A Hybrid Active and Reactive Power Control with Quasi Z-Source Inverter in Single-Phase Grid-Connected PV systems

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Abstract— **This paper presents a hybrid method of active power and reactive power control strategy with Quasi Z-source inverter (QZSI) in single phase grid connected photovoltaic (PV) systems. The maximum power from the PV panel is extracted and most of it is supplied as active power to the grid. The major portion of required reactive power exchange to the grid is done by means of thyristor switched capacitor (TSC) and thyristor switched reactor (TSR) to improve the generation capacity of the PV system. In the proposed topology inverter shares the minimum reactive power and large change in reactive power will be delivered/absorbed by the TSC-TSR to get smoother operation in reactive power control. The DC voltage controller and the AC current controller is discussed in brief. The mathematical analysis for grid synchronization method is presented in detail. The control algorithm for active power and reactive power is analyzed and discussed in the paper. The simulation results are shown for validating the proposed concept.**

Keywords—Solar PV, Quasi Impedance source inverters, Thyristor Switched Capacitor (TSC), Thyristor Switched Reactor (TSR).

I. INTRODUCTION

Distributed generators (DG), like fuel cell, wind, tidal, geothermal and solar photovoltaic (PV) are integrated to the utility grid. The trend of supplying reactive power to the utility grid has started. These DG's having the capability of supplying the reactive power to the grid will reduce the burden on central generation systems and also helps in grid voltage balancing [1-4]. Supporting injection or absorption of reactive power or grid voltage regulation by the distributed generators are not currently permitted by the IEEE 1547-2003 grid synchronization standards [5], future generation utility grid codes for DG's will amend the present codes to fulfill the required needs including reactive power control to support grid voltage [6]. This will result in the ability of grid tied inverters to incorporate reactive power compensation, which will drive compliance with next generation grid requirements.

Shunt compensation of reactive power gained boom in late 1960's, then development of thyristor led the power engineers to perform intelligent control of switched capacitors in 1970's, later combination of Thyristor switched capacitors (TSC), Thyristor switched reactors (TSR) and Thyristor controlled reactors (TCR) were used for providing variable reactive power. Here combination of TSCs and TSRs will provide no harmonics generation, low inrush transients and maximum of one half cycle delay but stepwise control for single phase systems [7-8]. However, use of TCR will lead to harmonics generation but it was advantageous because of smoother operation. Irrespective of the reactive power demand, smoother operation can be achieved by combination of TSC and TCR, as the capacitor banks (TSCs) connected in parallel configuration provide step change in reactive power and a single reactor (TCR's) with firing angle control operation will give continuous reactive power. But this static compensation method generates small amount of harmonics, which can be removed by adding filters [9-15].

The maximum power generated by the Photo Voltaic array should be fed to the power grid. In order to perform this, power generated by the PV array should be synchronized with the power grid. This requires design of a converter that will achieve synchronization even with disturbance on the grid (because of lesser or over reactive power and more distributed power generating systems). The design is challenging because the ac output of the converter should satisfy the conditions for grid synchronization (the two generators must have equal line voltage magnitude, frequency and phase) and must be able to supply or absorb reactive power. This is more challenging because of variable dc voltage generated from PV array [16]. Recently, Quasi Z Source Inverter is one such inverter in which the dc voltage generated by PV array is boosted using Quasi Z Source network and then inverted to ac voltage [17]. The unique feature of boosting the dc voltage and presence of the reactive components in the QUASI network helps in getting a higher ac rms output voltage and precise reactive power control compared to conventional converters [16-18].

The present day inverters connected to grid will control the active power and reactive power but supplying or absorption of reactive power will lead to loss of great portion of the real power [19]. Continuous growth in DG's is leading to voltage

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and frequency variations during overload and light load conditions. Hence the DG's themselves have to generate or absorb the reactive power to control the fluctuations [20-24]. The main idea of this topology is to deliver the maximum power to the grid even under the disturbance condition without reducing active power supply to certain percentage and managing required reactive power for smoother operation.

