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Electric Energy Management and Engineering in Solar Cell System

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Additional information is available at the end of the chapter

1. Introduction

Solar cell system has many competitive advantages in comparisson to other renewable ener-gy resources. For instance, wind-turbin is very dependable to geographical location and has very high noise pollution if applied in residential area. Other example is micro-hydro, which depends on altitude and available in very limited locations. Furthermore, nuclear energy should be forgotten since its high radioactive risk. On the other side, solar cell system has characteristics of zero pollution, no radioactive risk, compact, portable and can be installed in any residential areas and has relatively high energy availability in any location on the earth surface in a year round. In general, solar cell array, which cover a residential roof house can supply the basic electrical energy needs of the residences who live in the house, almost a year round. These competitive advantages of solar cell system over other renewa-ble energy resources, make solar cell system the most favorite renewable energy resource.

There are 2 main topics and will be discussed in accordance to energy management of re-newable energy resources, based on solar cell system. **The first topic** is how to keep the sys-tem sustainable to supply the applied electrical load. As we have already known that solar energy is not available continuosly in a day and year round. For instance, at noon, the avail-ability of solar energy is abundant, however, at night there is not available at all. In the rain or winter season, the availability of solar energy is less than in the dry or summer season. On the other hand, the needs of electrical energy may be in opposite situation of the availa-bility of solar energy. In order to keep the solar cell system able to serve the total electrical load, it is necessary to design the system, which has sufficient number of solar cells and bat-

teries to get and store the electrical energy from solar energy at the most available energy time (noon), and delivering to the consumers at the non-available solar energy time (night). In this first topic, in order to keep sustainable, it is conducted by designing the sufficient number of solar cells and batteries to supply the predicted electrical load.

In the first topic, the sustainability perspective in an energy network is emphasized in the form of designing the sufficient number of solar cells and batteries to supply the predicted electrical load. **The second topic** is sustainability to deliver energy perspective. It is focused on how conducting collaboration between several autonomy units of renewable energy system to build a renewable energy resource grid. Even, if possible, to do integration between autonomy units of solar system and the conventional electrical state own company. Here, we emphasize that the key problem of electric energy management of renewable energy resouces such as solar cell system is sustainability.

2. Electric energy management in an autonomy unit of solar cell system: A perspective

There are at least 2 strategic ways to implement renewable energy resources especially solar cell systems to fulfill the national electrical energy needs. The first strategy is to encourage the people to fulfill their own basic residential electric energy need by building private solar cell system. The second strategy is to let the Government as the regulator to drive a consortium of companies to build large plants of solar cell system to fulfill the regional or national electric energy need. Of course, the consortium will require a large amount of financial investment at the starting point, however along with the time, the long term electric cost will be getting lower and more cost effective, since solar cell system requires very minimum maintenance cost and free of solar energy.

A solar cell system as an autonomy energy resource unit must have an energy management control unit, which embedded in the system. In general, there are at least 5 parts should exist in a electrical renewable energy resource system, as shown on Fig 1 below, i.e.: (1) solar cell array; (2) management energy control system; (3) energy storage (s); (4) DC to AC and AC to DC converters and (5) delivery bus. Thus 5 parts should be designed such that the system becomes more efficient to manage the gathered electrical energy and to reach higher sustainability with low investment cost. We need 100% sustainability to fulfill the electrical energy need.

