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Low-Cost Grid Connected Photovoltaic System

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***Abstract*—In this paper a novel method for low-cost grid connection of photovoltaic systems is proposed. The main idea for cost reduction is based on usage of B4 four switch three-phase dc to ac inverter. Also, it is capable of reactive and harmonic compensation and if it is used in the neighborhood of nonlinear loads, separate equipments for load compensation will not be needed. In addition to all, during outage of grid, this system will continue to supply local loads. Finally, in order to validate the accuracy of the proposed control strategy, grid-connected PV system is simulated based on MATLAB/Simulink.**

Keywords- reactive and harmonic compensation, low-cost grid connected photovoltaic system, B4 inverter and hysteresis current control

I. INTRODUCTION

Certainly one of the best forms of energy is electrical energy. Now days it is generated by large, centralized power stations and Often is based on fossil fuels that may cause high loss in transmission and distribution lines. Therefore Distributed Generation(DG) have been widely used in recent years. Obviously, if the photovoltaic panels are used as electric power generator in DG systems, fossil fuels and related environmental pollution are also removed. For this reason photovoltaic system may be called *green* or *clean* energy. With increasing problems of environmental pollution and also reduction of fossil energy resources, the use of photovoltaic systems in recent years has risen rapidly [1] - [2].

Due to high cost, historically photovoltaic systems mainly have used to supply satellites, but with invention of low-cost thin film Panels, usage of photovoltaic power plants in recent years have increased[3]. Up to 2004, most of the photovoltaic systems were used separately from the utility, but recently with the emergence of high-voltage switches, grid connected photovoltaic power plants have been customary[4]. These systems require no battery for night time and for this reason total cost of the system may reduce strongly. This is shown in Fig.1. Main components of these systems are *photovoltaic panels* and *power electronic converters*. Considering *installation*، the comparative detail cost[5] is given in Fig.2. In this case the cost of thin film photovoltaic has been considered. In 2010 the price of a *60w* thin film panels is $110 in America which is much cheaper compared with the crystalline ones[6]. For this reason, the cost of power electronic converters determines the major portion of the total system cost. In this paper a practical and effective approaches is considered to reduce this part costs.

In recent years, lots of researches on grid connected photovoltaic systems has been done[7]-[14]. In [7] an efficient method for power factor correction of local loads with grid connected photovoltaic systems has been introduced. In [8] a simple control method has been proposed which is capable of local load compensation. Usage of high-efficiency DC-DC converters has been investigated in [9] to improve efficiency. In 1994 instantaneous reactive power theory has been proposed by H.Akagi for controlling of Active Power Filters(APF)[10], and in reference [11] such a method is used for reactive compensation and harmonic filtering of local loads in grid connected photovoltaic systems. However in 2008 this idea is used in [12] and many other similar articles. Transformerless photovoltaic systems is discussed in detail in [13] which may be considered as an important step in cost reduction. In [14] a new method for grid connection of photovoltaic panels using digital PLL has been proposed. In spite of these researches, still usage of grid connected photovoltaic systems are not economical in comparison with conventional generators. This case is more relevant in countries where low cost energy is available which is based on fossil fuels.

In this paper a new method for grid connecting of photovoltaic panels is proposed. Strategies used to reduce the final cost can be summarized as follows:

1) In grid connected photovoltaic systems, we could supply some portion of load power demand from utility during peak hours. Meanwhile, during light load hours, extra energy could be injected into utility. Also there is no need for backup battery and final cost will increase dramatically.

2) Photovoltaic inverters are used for grid connection and AC loads supply. This converter is an important part of the final cost. Since B4 inverter is proposed to be used in this paper and its cost is two thirds of the traditional inverters, the final cost of the system maybe reduced dramatically.