II. PROPOSED INVERTER TOPOLOGY

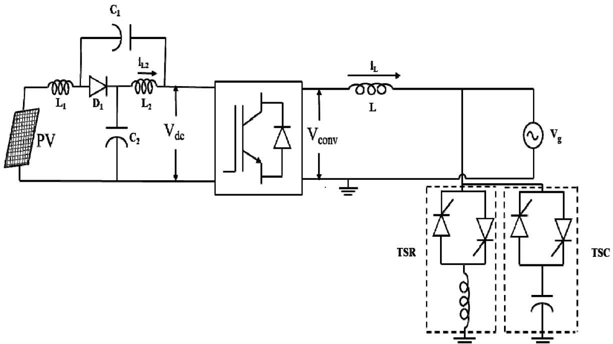

Fig. 1 – Proposed topology showing Quasi Impedance Source Inverter, TSC-TSR

Synchronization of power generated by the PV array to the grid is achieved using qZSI. To accomplish this, one need to control the magnitude and phase of the current injected by the converter into the grid. This requires the control of output voltage of the qZS Inverter. The output voltage magnitude should be controlled whereas frequency and phase should be same as that of the grid voltage. When synchronized with the grid, the converter will supply active power and exchange reactive power with the grid. Say if power factor is low, then a significant part of the power generated will be fed as reactive power to the grid. To minimize this and to maximize active power transfer to the grid, the power factor should be unity which is an ideal case [25-26]. This can be achieved by implementing a system in which qZSI only supplies active power to the grid. The reactive power demand will be met by thyristor based elements like TSC-TSR. The stepped response of TSC-TSR can be eliminated by exchanging the reactive power via qZSI (equal to half of step size of least rated thyristor based element. For example, if least rating of TSC is 100VAR then the amount of reactive power exchange from qZSI will be 50VAR). It means that qZSI will supply mostly active power to the grid and a minor part of reactive power whereas the major part of reactive power will be managed by TSC-TSR. Thus, the proposed topology is a combination of qZSI connected to PV array integrated with TSC-TSR.

It is well known that the output of the converter consists of pulses (having magnitude equal to dc bus voltage) of varying width according to sinusoidal signal of reference signal. The converter output will have a frequency same as reference signal. The magnitude of these pulses are not same as grid voltage at every instant [27]. This will allow an inrush current to flow into the converter because of instantaneous voltage difference. A filter is added at the converter output to prevent this. An inductor is connected as a filter between the converter and the grid.

