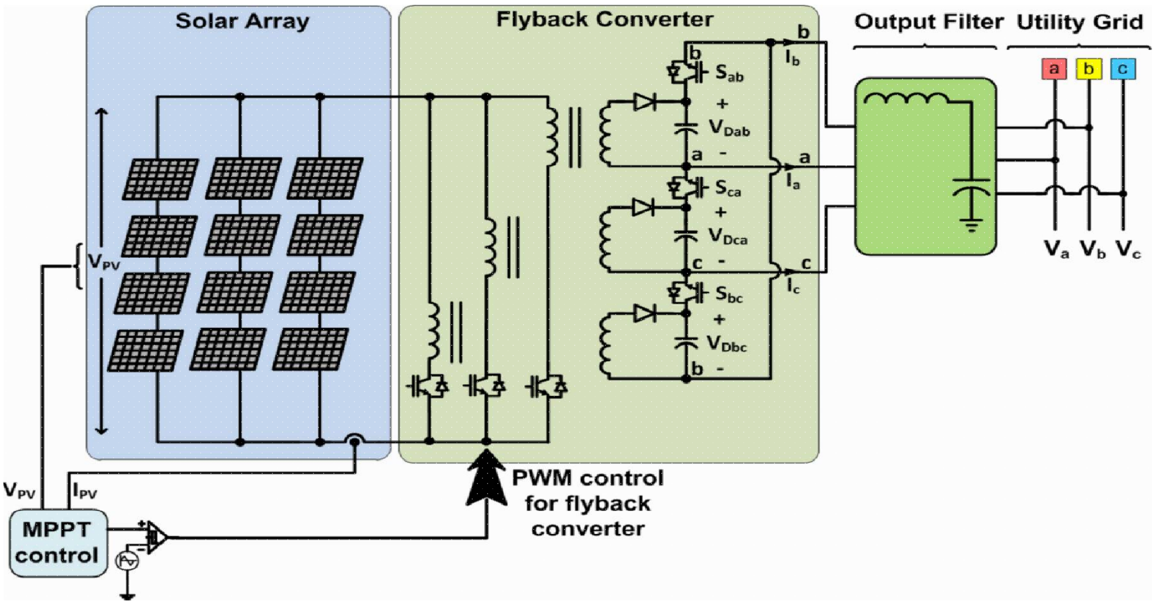


Fig. 7: Proposed Delta Inverter System (DIS) for interfacing large scale PV to utility grid via high frequency transformer isolation. Flyback DC-DC conversion stage provides MPPT control and better balancing of DC voltages at the delta inverter stage.

## IV.DESIGN EXAMPLE AND SIMULATION RESULTS

In this section a 30 kW/480 V commercial scale DIS design example is presented for each of the proposed topologies.

### *A.DIS with Front End Boost Converter Design*

The specifications and operating conditions given in Table II were considered for the design of this topology. The input voltage, $V_{pv}$, was selected to satisfy the safety standards imposed on PV installations. The modulation index and the DC link voltage were calculated according to the methods described in section II to achieve an inverter output voltage of 480 V.

TABLE II:SPECIFICATIONS AND OPERATING CONDITIONS 30KWCOMMERICAL DIS WITH BOOST (FIG.6)

| | |
|---|---|
| Input voltage ($V_{pv}$) | 600 V |
| DC link voltage ($V_{dc}$) | 740 V |
| Grid voltage (line-to-line rms) | 480 V |
| Inverter switching frequency | 18 kHz |
| Boost Converter switching frequency | 54 kHz |

The output filter capacitor and inductor were determined to be: $C_f$ = 150 µF and $L_f$ = 40 µH.
The IGBT's ($S_{ab}$, $S_{bc}$, $S_{ca}$) must be rated for a blocking voltage of at least 2.2 kV. The proposed commercial IGBT's that may be applied to this design are IXYS IXBH32N300. These devices have a $V_{CE}$ rating of 3 kV and 80 A collector current rating.

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### *B. DIS with Front End Flyback Converter Design*

For designing the DIS with front end flyback converter, the specifications shown in Table II were considered. Both the inverter switching frequency and the DC-DC converter switching frequency were kept the same as in the previous topology design.

TABLE III: SPECIFICATIONS AND OPERATING CONDITIONS USED FOR SIMULATION OF DIS WITH FLYBACK (FIG. 7)

| | |
|---|---|
| Input voltage ($V_{pv}$) | 500 V |
| DC Link Voltage | 740 V |
| Grid voltage (line-to-line rms) | 480 V |
| Inverter switching frequency | 18 kHz |
| Flyback switching frequency | 54 kHz |

