Design of Cascaded Modular Multilevel Converter for Grid Connected PV System

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Abstract

Today renewable energy sources are becoming more popular with ever increasing energy demand and environmental pollution due to non-renewable energy sources. Among the renewable energy sources, major portion of energy is generated using Photovoltaic system. Grid connected photovoltaic systems are gaining more importance. Large-scale grid connected PV systems can be easily and effectively interfaced with the modular multilevel converters when compared with conventional DC-DC converters. As modular multilevel converters have unique advantages like enhanced energy harvesting capability, scalability etc. they can be used for many applications such as STATCOM, harmonic compensator and so on. PV systems face tough challenges such as output voltage over modulation and power flow control due to irregular output voltages from PV arrays. This paper proposes a decoupled active and reactive power control method to improve the system performance. A 3-MW, 12kV PV system with the proposed control strategy is modelled and the results are verified using MATLAB simulation.

Key words - *Multilevel converters, decoupled active and reactive power control, photovoltaic systems.*

I. INTRODUCTION

Nowadays the uses of non-conventional energy sources are becoming more and more popular due to increased energy usage and environmental concerns from the conventional fossil fuels [1]-[3]. Due to this reason the world is attracted towards the renewable energy sources. In non-conventional energy sources the solar energy has the best advantage over all other energy sources like reduced dependence on fossil fuels, flexible locations, government incentives, modularity and scalability, less impact on the environment etc., [4]-[14] In general power generation in photovoltaic systems can be done in small scale grid connected PV system and large scale grid connected PV system.

The small scale grid connected PV systems are mainly used for residential applications. The main difficulty with photovoltaic distributed generating system is designing of the system with high voltage gain. In order to attain this high voltage gain the large scale grid connected photovoltaic system is best suitable in grid connected PV system. In Large scale grid connected PV system, converters and inverters are mainly used power electronic devices along with PV panels. Converters are mainly used for boost the PV output voltage and inverters are used to convert DC-AC and to achieve effective MPPT.

Cascaded modular multilevel converters have many merits like lower electromagnetic interference, improved harmonic spectra, less THD, low device rating, modularity etc., Cascaded multi level converter is very favourable for large scale grid connected photovoltaic system due to its unique advantages like independent MPPT (maximum power point tracking) for segmented PV arrays, high ac voltage capability etc., [11]-[14]

Although, Cascaded multi level converter in PV systems are desperate from some of their applications like medium voltage motor drive, static synchronous compensator (STATCOM), harmonic compensator and high voltage dc back-back intertie etc., [15]-[21] Photovoltaic systems with Cascaded multilevel converters faces tough challenges like solar power variability, mismatch of maximum power point from each converter module due to manufacturing tolerance, partial shading, dirt and thermal gradient etc.,

The input of the utility grid comes from the Cascaded modular multilevel inverter which converts the DC output voltage of CFDAB DC-DC Converter to AC for each phase of grid. If the output of inverter voltage is mismatch with requirements of utility grid then the active power generated in the system is unsymmetrical. This unsymmetrical active power results to over modulation in the system. To overcome these problems proper control strategies are developing for large scale grid connected PV systems.

Various control techniques are proposed for the cascaded PV system, with direct connection between individual inverter module and segmented PV arrays [22]-[26]. But the PV arrays cannot be directly connected to the individual inverter module in high voltage large scale PV system application due to the PV insulation and leakage issues. And also for low frequency medium voltage transformers between the PV converters and grid, there are still complicated ground leakage current loops among the PV converter modules. Therefore, these methods are not qualified for the large scale grid connected PV system. Moreover, reactive power compensation also not achieved. For achieving reactive power compensation active and reactive power control strategy has been applied in cascaded PV system with isolated dc-dc converters.

