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REACTIVE POWER COMPENSATION AND OPTIMIZATION STRATEGY FOR FUZZY LOGIC CONTROLLED CASCADED SOLAR SYSTEMS

Anjana.B, final year M.E (P.E.D)
Infant Jesus Engineering College
anjanabanu6@gmail.com

Abstract:

Cascaded multilevel converter structure can be appealing for high power solar photovoltaic (PV) systems thanks to its modularity, scalability, and distributed maximum power-point tracking (MPPT). However, the power mismatch from cascaded individual PV converter modules can bring in voltage and system operation issues. This paper addresses these issues, explores the effects of reactive power compensation and optimization on system reliability and power quality, and proposes coordinated active and reactive power distribution to mitigate this issue. A vector method is firstly developed to illustrate the principle of power distribution. Accordingly, the relationship between power and voltage is analyzed with a wide operation range. Then an optimized reactive power compensation algorithm (RPCA) is proposed to improve the system operation stability and reliability, and facilitate MPPT implementation for each converter module simultaneously. Furthermore, a comprehensive control system with RPCA is designed to achieve effective power distribution and dynamic voltage regulation. Simulation and experimental results are presented to demonstrate the effectiveness of the proposed reactive power compensation approach in grid-interactive cascaded PV systems.

I – INTRODUCTION

Worldwide renewable energy resources, especially solar energy, are growing dramatically in view of energy shortage and environmental concerns. Large-scale solar photovoltaic (PV) systems are typically connected to medium-voltage distribution grids, where power converters are required to convert solar energy into electricity in such a grid-interactive PV system. To achieve direct medium-voltage grid access without using bulky medium-voltage transformer, cascaded multilevel converters are obtaining more and more attraction due to their unique advantages such as enhanced energy harvesting capability implemented by distributed maximum power point tracking (MPPT), improved energy efficiency, lower cost, higher power density, scalability and modularity, plug-N-power operation, etc.Cascaded multilevel converters have been successfully introduced in medium to high voltage applications such as large motor drives, dynamic voltage restorers, reactive power compensations, and flexible AC transformation system (FACTS) devices, their applications in PV systems still face tough challenges because of solar power variability and mismatch of maximum power point from each converter module due to manufacturing tolerances, partial shading, dirt, thermal gradients, etc. In a cascaded PV system, total AC output voltage is synthesized by the output voltage from each converter module in one phase leg, which must fulfill grid codes or requirements. Ideally, each converter module delivers the same active power to grid; hence, symmetrical voltage is distributed among these modules. However, in the event of active power mismatch from these modules, the converter module with higher active power generation will carry more proportion of the whole AC output voltage, which may result in over modulation if the system is not oversized design. In serious scenario, the synthesized output voltage may not be enough to meet the system requirement. As a result, the active power mismatch may not only result in losses in energy harvesting but also system instability and unreliability due to the inadequate output voltage or over-modulation issues.

Motivations are towards addressing the aforementioned issues and approaching to mitigate the negative effect of active power mismatch. MPPT is achieved for each module in these approaches to enhance energy harvesting. However, only unity power factor control was considered and the inherent reactive power compensation capability of the cascaded PV system is ignored. As a result, the PV system still surfers from the degraded power quality and system reliability. It is recognized that reactive power compensation is able to provide strong voltage support in a wide range. Proper reactive power compensation can significantly improve the system reliability, and in the meantime help the MPPT

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implementation for the cascaded module under unsymmetrical condition as well as comply with the system voltage requirement simultaneously. All of these have spurred growing interest in reactive power compensation for the cascaded PV system.

A reactive power compensation strategy is integrated in the control system of the cascaded PV system in this work. However, this approach fails to consider the effect of voltage or current distortion caused by unsymmetrical active power on the power detection and distribution, and the converter module with high active power generation is not required to provide reactive power, which has limited the capability of reactive power compensation. Therefore, optimized solutions have yet to be found and it is very critical to develop an effective reactive power compensation strategy for the grid-interactive cascaded PV system. This paper proposes an optimized reactive power compensation method and evaluates the effect of reactive power compensation on system reliability and power quality in the grid-interactive PV system with cascaded converter modules. A proper reactive power compensation and distribution is considered to eliminate the over-modulation caused by unsymmetrical active power. In the proper reactive power management, one firstly emphasizes that the output voltage from cascaded PV system must to meet the grid code. The maximum reactive power compensation will be activated to mitigate this issue once active power mismatch occurs and voltage and current distortion are detected. In this way, correct active and reactive power can be calculated, and MPPT for each module can be achieved and grid code can be met simultaneously. However, over-compensation of reactive power may be provided, which increases the system burden. Therefore, reactive power compensation among modules is optimized and redistributed considering their respective active power contribution on the premise that MPPT can be achieved and grid code is fulfilled.

