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Design of Solar PV Cell Based Inverter for Unbalanced and Distorted Industrial Loads

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Abstract

PV cell is getting importance in low and medium power generation due to easy installation, low maintenance and subsidies in price from respective nation. Most of the loads in distribution system are unbalanced and distorted, due to which there will be unbalanced voltage and current occur at load and may disturb its overall performance. Due to these loads voltage unbalance, distorted voltage and current and variable power factors in each phase can be observed. An efficient algorithm to mitigate unbalanced and distorted load and source voltage and current in solar photo voltaic (PV) inverter for isolated load system was considered. This solar PV system can be applicable to remote located industrial loads like heating, welding and small arc furnace type distorted loads and also for unbalanced loads. The PV inverter is designed such that it will maintain nearly constant voltage magnitude and can mitigate harmonics in voltage and current near the load terminals. A MATLAB/ SIMULINK based solar PV inverter was simulated and results are compared with standard AC three phase grid connected system. The proposed shows that the inverter is having very less voltage and current harmonic content and can maintain nearly constant voltage profile for highly unbalanced system.

Keywords: *distorted load, unbalanced load, PWM inverter, total harmonic distortion (THD), voltage mitigation*

1. Introduction

Photovoltaic power generation is getting more significance over past decade. This increase can be expected due to the major factor like greenhouse effect, rapidly increasing fossil fuel price and diminishing resources. In tropical countries like India, sunlight is available for more than half of the time of the day; installation of solar cells is highly recommendable. It was observed that roof top solar panels are installed for water heating, reliable and economic power supply was increased in last five years [1-5]. The main advantages of solar PV cells are, it can be placed in the corner of the building where much sunlight is available; it requires very less maintenance and have more running life, excess energy can be stored in battery or can be pumped to grid.

The solar PV with battery energy storage system is helpful for maintaining continuous and reliable power supply to isolated agriculture type loads [6]. The solar panels can be applicable to residential loads by embedding on the roof top [7-9]. The solar panels are used for applications like road transport lighting and in electric power distribution network [10, 11]. There has been very less work been proposed for application for industrial loads like arc furnace etc. Application of PV cell for non-linear loads and its harmonics analysis was analyzed in [12, 13]. A three-phase DC to AC inverters with high efficiency, low cost, enhanced reliability are designed in [14- 17].

The present paper extended the application of photovoltaic cell to non-linear and unbalanced industrial AC loads by using DC to AC inverter. The PWM based inverter is designed to maintain nearly constant voltage profile for unbalanced load and harmonic mitigation for distorted non-linear diode rectifier RL load. In this, voltage and current unbalance and distortion values to be within limits and with optimum power factor value with inductance or capacitance loads. Equations for unbalanced load and source voltage and current with average power to be delivered by grid source or PV inverter are derived.

The paper describes modeling of the PV inverter system for distorted and unbalanced loads, mitigation of voltage and current harmonics with analytical explanation and control circuit

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of inverter was explained in forth coming sections. Later, simulation results are given and conclusion with appendix and references were presented.

2. Solar PV Based Inverter for Distorted and Unbalanced Loads

In general, small scale industrial loads in developing countries like India are welding, induction heating and small rating arc furnace loads. Most of the loads in the same industry or industrial locality are highly unbalanced. If these industries are located in remote places or rural areas, they may not get quality power supply and also power lasts for few hours during summer due to many reasons. In order to have reliable power, if industry generates their power by installing a captive power plant with solar photovoltaic (PV) system is a better alternative.

The solar photovoltaic based inverter for distorted and unbalanced isolated industrial loads is shown in Figure 1. The PV cell is a current source device with Dc supply as output. In order to extract maximum power from solar cell, maximum power point tracking (MPPT) algorithm is used. The 19 unique techniques for MPPT algorithm can be available [20]. The DC output voltage from PV cell is to be converted to AC as most of the loads are of AC supply. Capacitor near the bidirectional inverter is used to maintain nearly constant voltage and also acts as a reactive power supplier for maintain nearly constant voltage profile.