## V.EXPERIMENTAL RESULTS

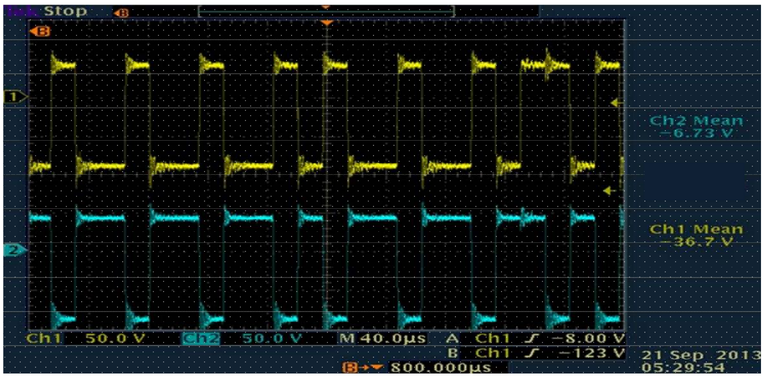


Fig. 12: PWM line-to-line output voltage $V_{ab}$ (yellow, Ch1) and $V_{bc}$ (cyan, Ch2). It is seen that the voltage swings between approximately +45 V and -90 V.

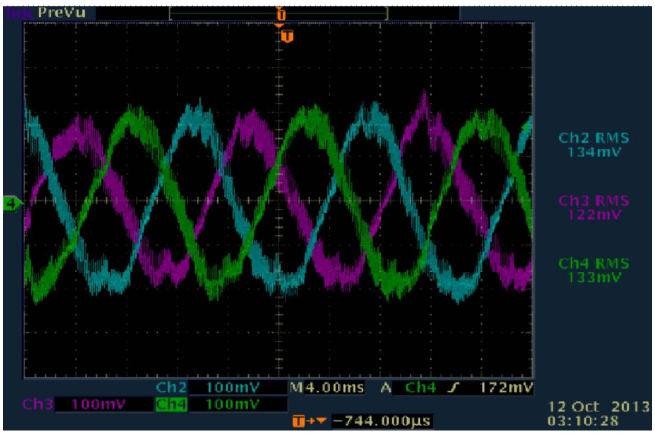


Fig. 13: Three phase line output currents of the delta inverter connected to an RL load. The currents are measured to be 1.3 A rms.

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## VI.CONCLUSION

A new grid-connected DIS for large scale solar photovoltaic power systems was introduced. The basic operation of the delta inverter was described and an advanced PWM control scheme was proposed for operation with unbalanced DC voltage sources. Two different configurations of the DIS for utility interface were proposed and discussed. These DIS topologies have advantages over centralized full bridge PV inverters, such as reduced component count and higher energy yield. A design example of a 30 kW commercial DIS was presented. Simulation results demonstrated the operation and feasibility of both topologies. High power factor and low THD operation were achieved with both topologies. Finally, a scaled-down laboratory prototype delta inverter was built and relevant preliminary experimental results showing the inverter's operation were presented.

## REFERENCES

[1] Jose Juan Sandoval, Jorge Ramos-Ruiz, Michael Daniel, Somasundaram Essakiappan, Prasad EnjetiDepartment of Electrical &Computer Engineering, Texas A&M University, College Station, USA.

[2] A New Delta Inverter System with MultiTapped Forward ConverterLimy Berly1, Reena R Rajan2PG Student [Power Electronics and Drives], Dept. of EEE, NCERC Pampady, India1Assistant Professor, Dept. of EEE, NCERC Pampady, India2.

[3] A Modified Delta Inverter System With a Single Switch Maneesh C.C *M.TECH student EEE Department, SJCET Palai* Teenu Techela Davis and Thomas Joseph *Assistant Professor EEE Department, SJCET Palai*.

[4] THREE PHASE DELTA INVERTER INTEGRATED WITH FORWARD CONVERTER FOR PV APPLICATION Ms Swathylakshmi C.M PG Scholar, Power Electronics EEE Department KMEA Engineering College Edathala, Kerala, India Ms Ann Mary Thomas Assistant Professor, EEE Department KMEA Engineering College Edathala , Kerala, India.

[5] Evans, Peter D.; Dodson, Reginald C.; Eastham, J. Fred,"Sinusoidal Pulse width Modulation Strategy for the Delta Inverter,"*IEEE Trans. on Ind. Applicat.*, vol. IA-20, no.3, pp.651-655, May 1984.

[6] Trishan Esram and Philip T. Krein,"Power Electronics Needs for Achieving Grid-Parity Solar Energy Costs" ,*IEEE Energy2O3O conf. 2008*, Atlanta, Georgia, USA.

[7] "A Cost-Effective High-Efficiency Power Conditioner with Simple MPPT Control Algorithm for Wind-Power Grid Integration ", *IEEE trans. on ind. Applicat.*, vol. 47, no. 2, march/april 2011.

[8] Mohammadreza Ashraf and Nasser Masoumi, "High efficiency boost converter with variable output voltage using a self-reference comparator", *Int.J. of Electron. And Commun. (*AEÜ).

[9] Wenxin Liu "A comparative study of three topologies of three-phase (5L) inverter for a PV system" .*Power Electron. Specialist Conf., 1999* ,Charleston ,pp 801-806 vol 2

[10] Berker Bilgin, and Ali Emadi ,"Reduced-Parts Three-Phase Inverters :A Comparative Study