II – RELATED WORK

In [1],JavadEbrahimi et al.,proposed a new topology of a cascaded multilevel converter. The proposed topology is based on a cascaded connection of single-phase sub-multilevel converter units and full-bridge converters. Compared to the conventional multilevel converter, the number of dc voltage sources, switches, installation area, and converter cost is significantly reduced as the number of voltage steps increases.The structure of the proposed topology is optimized in order to utilize a minimum number of switches and dc voltage sources, and produce a high number of output voltage steps.

David Meneses et al., presented a comprehensive review of stepup single-phase non-isolated inverters suitable for ac-module applications. A discussion of the analyzed topologies regarding the obtained ratings as well as ground currents is presented. Recommendations for topological solutions complying with the application benchmark are provided.

SouhibHarb et al., proposed a new methodology for calculating the mean time between failures (MTBF) of a photovoltaic module-integrated inverter (PV-MII). Based on a stress-factor reliability methodology, their technique applies a usage model for the inverter to determine the statistical distribution of thermal and electrical stresses for the electrical components. The salient feature of the proposed methodology is taking into account the operating environment volatility of the module-integrated electronics to calculate the MTBF of the MII. This leads to more realistic assessment of reliability than if a single worst case or typical operating point was used.

In [4], a high-frequency link multilevel cascaded medium-voltage converter is proposed. The common high-frequency link generates multiple isolated and balanced dc supplies for the converter, which inherently minimizes the voltage imbalance and common mode issues. An 11-kV system is designed and analyzed taking into account the specified system performance, control complexity, cost, and market availability of the power semiconductors.

Jun Mei et al., proposed an improved phase disposition pulse width modulation (PDPWM) for a modular multilevel inverter which is used for Photovoltaic grid connection. This new modulation method is based on selective virtual loop mapping, to achieve dynamic capacitor voltage balance without the help of an extra compensation signal. The concept of virtual sub module (VSM) is first established, and by changing the loop mapping relationships between the VSMs and the real sub modules, the voltages of the upper/lower arm's capacitors can be well balanced.

Literature [6]investigates the dynamic properties of a PV generator and demonstrates that it has a profound effect on the operation of the interfacing converter. The most important properties an input source should have in order to emulate a real PV generator are defined.

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III – PROPOSED SYSTEM

Figure 1 describes the system configuration of one two-stage grid-interactive PV system with *n* cascaded converter modules for each phase, which is very suitable for the medium/high voltage application. It can be immune to the leakage current and PV potential induced degradation issues. In this paper, three-phase PV converters are connected in "wye" configuration. They also can be connected in "delta" configuration.