In order to solve the aforementioned issues, this paper proposes a large scale grid connected cascaded PV system including current fed dual active bridge (CFDAB) DC-DC Converter and cascaded multilevel inverters as shown in Fig.3. A decoupled active and reactive power control system is developed to improve the system performance. In particular, the proposed PV system allows a large low frequency dc voltage ripple for each PV converter module, which will not affect the MPPT achieved by CFDAB DC-DC Converter. To enhancing the system life time conventional electrolytic capacitors are replaced by film capacitors.

This paper consists of two stage large scale grid connected PV system circuit topology in section II. And control methods used for both CFDAB DC-DC Converter and Multilevel inverters are briefly described in section III. In section IV simulation done by using MATLAB/Simulink with a three phase 3 MW/12 KV PV systems including 12 cascaded PV inverter modules with the proposed decoupled active and reactive power control strategy and finally ended with conclusion in section V.

II.CIRCUIT TOPOLOGY AND DESIGN PARAMETERS

A. *Circuit Topology*

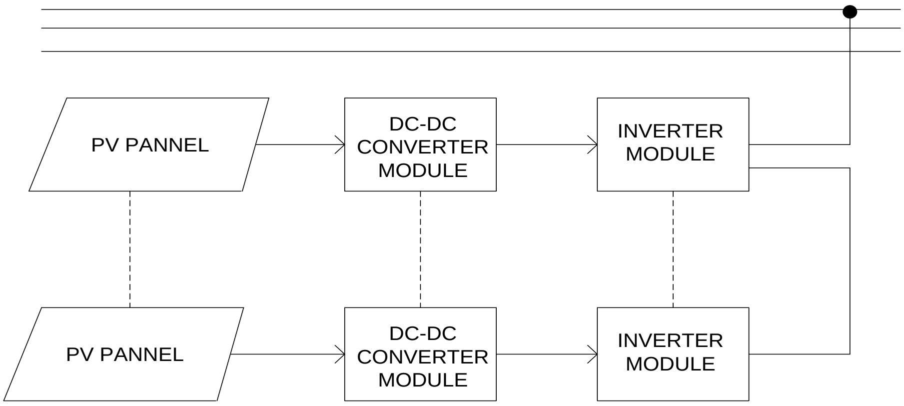


Fig.1 Block Diagram of cascaded PV system for one phase

The block diagram of single phase large scale grid connected PV system is shown in the Fig.1. Fig.2 and Fig.3 shows the proposed single phase grid connected PV system and proposed three phase grid connected cascaded PV system respectively. In this the power conversion takes place in two stages, in that stage one is power harvested from PV panel is given to DC-DC converter for Boost action to stabilize the voltage for this reason we are using Current Fed Dual Active Bridge(CF-DAB) DC-DC Converter. And second stage is these Converters are connected with cascaded modular inverter which contains High Voltage Insulation. The main advantage of this circuit topology compared with conventional methods is line frequency transformers are not required. Inverter modules are directly connected to the grid without any line frequency transformers. In this each inverter module is connected with individual DC-DC converter module and each converter module is connected with one individual PV panel. Due to this we are achieving MPPT for each and every section independently to harvest more solar energy.