3) It is completely common to use small grid connected generators in remote areas due to the limited capacity of transmission and distribution lines and in this case the use of these systems could improve dynamical stability of utility. Also usage of reactive compensators and switched capacitors in such areas is quite common. This capacitors can release capacity of lines due to local load reactive compensation. In this article in order to reduce the cost of grid connected photovoltaic systems, inverter control strategy is designed so that photovoltaic system compensates for reactive and

harmonic components of local loads. In other words, in addition of injecting active power into the utility, the photovoltaic system compensates for local loads. Such control method can be used as an appropriate policy to justify the photovoltaic systems (especially in remote areas and in the presence of nonlinear loads).

4) Typically photovoltaic systems are connected into the utility via heavy 50Hz transformers. This problem could be solved according to invention of new high voltage switches (especially IGBT).

In this paper, practical design process of hysteresis current controller is investigated at first. Then we'll introduce B4 inverter. In the third section, the control strategy which is used for grid connection of photovoltaic systems is presented. The proposed control strategy could compensate for nonlinear loads. Finally, the accuracy of proposed control strategy has been tested with simulation which is based on MATLAB / Simulink.

II. Structure of the Low-Cost Grid Connected Photovoltaic System

A. *Hysteresis current control technique: how to design and implementation details*

Current controlled inverters in grid connected photovoltaic systems is better because:

• Since utility is voltage source, it is only enough to control the current flow in order to control power flow between photovoltaic systems and the utility.

• If the voltage control method is used, small phase error in the output voltage of inverter may cause very large power current error[15].

Different methods have been proposed for current control of inverters; for example: *ramp comparison, predictive current control method* and *hysteresis band technique* [16]. Hysteresis current controller has been used widely due to fast dynamic response and its simplicity of implementation. Operation principal of hysteresis current control method is relatively simple. According to the situation of power switches in a single-phase inverter (Fig.3), two different area can be considered:

A) If we turn Q_1:on and Q_2:off, inductive load current (i_a) will increase.

B) If we turn Q_2:on and Q_1:off, load current will decreases.

It is clear that by applying appropriate switching, we can control the variation of output current and it will always remain inside of specific range.

TABLE I. Binary table used to design the controller(in this table S(t+1) is next switching state, A and B are comparators output and S(t) is the previous situation of the switch.)

S(t)	A	B	S(t+1)
0	0	0	0
0	0	1	0
0	1	0	1
0	1	1	*
1	0	0	1
1	0	1	0
1	1	0	1
1	1	1	*

This is done by defining a hysteresis band around the reference current (i_{ref}) (Fig.4):

$$\begin{cases} i_{ref(Up)} = i_{ref} + \frac{H}{2} \\ i_{ref(Down)} = i_{ref} - \frac{H}{2} \end{cases} \quad (1)$$

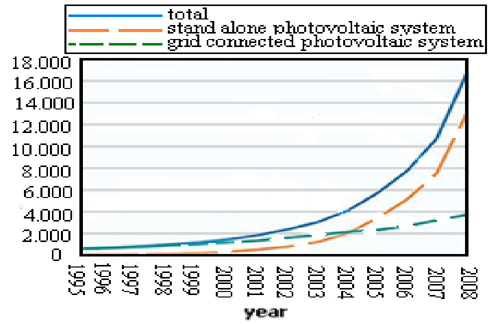

Figure 1. Grid connected and stand alone photovoltaic systems growth in recent years[4]

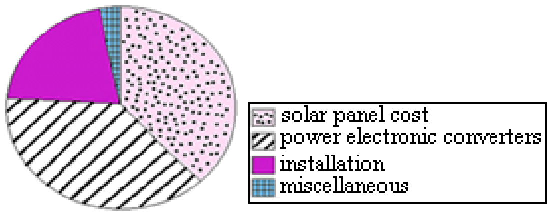

Figure 2. Different parts and comparative cost of grid connected photovoltaic systems[5]

