Simulation and Performance Analysis of a Grid Connected Multilevel Inverter Considering Either Battery or Solar PV as DC Input Sources

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***Abstract*— This paper proposes and analyzes the performance of a grid connected multilevel inverter topology with step up transformer for battery and Solar PV (SPV) as a dc source. The simulation is done in SIMULINK/ MATLAB Software. The RMS inverter output voltage at transformer's secondary side is kept slightly higher than the RMS grid voltage and the power transfer to the grid is controlled by controlling the phase lag angle of grid with respect to the inverter. It is shown that when the phase lag angle of the grid is changed, the THD in grid current, RMS grid current, active power and reactive power changes while RMS voltage at transformer primary & secondary and output voltage THD remains approximately the same. The simulation is done for battery as well as Solar PV and found that the results are approximately same. This paper shows that if the phases lag angle increases, the grid current THD reduces and RMS grid current increases. The simulation results with the variation of phase angle are tabulated and the variations of THD, P and Q with phase angle are shown graphically. These results are compared with those obtained from mathematical analysis and found to be in agreement.**

Index Terms— Grid connected SPV, H-Bridge inverter, Level Module (LM), multilevel inverter, Power Quality, Total Harmonic Distortion (THD).

I. INTRODUCTION

Recently, renewable energy resources are becoming popular due to the depletion of conventional fuel sources and their negative impacts on the environment. Solar energy is one of these alternative renewable energy resources. It is converted to the electrical energy by photovoltaic (PV) arrays [1]. PV arrays do not generate any toxic or harmful substances that pollute the environment and have long life. Another considerable feature of them is the requirement of low maintenance. Due to the development in photovoltaic technologies, the efficiency of the PV arrays has been improved. Therefore, studies on PV systems have increased gradually. Multilevel inverters have received increasing interest for power conversion in high-power applications due to their lower harmonics, higher efficiency and lower voltage stress compared to two-level inverters. Multilevel inverters generate a staircase waveform [2]. By increasing the number of levels in the output voltage, the harmonic content and therefore THD are reduced [3]. Therefore, they produce high quality output voltage by increasing the level number. The level number can be easily increased. As a result, voltage stress is reduced and the output voltage wave shape move closure to the sinusoidal shape [4-6]. In this paper, a single phase a 15 level inverter system is proposed. The principle of the proposed method will be explained for a 15-level inverter. However, the structure can be easily adapted to any number of levels.

II. PROPOSED INVERTER

The proposed multi-level inverter system consists of Level Module, H-Bridge inverter, Solar PV Module as dc voltage source and Grid through a small transmission line having small inductance along with small resistance. The proposed circuit with solar panel as source for three level modules is shown in Fig. 1. The level of output voltage shape depends on the level module used in the circuit.

No. of output Levels

$n = 2^{(m+1)} - 1$ where m is the no. of Level Module used.

The no. of switches used in the circuit

$n_s = 2m+4$

The input dc voltage fed to k_{th} module varies with particular module no. as:

$Vk = 2^{(k-1)} \cdot V_d$ Where k =1, 2, 3 … m.

The Simulink model of the proposed circuit is shown in Fig. 2. In the proposed circuit, 3 Level modules (LM), 1 H-Bridge inverter, and 3 Solar PV Array of output voltage V_1 (=V_d), V_2 (=2Vd) and V_3 (=4V_d) are used. Output wave has 15 levels and the total no. of switches used is 10. Total dc voltage used in the circuit is 7V_d.

