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Development of Control Strategy for Load Sharing in Grid-Connected PV Power System

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Abstract – In a power system of conventional parallel connected generators, share of real power and reactive var of an incoming generator are controlled by adjusting shaft power input and field excitation. The scenario of load sharing by a grid connected PV system is however different since no prime mover or excitation source are present. Due to serious power crisis, there are needs for transfer of PV power to grid systems. However, this needs intensive analysis on the load sharing phenomena. In this paper, aspects of load sharing of a grid connected PV system are analyzed, and a strategy is proposed where the load sharing task can be undertaken controlling both modulation index and phase angle of the inverter. It is seen that both real power and reactive var are affected upon change in index of modulation and phase angle of the PV inverter. Analysis and simulation results are presented to demonstrate effectiveness of the proposed control technique.

I. Introduction

In today's world, electricity is a vital ingredient for both economic and social development. Adequate, reliable and reasonably priced supply of electricity is an essential pre-requisite for national development. Due to the growing energy consumption around the world and the eminent exhaustion of fossil-fuel reserves, a great interest on alternative energy sources can be noticed nowadays. The threat of electrical energy rationing, blackouts, and overtaxes, in addition to the great environmental awareness, increases the requirement of research on alternative renewable energy systems. Among the clean and green power sources, the photovoltaic (PV) solar energy comes up as being a very interesting alternative to supplement the generation of electricity.

Photovoltaic (PV) arrays as an alternative energy source has been becoming feasible due to enormous researches and development work being conducted over a wide area. Interconnecting a PV system with utility is the current design trend. The advancement of power electronics and semiconductor technologies, the declining cost of solar panels, and the favorable incentives in a number of countries had profound impact on the commercial acceptance of grid-connected PV systems—which have been used in peak shaving, demand reduction, and supply of remote loads [1], [2]. Where utility power is available, consumers can use a grid-connected PV system to supply a portion of the power they need while using utility generated power at night and on very cloudy days. Grid-connected PV systems can provide most of a consumer's need. If the generation is greater than consumer's demand, the excess electricity can be fed through a meter back into the utility grid.

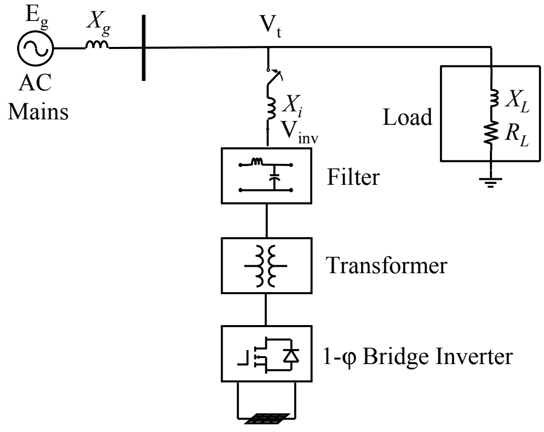
The dc power obtained from PV array is converted to ac through inverter and fed to the load. In case of conventional parallel connected generators, share of real power and reactive var of an incoming generator are controlled by adjusting shaft power input and field excitation. In grid connected PV system, no prime mover or excitation source are present. Therefore, its scenario of load sharing is different and needs intensive analysis on the load sharing phenomena.

Droop control method and average power control method are the load sharing techniques developed in stand alone ac power system based on the power flow theory of an ac system [3],[4]. To guarantee proper performance of load-sharing under the wire impedance mismatches, voltage/current measurement error mismatches, and interconnection tie-line impedance effect, combined droop control and average power control method is proposed [5]. Also to ensure sharing of harmonic contents of the load currents, a harmonic droop sharing technique is proposed [5]. To determine the power that the inverter can handle, a criterion is proposed [6] to find reactive power which can avoid sophisticated detections of phase and magnitude of the fundamental component of a nonlinear load current.