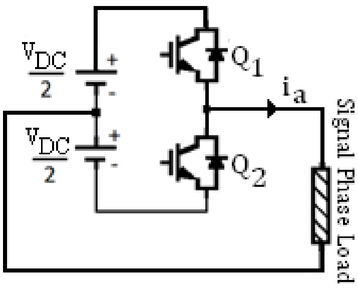

Figure 3. single phase half bridge inverter

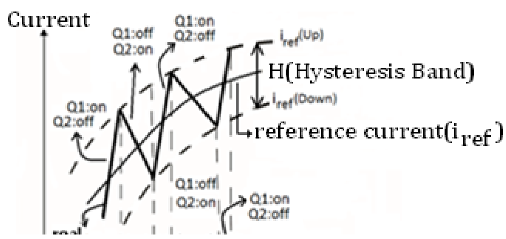

Figure 4. hysteresis current controller (i_{ref}(Up) and i_{ref}(Down), respectively, indicating high and low range of reference current and H is the hysteresis bandwidth.)

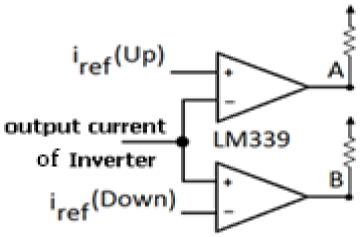

Figure 5. initial implementation of hysteresis current control circuit

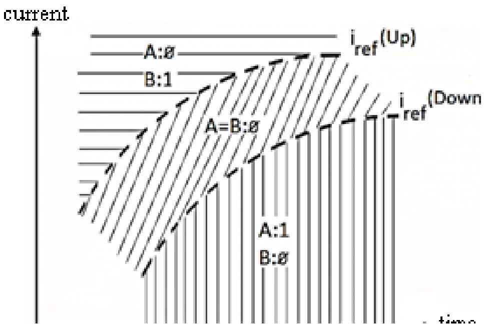

Figure 6. the comparators output values (A and B in Fig.5) in different parts of the current page

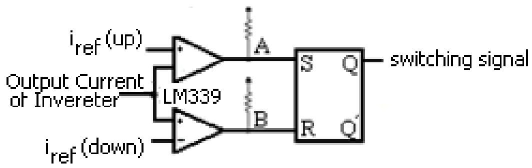

Figure 7. practical implementation of hysteresis current controller

Where H is called hysteresis band. Obviously reduction of hysteresis band decreases error, but on the other hand, the switching frequency and power losses will increase. During implementation of this method, actual output current of inverter is compared to i_{ref} (Up) and i_{ref} (Down) (Fig.5). Values of A and B in different regions is given in Fig (6). It is clear that due to nature of the system, state A=B:1 is not taking place and it is *don't care* state. This sequential circuit is specified in Table.1. This table is written for determination of desired switching command (S(t+1)) and according to the amount of A, B and the previous state of switch (S(t)). For example, when A=B:0, the current is in the desired range, and the switch should keep its previous state, thus: S(t+1)=S(t). Finally it is clear that Table.1 could be implemented with *Set/Reset Flip-Flop* simply.

B. B4 inverter structure

Usually from cost viewpoint, an important part of the grid connected photovoltaic systems is DC to AC inverter. In this paper B4 inverters is used instead of conventional B6. B4 inverters only employs four switches (in comparison, B6 inverters involve six). Usage of these inverters in low cost induction motor drive has been reported in [17] and[18]. Reduction of switch numbers not only saves the cost of required switches, but also decreases cost of related circuits such as driver, snubber, protection and so on. In fact, it can be said that almost 33 percent of the total cost decreases. Therefore it could be predicted that application of B4 inverter – that it is applied to grid connected photovoltaic systems in this paper – leads to widespread usage of these systems.

General operation principles of the B4 inverter is very simple and three-phase inverter could be implemented by connection of **two** half-bridge single phase inverter. Consider Fig.8. According to hysteresis current control method and with appropriate switching of Q1 and Q2, current i_a can be shaped easily. For example, suppose that:

$$i_a = I_m \sin(wt) \quad (2)$$

Also with control of Q3 and Q4 i_b be formed as follows:

$$i_b = I_m \sin(wt - 120^\circ) \quad (3)$$

According to presence of node N in a star connection of load (or null-point of utility) the following relationships can be considered:

$$i_c = -(i_a + i_b)$$
$$i_c = -(I_m \sin(wt) + I_m \sin(wt - 120^\circ))$$
$$i_c = I_m \sin(wt + 120^\circ) \quad (4)$$

Which shows that in a balanced three phase systems with star connection, current of phase C is formed without separate hardware and corresponding switches could be removed in order to reduce the final cost!