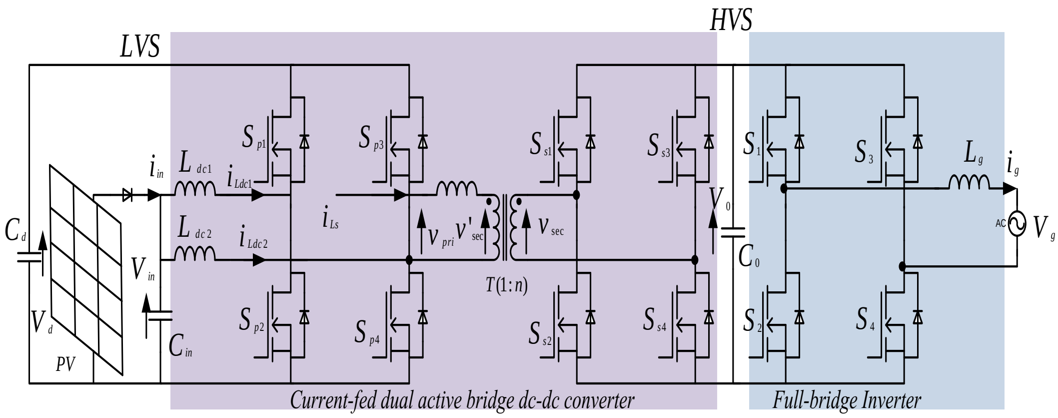


Fig.2 Proposed single phase grid connected PV system

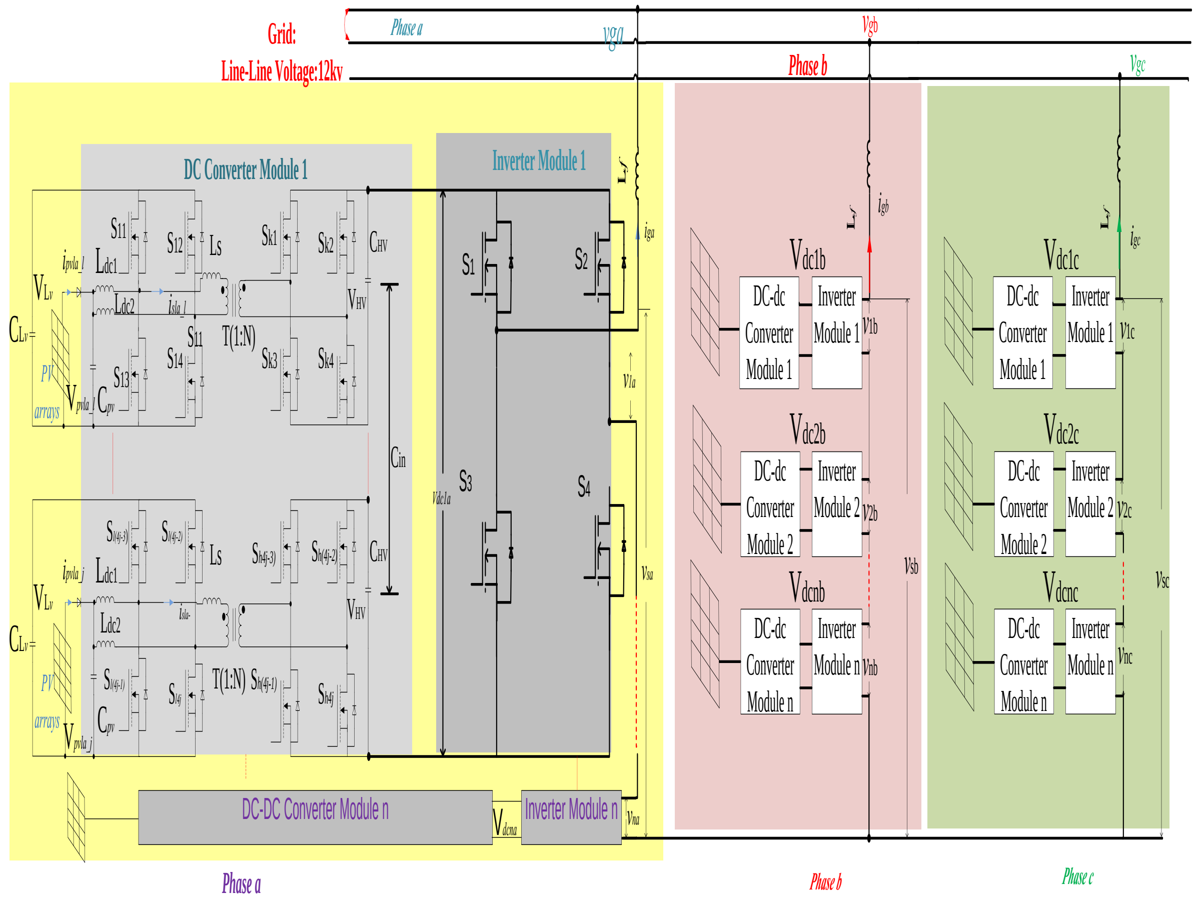


Fig.3 Proposed three phase grid connected cascaded PV system

B. Design Parameters

This paper presents a three phase 3MW/12KV line to line voltage PV system including 4 cascaded PV inverter modules. Each phase can produce 1MW and also each inverter module can produce 250MW. The average DC voltage of each inverter is 3000V. C_{PV} is high frequency capacitor which is connected in parallel with PV panel. The High frequency transformer with 1: N turns are connected in between Low voltage side and High voltage side of converters to Boost (or) Buck the voltage. L_{dc1} and L_{dc2} are the DC inductors and L_s is the leakage inductor in DC-DC converter. Hence, C_{LV} and C_{HV} are Low voltage side and High voltage side DC capacitors respectively. Film capacitor also used in this circuit to improve the system life time. The detailed circuit parameters are provided in Table I.

