A Grid Tied Short-Through Proof Solar PV Inverter

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Abstract. In this paper, a new grid tied short-through proof solar photovoltaic (PV) inverter that is short-through proof is presented. Detailed presentation of this new solar inverter is preceded by a brief explanation of the generalized solar PV inverter, its types and some representative grid tied solar inverters (mainly micro-inverters) that are currently trending in the solar PV power conversion industry. The merits of each of these briefly explained solar inverter types and power circuits are emphasized. The new grid tied galvanic isolated solar inverter power circuit is then explained in detailed, analyzed and the steady state time varying circuit voltages and currents given. In addition to being short through proof, the new grid tied solar inverter is scalable from solar PV micro-inverter to solar PV central inverter in output power capability unlike the conventional grid-connected single phase inverters.

Keywords: Grid, Short-through, Tie, Photovoltaic, Proof

1. Introduction
With the continuing rapid rate of improvement in the efficiency, power handling ability and high voltage and temperature, withstand capability of both power semiconductor devices [such as silicon carbide and gallium nitride (SiC & GaN) transistors and diodes] and energy storage batteries [such as Lithium ion and Liquid metal batteries], the world has the potential of making solar panel derived electric power a very significant percentage of its total electric power consumption [1, 2,3,4]. Consequently, the solar module harvested electric power (being the cleanest of all the renewable energy electric sources) is being, at a meteoric rate, developed and deployed as residential, commercial and industrial clean electric power supplies so as to help meet, by 2040, the global target of required low carbon emission into the earth’s atmosphere.

For the past 40 years, various types of solar modules (thin film, polycrystalline, monocrystalline) and solar inverter systems/applications have been developed/conceived and intensive research is ongoing to improve cells and inverter system efficiency and overall performance. The interconnection and number of the solar modules and the inverters in a given solar power supply system classify a given solar inverter system as either central, string or micro-inverter system [2,3].

In this paper, a generalized solar inverter supply system, solar inverter system types by PV panel interconnection and some representative solar inverter power circuits are first presented and briefly explained. The solar micro-inverter system has generally been shown to be more efficient, reliable and easier to maintain. Consequently, the representative solar inverter circuits given as examples in this paper are mostly grid tied micro-inverter circuits reported in the literature. Finally, a new grid-tied solar inverter circuit, which has the advantage of being short through proof, is described, analyzed and the circuit steady state performance presented. The short through proof capability of this described grid tied solar inverter system, which can be scaled as a string or micro inverter, is an advantage over most other solar inverters reported in [8]
2. A Generalized Solar PV Inverter Electric Power Supply System

Fig. 1 shows a generalized block diagram of the solar PV system based inverter electric power supply system as consisting of an interconnection of solar array/panels, the maximum power point tracker (MPPT) boost converter, a backup battery with bidirectional(BD) buck/boost charger, the inverter, the filter, the load and a control circuit that uses specified control algorithms and sensed variables (the solar array and load voltages and currents, e.t.c) to control the operation of the solar electric power supply system. The control circuit can be a programmed microcontroller. It can also be a hard wired logic circuit. The MPPT dc/dc booster performs the dual function of boosting the solar array voltage to the input voltage level required by the inverter stage as well as adjusting the solar array current and voltage to correspond to the values at the solar array MPPT values for any given solar radiation level. The MPPT boost converter is not needed in some inverters designed to perform the additional function of solar array voltage boosting and MPPT control action. The load can be passive or active and a feedback arrangement maintains the load voltage and/or current at desired values. Excess energy from the solar array source is stored in the back up battery through the BD dc/dc buck/boost battery charger operating in the bucking mode.

Fig.1: A Generalized Solar Inverter Electric Power Supply System

Under unacceptable level of solar radiation, the buck/boost charger operates in the boost mode to supply back up battery power to the load. The back-up battery with its charger (optional depending on given application) can alternatively be connected directly across the output of the MPPT dc/dc booster. The solar array can be assumed to deliver power to the load through an “optimized inverter”. The optimization of inverter involves conditioning the unregulated solar array dc supply (at its maximum power operating point for given sun radiation) to predetermined voltage/current and frequency values required by both the load and the back-up battery on charge.

2.2: Solar Inverter Supply System Types

There are three types of Solar PV Inverter Electric supply systems by the method of interconnection, number of solar panels and optimized inverters in a given solar supply system. These are the Central, the String and the Micro-inverter Solar Electric Supply systems [2, 3].