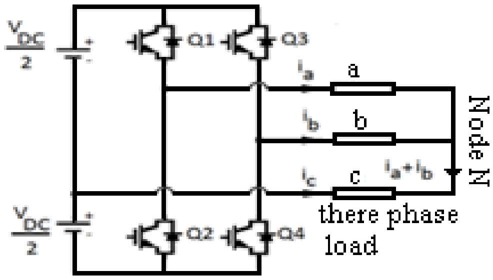

Figure 8. three-phase B4 inverter

III. STRATEGY OF LOW-COST GRID CONNECTED PHOTOVOLTAIC SYSTEM

Fig.9 shows low-cost grid connected photovoltaic systems in more detail. In this system, the photovoltaic array is connected into utility by a B4 voltage source inverter and boost chopper. This chopper is used for maximum power point tracking [19] which is not the subject of this paper.

From the viewpoint of the utility and according to control strategy, grid connected photovoltaic system may be considered as a AC power source, resistive load, inductance or capacitance, all with the same apparent power. In normal conditions, photovoltaic system can inject produced power by the photovoltaic arrays into the network and also compensates harmonic and reactive components of local loads current. In this case, current drawn or injected to the network perfectly will be sinusoidal and corresponding power factor will be unit. Also in general, control strategy of these systems must have the following abilities:

1.Production of reference current waveform in order to inject active power of photovoltaic panels to grid and load compensation

2.Voltage stabilization of input capacitors (DC side of inverter)In this section, instantaneous reactive power theory which is proposed by H.Akagi[10] in Active Power Filters will be used in order to calculate the reference currents. In this case if reference currents are generated by inverter then photovoltaic arrays power will be injected into grid and local loads compensation will be done completely. This theory is based on transformation of voltage and current variables to the αβ coordinates:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = [A]\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}, \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = [A]\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (5)$$

In this equations [A] is the transfer matrix:

$$[A] = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \quad (6)$$

These equations are valid if $V_a+V_b+V_c = 0$. Instantaneous active and reactive power on the αβ coordinates could be calculated by the following equation:

$$P(t) = v_\alpha(t)\, i_\alpha(t) + v_\beta(t)\, i_\beta(t) \quad (7)$$

$$Q(t) = -v_\alpha(t)\, i_\beta(t) + v_\beta(t)\, i_\alpha(t) \quad (8)$$

Currents i_α and i_β in terms of instantaneous power values can be written as follows:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{v_\alpha^2+v_\beta^2}\begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix}\begin{bmatrix} p(t) \\ q(t) \end{bmatrix} \quad (9)$$

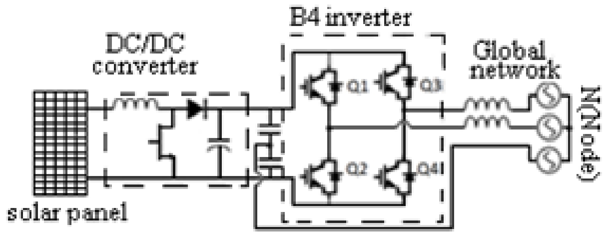

Figure 9. details of grid connected photovoltaic system based on B4 inverter

P and Q could be considered as the sum DC and AC components:

(10)

$$Q = \bar{q} + \tilde{q} \quad (11)$$

In these equations:

is DC component of instantaneous active power and it is related to the main component of active current.

is AC component of instantaneous power P which is related to those harmonic currents that are produced by the active component of instantaneous power.

is DC component of instantaneous power Q and it is related to the main component of reactive current. is AC component of instantaneous power Q which is related to those harmonic currents that are produced by the reactive components of instantaneous power.