Table I: System Circuit Parameters in Simulation

Parameters		Symbol	Value
PV inverter modules in each phase	Number	N	4
	DC Capacitor Voltage	$V_{dcki}\ (k = 1,2,..,n; i = a,b,c)$	3000V
	DC Capacitor Size	C_{in}	400µF
	Filter inductor	L_f	0.8mH
	Switching frequency	f_{SW_AC}	5kHz
	Number	J	5
	Capacitor voltage in low voltage Capacitor	V_{LV}	300V
	Capacitor voltage in high	V_{HV}	600V

CF-DAB DC-DC Converter module	voltage Capacitor		
	Transformer turns ratio	N	2
	PV arrays output voltage	$V_{pvk\,i_r}\,(k = 1,2,..,n; i = a,b,c; r = 1,2,..,j)$	100V-200V
	Leakage inductor	L_s	2.5μH
	DC inductor value	L_{dc1}, L_{dc2}	12.5μH
	Capacitor in high voltage side	C_{HV}	2mF
	Capacitor in low voltage side	C_{LV}	300μF
	PV arrays output capacitor	C_{PV}	100μF
	Switching Frequency	f_{SW_DC}	50kHz
Grid (Three Phase)	Rated real power	P_g	3MW
	Rated reactive power	Q_g	1.5MVAR
	Rated RMS line-line voltage	V_{gL-L}	12Kv

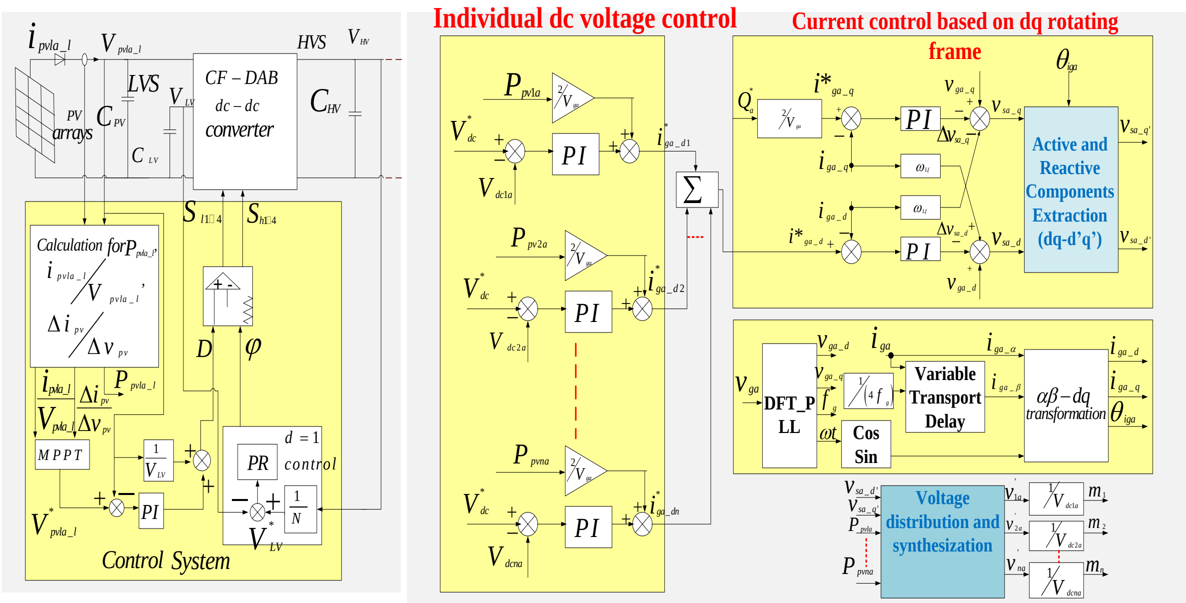
III. CONTROL SYSTEM DESIGN AND TECHNIQUE