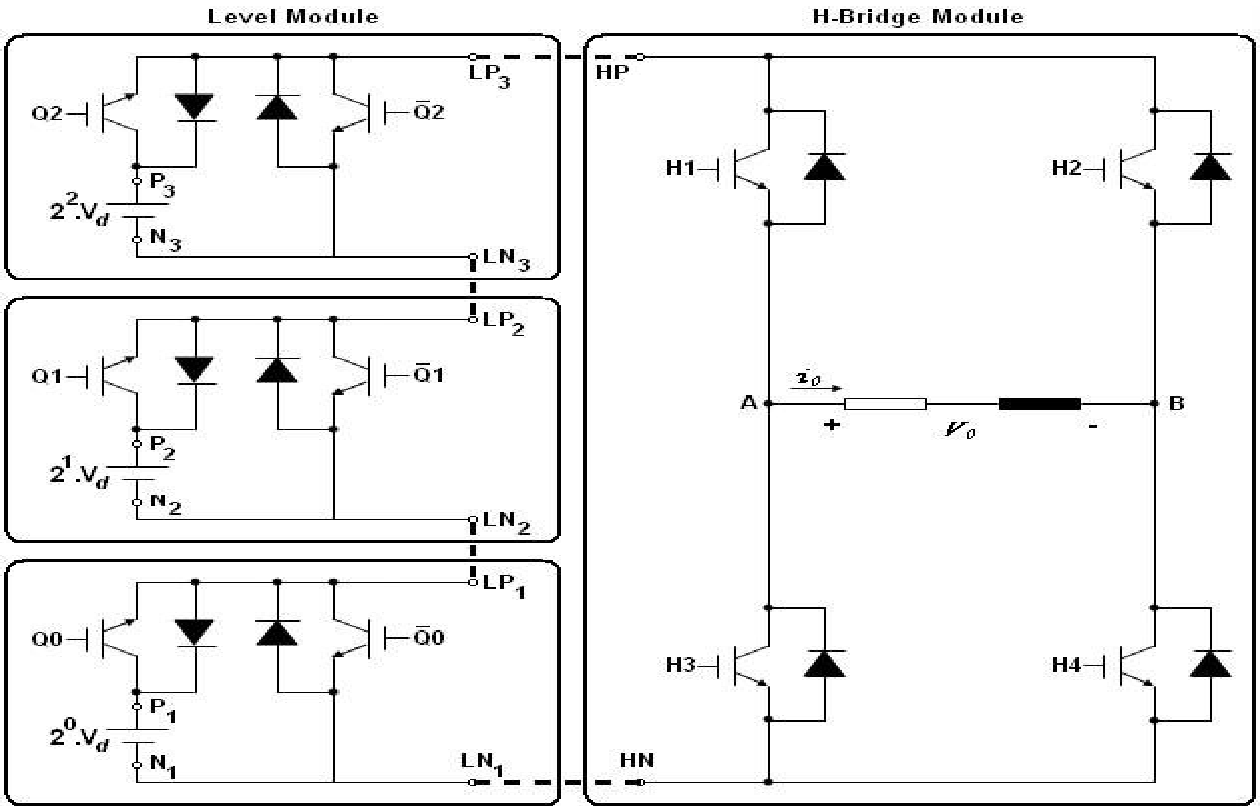

Fig.1 Proposed Multilevel inverter circuit with three Level Module

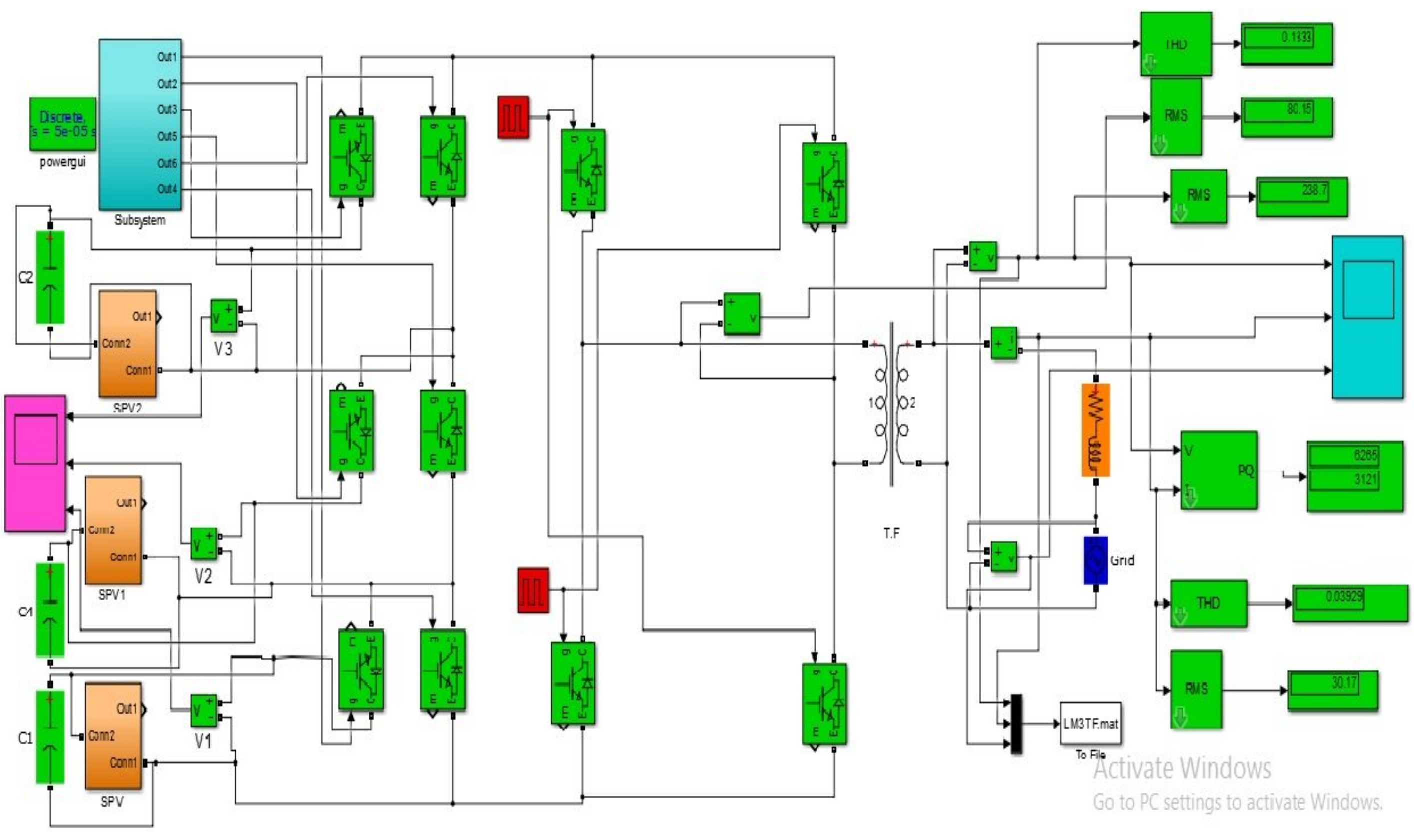

Fig 2. Matlab Model for the proposed inverter circuit

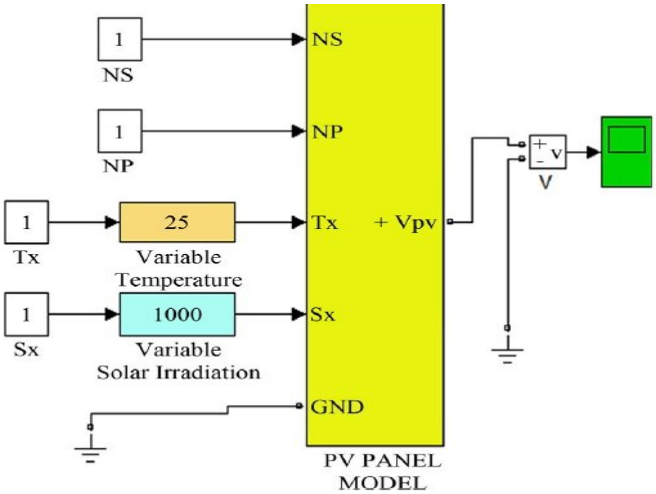

Fig 3. Solar PV Model used in the proposed circuit

The Simulink Model of Solar PV used in the above circuit is shown in Fig. 3 [4]. The pulse generation is done for LM switches [5]. The simulation is done for V_d=18Volt. Vd is measured when the PV model is open circuited. When the PV Array is loaded, some fluctuations in PV Voltage are measured.