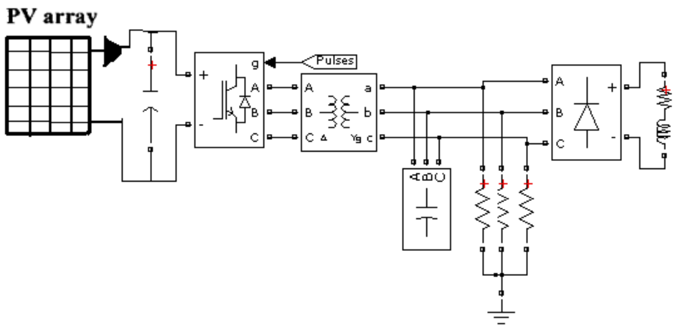

Figure 1. PV cell based inverter for distorted and unbalanced loads

The transformer is used for step-up or step-down voltage to meet voltage demand by the load. The star-delta combination of transformer is also used for suppressing third order (3n) harmonics and star point neutral grounding for protection, measurement and grounding unbalanced current. The diode rectifier with resistive (R) or resistive- inductive (RL) loads represents distorted loads like arc furnace, induction heating (low resistance, high inductance coil) or as welding type AC loads. The shunt type resistive loads if they are unequal, they represent unbalanced loads. The unbalanced load voltages can be represented as:

$$V_{lA}=V_{lmA}\sin(\theta) \quad (1)$$

$$V_{lB}=V_{lmB}\text{in}(\theta-120^0+b) \quad (2)$$

$$V_{lC}=V_{lmC}\sin(\theta+120^0+c) \quad (3)$$

Here V_{lA}, V_{lB} and V_{lC} are load voltages in A, B and C phases with RMS voltages in each phases A, B and C are V_{lmA}, V_{lmB} and V_{lmC}.

In this each phase difference is 1200 between them and due to unbalanced system; there is small voltage angle shift in phases B and C with small angles b and c. if the system is perfectly balanced, angles b and will be zero. The load currents are given by below equations:

$$I_{lA}=I_{lmA}\sin(\theta-\Phi) \quad (4)$$

$$I_{lB}=I_{lmB}\sin(\theta-120^0+b-\Phi) \quad (5)$$

I_{lC}=I_{lmC}sin(θ+120^0+c-Φ) (6)

Here I_{lA}, I_{lB} and I_{lC} are load voltages in A, B and C phases with RMS voltages in each phases A, B and C are I_{lmA}, I_{lmB} and I_{lmC}.

The angle Φ is power factor angle which will exist if the load contains resistive with inductance and or capacitance value. For unity power factor load with only resistance the angle Φ will be zero. The average power delivered by three phase source or inverter can be written as:

$$P_{l_{avg}}=\frac{1}{2}[V_{lA}I_{lA}+V_{lB}I_{lB}+V_{lC}I_{lC}]\cos(\Phi) \quad (7)$$

Substituting equations 1, 2, 3, 4, 5 and 6 in equation 7 we get average power to be supplied by three phase source or inverter supply.

The inverter or three phase supply current is given three equations as:

$$I_{sA}=\frac{2P_{l_{avg}}V_{lA}\llcorner-\Phi}{cos\Phi V_{lmA}(V_{lmA}+V_{lmB}+V_{lmC})} \quad (8)$$

$$I_{sB}=\frac{2P_{l_{avg}}V_{lb}\llcorner-\Phi}{cos\Phi V_{lmB}(V_{lmA}+V_{lmB}+V_{lmC})} \quad (9)$$

$$I_{sC}=\frac{2P_{l_{avg}}V_{lC}\llcorner-\Phi}{cos\Phi V_{lmC}(V_{lmA}+V_{lmB}+V_{lmC})} \quad (10)$$

The total three phase voltage to be supplied by PV cell based inverter is given by:

$$V_i=\frac{1}{2}[V_{iA}\alpha_A+V_{iB}\alpha_B+V_{iC}\alpha_C] \quad (11)$$

The three phase inverter voltages due to the existence of unbalanced and distorted loads are V_{iA}, V_{iB} and V_{iC} and the compensation voltage coefficients due to unbalanced and distorted loads are α_a, α_b and α_c.

$$\alpha_a=1, \alpha_b=\frac{\cos(\Phi+b)}{\cos(\Phi)}, \alpha_c=\frac{\cos(\Phi+c)}{\cos(\Phi)} \quad (12)$$