In this research work, analysis is performed on the aspects of load sharing of a grid connected PV system and a strategy is proposed where the load sharing task can be undertaken controlling both modulation index and phase angle of the inverter. It is found that both real power and reactive var are affected upon change in modulation index and phase angle of the PV inverter. Analysis and simulation results are presented to demonstrate effectiveness of the proposed control technique.

II. Fundamental Building Block Diagram

A PV power inverter system in parallel with a load and utility grid is shown in Fig. 1. X_g represents sum of synchronous reactance of generator and reactance of transmission line.



PV Power Inverter System

Fig. 1 Fundamental Building Block diagram of the grid-connected PV system

The dc voltage obtained from PV array is converted to ac through the inverter. The voltage is stepped up by transformer. An LC filter is connected to remove unwanted harmonics. The power is then fed to the load.

III. Principle of Load Sharing

The load sharing principle in case of parallel connected generators and grid connected PV system are described below separately.

A. In Parallel Connected Generators

Two parallel generators A and B shown in Fig. 2 supply a load of a certain power and power factor. Real and reactive power delivered from generators can be controlled by controlling the mechanical power input and excitation respectively.

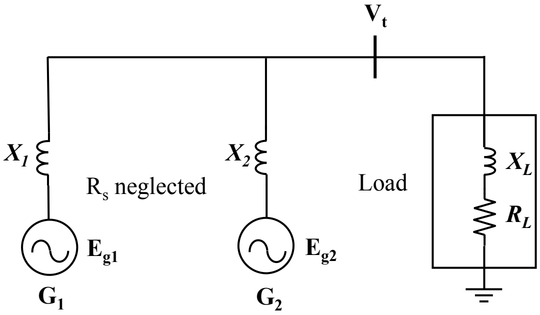


Fig. 2 Two parallel generators supplying a load

Control by changing mechanical power input

The input mechanical power or shaft power to the generator can be changed by changing the opening of the valves through which steam (or water) enters a turbine. Real power delivered by generator is given by

$$P = \frac{E_g . V_t}{X} \sin \delta \qquad (1)$$

If excitation I_f is kept constant, E_g will remain constant. Increasing the input shaft power will result the rotor speed start increasing. But rotor speed cannot exceed bus frequency. So δ will start to increase if V_t and X remain constant. The generator will start delivering more real power. Again the real power delivered is

$$P = V_t . I_a . \cos \theta \qquad (2)$$

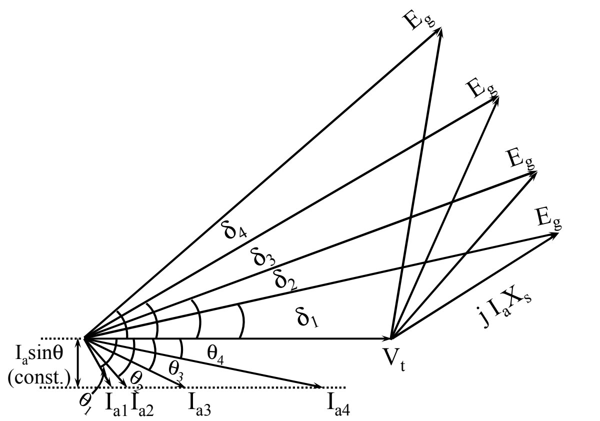


Fig. 3 Vector diagram of voltages and currents for change in shaft power input only in case of parallel generators

From the vector diagram shown in Fig. 3, we see that

$$E_g = V_t + jI_a X_s \qquad (3)$$

If δ is increased keeping E_g constant, $I_a X_s$ will increase. Since X_s is constant, I_a will increase. Again θ will decrease with the increase of δ. So $I_a \cos\theta$ will increase. Therefore, delivered real power $P = V_t . I_a . \cos\theta$ will increase. It is seen in the diagram that $I_a \sin\theta$ remains same with the increase of δ. So the reactive power $Q = V_t I_a \sin\theta$ will remain constant.