Grid connected inverter with Battery as DC source

The proposed inverter circuit is simulated for grid in SIMULINK/MATLAB software with battery as dc source [7]. The inverter output is increased by using step up transformer. The secondary of the transformer is connected to a grid through a small transmission line having small inductance along with small resistance. Battery Voltages are: V_1 =18V, V_2=36V, V_3=72V, RMS grid voltage Vg = 230V, L = 25 mH, R = 0.5 Ω.
The transformer ratings are as follows:
Single phase, 50 Hz, 500kVA, 200/600 V.
The phase angle between the inverter voltage and grid voltage controls the active power flow to the grid. Power is transferred from inverter to the grid through transformer, when the phase angle of the grid is lagging. As the lagging phase angle of the grid increases, RMS grid current, active power P and reactive power Q increases while THD in grid current deceases. The THD in load voltage remains approximately the same. TABLE I shows the variations of RMS inverter output voltage at transformer primary as well as secondary, RMS grid current I_r, active power P, reactive power Q, THD in output voltage and THD in output current with the variation of phase angle of the grid.

III. SIMULATION AND RESULTS

TABLE I
SIMULATION RESULTS FOR GRID CONNECTED MULTILEVEL INVERTER WITH BATTERY AS DC SOURCE

S. NO.	Grid Phase angle (°)	RMS voltage at transformer primary (Volt)	RMS voltage at secondary (Volt)	RMS Grid current (A)	P (W)	Q (Var)	THD in output Voltage (%)	THD in grid current (%)
1	-5	82.3	246.7	3.1	551	438	13.25	36.4
2	-10	82.3	246.6	5.3	1167	465	13.25	20.4
3	-15	82.3	246.5	7.75	1780	543	13.26	13.8
4	-20	82.2	246.3	10.3	2385	672	13.27	10.4
5	-25	82.2	246.1	12.85	2977	851	13.28	8.3
6	-30	82.2	245.9	15.4	3553	1079	13.29	7
7	-35	82.1	245.6	18	4107	1354	13.3	6
8	-40	82.1	245.4	20.6	4636	1673	13.32	5.3
9	-45	82.1	245.1	23.1	5135	2035	13.33	4.88
10	-50	82	244.8	25.7	5602	2437	13.34	4.5
11	-55	82	244.5	28.2	6031	2875	13.36	4.2
12	-60	82	244.2	30.7	6420	3347	13.37	4

Fig 4 and 5 shows the output voltage at transformer secondary, grid current and grid voltage for 30° and 60° lagging phase angle. Negative sign in the table shows that the phase angle of grid voltage is lagging with respect to the inverter output voltage.

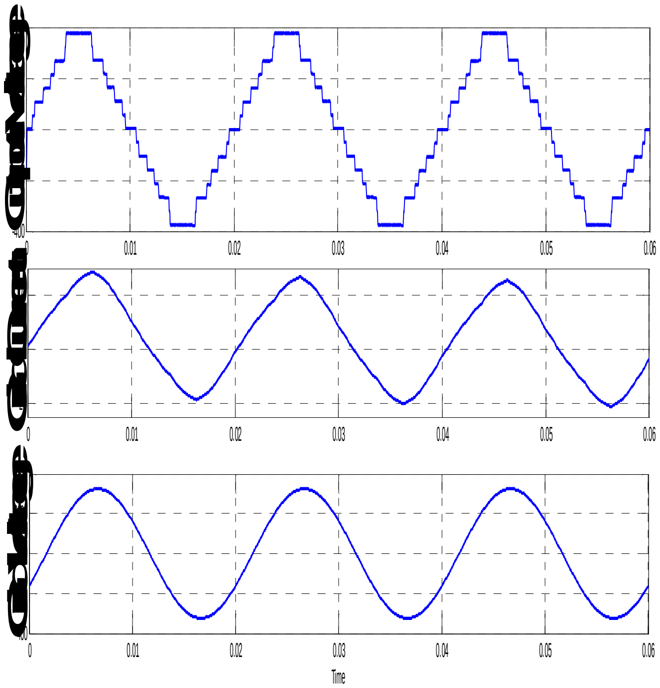

Fig 4. Inverter output voltage, grid current and grid voltage for 30° lagging phase angle with battery as dc source