Fig.4 represents the CF-DAB DC-DC converter control and Cascaded Multilevel inverter control of phase a. The same control technique can be applied for remaining two phases.

A. *Current Fed Dual Active Bridge (CFDAB) DC-DC Converter Control*

Fig.4 (a) shows the Current fed dual active bridge (CFDAB) DC-DC converters control for one unit in module 1 as shown Fig.1 [28]. The same control method can be used for all other modules. The name itself said that dual active bridge, due to this structure this control method has two degrees of freedom in that one is Duty cycle (D) another one is phase shift angle (φ), by which the PV voltage and Low Voltage Side (LVS) dc Link Voltage are controlled respectively. PV voltage is directly controlled by Duty Cycle, so it can be consider as reference voltage which is generated from MPPT algorithm [28].

In this paper the band width of duty cycle is about 10 KHz, which much higher than 120 Hz, and then the double frequency components in low voltage side and high voltage side are blocked. Due to this maximum MPPT is achieved on PV side. For simplicity, a high band width PI controller is used in this paper. The power transferred from Low Voltage Side (LVS) side to High Voltage Side (HVS) is determined by the phase shift angle (φ). To minimize the peak transformer, LVS Voltage is controlled by HVS Voltage to turns ratio (V_{HV}/N), due to this LVS and HVS voltages are balanced. To obtain enough gain at double frequency proportional resonant (PR) also used in this control method.



(a) (b)

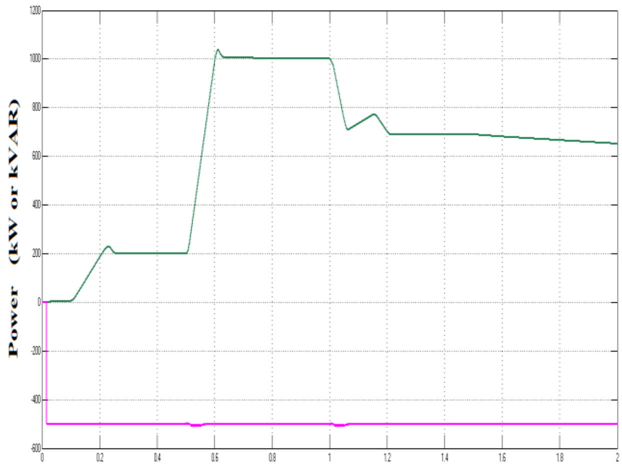
Fig.4 Control system of grid connected cascaded PV converters in phase a
(a) CFDAB DC-DC Converter control (b) Cascaded Multilevel inverter control

