



A SURVEY OF CURRENT SOURCE INVERTER TOPOLOGIES AND CONTROL SCHEMES FOR GRID CONNECTED PHOTOVOLTAIC SYSTEMS

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ABSTRACT

Grid connected photovoltaic systems (GCPS) can be a solution to meet the growing electricity demand and also for reducing the dependence on fossil fuels. The major role of the inverter in GCPS is to convert generated DC power to AC and inject the AC power into the grid. As compared to Voltage Source Inverters (VSI), advantages of Current Source Inverters (CSI) are better current quality, short-circuit protection, enhanced maximum power point tracking efficiency, better reliability, higher gain and reduced switching losses. However, grid connected CSI topologies are not used much for grid interface applications mainly because of the huge inductor required at the input side and effect of resonance due to the output filter. Either novel topologies or modified topologies and control schemes were suggested by researchers to reduce the value of input side inductor. This paper presents a detailed survey of various conventional and modified CSI topologies and different control schemes used in GCPS.

Keywords—*current source inverter, inductor, harmonics, control schemes, PV systems.*

INTRODUCTION

The grid-connected photovoltaic system (GCPS) is utilized to feed the generated power by Photovoltaic (PV) Systems to the AC grid. GCPS comprises of solar PV panel, power conditioning unit, control unit and grid [1]. Power conditioning unit can have single or double stage power processing stages with either a VSI or CSI. In single stage power conditioning, as shown in Fig.1, an inverter is placed between the solar PV panel and the grid. The inverter is controlled to convert the dc power generated by PV panel to ac, to track maximum power from PV panel and to synchronize with the grid. The overall GCPS is comparatively simpler and easier to implement as it is not necessary to use a battery for storage like Standalone systems [2].

For single-phase current source converters, there is an inherent limitation in DC-side which is low-frequency power oscillation. This oscillation happens at twice the grid frequency. In practice, these oscillations get transferred to the DC side and this results in low-frequency DC-link ripple. One possible solution is to use large DC-link inductance for attenuating the ripple. Due to this reason, CSI topologies are not that popular for grid-PV interface applications and most of the GCPS uses a Voltage Source Inverter (VSI) for interfacing with the grid.

The inductor value in CSI needs to be high because: (i) there exist an inherent decoupling problem at the input DC side of the current source inverter that makes the average power to be twice the fundamental frequency and (ii) the low frequency ripple at input leads to lower order harmonics in the grid current. The input ripple also affects the efficiency of maximum power tracking from the PV array. The size, weight and cost of the system increases if high value of inductor with high current handling capability is needed. However major advantages of CSI as

compared to VSI are: Better current quality, high reliability, voltage boosting capability, short-circuit protection, controllable output current, enhanced maximum power point tracking efficiency, reduced conduction losses [3]. In short, CSI provides better reliability and voltage boosting while interfacing a PV system to the ac power grid.

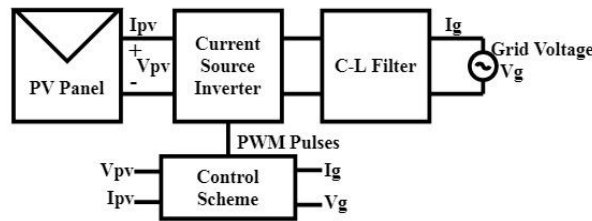


Fig.1. General Schematic of GCPS with CSI

Most of the GCPS uses a Voltage Source Inverter (VSI) as compared to CSI. An exhaustive survey was conducted by the authors to study the use of CSI and the control schemes for grid interface applications. It was found that various CSI topologies used for GCPS as an interface, can be categorized as conventional topology, modified topology, transformer-less topology etc. In section I, a brief review of the conventional CSI topology and its modifications are discussed. Section II presents topologies used for transformer-less GCPS. Various control schemes used for CSI are studied in detail and discussed in Section III. Conclusions are presented in Section IV, followed by references TABLE I

COMPARISON OF THE VSI AND CSI TOPOLOGIES

I. CONVENTIONAL CSI TOPOLOGY AND ITS MODIFICATIONS

This section presents a brief review of the conventional CSI and the modified CSI topology reported in the literature.

VSI	CSI
Electrolytic capacitor at input side	No electrolytic capacitor at input side
No Inductor at input side	High value Inductor at input side
Short circuit problem	No short circuit problem
Good dynamic response	Poor dynamic response
Size and weight is small	Size and weight is high
Buck based converter	Boost based converter

A. Conventional CSI

The conventional single phase CSI topology connected to AC grid is shown in Fig.2. [4]. High value of inductor is used at the input to take care of the decoupling problem as discussed in Section I.[5]. Either series diodes with the switches or reverse blocking IGBT's need to be used to enhance the reverse blocking capability of the switches. Besides this, a C-L filter is used at the inverter output to filter the high frequency harmonic component generated at the output. Filtering will help to produce a sinusoidal output current.