After perfect compensation b and c angles will become zero and α_b and α_c to be unity can be achieved by PV inverter topology. The load current with all the harmonics included can be represented as:

$$I_l=\sqrt{\sum_{n=1}^{\infty}[(I_{lA}^{2n\pm1})^2+(I_{lB}^{2n\pm1})^2+(I_{lc}^{2n\pm1})^2]} \quad (13)$$

Where n is the order of harmonics, with n=1 as fundamental. In this 3n and 2n order harmonics are cancelled due to symmetrical three phase supply. 2n±1 harmonics are present and based on control circuit and passive filters combination, higher order harmonics can be eliminated. The sum of all harmonics divided by fundamental harmonic gives total harmonic distortion (THD).

3. Mitigation of Voltage and Current Harmonics for Distorted and Unbalanced Industrial Loads

The rectified RL load will distort three phase voltage and current waveforms and linear R load of unbalanced load results in unbalanced voltage and current for Figure 1 can be written as:

$$L\frac{di_c}{dt}=-v_c+\frac{V_{pv}}{2}-L\frac{di_{load}}{dt} \quad (14)$$

$$L\frac{dv_c}{dt}=-i_c \quad (15)$$

$$i_m=\mathcal{P}i_c+\mathcal{Q}i_{load} \quad (16)$$

$$L\frac{di_m}{dt} = -\mathcal{P}v_c + \frac{\mathcal{P}V_{pv}}{2} - (\mathcal{P} - \mathcal{Q})L\frac{di_{load}}{dt} \quad (17)$$

$$\mathcal{P}C\frac{dv_c}{dt} = i_m - \mathcal{Q}i_{load} \quad (18)$$

In the above equations, L represent equivalent inductance of the transformer and smoothing reactor and C is the capacitance of shunt passive filter. V_{pv} is the PV cell output voltage and V_c is shunt filter capacitor voltage. i_m is main current flowing to filter and to the linear and non-linear loads, i_{load} is the current flowing through the two loads. $\mathcal{P}$ and $\mathcal{Q}$ are weights of capacitor current and load currents.

From Equation (1), (3), it can be observed that if load current in all phases are different then capacitance current flowing to filter in respective phases will be different and finally PV cell output voltage and capacitor voltage will be different. The weights ($\mathcal{P}$ and $\mathcal{Q}$) are so chosen to follow Equation (2) and (3), so that (5) is satisfied.

The voltage source inverter is designed such that based on i_m and i_{load} current in each phase, voltage in each leg of the inverter is switched ON or OFF to maintain constant load voltage. Current harmonics are also controlled by using above equations. The voltage harmonics are controlled by using reactive power compensation provided by the inverter side DC capacitor link and proper control strategy to eliminate higher order harmonics and 9th order harmonics are eliminated by passive shunt capacitance filter. Hence among lower order harmonics 5th and 11th are left to be eliminated by using above control strategy.

4. Control Circuit of Inverter

The control circuit for solar PV based inverter for distorted and unbalanced loads is shown in Figure 2.

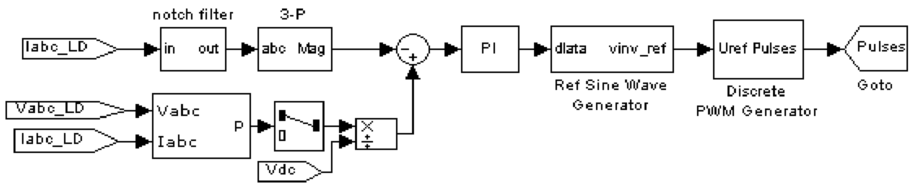

Figure 2. Control circuit for solar PV based inverter for distorted and unbalanced loads

The three phase load current is taken as input and is filtered by using notch filter in order to pass few harmonic order waveforms. The phase currents are converted into magnitude to get actual magnitude of load current. The load real power is divided with PV cell or inverter capacitor voltage to get reference load current. The difference between reference and actual load currents is error in current waveform. This error can be minimized by using optimal tuned proportional and integral controller (PI), which helps also in maintaining stability during rapid switching of pulses and due to other small disturbances and its output is fed to the reference sine wave generator to produce three phase voltage waveform. The circuit for reference sine wave generator is shown in Figure 3.