In order to compensate nonlinear loads completely, reference current of grid connected photovoltaic system should involve , and . In this case, these harmful components don't enter into the utility. An important advantage of this theory is that in this case main components of active and reactive power are in the DC form and could be easily removed if it is necessary.

Beside reactive and harmonic compensation, the control strategy of grid connected photovoltaic systems must inject active power generated by the photovoltaic arrays into the grid. According to the maximum power point of photovoltaic cells, total active power which should be injected into grid could be determined as follow [19]:

$$P_m = V_m I_m \quad (12)$$

In the above equation V_m and I_m are voltage and current of photovoltaic cell in maximum power point and these both could be measured/calculated easily[19]. According to equation (9), reference currents of photovoltaic systems in αβ coordinates which will compensate for nonlinear load and also injects photovoltaic panels active power into grid could be expressed as follow:

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{1}{v_\alpha^2+v_\beta^2}\begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} \bar{p}_L + P_m \\ \bar{q}_L + \tilde{q}_L \end{bmatrix} \quad (13)$$

In the above equation, v_α and v_β are grid voltage and $(i_\alpha)^*$ and $(i_\beta)^*$ are reference currents of photovoltaic system at αβ. Reference current could be written in abc coordinates as follow:

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} \quad (14)$$

If output current of B4 inverter equals $(i_a)^*$ and $(i_b)^*$, according to the previous discussion $(i_c)^*$ will be produced without switching and therefore

(a) Maximum power produced by photovoltaic panels will be injected into grid.

(b) Load reactive and harmonic compensation will be done completely and unity power factor will be achieved.

Finally note that, for balancing and controlling of DC capacitors voltage, converter may absorb small amount of active power from the utility which is not subject of this paper.

IV. Semulation Results

In this section, in order to investigate accuracy of proposed control strategy, grid connected photovoltaic system is simulated according to equations of section III with MATLAB / Simulink. In this simulation the DC link capacitors totally assumed to be 10 miliFarad and coupling inductor is 500 MicroHenry. The hysteresis width is adjusted so that the switching frequency of inverter is near 5 kHz.

Performance of B4 inverter in sinusoidal reference current situation is shown in Fig.10. Currents of phase a and b is produced with switching and current of phase c is based on the previously described equations.

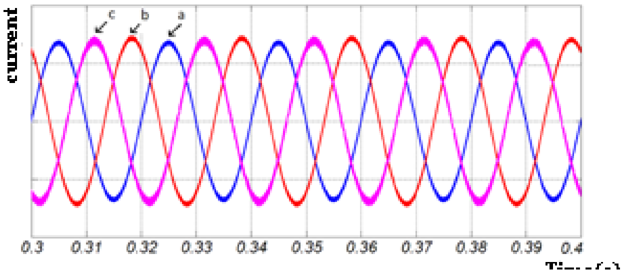

Figure 10. Three-phase output current waveforms of B4 inverter (sine current reference is used)