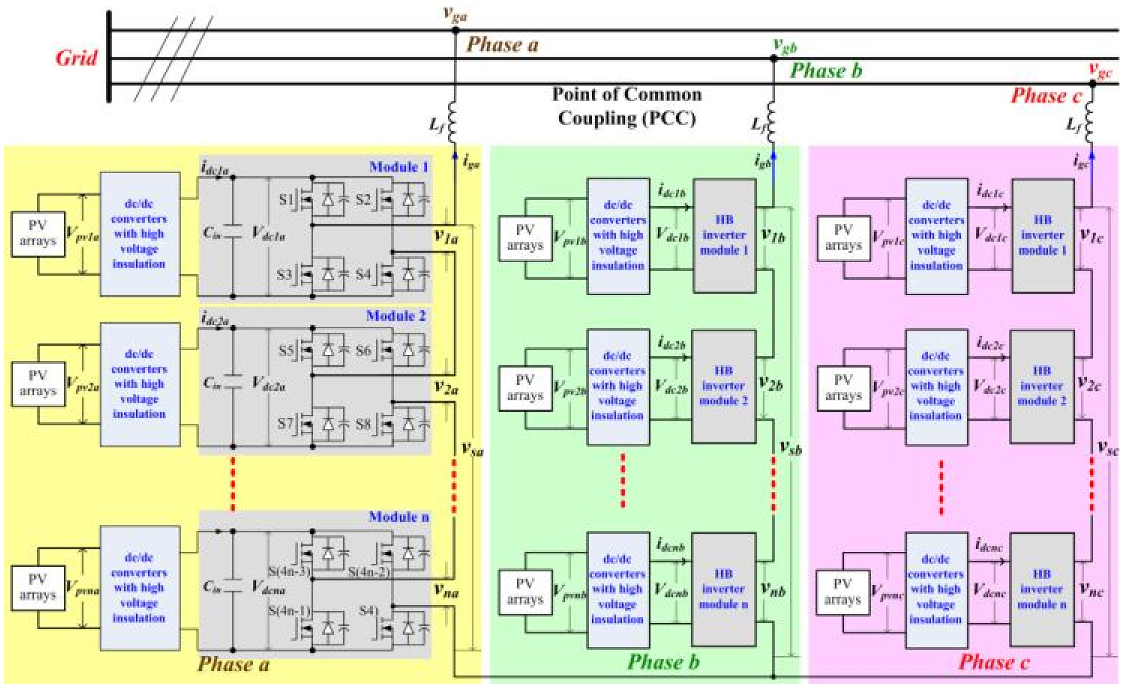

Figure 1 Proposed system Topology

In the two-stage PV system, the first-stage dc/dc converters with high voltage insulation can achieve the voltage boost and MPPT for the segmented PV arrays. The second-stage three-level H-bridge (HB) converter modules are cascaded to augment the output voltage, deliver active power to grid, and provide reactive power compensation. The dc-link voltage can be controlled to be constant and same in each converter module. For the low voltage application, single-stage system configuration can be considered, where the dc/dc converters in Figure1 can be replaced by Quasi-Z-Source network or be removed according to systemrequirement. The single-stage PV system features simple configuration and fewer devices integration in each module. However, additional methods need be developed to solve the leakage current issues. In addition, the system may need to be oversized to accommodate the wide input voltage variation. In these configurations, unsymmetrical active power may be harvested from the cascaded modules due to PV module mismatch, orientation mismatch, partial shading and so on.

A. Reactive Power Compensation Algorithm

Appropriate reactive power compensation will enhance the cascaded PV system reliability and improve power quality, especially for unsymmetrical active power generation. Fig. 9 shows the proposed reactive power compensation algorithm for the cascaded PV system in phase a. The same algorithm can be used in phase b and c. The reactive power compensation requirement Q^*_{ga} is associated with modulation index of output voltage from cascaded PV converter modules, PCC voltage and MPPT control implementation which will determine the active power reference P^*_{ga}. In the initial state, MPPT control for each PV converter module is enabled and unity power factor is implemented considering symmetrical operation condition acts on these cascaded modules. In this scenario, Q^*_{ga} is zero and P^*_{ga} is derived from the sum of maximum active power from the individual PV arrays $\sum_{j=1}^{n} P_{pvja}$ subtracting power loss, which is defined as $k_1 P_{ga\_rated}$. Consider the known P_{ga_rated}, k_1 can be calculated as P^*_{ga}/P_{ga_rated}. It is determined by the MPPT control and dc voltage