In order to reach 100% sustainability, first of all, the designer has to know how much energy need in average in every single day (prediction). Then, the designer must consider the region, where the solar cell system is located and it relates to the earth latitude. Further, it counts to the statistical condition of how long the total time the sun shines on thus region in a year round. Another important info is the statistical info of the longest duration of NO sunshine days, which relates to the seasons and weather. Thus are the most critical information to determine the requirement of the total number of solar cells and batteries in the system.
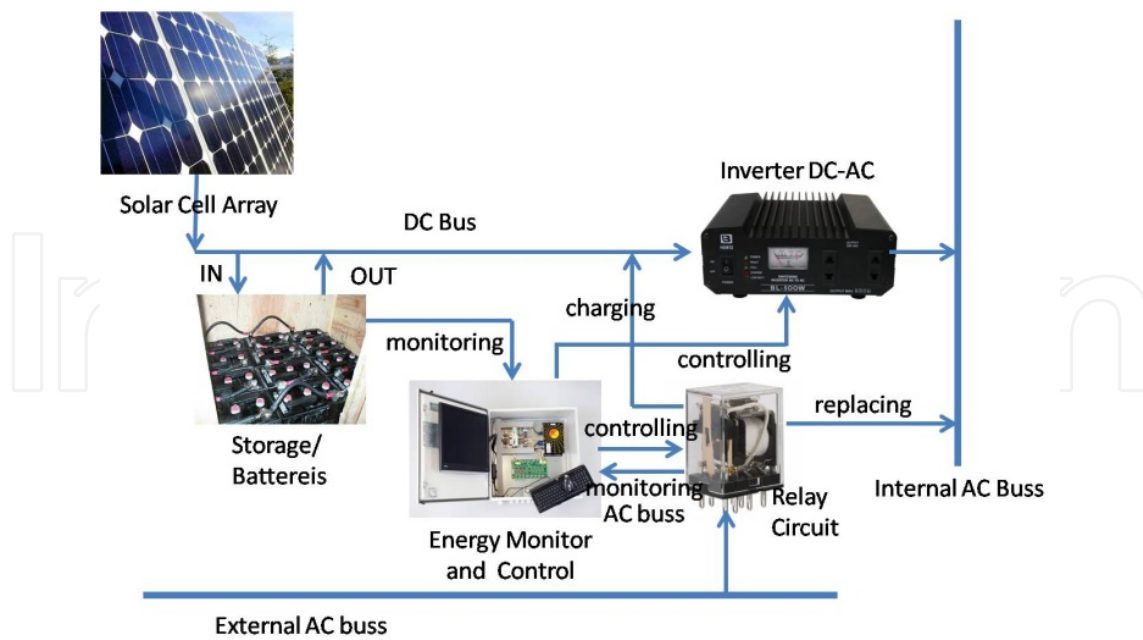
Figure 1. Big picture of Solar Cell Based Renewable Energy Unit System.

Solar cell produces DC electrical energy, which fits to be storage in batteries. In designing solar cell system, as explained above, it must be determined the assumption of average need of energy per day, for example A Watt-hour/day. Further, the estimate of statistical condition of how long the total time of NO sunshine days on thus region in a year round must be determined, for example N days. The amount of solar cells and batteries needed by the system is written in the following equation:

$$(1+c) \cdot N \cdot A \quad Watt\,hour \tag{1}$$

where c is a leak energy coefficient of the battery. In general, it has been known that the battery is not perfect to store DC electrical energy, it is always a part of stored energy in battery leaks. This is a inefficiency factor of battery and presented as "c" coefficient.

Solar cell system performance fully depends on the performance of thus 5 parts in building the system; which has been listed above (Fig 1). The following is explanation of every part.

3. Solar cell and eficiency

The main characteristic of solar cell is I-V curve. It has several derivative parameters such as I_{sc} (short circuit current), V_{oc} (open circuit voltage) and the maximum possible delivered energy $P_{mp} = V_{mp} \cdot I_{mp}$, as shown on the following Fig 2.
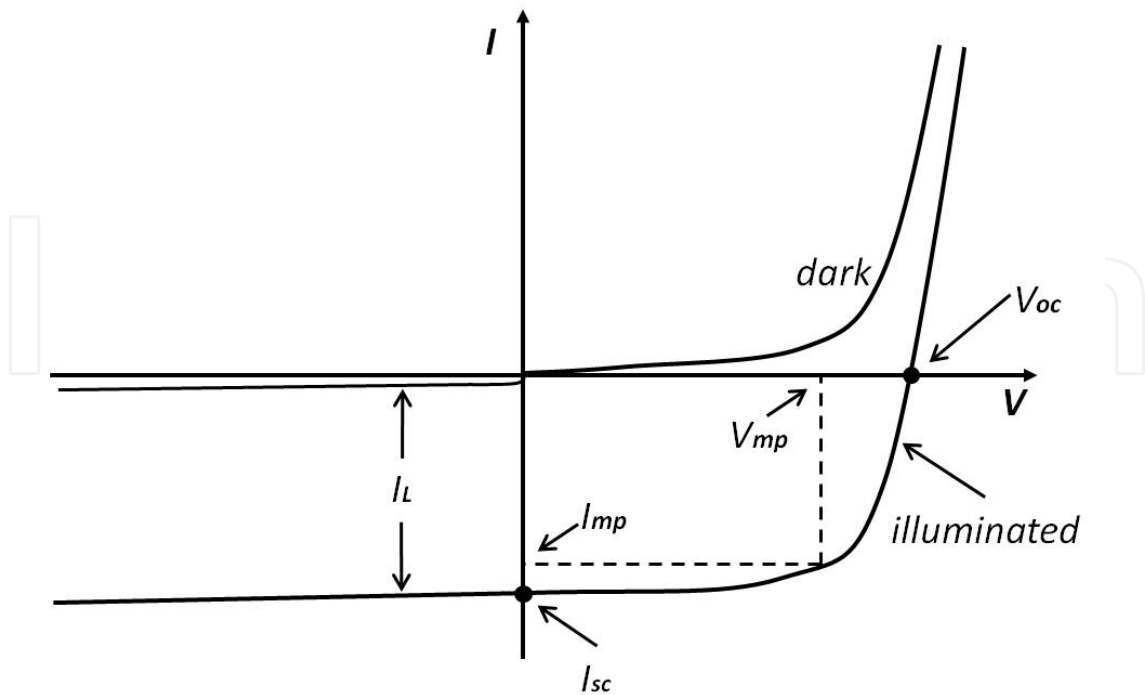
Figure 2. The Graph of the I-V characteristics of an ideal diode solar cell when non-illuminated (dark) and illuminated [1].

