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SINGLE PHASE TRANSFORMER-LESS GRID CONNECTED PV SYSTEM

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***Abstract*— This paper presents a single-phase, single-stage current source inverter (CSI) based photovoltaic system (PV) for grid connection. A double-tuned parallel resonant circuit is designed to attenuate the second- and fourth- order harmonics at the inverter dc side. It helps to improve the power quality and system efficiency. A modified carrier based modulation technique for the current source inverter is studied to magnetize the dc-link inductor and to control the switching pattern for the single phase grid-connected CSI. The operation of Single Phase Transformer-less grid connected PV system is verified by the simulation using MATLAB/Simulink software. The results are analyzed and presented.**

Index Terms*— Current source inverter (CSI), grid-connected, photovoltaic (PV), carrier based pulse width modulation (CPWM).

I. INTRODUCTION

The Conventional sources of energy are rapidly depleting. Moreover the cost of energy is rising and therefore photovoltaic (PV) system is a promising alternative. They are abundant, pollution free, distributed throughout the earth and recyclable. The hindrance factor is its high installation cost and low conversion efficiency. Therefore our aim is to increase the efficiency and power output of the system. It is also required that constant voltage is supplied to the load irrespective of the variation in solar irradiance and temperature. some of the standards that inverters for PV and grid applications must fulfill is presented in [1]. A cascaded H-bridge multilevel converter has several advantages such as the generation of high-quality currents, the capacity to operate at a lower switching frequency than a two-level converter, and the modularity that can reduce the cost of the solution [2]. A grid-connected PV power system with high voltage gain is presented in [3]. A novel single-phase multilevel cascaded H-bridge inverter for PV applications with fuzzy logic control has been analyzed and it reduces the influence of perturbations caused by cloud darkening [4]. A new P&O technique works by perturbing more than one control variable and observing the value of a performance function is presented in [5]. A transformer-less topology is studied and given an alternative solution for the bidirectional switch, used to generate the zero-voltage state [6]. An optimized transformer-less grid-connected PV inverter has been analyzed and has the following advantages of the common-mode voltage and the good differential-mode characteristic [7]. In distributed generation applications, the PV system operates in two different modes: grid-connected mode and island mode [8], [9]. The output of photovoltaic generation shows serious fluctuations caused by variation in circumstance, which leads to increasing problem of system stability [10].

The current source inverter (CSI) could be a viable alternative technology for PV distributed generation grid connection for the following reasons:

1) The dc input current is continuous which is important for a PV application.
2) System reliability is increased by replacing the shunt input electrolytic capacitor with a series input inductor.
3) The CSI voltage boosting capability allows a low-voltage.

The aim of this project is to improve power quality and system efficiency, a double tuned resonant circuit is studied to attenuate the second and fourth order harmonics at the inverter dc side. Carrier based PWM Technique is analyzed to generate switching pattern for the IGBT switch of CSI.

II. BASIC CURRENT FED INVERTER WITH PARALLEL RESONANT LOAD

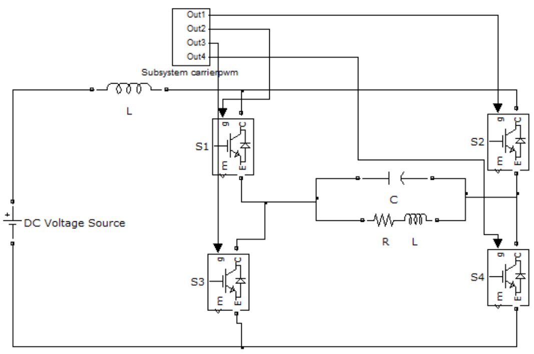


Fig.1. Basic current fed inverter with parallel resonant load.

The current fed bridge inverter with a parallel resonant load is taken for analysis. In above circuit the inductance L_{dc} is so large that input current remains constant and a square-wave current is impressed on the resonant-load circuit. The load voltage is nearly sinusoidal. The IGBT switch are turned off by the reactive power supplied by the load itself, provided the inverter operating frequency is equal to the resonance frequency of the load. In this circuit no separate turn-off arrangement is required.