C. Cascaded multilevel inverter control

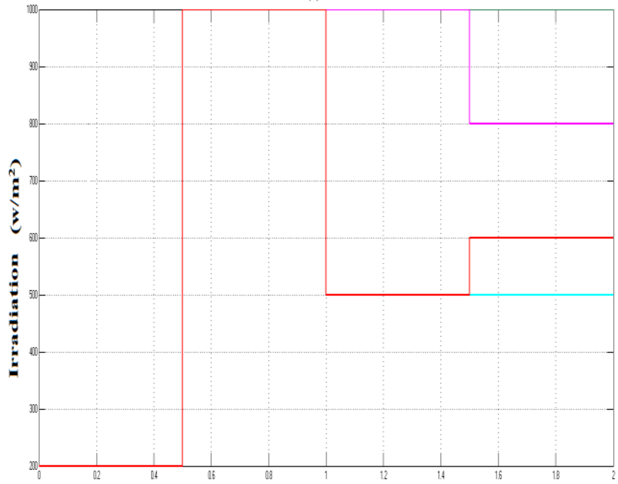
Fig. 4(b) shows the cascaded multilevel inverter control. The active power distribution between cascaded PV converter modules is decided by the individual maximum power available from PV arrays. By considering the dc capacitors which have the same capacitance are connected with cascaded multilevel inverter modules. The control technique used for cascaded multilevel inverter control can be called as Decoupled active and reactive power distribution control. The double-loop dq control based on Discrete Fourier Transform (DFT) PLL method [8] is applied to achieve the active and reactive power distribution. The unique features of this control method are the active and reactive power in each module is synchronized with grid current which are not achieved in traditional methods. Due to same grid current goes through AC side of each module, the grid voltage synchronization is not able to perform the active and reactive power separation in each module under unsymmetrical active power generation. Therefore, the maximum power harvested from PV arrays along with CF-DAB DC-DC converter control can be effectively delivered to the utility grid. After that the maximum power is fed back to minimize the inner loop action. This allows closed loop compensators to have smaller gains and hence increased robustness [29]-[31]. The d-axis component command of grid current $i^*_{ga\_d}$ is synthesized by the multiple outputs from the n individual voltage loops. The q-axis component command of grid current is $i^*_{ga\_q}$ obtained based on the desired reactive power Q^*_a. The decoupled current loop controls the dq components of grid current i_{ga_d} and i_{ga_q} to track the references $i^*_{ga\_d}$ and $i^*_{ga\_q}$, and then generates the total output voltage regulation Δv_{sa_d} andΔv_{sa_q}, are feed back to the output voltage to improve the system dynamic performance, respectively [28]. The output voltage signal Δv_{sa_d} is synthesized by Δv_{sa_d} Δv_{ga_d}, and decoupled variable$\omega L_f i_{ga_q}$. The output voltage signal Δv_{sa_q} is composed of Δv_{sa_q} Δv_{ga_α} and decoupled variable $\omega L_f i_{ga\_d}$. Subsequently, Δv_{sa_d} and Δv_{sa_q} are sent to the "active and reactive components extraction" module, which produces the decisive active and reactive components, $v_{sa\_d'}$ and$v_{sa_q'}$, by synchronizing withi_{ga}. Then the "voltage distribution and synthesization" module divides the $v_{sa\_d'}$ and$v_{sa_q'}$, into the n cascaded PV inverter modules according to their respective active and reactive power contributions [27].

IV. SIMULATION RESULT

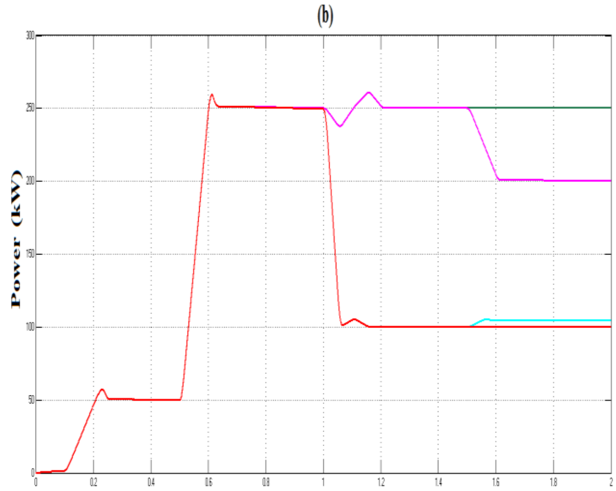
The Large scale grid connected PV system with the proposed control strategy is simulated in MATLAB/Simulink. Fig.5 shows the simulation results of traditional control strategy in phase a. The same results will come in phase b and c. The simulation results of proposed control strategy in three phases are shown in Fig.6.