The main parameter that determines the solar cell efficiency is the maximum square area (power) as form of multiplication I-V ($P_{mp} = V_{mp} \cdot I_{mp}$), which is a maximum square formed inside I-V curve as shown on Fig 2 above. The next derivative parameter is fill factor *FF* that represents the ratio PMP to the product V_{OC} and I_{SC}. This parameter gives an insight abouthow "square" is the output characteristic.

$$FF = \frac{P_{MP}}{V_{OC} \cdot I_{SC}} = \frac{V_{MP} \cdot I_{MP}}{V_{OC} \cdot I_{SC}} \tag{2}$$

In the case of solar cell with sufficient efficiency, in general, it has FF between 0.7 and 0.85. The energy–conversion efficiency, η can be written as [2]

$$\eta = \frac{V_{MP} \cdot I_{MP}}{P_{in}} = \frac{V_{OC} \cdot I_{SC} \cdot FF}{P_{in}} \tag{3}$$

where P_{in} is the total power of light illumination on the cell. Energy-conversion efficiency of commercial solar cells typically lies in between 12 and 14 % [2]. In designing a good solar cell, we have to consider and put any effort to make those four parameters I_{SC}, V_{OC}, FF and η as optimum as possible [1]. We like to use term optimum than maximum, since the effort to obtain one parameter to be maximum ,in designing solar cell, will degrade other parameters. Hence the best is considering the optimum efficiency of solar cell.

4. Buss system

Solar cell produces DC electric energy. For solar cell system, where the solar cell array has radius not more than 100-m to batteries and electrical loads, it is effective and cost efficient to be connected by DC buss system. By using DC buss system, in order to transfer electrical energy from solar cells to batteries and loads, the parameter needs to be considered is voltage. The DC buss is the most efficient and cost effective, since it does not require electrical conversion from DC to AC. DC buss can be extended for more than 100-m, even can be more than several kms. In order to lower the DC electric power loss in the transmission from solar cells to batteries and loads, the DC transmission voltage should be increased, hence, to deliver the electrical power it requires only a very low current. This method is very popular used in AC electric transmission for long distance by using high voltage AC. The DC electric power transmission loss is written by the following equation:

$$P_L = I_{DC}^2 R_{tr} \qquad (4)$$

P_L is power loss in the DC transmission line, R_{tr} is the total transmission line resistance and I_{DC} is the DC current on DC buss transmission line. Hence, to lower power loss and R_{tr} kept same, then I_{DC} must be decrease much lower with consequence of V_{DC} must be increase proportionality to the decrement of I_{DC}. To increased voltage V_{DC}, in general conducted by using boost converter method.

4.1. Boost converter for DC buss system

Boost converter is an electronic circuit for *DC to DC converting*. It functions to increase voltage V_{DC} higher, i.e. by controlling the signal driver duty cycle. *Boost Converter* base circuit requires only 4 fundamental components, which are: inductor, electronic switch, diode and output capacitor, shown on Fig 3. The converter circuit can be operated in 2 modes, which depends on the energy storage capacities and the relative length of the switching period [3]. Those 2 methods are CCM (*Continuous Conduction Mode*) and DCM (*Discontinuous Coduction Mode*), where CCM is for efficient power conversion and DCM is for low power conversion[3].

4.1.1. Continuous Conduction Mode (CCM)

Mode 1 (0 < t ≤ t_on),

Mode 1 starts, when switch S (MOSFET) switched on at $t = 0$ until $t = t_{on}$. The equivalent circuit for Mode 1 is shown on the following Fig 4a. By assuming that the serial resistance value DC voltage source is relatively low, there will be an inductor current transient $i_L(t)$ larger than zero and increase linearly at the beginning of transient. Inductor voltage is $V_L = V_i$.