The Central Solar Inverter System (CSIS) (Fig. 2a), which is by far the most deployed globally, comprises PV array number of groups of \( N_p \left( 2 \leq N_p \leq 10 \right) \) series connected solar panels connected in parallel to supply high power rated load through one optimized inverter. For high power (typically greater than 30 kW), the CSIS is the simplest and the cheapest option but its overall efficiency can be significantly degraded by the fact that if one or more of the solar panels of a series string of the solar array is shaded during any part of the day, the affected series string can only produce as much electricity as that equal to its least productive panel.

A String Solar Inverter (Fig. 2b) is made up of \( N_p \left( 2 \leq N_p \leq 10 \right) \) series connected solar panels whose unregulated dc output is conditioned by an optimized inverter to produce ac output to a load. For increased power output to a load, a number of string solar inverters have their ac outputs...
connected in parallel and fed to the load. For the same power output, the string inverter system is
costlier than the central inverter system but to a much lesser degree, its efficiency is also degraded by
clouding or shading on one or more of any of the series sting solar panels in the solar array. For solar
inverter supply systems with distinct MPPT DC/DC boost stage, Fig. 2c is an alternative string
inverter supply system where the boosted dc outputs of the panel strings are connected in parallel to
feed an inverter that supplies filtered ac voltage to a load.

Fig. 2: Solar Inverter System Types: (a) CIS, (b & c) Alternate forms of the String Inverter Systems, (d) Micro
inverter System.

A Solar Micro-inverter (Fig. 2d) consists of one solar panel connected to an optimized inverter to
produce required ac output of power range up to 500W [1,2,3,4,5]. It is designed to have small size,
light weight and very high efficiency (nominally 98%) and therefore the optimized inverter is nearly
always integrated into the solar panel. For high power, a number of micro-inverters have their outputs
connected in parallel to supply a given load. In parallel connected form, shading and or clouding on
one or more panels of the solar micro inverter system leaves the other panels supplying their
respective maximum power for a given sun radiation level. Because of its relative merits (very high
efficiency, small size, light weight, scalability and ease of maintenance), the development and
deployment of solar micro-inverter supply systems are rising at such a high rate.

3. Some Representative Solar Inverter Circuits
Fig. 3a to 3f show some representative solar electric inverter power circuits, out of very many that
have been reported in the literature. Emphasis is given to solar inverter power circuits with galvanic
transformer isolation as the usually preferred circuits especially for utility tied applications.

Fig. 3a shows one of the simplest and most commonly used single stage solar inverter power
circuits. The tertiary wound transformer boosts the switched solar array voltage \(v_{pv}\) to the required ac
voltage \( v_{st} \) that feeds the load (which can be passive or active) through an LC filter. For the transistor \( T_1 \) on and \( T_2 \) off, \( v_{st} = n v_{pv} \); for \( T_1 \) off and \( T_2 \) on, \( v_{st} = -n v_{pv} \); for both \( T_1 \) and \( T_2 \) on, \( v_{st} = 0 \).

Fig. 3a: The Push-Pull Solar Micro-inverter where \( n \) is the secondary to any of the primary winding turns ratio. The load voltage/current is easily regulated by pulsewidth modulation of the transformer secondary voltage \( v_{st} \). For lighting application at 230V/120V, 50Hz/60Hz supply, modulation and filtering of the secondary transformer output voltage is unnecessary for low power applications. The inverter circuit has the merit of being short through-proof but the required low frequency transformer is relatively bulky.

Fig. 3b is an example of a two-stage Solar Micro-inverter consisting of a centre tapped fly-back high frequency transformer, an input decoupling capacitor \( C_i \), a primary switch \( T_{11} \), bidirectional transistor switches \( T_{21}, T_{22}, T_{23} \) and \( T_{24} \) at the transformer secondary side and an output CL filter connected to the utility grid [1]. A train of triangular shaped transformer magnetizing inductor current pulses generated by tuning on and off the primary side transistor \( T_{11} \) at relatively high frequency is transferred through the secondary winding and the output CL filter to the grid as filtered positive current for transistors \( T_{21} \) on and \( T_{23} \) off during the positive half cycle interval of the grid voltage and as filtered negative current for transistor \( T_{21} \) off and \( T_{23} \) on during the negative half cycle interval of the grid voltage. The peaks of the triangular current pulses are bounded by a sinusoidal reference envelope and the duty cycles of the triangular current pulses increase/decrease as the sinusoidal reference envelope increases/decreases. The triangular pulse current short polarity reversal interval provided by the appropriate turning ON and OFF of transistors \( T_{22} \) and \( T_{24} \) makes all the inverter transistors to be soft switched thus making the efficiency very high. Power control and consequently MPPT control are achieved by the variation of the amplitude of the sinusoidal reference envelope. Fig. 3c is a grid tied micro-inverter comprising of two conversion stages namely the single phase full bridge high frequency series resonant inverter with output boost high frequency isolation transformer and a cycloconverter that converts the inverter high frequency resonant current into 50Hz/60Hz current injected into the utility grid of voltage \( v_g = \sqrt{2} v_{gr} \sin(\omega t) \) [3].
The series resonant inverter is pulse width modulated to have one half cycle output voltage pulse of angular length $\delta$ radian ($0 < \delta \leq \pi$) and is operated at a frequency higher or equal to its series LC resonant frequency \(\frac{1}{2\pi\sqrt{LC}}\).