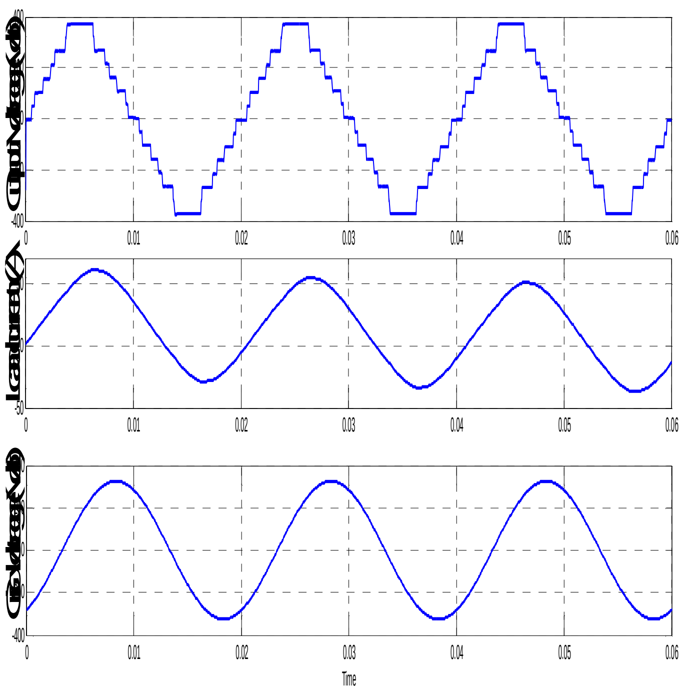

Fig 5. Inverter output voltage, grid current and grid voltage for 60° lagging phase angle with battery as dc source

The variation of THD in output voltage and output current with the phase angle is shown in Fig. 6. The graph shows that the load voltage THD is nearly constant while the load current THD is continuously decreasing with the phase angle of the grid.

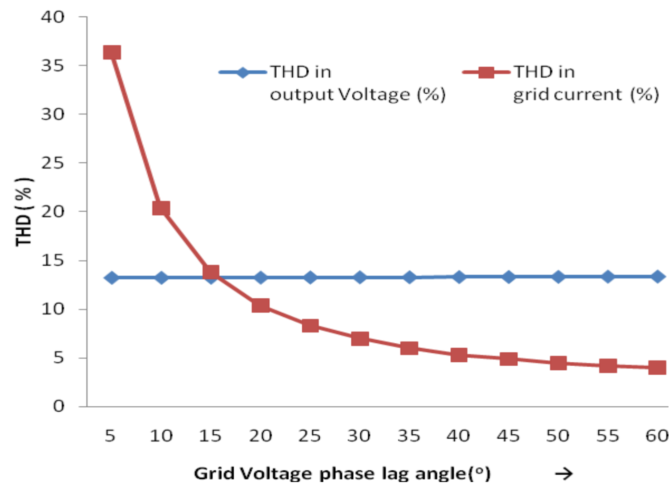

Fig 6. Variation of output voltage THD and grid current THD with phase angle

Grid connected inverter with Solar PV as DC source

The same inverter circuit is simulated for Solar PV as DC source. Panel Output Voltages are: $V_1(=V_d)$ =18V, V_2=36V, V_3=72V. PV panel voltage is measured when the PV model is open circuited. When the PV Array is loaded, some fluctuations in PV Voltage are measured. The simulation is carried out for 50mF capacitances across PV panel. TABLE II shows the variations of RMS inverter output voltage at transformer primary as well as secondary, RMS grid current I_r, active power P, reactive power Q, THD in output voltage and THD in output current with the variation of phase angle of the grid. Fig 4 shows the output voltage at transformer secondary, grid current and grid voltage for 30° lagging phase angle.