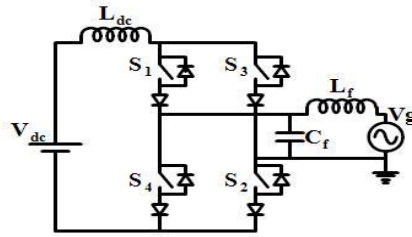


Fig.2. Conventional Single Phase CSI Topology connected to Grid

An L-C filter is not preferred at the output of CSI. This is because the high frequency current through the inductor at the inverter output may cause high voltage ($L di/dt$) and that may damage the switches. Therefore, C filter is connected across the output of inverter. The higher order harmonic content depends on the modulation technique used in the inverter. The issue of C-L filter is the interaction between order of harmonics generated and grid impedance that can lead to series resonance. In that case, current of that order of harmonics increases and damping becomes essential. Otherwise the quality of current gets affected. The resonant mode of operation has to be damped without affecting the inverter efficiency.

B. Modified CSI

Few modified CSI topologies used for GCPS are presented in Fig.3. [6-7].

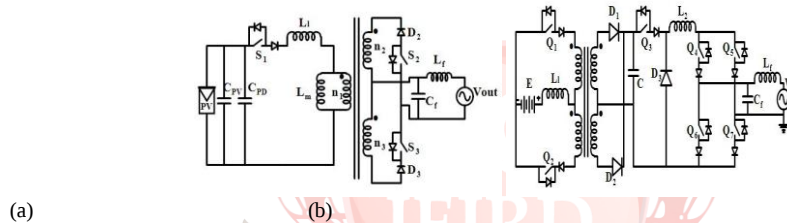


Fig.3. Modified CSI topologies used for GCPS (a) Conventional grid-connected flyback inverter. (b) CSI with a power decoupling circuit.

An approach depicting the modified CSI topology used for GCPS is as shown in Fig. 3(a) [6]. The topology consists of a power decoupling circuit comprising of a high value inductor (L_1) and thin-film capacitor (C_{pp}). In this topology, the inverter extracts maximum power from PV and produces output current with low total harmonic distortion (THD). The energy storage element plays a vital role in maintaining a balanced power. The capacitor C_{pv} reduces the ripple power generated at the PV side. The value of C_{pv} depends on the DC voltage, ripple content and capability of storing energy. Another modified approach is shown in Fig. 3(b) [7], that includes a generating circuit along with the decoupling unit. The inductor and the switch at the input side provide the buffering action. Due to higher value of the inductor, the system becomes bulkier, expensive and the overall efficiency of the system is reduced. The major challenge here is to achieve a good quality grid current with a reduced inductor value when implemented in a grid connected PV system.

II. CSI TOPOLOGY FOR TRANSFORMER-LESS GCPS

The efficiency of the CSI based GCPS can be improved by eliminating the line frequency transformer from the output side. This can be easily done due to the inherent voltage boosting capability of CSI unlike VSI. In that case integration of PV panels of lower output voltage is feasible as it reduces the need for series connection of PV panels. CSI for transformer-less grid integration is not much researched by researchers. However, there are few CSI topologies reported for the transformer-less grid interface as shown in Fig.4. [8-11].

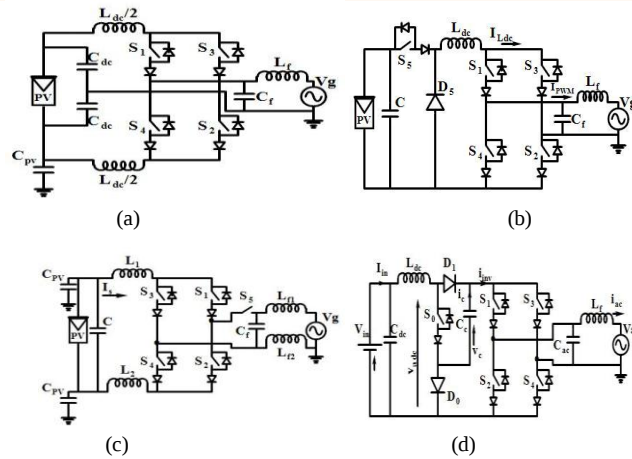


Fig.4.Modified CSI topologies for the transformer-less grid interface (a) Modified CSI structure with split capacitor; (b) Current source grid tie converter (c) CH5 inverter and (d) CSI topology with an additional switch

A CSI structure for the transformer-less GCPS is as shown in Fig.4(a) [8]. The structure differs from the conventional CSI as it involves a split capacitor and a common mode inductance arrangement. The center point of the split capacitor is connected to the grid neutral. This approach attenuates the leakage current and through a modification in the conventional control method, a low value inductor is used at the input DC-side of the inverter. The input inductor value is reduced assuming that the system consists of a lossless inverter. Based on the above assumptions the input PV panel voltage is selected to be lesser than half the value of grid voltage.