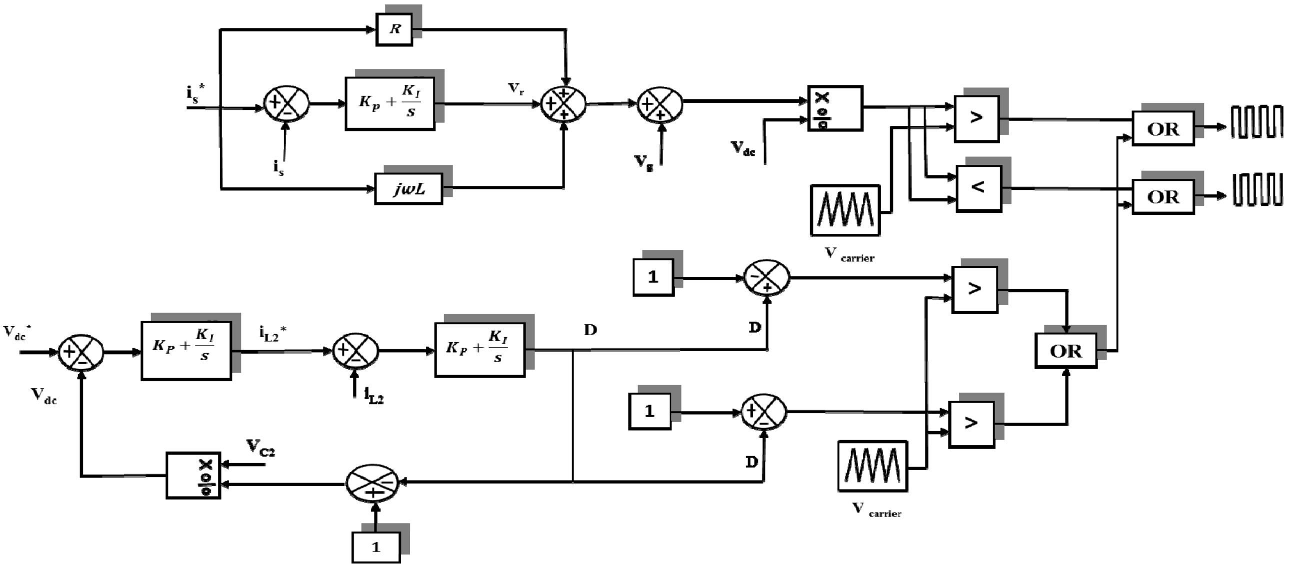

Fig. 2 – Control Algorithm for DC Bus Control and Converter Current control

III. PROPOSEC CONTROL ALGORITHM

The control algorithm for controlling dc bus voltage and converter current of qZSI is as shown in Fig. 2.

a) *DC Bus Control*

DC bus control here is different compared to conventional converters wherein control of voltage across a capacitor is required. Here the challenge is to control the virtual dc bus V_{dc} as shown in the Fig. 1. The voltage measured at that point will be sum as of voltage across capacitors C_1 and C_2. The current flowing through the inductor i_{L2} can be defined as:

$$i_{L2}(s) = \frac{V_{c2} - V_{dc}}{R_{L2} + sL_2} \dots (1)$$

For controlling this current i_{L2}, the voltage across the capacitor C_2 should be controlled. However, it is known that the voltage s V_{c1} and V_{c2} can be described as a function of dc bus V_{dc} and shoot through duty ration D.

Based on this theory the control algorithm is developed, this loop senses actual V_{dc} and compares it with the reference dc link voltage. This error is passed through PI controller to give i_{L2} reference. It is compared with actual i_{L2} and error is processed with PI controller to yield the shoot through factor D. Then 1-D and D-1 are compared with carrier wave to give boosting pulses.

b) *Pulses generation for TSC TSR*

For a given reactive power demand, comparison is done to generate pulses for TSC-TSR. The control diagram is as shown in Fig. 3. The remaining reactive power demand is converted into a current reference. This value is multiplied with Coswt. This forms the reactive current component of the converter current reference.

Switching in and out of TSC-TSR should not create any voltage and current transients. So that, the TSC is switched in and out at the negative and positive peak value of the input voltage to avoid current transients, a small reactor is placed in series with the capacitor to avoid inrush current. The TSR have to switch in and out at the zero crossing of the currents to avoid transients [7].

C) *Converter Current Control*

Given active power demand is converted into a current which is multiplied with Sin (wt). This current is added with reactive component of converter current to give converter current reference. This current reference is compared with actual converter current. The error generated is passed through PI controller to give control voltage. This is added with compensation of inductor voltage drop and grid voltage to give voltage reference for inverter. This reference is divided with sensed dc bus voltage to get modulation signal. This signal is compared with carrier waves to get the pulses. OR operation is performed between these pulses and pulses generated in DC Bus Control loop. The resultant pulses are used for switching of inverter legs (IGBTs).

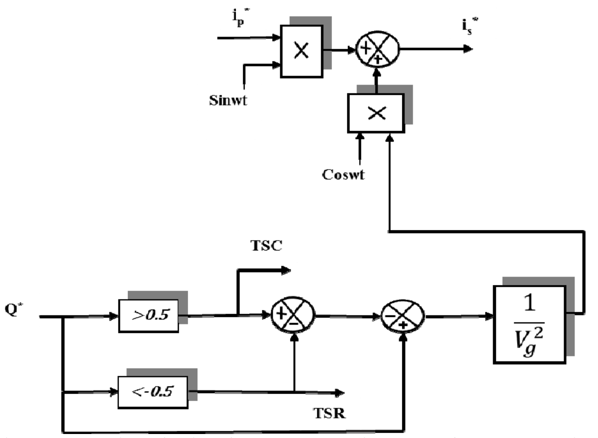

Fig.3 – Generation of pulses for TSC TSR and current reference generation

IV. SIMULATION RESULTS

The proposed QZSI with TSC-TSR is simulated using Matlab/Simulink software. For validating the control algorithm, one need to make sure that dc bus voltage is tracked, converter current is controlled and TSR-TSC are switched according to the demand of reactive power. The parameters used for the simulation purpose are given in Table 1:

Table 1 Simulation Parameters

Input DC voltage	220V
Output grid voltage	310Vac(peak)
Grid frequency	50Hz
DC Bus Reference	500V
Output power (Inverter)	760W
Switching frequency	10kHz
$L_1 = L_2$	2mH
$C_1 = C_2$	2000uF
TSR reactor	150mH
TSC capacitor	68uF

DC Bus Voltage Tracking:

To ensure that intended operation is performed, it is required to control the dc bus voltage at the output of the quasi Z Source Network. In this simulation, reference of dc bus voltage is kept at 500V.