TABLE II
SIMULATION RESULTS FOR GRID CONNECTED MULTILEVEL INVERTER WITH SOLAR PV AS DC SOURCE

S. No.	Grid Phase angle (°)	RMS voltage at transformer primary (Volt)	RMS voltage at secondary (Volt)	RMS Grid current (A)	P (W)	Q (VAr)	THD in output Voltage (%)	THD in Grid current (%)
1	-5	80.8	242.2	2.7	527	294	13.3	41.2
2	-10	80.7	242	5	1130	316	13.3	21.2
3	-15	80.7	241.7	7.5	1730	390	13.3	14
4	-20	80.6	241.4	10	2322	513	13.3	10.45
5	-25	80.5	241.1	12.6	2902	686	13.3	8.35
6	-30	80.5	240.8	15.1	3465	906	13.3	6.8
7	-35	80.4	240.5	17.7	4006	1173	13.3	6
8	-40	80.3	240.1	20.2	4523	1483	13.3	5.3
9	-45	80.3	239.8	22.7	5011	1836	13.3	4.8
10	-50	80.2	239.4	25.3	5465	2228	13.3	4.4
11	-55	80.2	239.1	27.7	5884	2657	13.3	4.15
12	-60	80.1	238.7	30.2	6265	3121	13.3	3.9

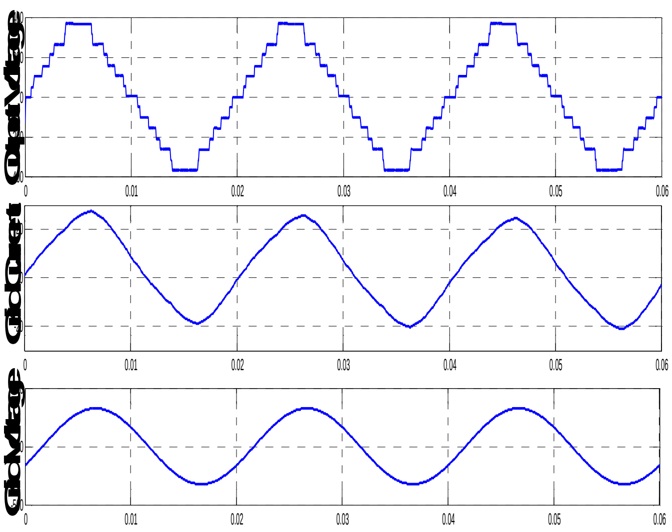

Fig 7. Inverter output voltage, grid current and grid voltage for 30° lagging phase angle with Solar PV as dc source

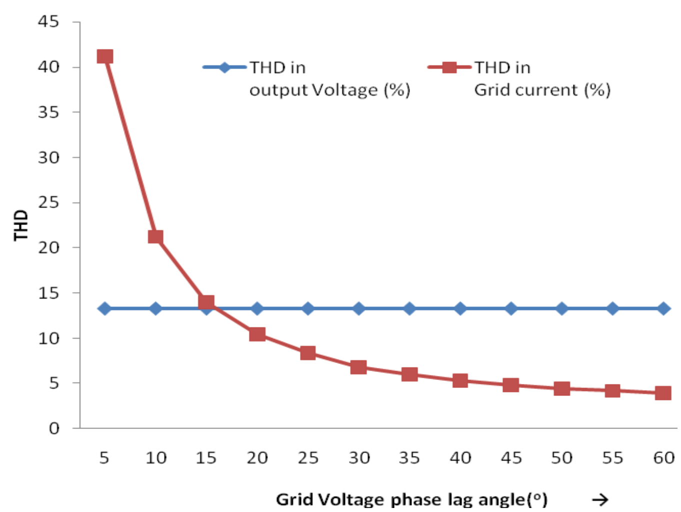

Fig 8. Variation of output voltage THD and grid current THD with phase angle

IV. ANALYTICAL RESULTS

The power transfer between two sinusoidal voltage sources [7], when the phase of one source is taken as reference and neglecting resistance between the sources is given by:

Active power $P=\frac{V_{inv}V_g}{X}\sin\delta$

where δ is the phase angle of voltage source, X is the reactance between the two sources.