During the positive half cycle of the grid voltage, transistors $T_{23}$ and $T_{24}$ of the cycloconverter are turned on while $T_{21}$ and $T_{22}$ are alternatively turned on and off at 50% duty cycle and at the resonant inverter operating frequency to allow the flow of positive half cycle resonant current from the resonant inverter to the utility grid. Similarly, during the negative half cycle of the grid voltage, transistors $T_{21}$ and $T_{22}$ of the cycloconverter are turned on while transistors $T_{23}$ and $T_{24}$ are alternatively turned on and off at 50% duty cycle and at the resonant inverter operating frequency to allow the flow of negative half cycle resonant current from the resonant inverter to the utility grid. MPPT control is achieved by appropriate adjustment of the resonant inverter operating frequency and/or the resonant inverter output voltage per half cycle pulse length $\delta$ in such a way that the resonant current amplitude at any sampling instant scales linearly with the instantaneous value of the grid voltage. The phase of the resonant inverter current relative to both the resonant inverter output voltage and the grid voltage is controlled to ensure zero voltage soft switching for all the eight transistor switches of the micro-inverter. The micro-inverter has the disadvantage of being prone to short-through faults under dysfunction of the transistor switching signal control because of the series connection of inverter leg transistor switches across the resonant inverter input voltage supply. Fig. 3d is a micro-inverter comprising of a high frequency half bridge boost forward converter and a pulse width modulated full bridge inverter which has its output connected to the utility grid through an LCL filter [4,5]. The half bridge boost converter steps up the solar panel voltage $v_{pp}$ to a value equal to \((\pi n/1-D) v_{pp}\) at the full bridge inverter input

Where $D$ is the turn on duty cycle of transistor $T_{12}$ and $n$ the secondary to the primary turns ratio of the boost converter high frequency transformer. The full bridge (H) inverter is modulated in a way that the solar derived current is injected into the grid at unity power factor. MPPT control is affected by proper adjustment of transistor $T_{12}$ duty cycle $D$. Because of the series connection of the complementary transistors of the legs of both the booster converter and the full bridge inverter, this micro-converter is susceptible to short-through faults. The grid tied micro inverter shown in Fig 3e has a boost bidirectional (BD) dual active bridge (DAB) as its input stage and a pulse width modulated full bridge inverter with an output LCL filter as the output stage [5,7]. The BD boost dual active bridge converter boosts the solar module voltage to a value required at the H inverter input and also provides MPPT control by appropriately adjusting the relative phase difference between the high frequency transformer primary and secondary voltages. Being BD, power can also flow from the grid to charge the input capacitor, $C_i$ or a backup battery that may be connected across, $C_i$. Because of the series connection of the complementary transistors of the inverter legs of both the DAB booster converter and the H inverter, this micro-converter is also susceptible to short-through faults.

4. A New Grid Tied Short-Through Proof Solar Inverter
Fig 4a shows a grid tied two stage solar inverter topology that has the advantage of being short through proof, unlike solar inverters such as those given in Figs. 3c to 3e that contain the conventional H-Bridge inverter legs susceptible to short through faults under dysfunction of the transistor switch gating signal control. The two stages are the high frequency push-pull dc link boost converter and the short-through proof current controlled inverter.

For the push-pull boost converter, switches $T_{11}$ and $T_{12}$ are alternatively switched on and off at relatively high frequency to give $v_{pt1} = v_{pt2} = v_{pp}$, $v_{st} = n v_{pp}$ for $T_{11}$ on and $T_{12}$ off and $v_{pt1} = v_{pt2} = - v_{pp}$, $v_{st} = - n v_{pp}$ for $T_{11}$ off and $T_{12}$ on. The square wave secondary transformer voltage $v_{st}$ is rectified by the full bridge diode rectifier to give an input inverter dc voltage $V_{dc}$ usually higher than the peak value of the ac grid voltage ($v_g = 230\sqrt{2}\sin(\omega t)$) for proper operation of the current controlled inverter. Fig. 4b shows the time variations of the voltages of the high frequency transformer windings at the boost converter operating frequency of 20 kHz and the solar panel voltage of 48V.