The initial condition when IGBT S1 and IGBT S4 are switched on is

$$i\,|_{t=0} = I_0 \quad (1)$$

$$v_c\,|_{t=0} = -V_{c0} \quad (2)$$

The circuit equations are

$$iR_L + L\frac{di}{dt} = v_c \quad (3)$$

$$i + C\frac{dv_c}{dt} = I_{in} \quad (4)$$

Where i, v_c, R_L, L, C and I_{in} represents output inductor current, output capacitor voltage, internal resistance of inductor, ac line resonant inductor, ac line resonant capacitor and input current of current source inverter respectively.

III. System Description

PV array is connected to grid using a single phase current source inverter (CSI). A grid-connected PV system using a single-phase CSI is shown in Fig. 2. The inverter has four insulated-gate bipolar transistors (IGBTs) (S1–S4) and four diodes (D1–D4). Each diode is connected in series with an IGBT switch for reverse blocking capability. A doubled-tuned parallel resonant circuit in series with dc-link inductor L_{dc} is employed for smoothing the dc link current. To eliminate the switching harmonics, a *C*–*L* filter is connected into the inverter ac side.

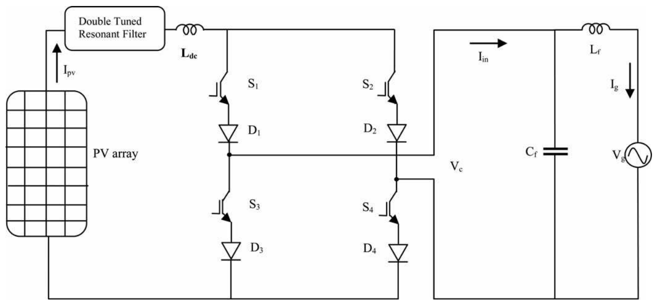


Fig.2. Single phase grid connected current source inverter.

IV. Double Tuned Resonant Filter

While power electronic devices are getting a great improvement, the method of filtering harmonics is diverse. Passive filter has been widely used in filtering harmonics in power system by now, because it has a simple structure, low cost, high reliability, and so on.

Usually, there are multiple frequency harmonics in a power system, so a group of single tuned filters are needed to filter harmonics. This filtering method covers a large area and has a high cost. Double-tuned filter has the same function that both of them can filter two different frequency harmonics. However, double-tuned filter has a lower cost than the two parallel single tuned filters. In order to tune the resonant filter to the desired harmonic frequencies, the impedance of *C*1 and the total impedance of *L*1, *L*2 and *C*2 should have equal values of opposite sign. For simplicity, assume component resistances are small, and thus can be neglected in the calculation.

$$Z_{C1} + Z_t = 0. \quad (5)$$

From (5), the capacitances are represented by the following equations:

$$C1 = \frac{(L2C2 - \frac{1}{\omega 2})}{(\omega 2 L1L2C2 - L1 - L2)} \quad (6)$$

$$C2 = -\frac{(L2)}{\left(\frac{L2}{C1} - \omega 2 L1L2\right)} + \frac{1}{\omega 2 L2} \quad (7)$$

Where *C*1 and *C*2 are the resonant filter capacitances, *L*1 and *L*2 are the resonant filter inductances, Z_{C1} is *C*1 impedance, Z_t is the total impedance of *L*1, *L*2 and *C*2, and ω is the angular frequency of the second- or fourth-orders harmonics. After selecting the inductance values, which are capable of allowing the maximum $\frac{di}{dt}$ at rated current, the angular frequency of the second harmonics in (6) and the angular frequency of the fourth harmonic in (7) are used. The desired capacitances are calculated by numerically solving (6) and (7). The filter is capable of eliminating both the second- and fourth-order harmonics. In order to obtain the relationship between the resonant inductances (*L*1 and *L*2), (5) and (6) are solved for *C*1.

$$C1 = \frac{\sqrt{\left(L1(L1\omega 1^4 + L1\omega 2^4 - 2L1\omega 1^2\omega 2^2 - 4L2\omega 1^2\omega 2^2)\right)} + L1\omega 1^2 + L1\omega 2^2}{(2L1^2\omega 1^2\omega 2^2 + 2L1L2\omega 1^2\omega 2^2)} \quad (8)$$