Reactive power $Q=\frac{V_{inv}}{X}(V_{inv}-V_g\cos\delta)$

In this paper, solar inverter feed the power into the grid. V_{inv} is Solar PV inverter rms output voltage (transformer secondary). Vg is the grid rms voltage. The phase angle of the inverter is taken as reference. And the phase angle of grid is reduced from zero i.e. increased with negative sign. Now in the above formulae, δ is assumed to be grid phase angle (negative sign included).
Table III shows the results of active power and reactive power from formulae for different phase angle.

TABLE III
SIMULATION RESULTS FROM FORMULAE FOR GRID CONNECTED MULTILEVEL INVERTER

S. No.	Grid Phase angle (°)	RMS voltage at Transformer secondary (Volt)	Grid RMS Voltage (Volt)	P (W)	Q (VAr)
1	-5	242.2	230	630	552
2	-10	242	230	1254	631
3	-15	241.7	230	1868	764
4	-20	241.4	230	2467	946
5	-25	241.1	230	3046	1180
6	-30	240.8	230	3601	1462
7	-35	240.5	230	4126	1788
8	-40	240.1	230	4620	2162
9	-45	239.8	230	5076	2573
10	-50	239.4	230	5492	3021
11	-55	239.1	230	5866	3504
12	-60	238.7	230	6194	4016

V. COMPARISON

Active Power Comparison

The power transfer from the inverter to the grid obtained from the simulation is compared with the power calculated from the formulae.

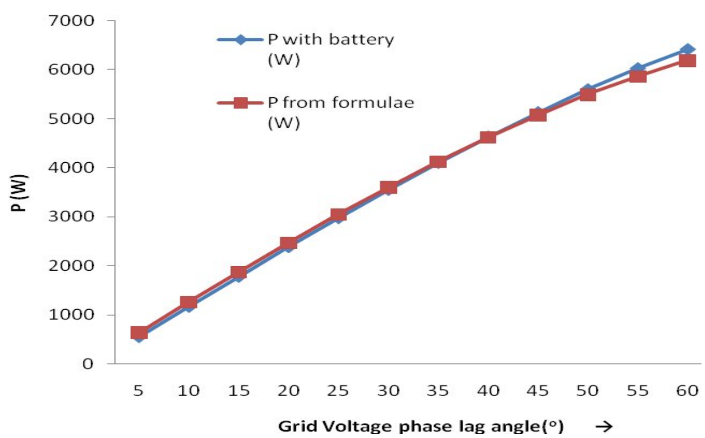

Fig 9. Variation of Active power results with phase angle obtained from simulation and formula for battery as source

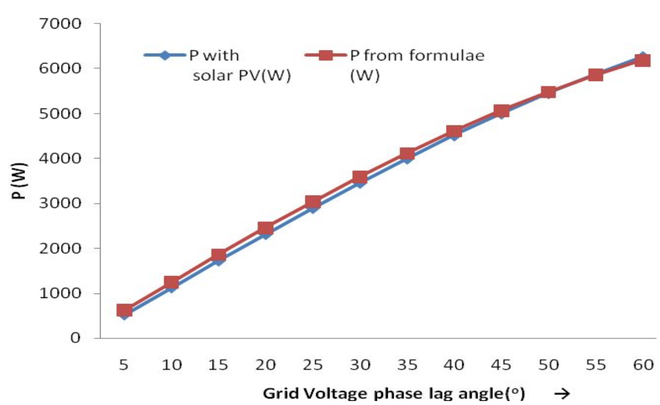

Fig 10. Variation of Active power results with phase angle obtained from simulation and formula for solar PV as source

The power transfer from the inverter to the grid obtained from the simulation is compared with the power calculated from the formulae for both battery and solar PV as source. It is found that the Active Power P results obtained from simulation and formula from battery as source are very close to each other. At starting, P from formula is more as compared to P from simulation. And for phase lag angle of grid of 45° or more, the power from simulation becomes large. The variation of P with grid voltage phase angle for battery as a source is shown in Fig. 9.