Another modified approach that eliminates the need of transformer is as shown in Fig.4(b) [9]. This modified topology comprises of an additional storage element, diodes and power semiconductor switches. This approach exhibits the ability to connect the input PV panel to a voltage lower than the peak voltage of the grid. The converter reliability is improved as the switching losses are reduced due to the absence of the dead band in the power switches. Also, the maximum power point tracking (MPPT) becomes simpler based on the ability to charge the inductor. Though a high quality sinusoidal current with a reduced THD gets injected into the grid interface, the THD appears to be a drawback of the topology.

Fig.4(c) represents another topology with modifications in the existing conventional structure of CSI known as CH5 inverter. The CH5 inverter is a single-phase transformer-less CSI with an additional switch in its construction. The switch with a fast recovery time appears to be in parallel with the grid in order to meet the duality principle which leads to a common mode voltage (CMV). The CMV appears to be half of the grid voltage as the inverter is operated with zero switching mode of operation. The methodology of optional switching state isolates the PV panel from the grid system thereby reducing the leakage current and switching losses. High frequency CMV is completely eliminated whereas low frequency grid voltage exists. In this approach a smaller value of leakage current appears due to its dependency on low frequency grid voltage [10].

Another topology with a modified circuit configuration for a single phase CSI is as shown in Fig.4(d) [11]. An active buffer provides the decoupling from PV panel to grid system thereby reducing the input voltage ripple. As compared to the conventional topology, the number of passive components is reduced. An efficient control scheme yields lower switching losses. The diodes operate with free-wheeling action in the active buffer-mode. As the current flow path is not designated through the switch, the recovery of diode does not occur. Thus the overall efficiency increases with a lower value of input side inductor. A comparison of CSI topologies is given in Table II.

TABLE II

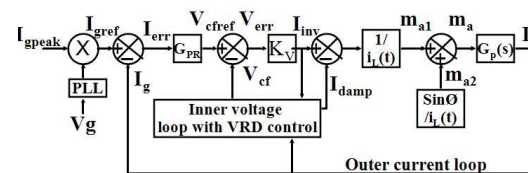
COMPARISON OF THE CSI TOPOLOGIES

Features	[12]	[13]	[14]	[15]
Components	*4-0-2-3	*4-4-3-3	*4-4-2-1	*4-4-2-2
THD	4.78%	2.73%	2.2%	1.44%
Power rating	250W	500W	1.5KW	Not reported
Switching frequency	-	4KHz	10KHz	5KHz
Leakage current	Negligible	Not reported	Not reported	Not reported

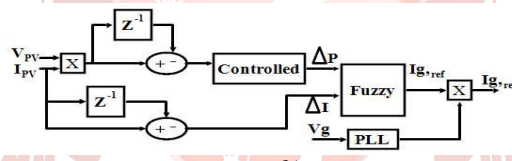
(* switch-diode-inductor-capacitor)

CONTROL SCHEMES

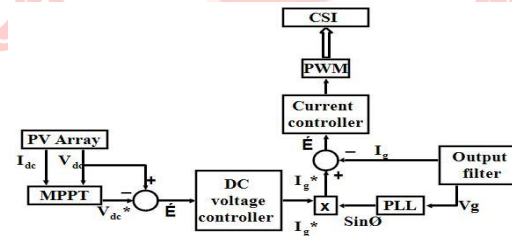
A survey of various control schemes reported in literature for grid connected systems is carried out and results are discussed in this section. The control schemes are shown in Fig.5 [12-15].



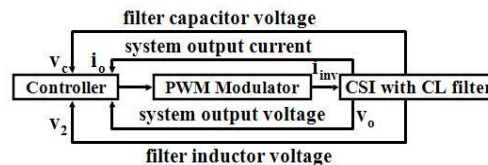
(a)



(b)



(c)



(d)

Fig. 5. Block diagram of various control schemes. a) Control scheme with outer current and inner voltage loop. b) FLC-based MPPT with AC current and voltage loops. c) Control diagram of the PV energy conversion system. d) Block diagram with feedback control.