The response of the system to reference is as shown in the Fig. 4. The ellipse marked are the instants of change in the reactive power reference for qZSI but the dc bus voltage is maintained at desired value.

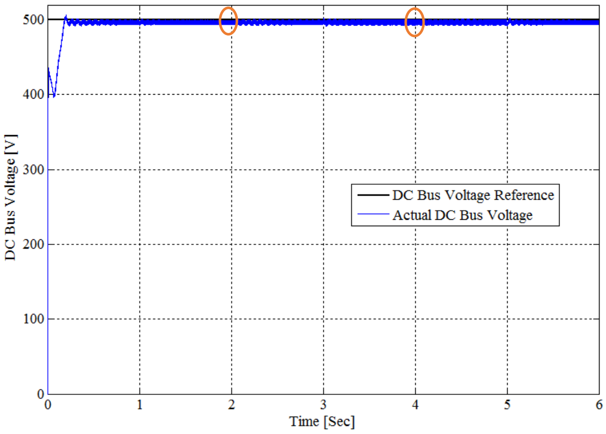

Fig. 4 – DC Bus Voltage Tracking during operation

To validate the proposed concept, the active and reactive demand should be such that all the possible modes of operation are observed. The reference for the system is shown in the figure 5.

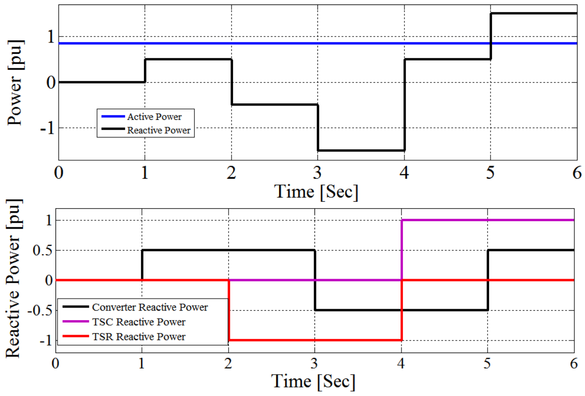

Fig. 5 – Active and Reactive Power per unit Demand for the system. The below graph gives the contribution of each unit as a function of time

Active reactive power control:

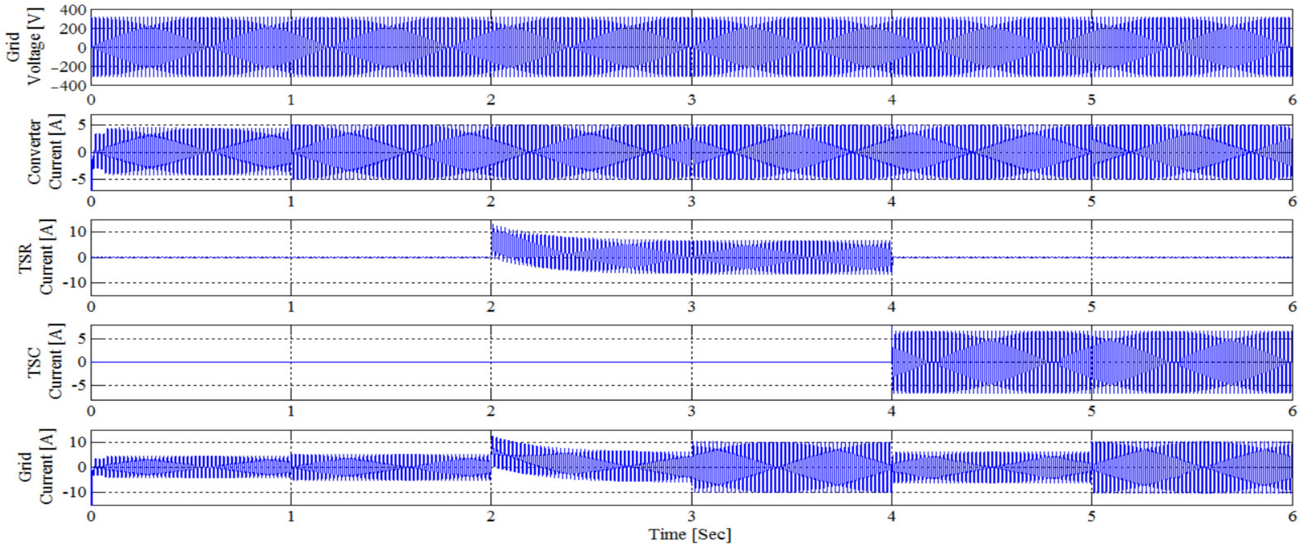

Fig. 6(a) – Response of the system for the given active and reactive power reference.

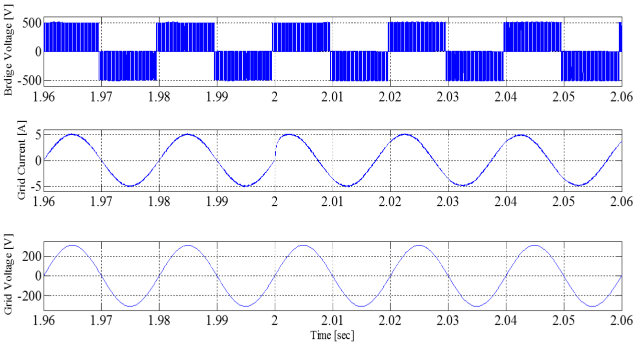

Fig. 6(b) – System Response at t = 2sec

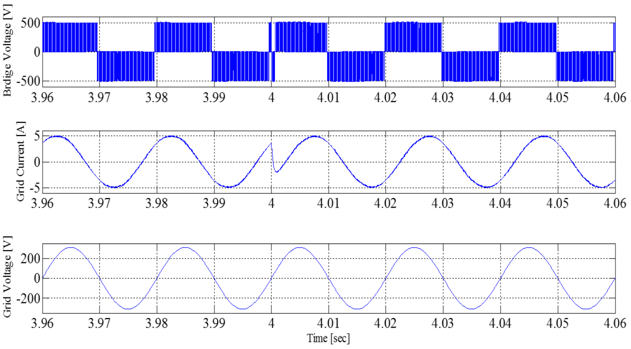

Fig. 6(c) – System Response form at t = 4 sec

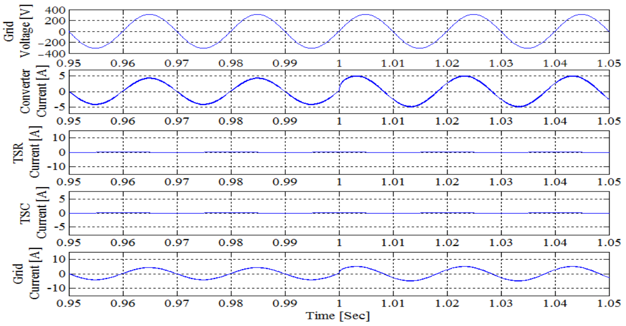

Fig. 7(a) – System Transient response with only qZSI on.

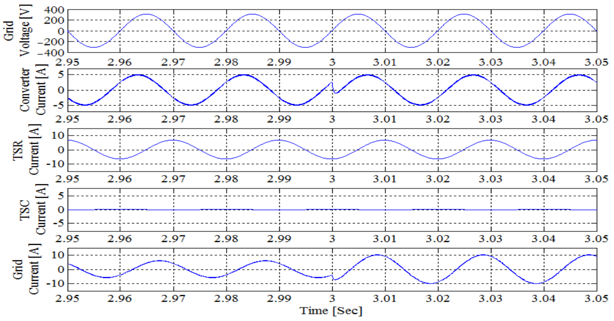

Fig. 7(b) – System transient response with qZSI and TSR on.