Control by changing excitation

Let us reduce excitation I_f keeping input shaft power constant. Since input shaft power is constant, delivered real power will be constant. It implies that $E_g \sin\delta$ will remain constant. A reduction in I_f must reduce E_g. So $\sin\delta$ increases i.e. δ increases. Since V_t is considered constant, $I_a \cos\theta$ must remain constant for constant output real power. From the vector diagram shown in Fig. 4 it is seen that $I_a \sin\theta$ varies with the change of excitation. So the reactive power $Q = V_t I_a \sin\theta$ varies. Therefore it can be inferred that changing excitation only varies reactive power if input shaft power is kept constant.

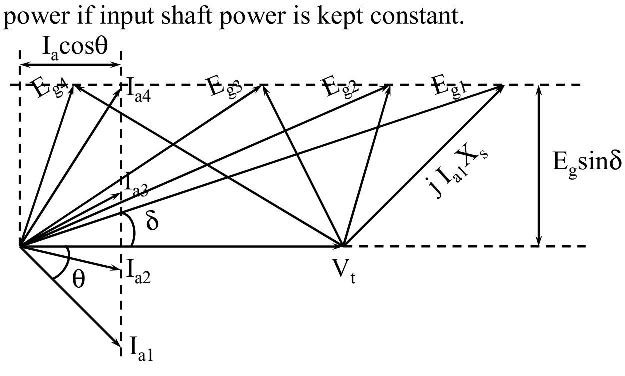


Fig. 4 Vector diagram of voltages and currents for change in excitation only in case of parallel generators

B. In grid-connected PV system

In the present grid-connected PV system scheme as shown in Fig. 5, power is fed to the load from the PV array. If the generation of power from PV array is not sufficient to serve the load demand, the deficit can be compensated from the grid. If the generated power is greater than the load demand, the excess power can be fed back to the grid.

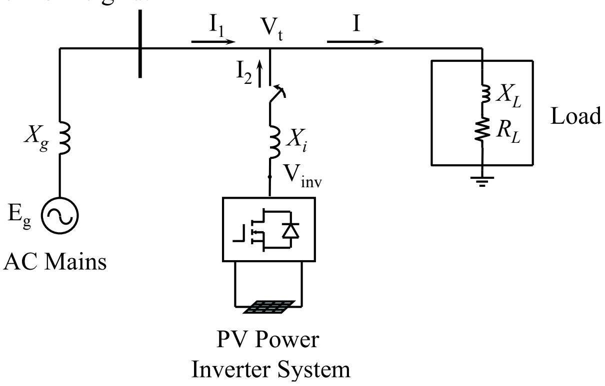


Fig. 5 Block diagram of the grid-connected PV system showing the sharing of load.

The vector diagram comprising the voltage and current vectors for the grid-connected PV system is shown in Fig. 6.

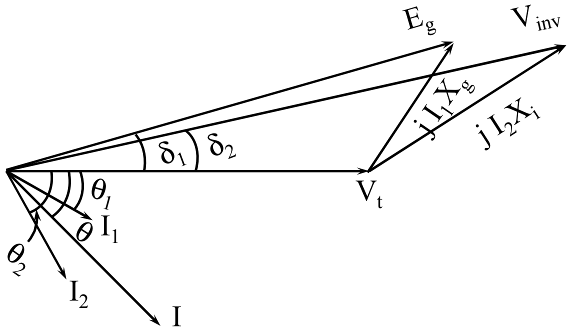


Fig. 6 Vector diagram for voltages and currents in grid-connected PV system

The active power supplied from the inverter side is

$$P = \frac{V_{inv} . V_t}{X_i} \sin \delta \qquad (4)$$

And the reactive var supplied is

$$Q = \frac{|V_t|}{X_i} \left(|V_{inv}| \cos \delta - |V_t| \right) \qquad (5)$$

The control parameters to vary the real power and reactive var to be supplied from inverter side are modulation index and phase angle. The vector diagrams comprising voltages and currents may not be exactly same as those of parallel connected generators. This should be examined through simulation.