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control, which will be introduced in the following sub-section *B*. During the system operation, unsymmetrical active power may be generated from these modules due to PV module mismatch, orientation mismatch, partial shading, etc. As a result, over-modulation may occur on the PV converters output voltage, especially for the converter module with higher active power output, which seriously impairs the MPPT of each module and system reliability. Once the over-modulation is identified, the intentional reactive power compensation is activated to mitigate the over-modulation with grid code authorization. If PCC voltage is high, maximum reactive power will be absorbed from grid to bring down the PCC voltage with the normal voltage range according to the IEEE Std. 1547, as well help possible MPPT implementation for each converter module simultaneously. k_2 =1 is designated to achieve the maximum reactive power absorption. The PV system operates like an inductor. Otherwise, the maximum reactive power is injected into grid to provide the PCC voltage support. k_2 = -1 is designated to execute the maximum reactive power injection. The PV system operates like a capacitor. If the maximum reactive power compensation still cannot eliminate the over-modulation, MPPT control will be disabled to ensure the security and stability of the cascaded PV system. Instead, reactive power compensation can be optimized, that is the selection ofk_2, to reduce the risk of overvoltage or undervoltage caused by the maximum reactive power compensation. There are different ways to optimize reactive power distribution in the cascaded PV converter modules. It is noted that the selected dc voltage and allowed voltage ripple will also impact on the reactive power compensation optimization.

B. Control System Design

A cascaded PV control system with the proposed RPCA in phase A is depicted in Figure 2. The same control system is applied in phase b and c. particularly; the proposed PRCA can be applied for any type of cascaded PV system, such as single-stage and two-stage PV system. The active and reactive power is regulated in the *dq*synchronous reference frame. PLL is used to synchronize the output voltage of the cascaded PV converters, grid current with so that the desired power control can be achieved. The RPCA provides the desired reactive power during unsymmetrical active power from the cascaded PV converter modules. The *q*-axis component command of grid current can be derived from the desired. The maximum active power harvesting from each module can be implemented by MPPT control and dc-link voltage control. In the one-stage cascaded PV system, the dc-link voltage reference is obtained by the MPPT control for individual PV arrays. In the two-stage cascaded PV system, is designated based on the grid voltage requirement. The on each PV converter module is controlled to track to generate the *d*-axis component command of grid current, which will coordinate the MPPT implementation. The decoupled current control loop is developed to implement the current track of i_{ga_d} and i_{ga_q} and generates the *d-q* components v_{sa_d} and v_{sa_q} of v_{sa} in the *dq*synchronous reference frame. In order to achieve the independent control of active and reactive power from each module, v_{sa_d} and $v_{sa_q}$are converted to and in the *d'q'* synchronous reference frame. The active power from each module P_{pvja} can be obtained from the MPPT control. Therefore, the voltage $v_{ja\_d'}$ for the j^{th} converter module with respect to the activepower is calculated. The $v_{ja\_q'}$ related to reactive power can be obtained based on the $v_{ja\_d'}$ and (6). Consequently, the output voltage v_{ja}(j=1,2,…,n) from each converter module can be synthesized. The modulation index of output voltage can be obtained by $m_{ja}=\frac{v_{ja}}{v_{dcja}}$. As a result, the active and reactive power can be properly distributed in each converter module, which achieves the MPPT and augments the security and stability of the cascaded PV system operation simultaneously.

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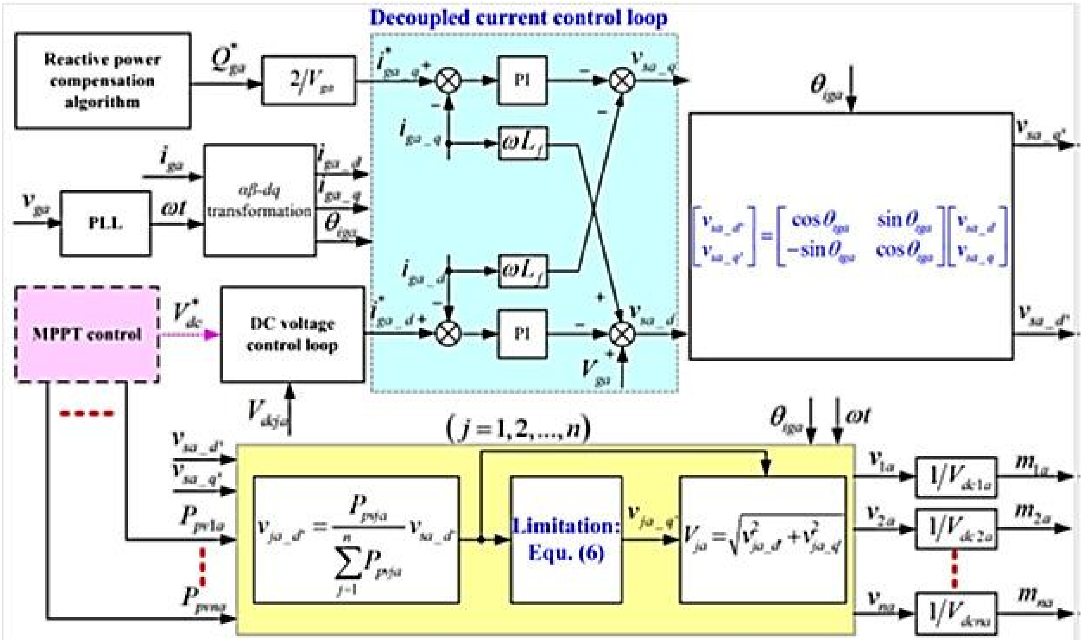