Control scheme based on the principle of multi-loop control for a CSI based GCPS is as shown in Fig. 5. (a) [12]. If the input ripple current increases, it leads to lower order harmonics (LOH) for a lower value of inductor. In Fig.5 (a), a control scheme employing modified sinusoidal pulse width modulation (SPWM) compensates for the input ripple. For a SPWM, carrier is multiplied with the inductor current prior to the modulation process. This leads to reduced input ripple and an inductor of lower value can be selected. The process generates two modulating signals and compares it with the carrier wave. The inductor current is easily available from the maximum power point tracking (MPPT) process. Virtual damping is also incorporated in this scheme.

Another control scheme reported in Fig.5(b) [13], is based on a Fuzzy logic controller (FLC) that is used to

TABLE III

COMPARISON BASED ON THE PERFORMANCE FEATURES FOR DIFFERENT CONTROL SCHEMES

Performance Features	[15]	[16]	[19]	[20]	[22]	[23]	[24]	[25]	[26]
Reference tracking	Good	Good	-----	-----	Good	Good	Good	Good	-----
Disturbance rejection	Good	Not reported	Not reported	Moderate	High (less distortions)	Not reported	Better	Not reported	Good
DC link voltage ripple	Not reported	Reduced up to 70%	Reduced up to 75%	Not reported	Not reported	Not reported	Low	Not reported	Not reported
Type of control	Current	Voltage	Current	Current	Voltage	Voltage	Voltage	Current	Current
Fastness	Fast dynamic response	Fast dynamic response	Degraded dynamic response	Not reported	Improved dynamic response	Fast dynamic response	Fast dynamic response	Not reported	Fast dynamic response
Execution time	High	Low	Low	Moderate	High	Low	Low	Moderate	High
Complexity	Complex	Less complex	Complex	Complex	Less complex	Less complex	Highly complex	Less complex	Complex
Control method	Multi loop control	Predictive DC voltage control	Voltage Feed-forward control	Hybrid Multilevel -CSI control	Controller with Feedback linearization	Novel MPPT controller	New algorithm for MPPT	Control scheme for MPPT	Current Control

maintain the maximum power point. FLC comprises of four fuzzy subsets leading to a fuzzy algorithm of 16 fuzzy control rules. FLC generally consists of a Fuzzification, defuzzification, decision-making and a knowledge base unit. The mode of operation involved in a FLC is to obtain the fuzzy value using the process of fuzzification, followed by a list of fuzzy rules for the controller. Finally, the crisp value is obtained by defuzzification process. In the block diagram shown in Fig.5(b), Mamdani's method with Max-Min composition is used for fuzzification and the center of area algorithm (COA) is used in the defuzzification process.

Fig. 5(c) [14] depicts another control structure for the PV power conversion system. The structure comprises of phase locked loop (PLL) synchronization algorithm, the MPPT, the input power control and PWM incorporated grid current controller. The dc link inductor and the switch are modulated to produce an unipolar sinusoidal pulse width modulation (SPWM) output current. PLL synchronizes the inverter output current and grid voltage to produce a clean sinusoidal current reference. MPPT algorithm tracks the maximum power from the PV array irrespective of the weather and load conditions. PR controller is used as the current controller and the output of the controller is compared with the repetitive waveform for the PWM process.

Multi-loop control schemes are extensively used to control inverter topologies for power conversion applications as shown in Fig. 5(d) [15]. The system consists of a higher order CL passive filter. The strategy includes two control loops, the outer loop used for reference tracking and the inner loop to compensate for system disturbances thereby improving the system stability. The filter inductor voltage feedback control provides a better elimination of output voltage variations than the capacitor voltage feedback. A delay term is introduced due to the CSI PWM modulator and it affects the system stability. To compensate for the delay a lead network is added to the inner control loop. Thus the multi-loop control strategy provides improved system

efficiency. A comparison based on the performance features of various control schemes for the CSI topology is summarized in Table III

CONCLUSIONS

An exhaustive survey of Current Source Inverter (CSI) topologies and control schemes suitable for grid connected photovoltaic system is conducted and results are presented in this paper. Various CSI topologies are explored with respect to numerous performance parameters such as the total number of semiconductor switches, harmonic distortion in the output (THD), power rating, switching frequency and leakage current. Furthermore, several control schemes used for grid-PV interface are studied and compared to provide more insight in to the understanding of grid connected PV systems. Control schemes are compared based on tracking ability, disturbance rejection, ripple, dynamic response, execution time and the method of control. The results of comparison are summarized in tabular form in the paper.

It can be inferred from the study that if the value of dc side inductor and the effect due to the resonance of the output filter of CSI can be taken care of, then CSI based systems will be a good candidate for grid interfaced PV systems.

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