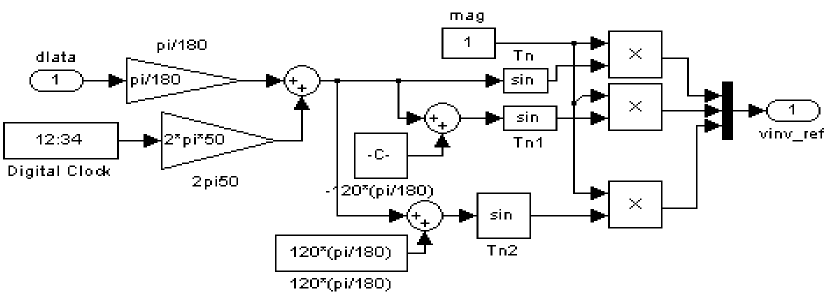

Figure 3. Reference sine wave generator from PI controller output

The three phase reference sine wave is converted into magnitude and angle and is further given to PWM based inverter to generate pulses for voltage source inverter (VSI) which is a bidirectional IGBT switch.

5. Simulation Results

The implamentation of MATLAB/ SIMULINK for grid connected and PV inverter for distorted and unbalanced load is shown in Fig.4 and 5. Now comparison is made between these two circuits for same rated load in case-A and case-B, case-A is grid connected and case-B is with inverter type load. The ratings of the parameters are given in Appendix.

Case-A: Conventional Three phase grid source

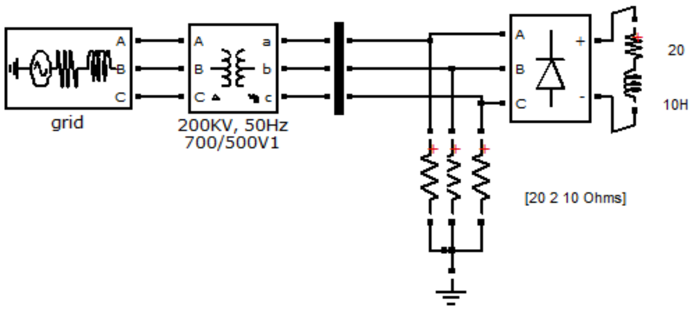

Figure 4. Simulink diagram of grid circuit for distorted and unbalanced load

The load voltage and current waveforms for grid connected distorted and unbalanced loads are shown in Figure 5. It can be observed that all the three phases' voltages are not same, the red color waveform is having 650V, blue is having 300 volts and green is having 550 volts. Similarly red color current waveform is 50A, blue color current wave is 165A and green color phase current is 65A. Both voltage and current are unbalanced.

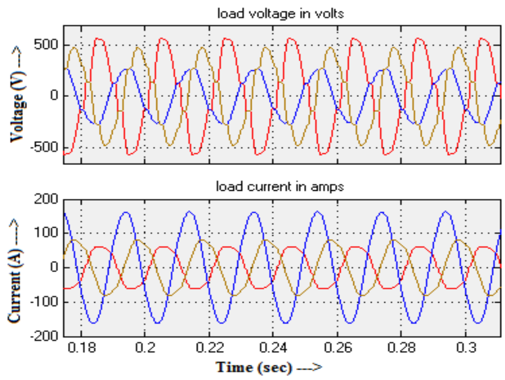

Figure 5. Load voltage and current waveforms for grid supply circuit

The total harmonic distortion (THD) of voltage and current waveform for blue color phase for grid connected non-linear and linear loads are shown in Figure 6 and 7.

It can be observed that voltage THD is 7.25% and current THD is 1.17% for blue phase. For red color phase voltage and current THDs are 4.80 and 6.77%, green color phase is having 6.34 and 3.43%. However it can be observed that power factor is almost unity as resistive load is more dominating than inductive load.