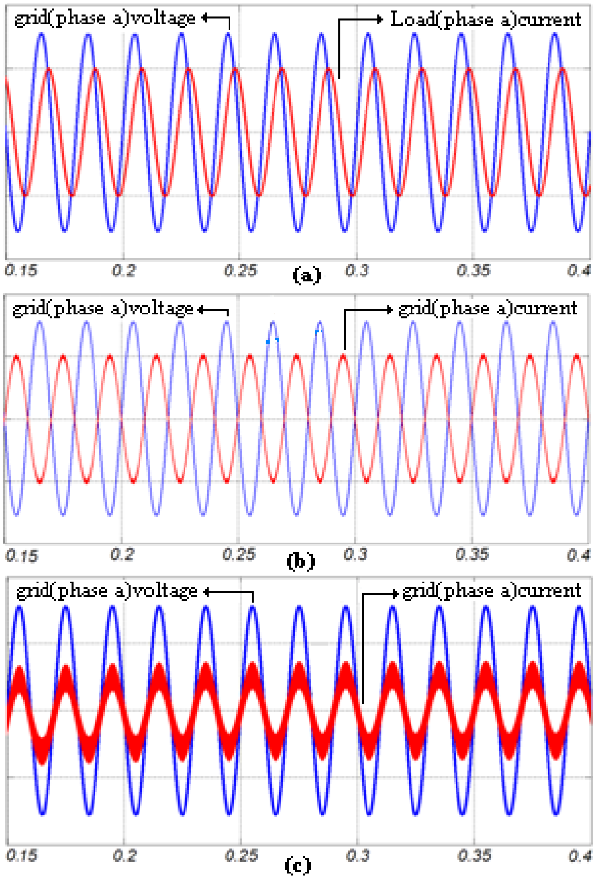

Figure 11. performance of low-cost grid connected photovoltaic system during reactive compensation (a):load voltage and current(reactive) (b):grid voltage and current during day(Photovoltaic active power is injected into grid and reactive compensation of the load is done simultaneously.(c): grid voltage and current during night(only compensation of the load is possible)

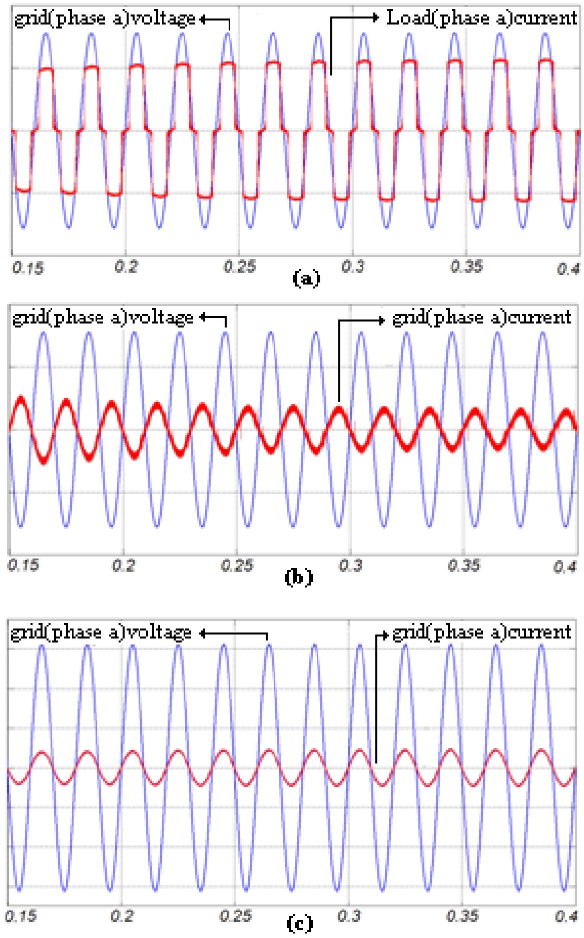

Figure 12. performance of low-cost grid connected photovoltaic system during reactive and harmonic compensation of load current (a):load voltage and current(nonlinear) (b):grid voltage and current during day(Photovoltaic active power is injected into grid and compensation of the load is done simultaneously. (c): grid voltage and current during night(only compensation of the load is possible)

Performance of low-cost grid connected photovoltaic system during reactive power compensation is illustrated in Fig. It could be seen that in spite of phase difference between voltage and current of load, photovoltaic system compensates all reactive power demand of load and finally grid voltage and current are in the phases (Fig. 11). It should be mentioned that during day-hours that photovoltaic panels could generate active power and it is injected into the network, there will be 180 degree phase difference. Finally, response of the proposed control strategy beside nonlinear loads is shown in figure (12). It is observed that in despite of severe harmonic components in load current (three-phase diode rectifier with highly inductive load is used as a non-linear load in this case) grid current is perfectly sinusoidal without harmonics.

V. Conclusion

In this paper novel idea of using B4 inverter in grid connected photovoltaic systems is proposed in order to reduce final cost of these renewable energy sources. The proposed control strategy is capable of injecting maximum generated power of photovoltaic panels into grid and load compensation both simultaneously. Also during power outage, this system could operate as an uninterruptable power supply(UPS).

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