It is also found that the Active Power P results obtained from simulation and formula from solar PV as source are very close to each other. At starting, P from formula is more as compared to P from simulation. And for phase lag angle of grid of 45° or more, the power from simulation and from formula becomes almost same. The variation of P with grid voltage phase angle for battery as a source is shown in Fig. 10.

Reactive Power Comparison

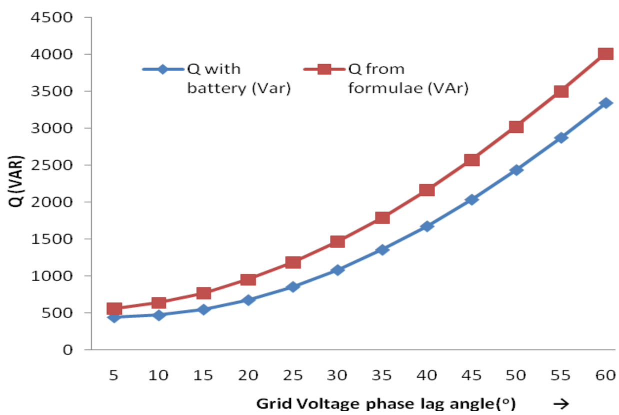

Fig 11. Variation of Reactive power results with phase angle obtained from simulation and formula for battery as source

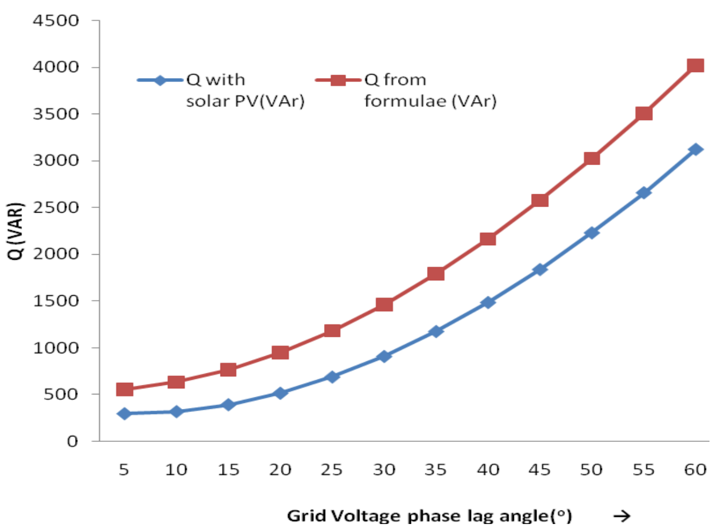

Fig 12. Variation of Reactive power results with phase angle obtained from simulation and formula for solar PV as source

The Reactive Power Q from formula is large as compared to Q from simulation for both battery and solar PV as a source. The difference is attributed to the presence of small resistance between inverter and the grid that has been neglected. It is found that as the phase lag angle increases; the reactive power flow also increases. The variation of reactive power Q with grid voltage phase angle obtained from simulation and formula for both battery and solar PV as a source is shown in Fig. 11 and Fig. 12.

VI. CONCLUSION

In this paper, a grid connected multilevel inverter circuit with step up transformer for battery and Solar PV (SPV) as a dc source is proposed and analyzed the performance. The RMS inverter output voltage at transformer's secondary side is kept slightly higher than the RMS grid voltage and the power transfer to the grid is controlled by controlling the phase lag angle of grid with respect to the inverter. It is conclude that when the phase lag angle of the grid is changed, the THD in grid current, RMS grid current, active power and reactive power changes but RMS voltage at transformer primary & secondary and output voltage THD remains approximately the same and it is shown that if the phases lag angle increases, the grid current THD reduces and RMS grid current increases. Finally the results obtained from simulation are compared with that obtained from formulae and found to be in conformity with theory. The results are tabulated and also elaborated graphically

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