From (8), to avoid complex numbers in the solution, the relationship between *L*1 and *L*2 should be

$$L2 \leq 1.778\, L1. \quad (9)$$

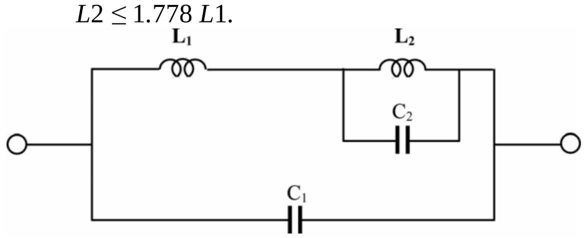


Fig.3. Double tuned resonant filter.

To select the optimum values for the proposed filter components, the effects of varying resonant circuit inductance are analyzed. It can be shown that *C*1 is not significantly affected when varying *L*1 and *L*2, whereas *C*2 is affected mainly by *L*2. As *L*2 decreases, the value of *C*2 increases. Therefore, increasing the capacitance leads to reduced overall system weight and size by reducing the dc-link inductance.

TABLE I. Design Values of Resonant Filter

RESONANT FILTER INDUCTOR , L1	(mH)	10
RESONANT FILTER INDUCTOR , L2	(mH)	5
RESONANT FILTER CAPACITOR , C1	(μF)	125
RESONANT FILTER CAPACITOR , C2	(μF)	250

V. Modified Carrier Based Pulse Width Modulation

Modified carrier-based pulse width modulation (CPWM) is studied to control the switching pattern for the single-phase grid-connected CSI. In order to provide a continuous path for the dc-side current, at least one top switch in either arm and one bottom switch must be turned ON during every switching period.

CPWM is studied to provide sufficient short-circuit current after every active switching action. CPWM consists of two carriers and one reference. The reference and carrier waveforms, along with the switching patterns are shown in figure. The carrier with the solid straight line shown in figure is responsible for the upper switches, while the dashed line carrier is responsible for the lower switches and is shifted by 180◦.

TABLE II. SWITCHING COMBINATION SEQUENCE

\ REGION	COMBINATION SEQUENCE
T1	(S1-S3)(S1-S4)(S2-S4)(S1-S4)
T2	(S1-S3)(S1-S4)(S2-S4)(S1-S4)
T3	(S1-S3)(S1-S4)(S2-S4)(S1-S4)
T4	(S1-S3)(S1-S4)(S2-S4)(S1-S4)
T5	(S1-S3)(S1-S4)(S2-S4)
T6	(S1-S3)(S2-S3)(S2-S4)(S2-S3)
T7	(S1-S3)(S2-S3)(S2-S4)(S2-S3)
T8	(S1-S3)(S2-S3)(S2-S4)(S2-S3)
T9	(S1-S3)(S2-S3)(S2-S4)(S2-S3)
T10	(S1-S3)(S2-S3)(S2-S4)