The transistors switches ($T_{21}$-$T_{24}$) are controlled to inject a sinusoidal current $i_o$ into the utility grid at unity power factor by closely tracking a reference sinusoidal current $i_{ref} = I_o \sin(\omega t)$ where the peak of the sinusoidal reference current is continuously adjusted by the MPPT control to ensure optimum delivery of available solar power to the grid. In the positive cycle interval of the grid voltage $v_g$, $T_{23}$ and $T_{24}$ are off and transistor $T_{21}$ is on while $T_{22}$ is turned on or off according as the grid injected current $i_o$ is equal/lower than ($i_{ref} - \Delta I$) or equal/higher than ($i_{ref} + \Delta I$) where $2 \ast \Delta I$ is the sinusoidal reference current hysteresis band (Fig. 4c). When $T_{22}$ is on (during the positive cycle of $v_g$), grid injected current $i_o$ flows in the loop comprising $V_{dc}$, $T_{21}$, $D_{21}$, $L_{o}$, $V_{g}$, $L_{1}$ and $T_{22}$ to increase $i_o$. When $T_{22}$ is off, grid injected current $i_o$ flows in the loop comprising $T_{21}$, $D_{21}$, $L_{o}$, $V_{g}$, $L_{o}$, $V_{g}$, $L_{1}$ and $D_{22}$ to decrease $i_o$. In the negative cycle interval of the grid voltage $v_g$, transistors $T_{21}$ and $T_{22}$ are off and transistor $T_{23}$ is on while $T_{24}$ is turned off or on according as the grid injected current is equal/lower than ($i_{ref} - \Delta I$) or equal/higher than ($i_{ref} + \Delta I$). When $T_{24}$ is on (during the negative cycle of $v_g$), grid injected current $i_o$ flows in the loop comprising $V_{dc}$, $T_{23}$, $D_{23}$, $L_{o}$, $L_{2}$ and $T_{24}$, to decrease $i_o$. When $T_{24}$ is off (during the negative cycle of $v_g$), grid injected current $i_o$ flows in the loop comprising $T_{23}$, $D_{23}$, $V_{g}$, $L_{o}$, $L_{2}$ and $D_{24}$ to increase $i_o$. Fig. 4c shows the time variations of the sinusoidal reference current $i_{ref}$ and the resultant gating signals ($v_{pt1}$ - $v_{pt2}$) to transistor switches $T_{21}$, $T_{22}$, $T_{23}$ and $T_{24}$ while Fig. 4d shows the time variation of grid voltage $v_g$, the primary transformer current $i_{pt1}$ the inductor currents ($i_{L1}$, $i_{L2}$) and the injected grid current $i_o$ under hysteresis current control of the grid tied PV of Fig. 4d.
Fig. 4c: Time variation of the reference sinusoidal current \( i_{	ext{ref}} = 2\sin 100\pi t \) and transistors \( T_{21} - T_{24} \) gating signals \( (v_{g21} - v_{g24}) \).

Fig. 4d: Steady State Time Variations of the grid voltage \( v_g = 230\sqrt{2}\sin 100\pi t \), transformer primary current \( v_{\text{out}} \), inductor \( L_1 \) current \( i_{L1} \), inductor \( L_2 \) current \( i_{L2} \) and the injected current \( i_o \) at unity p.f into the utility grid \( (L_m=1.0 \mu H, L_1 = L_2 = 500 \mu H, I_{	ext{in}}=2 A, \Delta i=0.1A) \).

5. Conclusion
In this paper, a grid tied, galvanic isolated, short-through proof, two stage solar PV inverter has been presented, analyzed and the solar inverter control and performance steady state time varying voltage and current waveforms given. The short through proof feature of the presented solar inverter has, by comparison, been shown to be an advantage over nearly all the other trending grid tied solar inverters briefly referenced in this paper. With the input push pull de link stage operating at relatively high frequency and with the use of very low loss and high performance SIC MOSFET transistor switches and diodes as the power circuit semiconductors in the described short through proof solar inverter, the solar inverter size, bulkiness and weight for a given power output are substantially reduced and the efficiency significantly improved.

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