Mode 2 (t_on < t ≤ T_s),

Mode 2 starts, when switch S (MOSFET) switched off at $t = t_{on}$ until $t = T_s$. The equivalent circuit for Mode 2 is shown on Fig 4b. Inductor voltage, V_L in this period is $V_i - V_o$. In this case $V_i < V_o$, it means in Mode 2, V_L is in opposite direction to V_L in Mode 1.
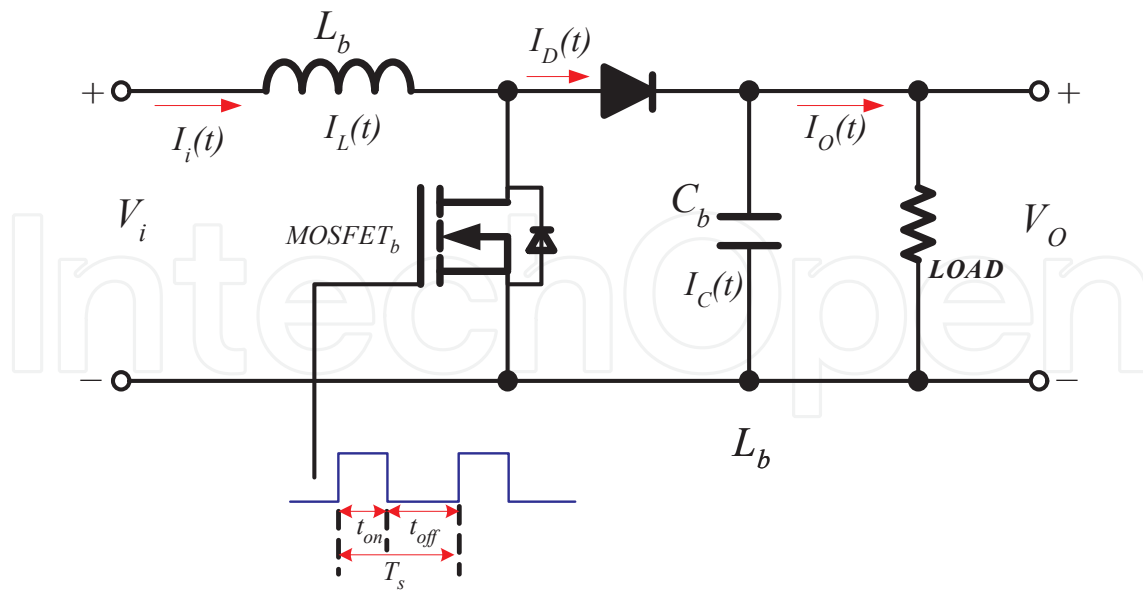
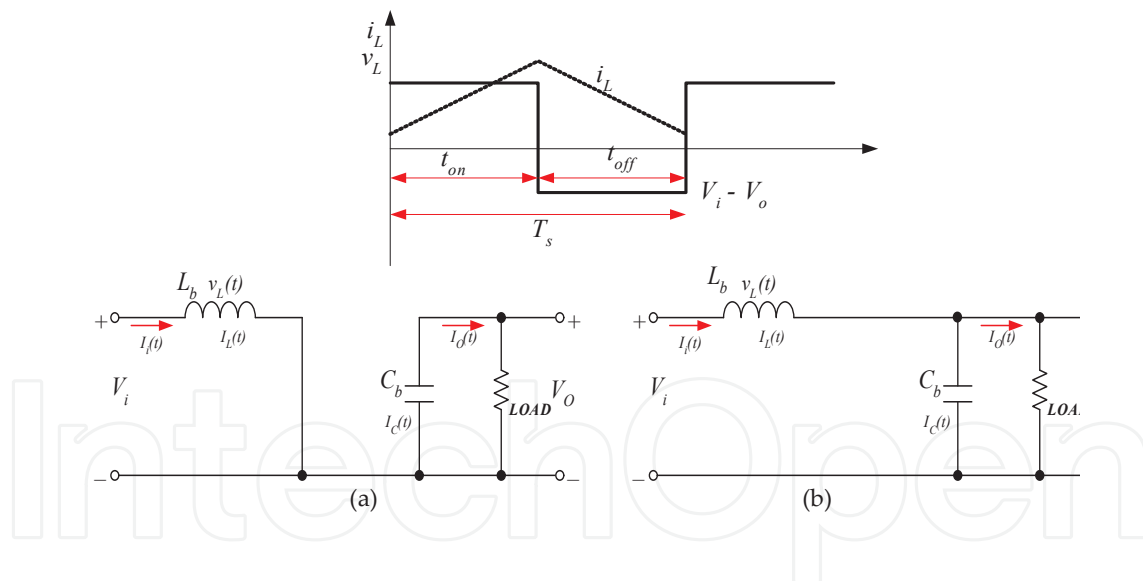**Figure 3.** Basic DC Voltage Boost Converter Circuit [3]