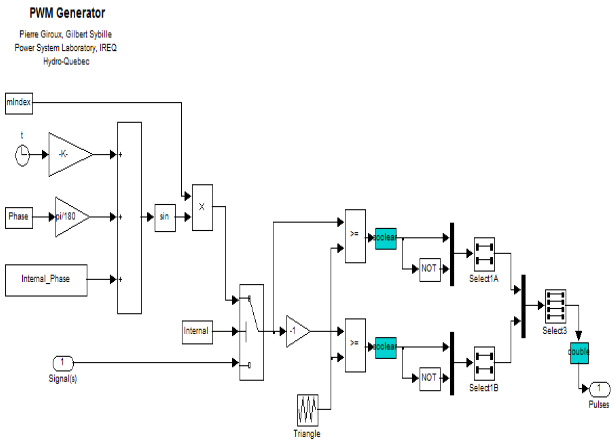
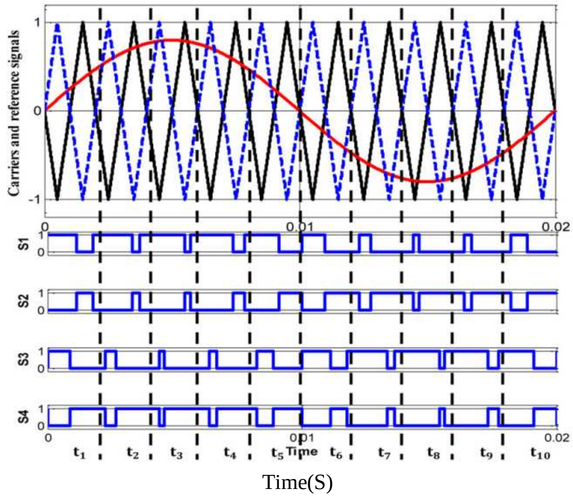
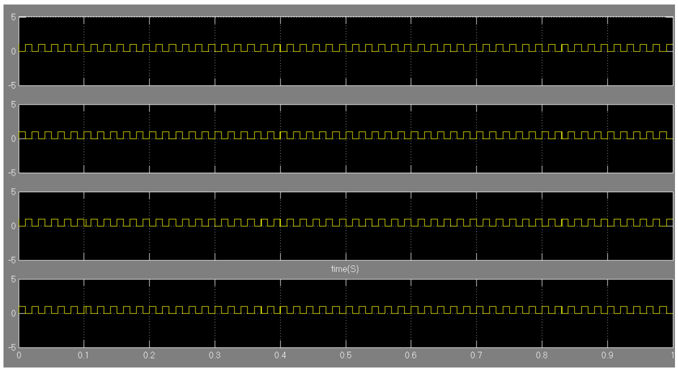


Fig.4. Simulink diagram of CPWM



(a)



(b) Time(S)

Fig.5. (a) CPWM with sine reference signal and (b) Switching pattern generated.

Here the modified carrier based PWM technique is analyzed and the switching combination sequence is also presented.

VI. System Control Techniques

To design a grid-connected PV system using a CSI, the relationship between the PV output voltage and the grid voltage is derived as follows.

By neglecting inverter losses, the PV output power is equal to the grid power.

$$V_{PV}I_{PV} = ½*I_{g,\,peak}*V_{g,\,peak}\cos\theta \quad (10)$$

where θ is the phase angle, V_{PV} and I_{PV} are the PV output voltage and current, respectively, while $V_{g,\,peak}$ and $I_{g,\,peak}$ are the grid peak voltage and current, respectively. The grid current is equal to the PV output current multiplied by the inverter modulation index M .

$$I_{g,\,peak} = M*I_{PV} \quad (11)$$

Substituting (10) into (11), assuming unity power factor, the equation describing the relationship between the PV output voltage and the grid voltage is

$$V_{PV} = 1/2*M*V_{g,\,peak} \quad (12)$$

Therefore, in order to interface the PV system to the grid using a CSI, the PV voltage should not exceed half the grid peak voltage.

VII. SIMULATION RESULTS

In order to validate the theoretical analysis, closed loop operation of single phase current source inverter grid connected using photovoltaic system is simulated on MATLAB/Simulink. The simulated closed loop system has taken the circuit parameter values are shown in table III. The system control mainly consists of an Agilent modular solar array block to emulate PV system operation, a phase-locked loop (PLL) block to ensure synchronization between grid current I_g and voltage V_g respectively. The Double Tuned Resonant Filter to attenuate the harmonics is presented in dc side of CSI. Modified Carrier based PWM block is presented with a 4-kHz switching frequency to provide a sufficient short circuit current after every switching action and to track the maximum power point and also to interface the PV system to the grid.

The singe phase transformer-less grid connected using PV system is simulated in MATLAB/Simulink software.