The maximum power that can be delivered from the inverter side is limited by the maximum power rating of the PV array. The losses in the switching devices and transformer should also be taken into account.

IV. Inverter branch: Equivalent circuit and analysis for voltages and currents

The PWM voltage is fed to the transformer and its output is then filtered. The filtered voltage is fed to the grid through an inductance X_i. The grid voltage is V_t whose variation must be within a specified range.

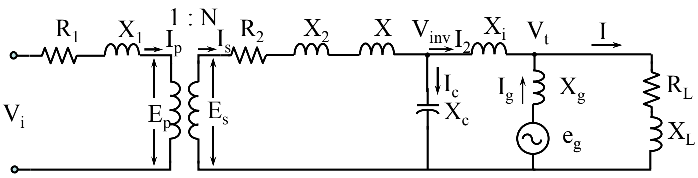


Fig. 7 Equivalent circuit of the grid-connected PV system

The transformer shown in Fig. 7 is expressed by its equivalent circuit. If all the parameters on the primary side are referred to the secondary then the above circuit takes the form shown in Fig. 8.

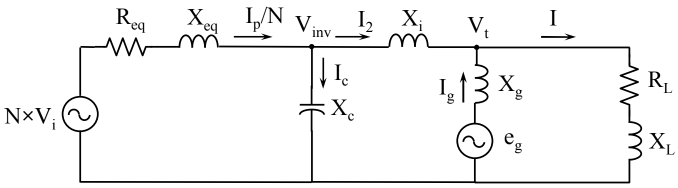


Fig. 8 Primary parameters of inverter branch of Fig. 8 referred to secondary

Here, $R_{eq} = R_1 N^2 + R_2$; $X_{eq} = X_1 N^2 + X_2 + X$

A. Formation of equation for voltages and currents to draw their vector diagrams and waveshapes

Applying superposition theorem in the circuit shown in Fig. 8, the equation for I_2, I_g and I can be developed.

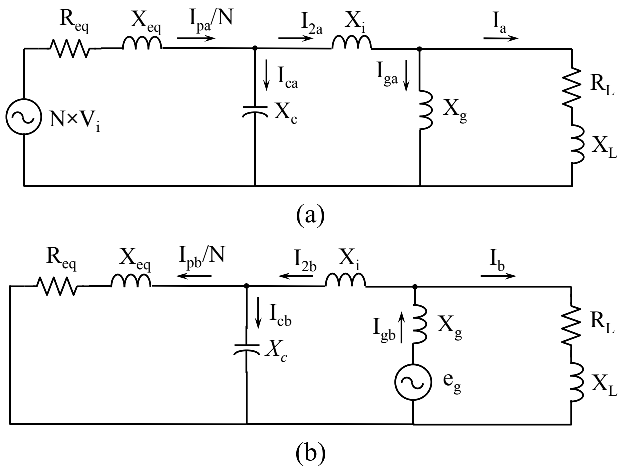


Fig. 9 Applying superposition theorem in the circuit of Fig.8, (a). When $N*V_i$ present only (b). When e_g present only

From Fig. 9(a),

$$\frac{I_{pa}}{N} = \frac{N \times V_i}{Z_{eq} + (-jX_c) \| (jX_i + Z_a)}$$

where, $Z_a = (jX_g) \| (R_L + jX_L)$

$$I_{2a} = \frac{I_{pa}}{N} \times \frac{-jX_c}{-jX_c + jX_i + Z_a}$$

$$I_{ga} = I_{2a} \times \frac{R_L + jX_L}{R_L + jX_L + jX_g} \; ; \; I_a = I_{2a} - I_{ga}$$