Figure 2. Control System blocks for the proposed system

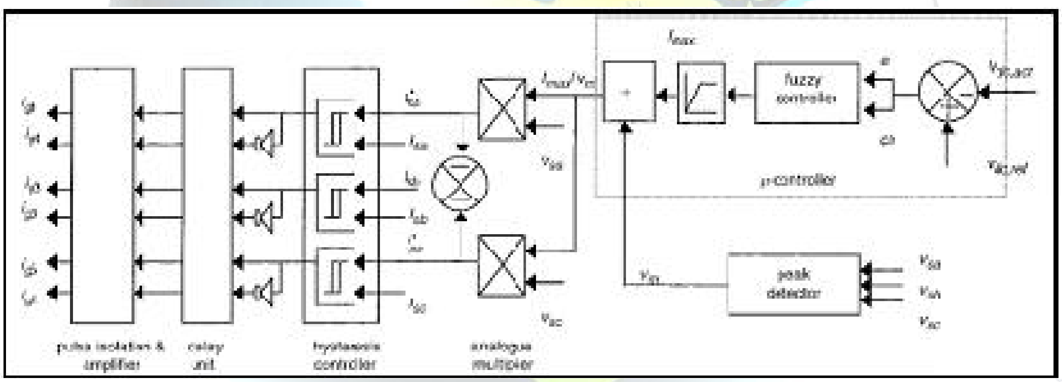

Figure 3. Fuzzy logic control scheme

C. Fuzzy Logic Controller Design

For implementing the control algorithm of a shunt active power filter in closed loop, the DC capacitor voltage is sensed and compared with a reference value.

The obtained error $e(n) = V_{dc,ref}(n) – V_{dc,act}(n)$

Change in error $ce(n) = e(n) – e(n-1)$

At the nth sampling instant are taken as inputs for the fuzzy processing. The control scheme is shown in Fig. 3. After a limit, the output of the fuzzy controller is considered as the amplitude of the reference current I_{max}. This current I_{max} takes care of the losses in the system and the active power demand of load. By comparing the actual source currents (isa, isb, and isc) with the reference current templates (isa*, isb*, and isc*) in the hysteresis current controller, the switching signals for the PWM converter are obtained [6]. After proper amplification and isolation, the switching signals so obtained, are given to switches of the PWM converter.

The internal structure of the fuzzy controller is shown in Figure 3. The error 'e' and change in error 'ce' are the real world numerical variables of the system. The following seven fuzzy levels or sets: NB (negative big), NM (negative medium), NS (negative small), ZE (zero), PS (positive small), PM (positive medium), and PB (positive big) are chosen to convert these numerical variables to linguistic variables as shown in Figure 4. The characterization of fuzzy controller is as follows: i. seven fuzzy sets for each

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input and output. ii. Triangular membership functions for simplicity. iii. Fuzzification using continuous universe of discourse. iv. Implication using Mamdani's 'min' operator. v. Defuzzification using the 'centroid' method.

The elements of the rule base table are determined based on the theory that in the transient state, large errors need coarse control, which require coarse input/output variables and in the steady state, small errors need fine control, which require fine input/output variables. Based on this the elements of the rule table are obtained as shown in Table.1, with „e" & „ce" as inputs.