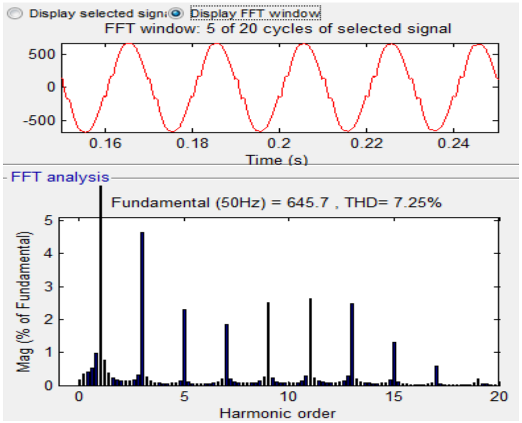

Figure 6. THD of blue color waveform for grid connected load voltage

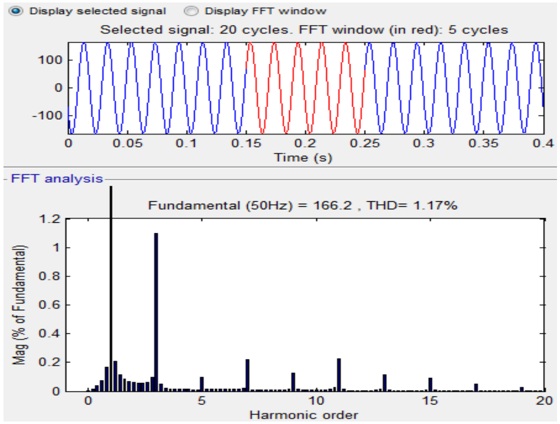

Figure 7. THD of blue color waveform for grid connected load current

Case-B: Inverter Type Load

The PV cell based inverter for same linear and non-linear loads is given in Figure 8.

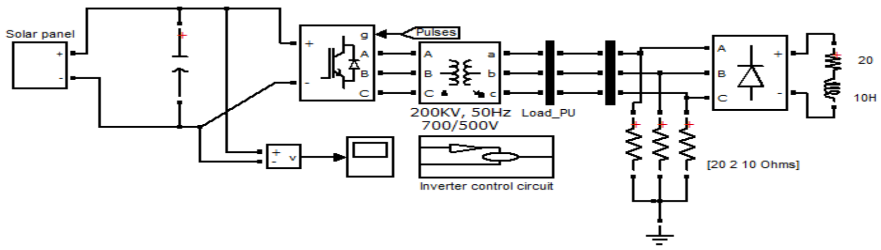

Figure 8. Simulink diagram of PV inverter for distorted and unbalanced load

It can be observed that all the three phase voltages are nearly same and have 650V as peak-to-peak value and current in red phase is 52A, blue phase is 290A and green phase is 82A respectively as shown in Figure 9. The three phase's voltages are 650, 625 and 550 Volts respectively.

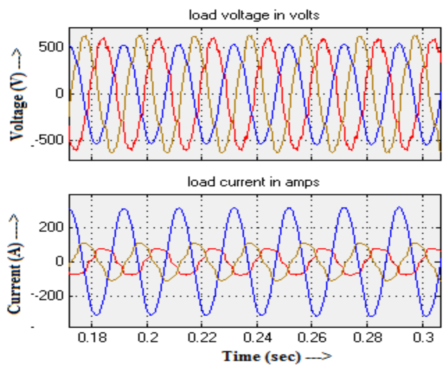

Figure 9. Load voltage and current waveforms for PV inverter circuit

The difference in three phase currents for grid connected and inverter fed loads are different simply due to the fact of voltage unbalance and balance in these cases.

The output voltage, current and power waveforms for solar PV system is shown in Figure 10. In this analysis, the sun irradiation is constant solar cell is working in normal conditions with good cooling and appropriate MPPT algorithm. The output of solar cell is maintained at 900 volts and current varying between 100 and 150Amps. The output power is about 135KW.