Figure 4. *Continuous Coduction Mode*:(a) Close switch, (b) Open switch

In steady state operation, the signal formed due to switching is repeated over all the time. The integral of inductor voltage v_L in one period must be equal to zero, where $T_s = t_{on}+t_{off}$. Therefore, the total summation of inductor voltage at open switch and close switch must be equal to zero.

$$V_i t_{on} + \left(V_i - V_o\right)t_{off} = 0 \tag{5}$$

Where:

V_i: input voltage

V_o : the average of output voltage

t_{on} : time *on*

t_{off} : time off

T_s: switching period

By arranging and separating V_i and V_o, and then dividing the both sides by T_s, it results in

$$\frac{Vo}{Vi} = \frac{Ts}{toff} = \frac{1}{1 - D} \qquad (6)$$

where D is duty cycle.

By assuming that the circuit has 100% efficiency, i.e $P_i = P_o$

$$I_i V_i = I_o V_o \qquad (7)$$

$$\frac{Io}{Ii} = 1 - D \qquad (8)$$

where

I_o : the average output current

I_i : the average input current

When the switch is close,

$$V_L = V_i; L \frac{di_L}{dt} = V_i; \frac{di_L}{dt} = \frac{V_i}{L}$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} \quad \rightarrow \quad \frac{di_L}{dt} = \frac{V_i}{L}$$

$$\Delta i_{L \ (close)} = \frac{V_i DT}{L} \qquad (9)$$

When the switch is open,

$$V_L = V_i - Vo; L \frac{di_L}{dt} = V_i - Vo; \frac{di_L}{dt} = \frac{V_i - Vo}{L}$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1 - D)T} \quad \rightarrow \quad \frac{di_L}{dt} = \frac{V_i - Vo}{L}$$

$$\Delta i_{L \ (open)} = \frac{(V_i - Vo)(1 - D)T}{L} \qquad (10)$$

At the transient time, where V_o is going to steady state condition, $\Delta i_{L\ (open)}$ or i_L slope at Mode 2 also experience transient following the gradient of V_o transient. At the time V_o achieves steady state condition, then $\Delta i_{L\ (open)}$ achieves steady state as well.

4.1.2. Discontinuous Conduction Mode (DCM)

At this mode, the inductor current will drop to zero before finishing one switching period, as shown on Fig 5. As the CCM analysis, the voltage inductor integral during one period is zero.

$$ViDTs + (Vi - Vo)D_1Ts = 0 \tag{11}$$

Then

$$\frac{Vo}{Vi} = \frac{D_1 + D}{D_1} \tag{12}$$
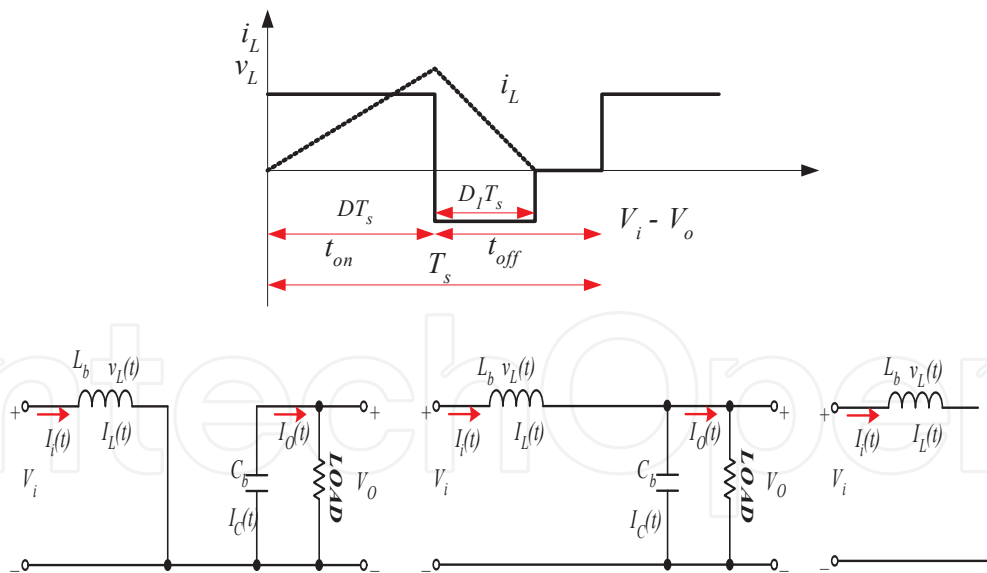
and

$$\frac{I_o}{I_i} = \frac{D_1}{D_1 + D} \tag{13}$$

Figure 5. Equivalent circuit for DCM mode.