From Fig.9(b),

$$I_{gb} = \frac{e_g}{(R_L + jX_L) \| (Z_{aa} + jX_i) + jX_g}$$

where, $Z_{aa} = (-jX_c) \| (R_{eq} + jX_{eq})$

$$I_{2b} = I_{gb} \times \frac{R_L + jX_L}{R_L + jX_L + Z_{aa} + jX_i} \; ; \; I_b = I_{gb} - I_{2b}$$

$$I_2 = I_{2a} - I_{2b} \; ; \; I_g = I_{gb} - I_{ga} \; ; \; I = I_a + I_b$$

V. Simulation Results

The proposed scheme is simulated using Matlab and PSpice for various modulation indices and phase angles. Sine PWM (SPWM) technique is used for the generation of PWM patterns for switching signals of inverter. SPWM patterns are formed comparing a modulating sinusoidal wave with a high frequency triangular carrier wave.

The maximum power rating of the PV array used in the scheme is 1500 watt. The rated power, rated voltage and power factor of the load are 1000 watt, 240 V and 0.8 (lagging) respectively.

Control of real power

The modulation index and phase angles were adjusted in such a way that real power delivered from the inverter side varied while reactive var remained constant. The vector diagram of voltages and currents are shown in Fig. 10.

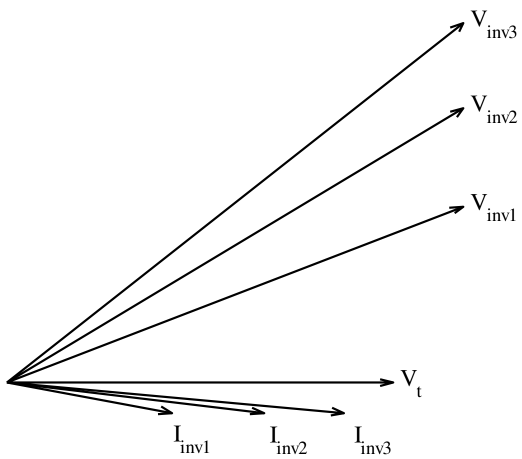


Fig. 10 Vector diagram showing voltages and currents when active power is controlled keeping reactive var constant (M_1 = 0.5, $Phase_1$ = 43.56^0; M_2 = 0.6, $Phase_2$ =54.55^0; M_3= 0.7, $Phase_3$ =61.4^0)

The data obtained from the simulation is given in Table 1

Table 1 Data for real power control

M	*Phase (deg)*	V_{inv} *(volt)*	δ_{inv} *(deg)*	I_{inv} *(amp)*	P_{inv} *(watt)*	Q_{inv} *(var)*
0.4	15	283.47	2.34	0.71	44.10	-165.4
0.5	43.56	325.88	29.64	2.66	615.43	-165.38
0.6	54.55	378.3	41.50	4.05	957.26	-165.66
0.7	61.4	433.93	49.27	5.28	1255.57	-165.06

From Table 1 it is seen that by increasing both M and Phase angle simultaneously, the real power delivered can be increased. The adjustments of M and Phase angle are done in such a way that real power delivered is varied but reactive power remained constant. From the vector diagram shown in Fig. 10 it is seen that the inverter output voltage is not constant. This differs with the parallel connected generators where generated voltage of generator remains constant while varying real power keeping reactive var constant.

Control of reactive power

The modulation index and phase angles were adjusted in such a way that reactive var delivered from inverter side varied while real power remained constant. The vector diagram of voltages and currents are shown in Fig. 11.

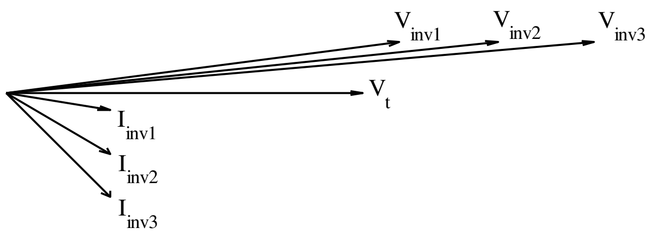


Fig. 11 Vector diagram showing voltages and currents when reactive var is controlled keeping active power constant (M_1 = 0.4, $Phase_1$ = 30.01^0; M_2 = 0.5, $Phase_2$ =24.93^0; M_3= 0.6, $Phase_3$ =21.63^0)

The data obtained from the simulation is given in Table 2.