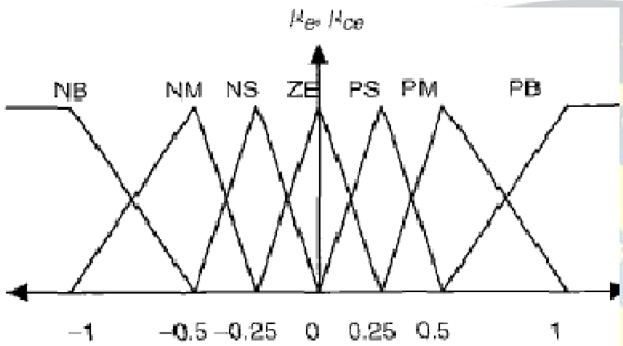

Figure 4 Input Membership function

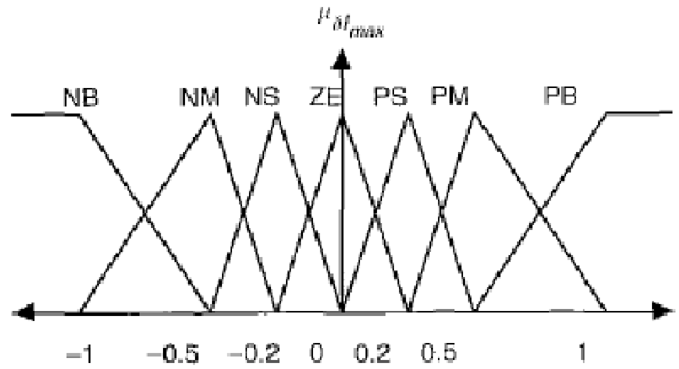

Figure 5 Output Membership function

Table1. Fuzzy rule table

e \ ce	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NB	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

IV SIMULATION RESULTS

The proposed work is completed on MATLAB software on the version of R2013a. The designed circuits were drawn and simulated using MATLAB Simulink and Sim power system toolboxes. The following table represents the specifications of the proposed system

Table2. Specifications of the proposed system

Grid Voltage	380V
Phase	0 deg
Frequency	50 Hz
Load real power	5kW
Load reactive power	5kVAR
PV panel power	150W/panel
No. of PV panels	72
Insolation	1000W/m^2
Temperature	25°C

Kp (Proportional gain)	0.025
Ki (Integral gain)	.025

The following figures represents the simulation results for the proposed system where it is very clearly to see that, the power factor is on the range of 0.95 -0.93.

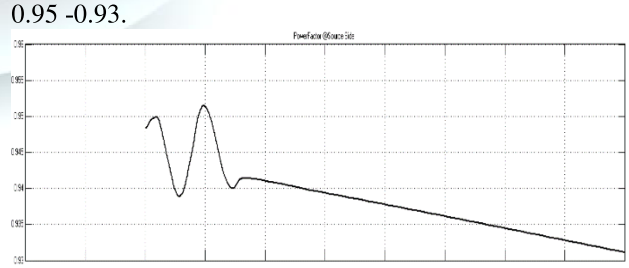

Figure 6. Power factor at source side

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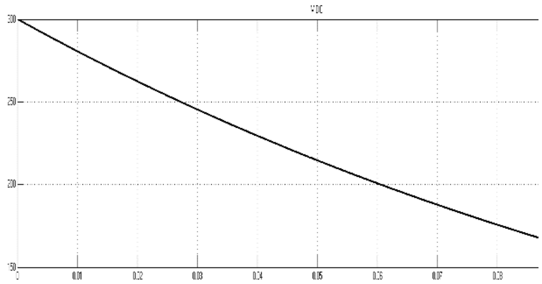