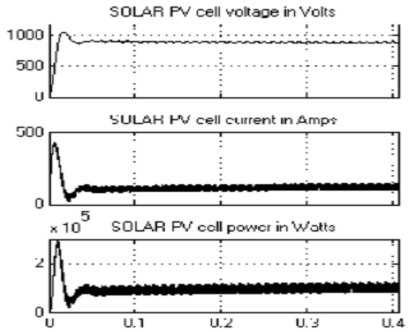

Figure 10. Solar PV cell output voltage, current and power waveforms

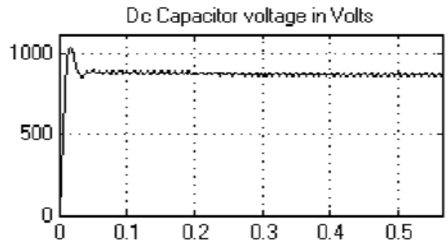

Figure 11. DC link capacitance voltage in volts

The output voltage waveform of DC link capacitor is given in Figure 11 and its value is nearly constant at 850V and the ripples are also minimum. The THD of voltage and current waveform for blue phase is shown in Figure 12 and 13. The load voltage THD is 2.06% and current THD is 1.80% for blue color waveform. The red color wave is having 3.36% and 2.80%, while green color wave is having 4.8% and 1.25% THD. Table 1 shows the output voltage and current with THD values for grid and PV Inverter.

Table 1. Output Voltage and Current With THD Values For Grid And PV Inverter

	3 Phase Grid Supply				*PV Cell Inverter*			
Ph	*V_mag Volts*	*I_Mag Amps*	*V_THD %*	*I_THD %*	*V_Mag Volts*	*I_MAG Amps*	*V_THD %*	*I_THD %*
A	*650*	*50*	*7.25*	*6.77*	*690*	*52*	*2.06*	*2.8*
B	*550*	*65*	*4.80*	*1.77*	*625*	*82*	*3.36*	*1.80*
C	*300*	*165*	*6.34*	*3.43*	*550*	*290*	*4.8*	*1.25*

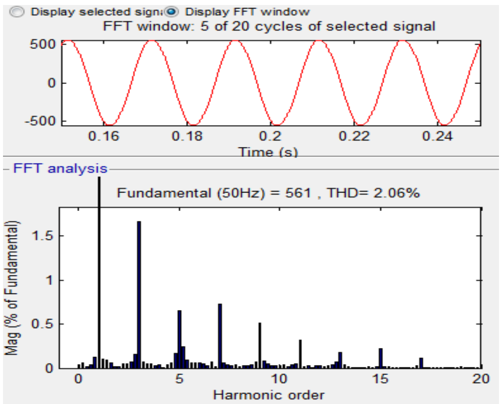

Figure 12. THD of blue color waveform for inverter connected load voltage

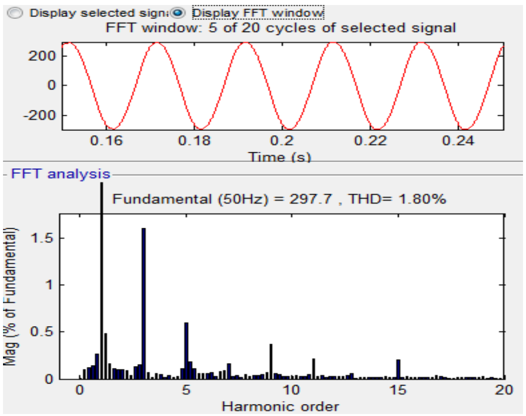

Figure 13. THD of blue color waveform for inverter connected load current

6. Conclusion

For normal grid connected supply, the three phase voltages are different due to unbalanced loads and their voltages are 650, 550 and 300 volts respectively and their voltage THDs are 4.8, 6.34 and 7.16% and current THDs are 6.77, 4.43 and 1.17%. The source or load voltages are unbalanced and have THD in two phases more than 5%, which may not be acceptable. So an additional passive filter is required to mitigate harmonics and active filter to compensate decreased voltage due to load. With the proposed control strategy, the voltage in the three phases is 650, 625 and 550 volts and current is 82, 290 and 52Amps respectively. The same phase's voltage THDs are 2.06, 3.36 and 4.8% while current THDs are 1.8, 2.8 and 1.25%. Hence in all the three phases, maintained nearly constant voltage profile and is also having THD less than 3%. But compared to grid source, current THD is high and in two phases it is more than 3% and however is acceptable to keep a passive filter to decrease this content. The proposed scheme will have 5, 7 and 11 order harmonics in voltage and current waveforms and has to be minimized by using a band pass filter. Therefore our proposed scheme can suppress voltage harmonics due to load and also do not produce much destructive harmonics and is highly capable to maintain load voltage almost constant. DC voltage ripples are minimum and control scheme is easy to implement compared to Park's transformation or phase sequential methodologies.

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