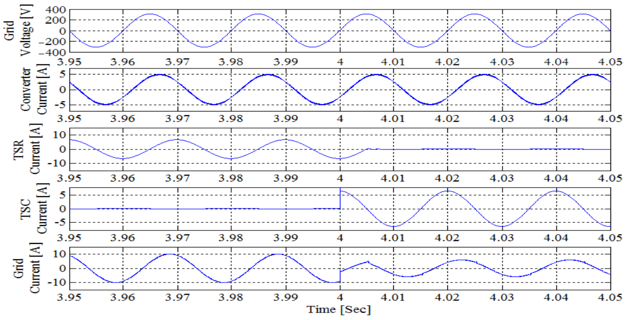

Fig. 7(c) – System Transient response with qZSI and TSC on.

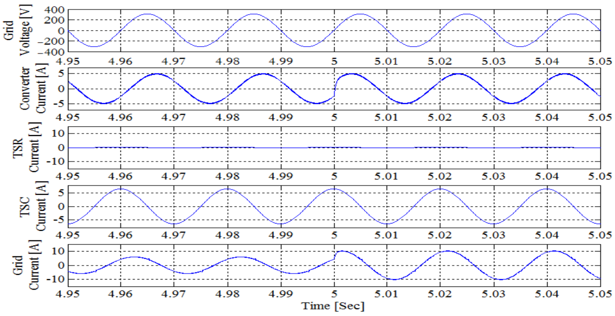

Fig. 7(d) – System Transient response with qZSI and TSC on.

From 0 < t < 1 sec: For this duration, reactive power reference is zero and active power reference is 0.84pu. The converter current response is in phase with the grid voltage and the magnitude of current is 4.2A (peak). The response of the system is shown in Fig. 7(a). Throughout the entire operation from 0 < t < 6 sec, the active power supplied is constant.

From 1 < t < 2 sec: For this duration, active power is kept constant at 0.84pu (same as above). The reactive power reference is 0.5pu. Reactive Current Component of 2.5A rms leading is added to 4.2A in phase component. The resultant current reference is supplied by the converter to the grid thereby meeting the active and reactive power demand. The response of the system is shown in Fig. 7(a).

From 2 < t < 3 sec: For this duration, reactive power reference is changed to -0.5pu. Already converter is supplying 0.5pu reactive power to the grid. To meet the remaining reactive power, TSR is turned ON. With this combination, reactive power from -1pu to -0.5pu can be met in a stepless and smooth manner. Response of the system is shown in Fig. 7(b).

From 3 < t < 4 sec: For this duration, reactive power reference is changed to -1.5pu. In addition to TSR, converter current reference should be made lagging instead of lagging. The resultant converter current and the response of the system is as shown in Fig. 7(b). With this combination, reactive power demand can be met from -1pu to -1.5pu.

From 4 < t < 5 sec: For this duration, reactive power reference is changed to 0.5pu. Here TSR is turned OFF and TSC is turned ON. The converter current is lagging in nature and the resultant reactive power supplied to the grid is 0.5pu. The response of the system is shown in Fig. 7(c). With this combination, reactive power demand can be met from 0.5pu to 1pu.

From 5 < t < 6 sec: For this duration, reactive power demand is changed to 1.5pu. The converter current reference is changed to leading with TSC kept ON. With this combination, reactive power can be supplied from 1pu to 1.5pu. The response of the system is shown in Fig. 7(d).

With above discussion, it can concluded that converter can exchange reactive power from -0.5pu to 0.5pu. By combination with TSC TSR, the reactive power management can be done from -1.5pu to 1.5pu meanwhile active power is kept constant at 0.84pu.

V. CONCLUSION

The proposed topology for controlling the active power and reactive power is successfully implemented. Here the minimum amount of reactive power is generated from the inverter by utilizing the active power from the solar panels and the larger amount of reactive power is generated from the TSC-TSR. The reactive elements TSC-TSR switching technique also gives satisfactory performance with no sudden transients in the system.

Synchronization of PV array via qZSI is successfully implemented and the converter is controlled for delivering lagging, leading and in phase current to the grid. DC bus tracking control algorithm is successfully implemented, this is critical because rms value of the output voltage of converter depends on the virtual dc bus at the output of the quasi Z Source Network. Integration of qZSI with the thyristor based TSC-TSR is done so that the reactive power can be controlled in a stepless and smooth manner from -1.5pu to 1.5pu.

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