Figure 7. DC link voltage

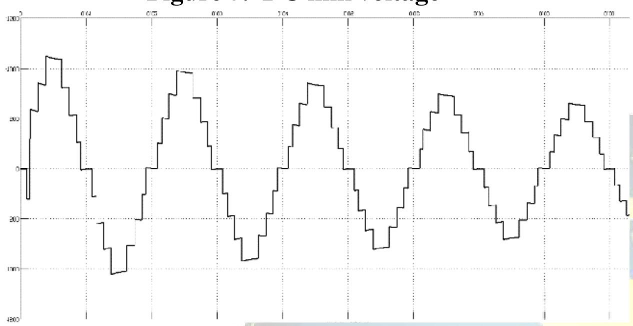

Figure 8. Inverter response

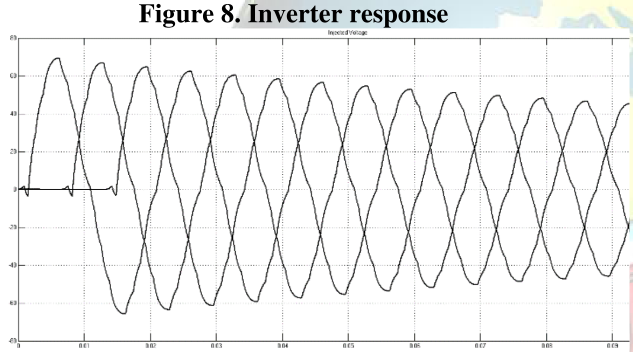

Figure 9. Injected voltage

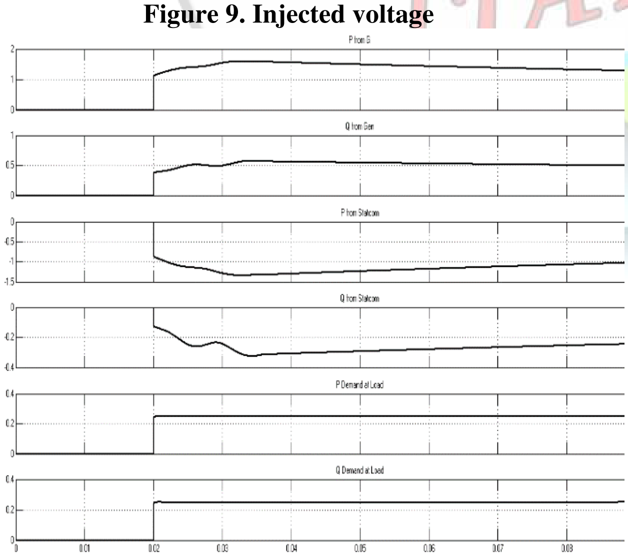

Figure 10.Real and reactive power comparison

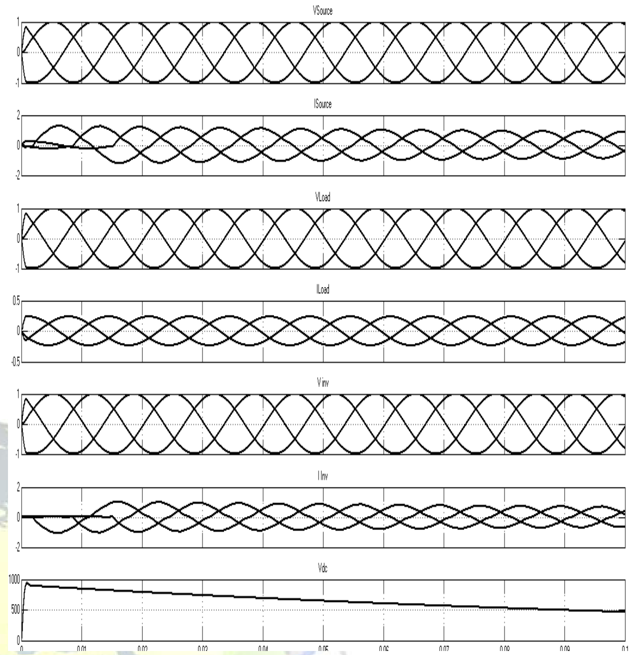

Figure 11. Overall Waveforms of proposed system

V. CONCLUSION

This paper addressed the effect of reactive power compensation on system operation in grid interactive Fuzzy logic controlled cascaded PV system. The stability and reliability issue caused by unsymmetrical active power was specifically analyzed. Reactive power compensation and distribution was introduced to mitigate this issue. The output voltage of each module was verified to directly determine the power distribution was illustrated with a wide power change range. An optimized RPAC was proposed considering the MPPT implementation, grid voltage and over-modulation. Moreover, the RPAC eligible to be integrated into different types of cascaded PV system. Correspondingly, the control system with MPPT control and optimized RPCA was developed and validated by the simulation result under different scenarios. The approach was demonstrated to be able to effectively enhance system operation stability and reliability, and improve power quality

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