(a)



(b)



(c) Time (s)

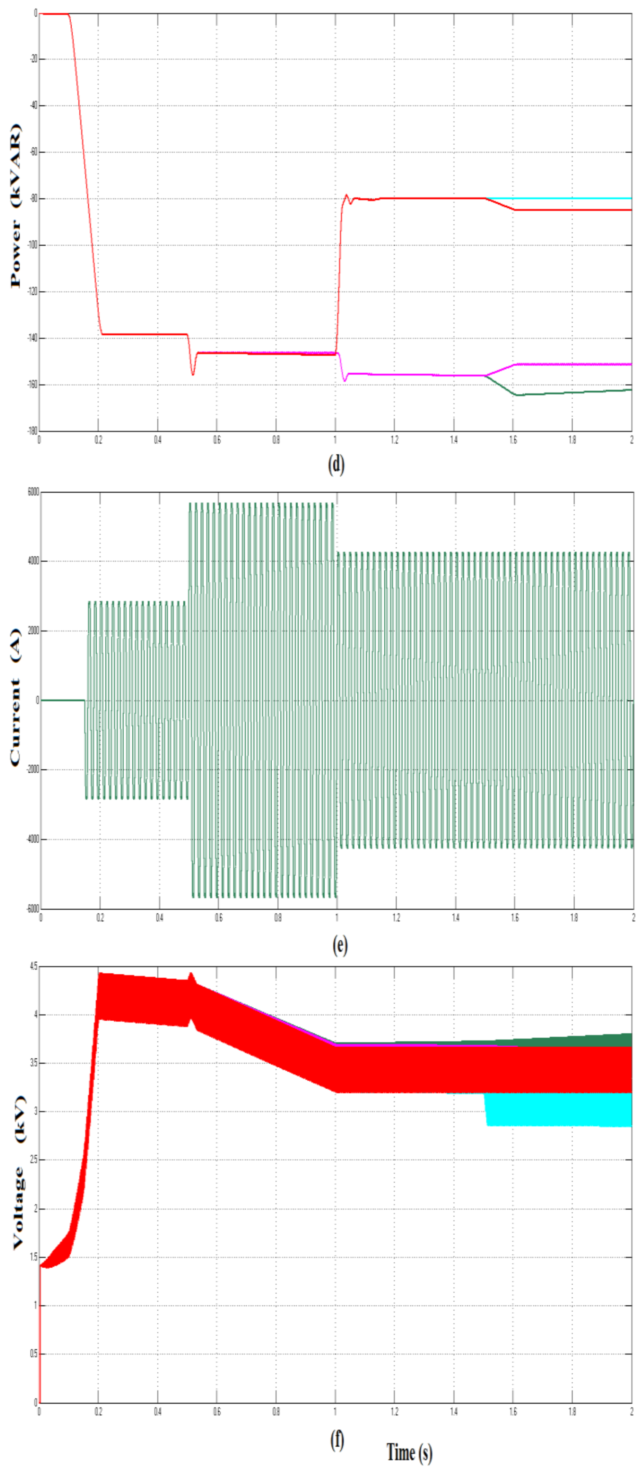


Fig.5: Simulation results of PV system with Active and Reactive power control in phase a
(a) Grid Power (b) PV array Irradiation (c) Active Power of PV modules (d) Reactive Power of PV modules (e) Grid Current (f) DC Grid Voltage