TABLE III. DESIGN SPECIFICATION AND CIRCUIT PARAMETERS

ITEM			VALUE
PV OPEN CIRCUIT VOLTAGE	V_{oc}	(V)	80
PV SHORT CIRCUIT CURRENT	I_{sc}	(A)	15
PV ARRAY RATED POWER	P_R	(W)	500
RESONANT FILTER INDUCTOR	L1	(mH)	10
RESONANT FILTER INDUCTOR	L2	(mH)	5
RESONANT FILTER CAPACITOR	C1	(μF)	125
RESONANT FILTER CAPACITOR	C2	(μF)	250
DC LINK INDUCTOR	L_{dc}	(mH)	5
SWITCHING FREQUENCY	F_s	(kHz)	4
AC LINE INDUCTOR	L	(mH)	1
AC LINE CAPACITOR	C	(mF)	400
GRID VOLTAGE	V_{grms}	(V)	110

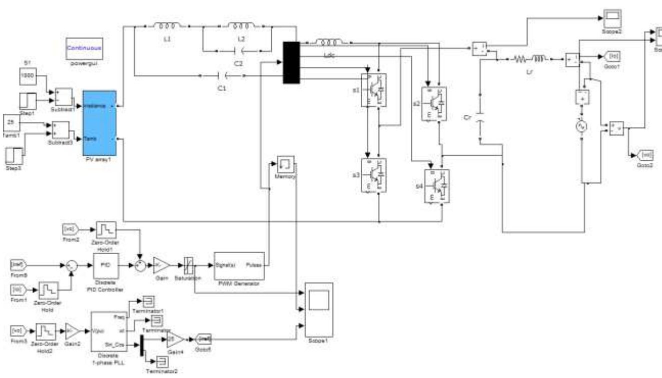
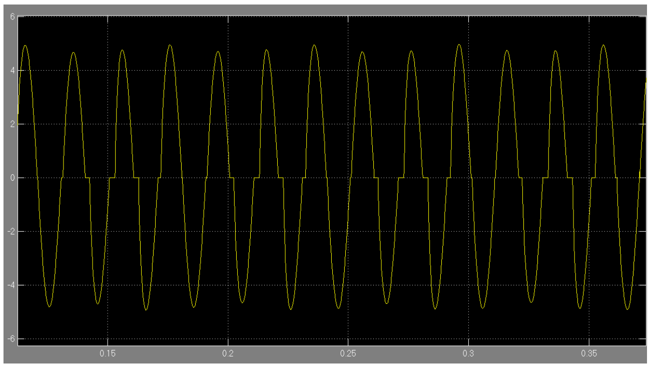
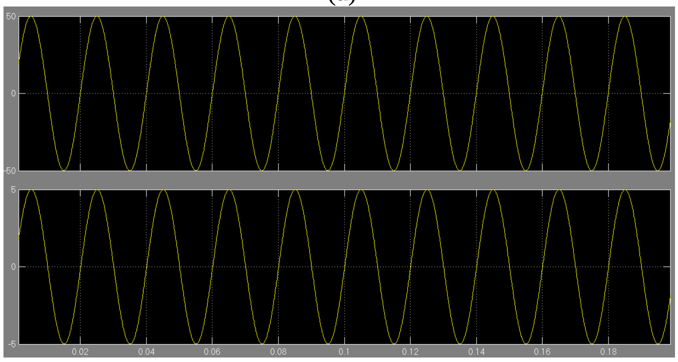


Fig.6. Simulink diagram of closed loop operation of single phase transformer-less grid connected using photovoltaic system



(a)



(b)

Fig.7. Output waveforms (a) CSI output current waveform and (b) grid voltage and grid current waveform

The CSI output current waveform and the Grid voltage Vg and Grid current Ig are verified through simulation results.

VIII. CONCLUSION

A single-phase single stage transformer-less grid-connected photovoltaic system has been studied that can meet the grid requirements without using a high dc voltage or a bulky transformer. Since the system consists of a single-stage, the PV module power is delivered to the grid with high efficiency, low cost, and small footprint. A modified carrier-based modulation technique has been presented to provide a short circuit current path on the dc side to magnetize the inductor after every conduction mode. Moreover, a double-tuned resonant filter has been designed to suppress the second- and fourth-order harmonics on the dc side with relatively small inductance. The operation of Single Phase Transformer-less grid connected using photovoltaic system is verified by the simulation using MATLAB/Simulink software. The simulation results are also presented.

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