a. Mode 1 ($0 < t \le t_{on}$);

b. Mode 2 ($t_{on} < t \le (D+D_1)T_s$);

c. Mode 3 ($D + D_1)T_s < t \le T_s$

From Fig 5.c, the average input current is equal to the inductor current,

$$I_i = \frac{V_i}{2L_b} D T_s (D + D_1)$$
(14)

By using equation (13),

$$I_o = \left(\frac{V_i T_s}{2L_b}\right) D D_1$$
(15)

In practice, *duty cycle* D should change to respone the V_i change, such that obtaining constant V_o. It requires an electronic feedback control system, as a function of loading curent for the change of V_i/V_d. This functions to control *duty cycle*. By using equations (12) and (15), we obtain:

$$D = \left[\frac{4V_0}{27V_i} \left(\frac{V_o}{V_i} - 1\right) \frac{I_o}{I_{o,avg,max}} \right]^{0.5}$$
(16)

Where $I_{o,avg,max}$ is the average of maximum output current, which is obtained via the following equation:

$$I_{o,avg} = = \frac{T_s V_0}{2L_b} D(1 - D)^2$$
(17)

The average output current will be maximum, when D = 1/3

$$I_{o,avg,max} = \frac{2}{27} \frac{T_s V_o}{L_b}$$
(18)

The critical inductance L_{bc}, is defined as inductance at the region of boundary, between *continuous* and *discontinuous modes*, and defined as:

$$L_{bc} = \frac{RD(1 - D)^2}{2F_s}$$
(19)

where:

R : equivalent load, Ohm

Fs : switching frequency, Hz

4.2. DC to AC inverter for AC buss system

When the distance between renewable energy clusters of solar cells, batteries and electrical loads is relatively far (can be hundred kms) and the electrical loads mostly are AC electrical loads, then it is necessary to consider to use AC buss system, which supported by DC to AC

inverters. By utilizing AC buss system, for long distance electrical transmission, the increase of AC voltage can be conducted by using passive transformator, which is common to be used. However, the integration process of several renewable energy autonomy systems is relatively more complex than integration in DC buss system. The problems in AC buss integration are due to more parameters that must be synchronized, such as voltage, frequency and phase. While in DC buss integration, it is only facing voltage synchronization.

In general, AC electrical power transmission is delivered in 3 (three) phases, especially for 3-phase electrical-mechanical motor loads, in order to be more smooth and more efficient in operation. 3-phase system is inherent in electrical generator based on mechanical generator, by arranging the three generator coils in three different locations by 120^0 phase angle in the generator. It also happens in the DC to AC inverter 3 phase. The sine generator generates 3 equal sine wave with different phase each of 120^0. DC-to-AC 1-phase inverter system is the fundamental to develop 3-phase system. The knowledge of working mechanism of 1-phase system is very helpful to understand 3-phase system.

In this chapter, we will discuss the working mechanism of DC to AC inverter 1-phase system in general. Then it is continued by discussion of the methods to synchronize thus three parameters of AC buss system, i.e: voltage, frequency and phase. In general, the use of DC or AC buss depends on the distance between sources, batteries and loads, also the variances of the loads. The ultimate consideration is energy efficiency and cost effective of the solar cell sytem.

4.2.1. Full bridge inverter

DC-AC inverter is a vital component in the solar cell system in order to support AC buss system for AC load. DC to AC inverter technology has been developed since the beginning of electronics technology era. At the beginning, DC-to-AC inverter was developed based on sinusoidal oscillator, which is amplified by push-pull amplifier of B class that has maximum efficiency of 50%. The 50% power loss is due to instantaneous drop-voltage at the final transistors on the push-pull amplifier. The fact of the 50% power loss is due to the sinusoidal form of the current and voltage running through the final transistor in DC to AC inverter circuit.

By realizing that push-pull final has maximum 50% efficiency, then full-bridge inverter technology was developed to increase the efficiency of DC to AC inverter. The work mechanism of bridge inverter is based on switching methods, as shown on the circuits of Fig 6 and 7, where at switch "on" the load current (I_L) goes through maximum, however the voltage drop (V_{DR}) across switch is very minimum. While at switch "off" the load current (I_L) goes through minimum, however the voltage drop (V_{DR}) across switch is maximum. Hence, it can be expected that power loss in the final transistors in the bridge inverter method is very small, which can be represented in equation:

$$P_L = V_{DR}I_L \quad \text{always minimum} \tag{20}$$

P_L or power loss is always minimum, either when switch "on" or "off".