Table 2 Data for reactive power control

M	*Phase (deg)*	V_{inv} *(volt)*	δ_{inv} *(deg)*	I_{inv} *(amp)*	P_{inv} *(watt)*	Q_{inv} *(var)*
0.4	30.01	274.53	15.49	1.23	280.00	-94.07
0.5	24.93	339.06	12.49	1.86	280.14	-347.85
0.6	21.63	402.58	10.5	2.74	280.25	-595.30
0.7	19.3	465.57	9.06	3.69	280.17	-839.41
0.8	17.57	528.24	7.98	4.65	280.18	-1081.47
0.9	16.23	590.7	7.13	5.63	280.11	-1322.25

From Table 2 it is seen that by increasing M and decreasing phase angle simultaneously, the reactive var delivered can be increased. The adjustments of M and phase angle are done in such a way that reactive var delivered is varied but real power is kept constant. The vector diagram comprising voltages and currents shown in Fig. 11 is same as that of parallel connected generators shown in Fig. 4.

Control of real and reactive power maintaining currents in phase or 180^0 out of phase

Again the modulation indices and phase angles are adjusted in such a way that both real power and reactive var are controlled while the currents remain in phase or 180^0 out of phase. Fig. 12 shows vector diagrams and waveshapes for different M and phase angle.

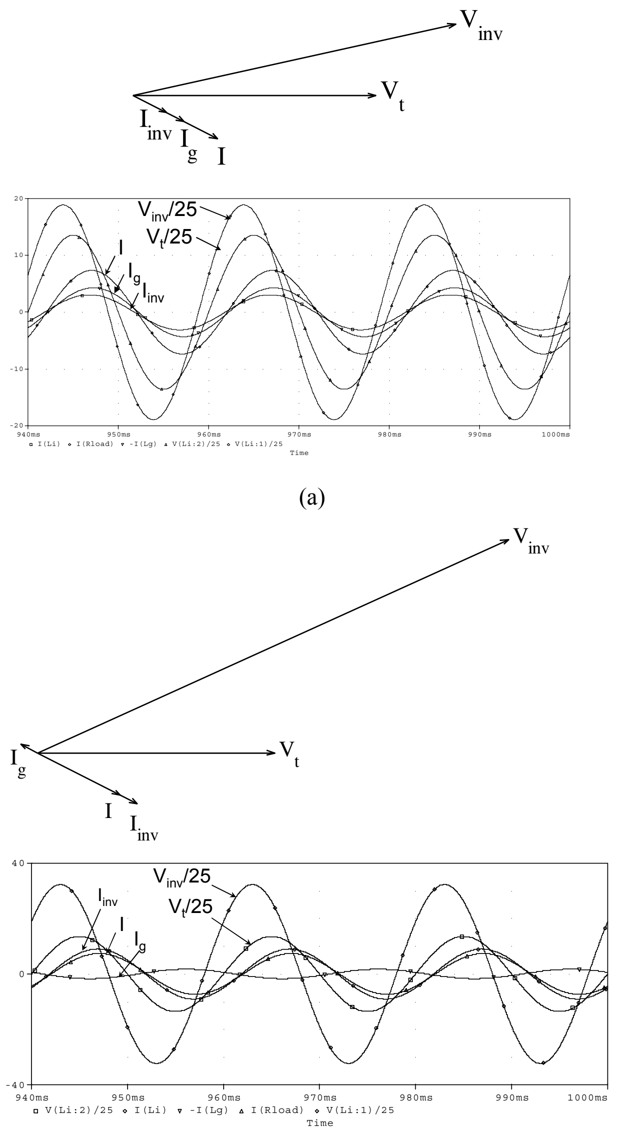


Fig. 12 Vector diagrams of voltages and currents when currents are in phase or 180^0 out of phase (a). M = 0.5, Phase = 31.1^0 ; (b). M = 0.9, Phase = 43.9^0