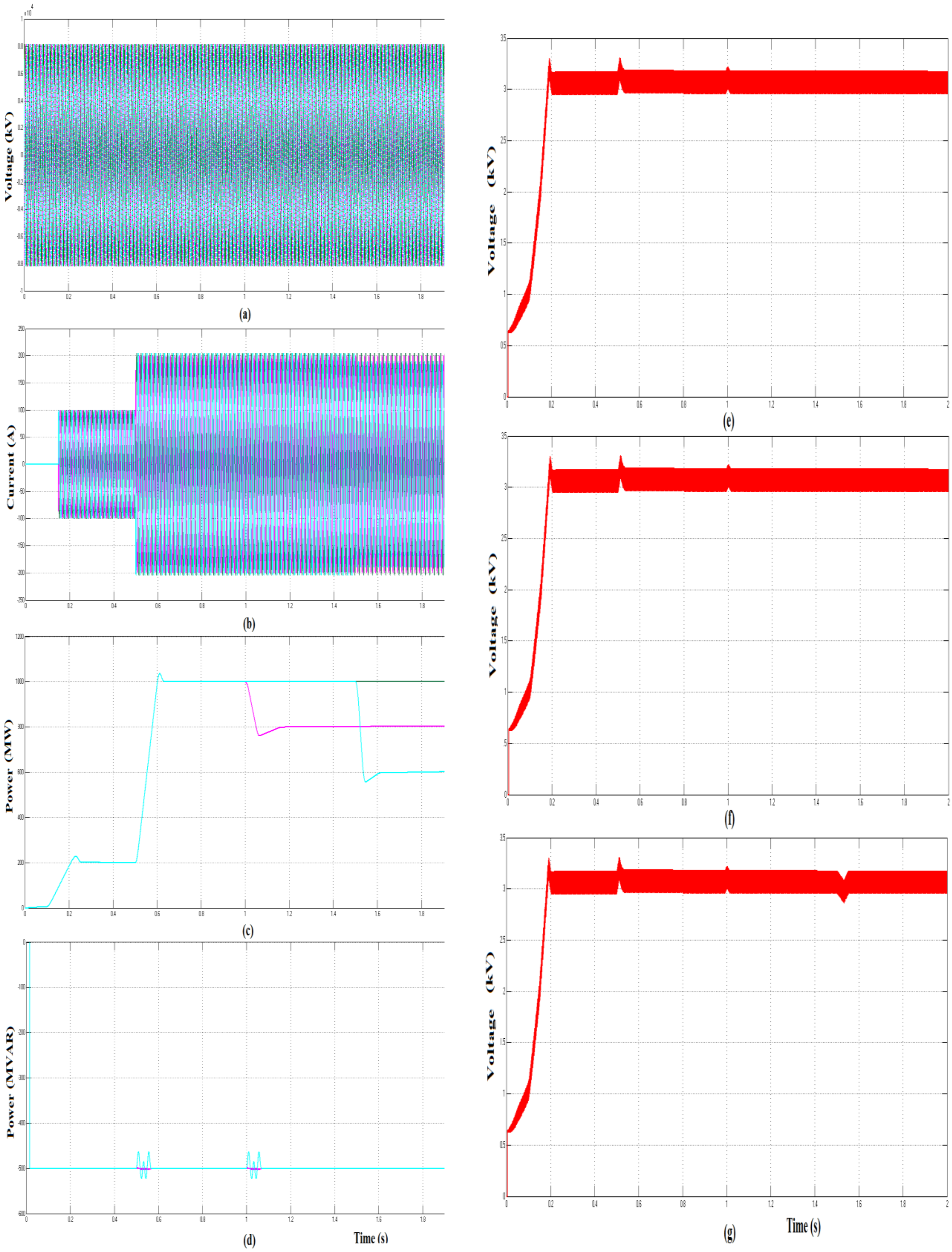


Fig.6: Simulation results of PV system with the proposed control in three phases (a)Three Phase Grid Voltage (b) Three Phase Grid Current (c) Active Power to Grid (d) Reactive Power to Grid (e) DC Grid Voltage in Phase a (f) DC Grid Voltage in Phase b (g) DC Grid Voltage in Phase c

V. CONCLUSION

This paper addresses the active and reactive power distribution among cascaded PV inverter modules and their impacts on power quality and system stability for the large scale grid connected cascaded PV system. To attain independent active and reactive power distribution, the output voltage in each and every module is separated based on grid current synthesization. The proposed compensation capability irrespective of amount of active power generated.

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