In order that bridge inverter idea realized, then the power input to the final transistors must be a constant voltage V_{cc} and on-off discrete signal to control bride-inverter switches. The on-off signal is in the form of discrete signal. The advantage of using bridge inverter (either half or full) is improving the electrical power conversion DC to AC efficiency, where the ideal is close to 100 %. The high output efficiency makes the bridge converter technique replaces push-pull B class amplifier for DC to AC inverter. There are at least 2 (two) basic fundamental of bride inverter configurations exist, i.e half bride inverter (Fig 6) and full bridge inverter (Fig 7).

4.2.1.1. Half-bridge inverter

The following Fig 6 shows the circuit configuration of half bridge inverter. The circuit consists of 2 switching elements, S_1 dan S_2. Each element has one anti parallel diode. The switching element can be transistor, MOSFET, or IGBT.
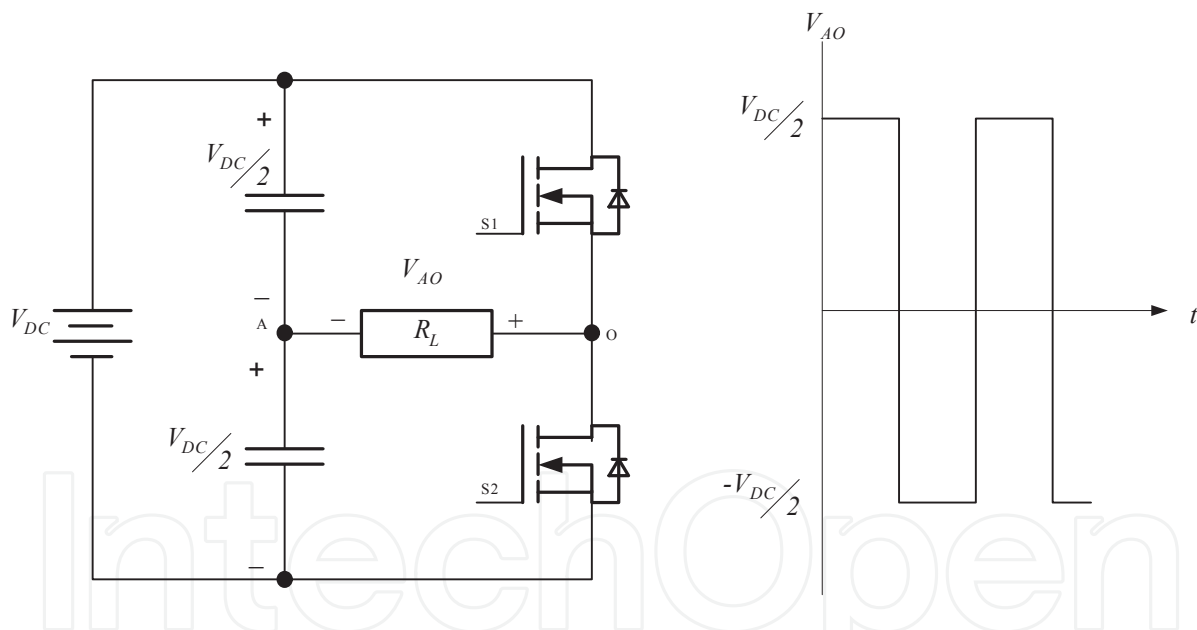
Figure 6. The circuit configuration of half-bridge inverterand example of output signal

The basic operation of half-bridge inverter circuit consists of 2 conditions:

1. At S_1 ON during 0 - T/2 period, the output voltage will drop on the load with value of $V_{dc}/2$;

2. At S_2 On during T/2 − T period, the output voltage will drop on the load with value of $-V_{dc}/2$.

The switching process for S_1 and S_2 must be designed such that both are not in "ON" condition at the same time. If this happens, it will happen short connection input V_{dc}, which will cause damage on the switching elements.

4.2.1.2. Full-bridge Inverter

Fig 7 shows the circuit configuration of full-bridge inverter 1-phase. The circuit consists of 4 switching elements: S_1, S_2, S_3, and S_4. The circuit operation consists of 2 conditions:

1. At S_1 and S_4 ON, S_2 and S_3 OFF, in the first half period, then the output voltage will drop on the load with value of Vdc.

2. While at S_2 and S_3 ON, S_1 and S_4 OFF, in the second half periode, then the output voltage will drop on the load with value of -Vdc.