The data obtained from the simulation is given in Table 3:

Table 3 Data for power control with currents in phase or 180^0 out of phase

M	*Phase (deg)*	V_{inv} *(volt)*	δ_{inv} *(deg)*	I_{inv} *(amp)*	P_{inv} *(watt)*	Q_{inv} *(var)*
0.4	23.4	278.72	9.65	0.93	178.46	-133.09
0.5	31.1	334.99	18.11	2.07	397.55	-299.62
0.6	36.0	392.87	23.81	3.16	605.77	-456.25
0.7	39.5	451.71	28.01	4.22	810.31	-606.53
0.8	42.0	511.30	31.11	5.25	1008.99	-755.47
0.9	43.9	571.38	33.50	6.27	1204.72	-903.23

From Fig. 12 and Table 3 it is seen that by increasing M and phase angle simultaneously both the real power and reactive var from the inverter side can be increased keeping the currents in phase or 180^0 out of phase. The vector diagram and waveshapes are in consistent in respect of both magnitude and phase angle.

In Table 1, Table 2 and Table 3 we can see that the active power delivered in all three cases are within the specified limit considering the maximum power rating of the PV array and the losses.

V. Conclusion

A control strategy for proper load sharing in the grid-connected PV system is designed in this research paper. It is different from that of conventional parallel connected generators since no prime mover or excitation source are present. The load sharing task can be performed controlling both modulation index and phase angle of the inverter. Sine PWM technique is adopted for generating switching signals for the inverter.

It is shown that by adjusting modulation index and phase angle, the real power delivered by the inverter branch can be adjusted keeping reactive var constant. The reactive var is also shown to be adjusted keeping real power constant. Again both the real power and reactive var are shown to be adjusted keeping the currents in phase or 180^0 out of phase. The PV power inverter can supply the total load or share a portion of it according to the demand. The excess power developed by the PV array can be fed back to the utility. The power delivered from the PV branch is shown to be within the specified limit defined by the maximum power rating of the PV array considering the losses.

References

[1]. C. J. Hatiziadoniu, F. Chalkiadakis, and V. Feiste, "A power conditioner for a grid-connected photovoltaic generator based on the 3-level inverter," *IEEE Trans. Energy Conv.*, vol. 14, no. 4, pp. 1605–1610, Dec. 1999.

[2] K. Y. Khouzam, "Technical and economic assessment of utility interactive PV systems for domestic applications in South East Queensland," *IEEE Trans. Energy Conv.*, vol. 14, no. 4, pp. 1544–1550, Dec. 1999.

[3] Chandorkar M.C., Divan M.D., Adapa R., "Control of parallel connected inverters in standalone ac supply systems" *IEEE Transactions on Industry Applications*, Vol. 29 No 1, 1993, pp. 136 –143

[4] Anil Tuladhar, Hua Jin, Tom Unger, and Konrad Mauch, "Control of parallel inverters in distributed ac power systems with consideration of line impedance effect," *IEEE Trans. Ind. Applicat.*, vol. 36, pp. 131–138, Jan./Feb. 2000.

[5] Marwali, M.N. Jin-Woo Jung Keyhani, "A. Control of distributed generation systems - Part II: Load sharing control," *IEEE Tran.,. Power Electron.,* Vol. 19, Issue. 6, pp. 1551-1561. Nov. 2004

[6] Wu, T.-F., Shen, C.-L., Chang, C.-H. Chang, and Chiu, J.-Y., 2003a, "A 1φ3W Grid-Connection PV Power Inverter with Partial Active Power Filter," *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 39, No. 2, pp. 635-646, 2003