As explained in *half-bridge inverter*, to avoid short condition on V_{DC}, the switching process should be designed such that at $S_1$and S_4ON, $S_2$and S_3must be *OFF* and vice versa. For the sake of this purpose, *gate* driver should use *dead time* mechanism.
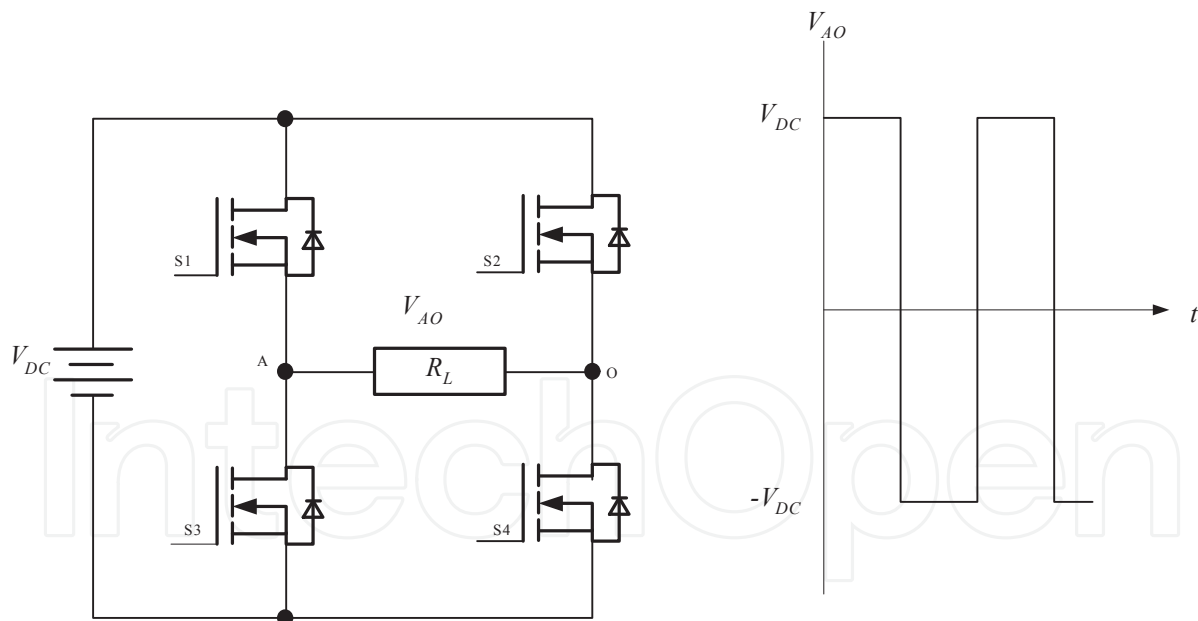

Figure 7. The circuit configuration of full-bridge inverterand example of output signal.

From Fig 6 and Fig 7, it can be concluded that the peak-to-peak output voltage of half-bridge configuration is a half of full-bridge one. The square wave output voltage has spectrum as shown on the following Fig 8.
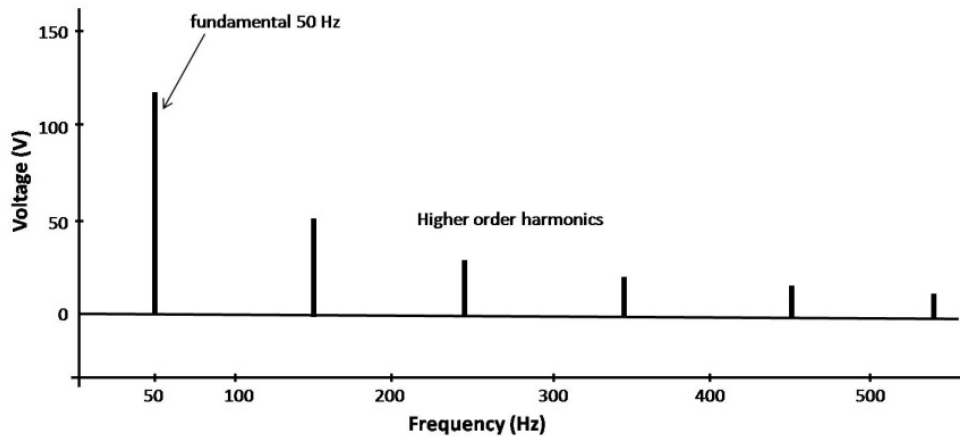
Figure 8. Square-Wave Harmonics Analysis of Unfiltered Output[4]

If all spectral components of power exist on the spectrum, are added together and assumed to be the output of the bridge-inverter, then the output efficiency can reach close to 100%. However, the higher order harmonics in the spectrum are not useful, even possible have ruining effects on the electro- mechanical loads. If higher order harmonics are substracted from the total output (by filtering), hence only the fundamental signal left, and the output efficiency is just 70%. To improve the output efficiency (in bridge inverter context), the discrete switch input control can be modified on to: (1) modified sine wave or (2) pulse width modulation (PWM). The following Fig 9 illustrates comparisson between pure sine wave, modified sine wave and square wave.
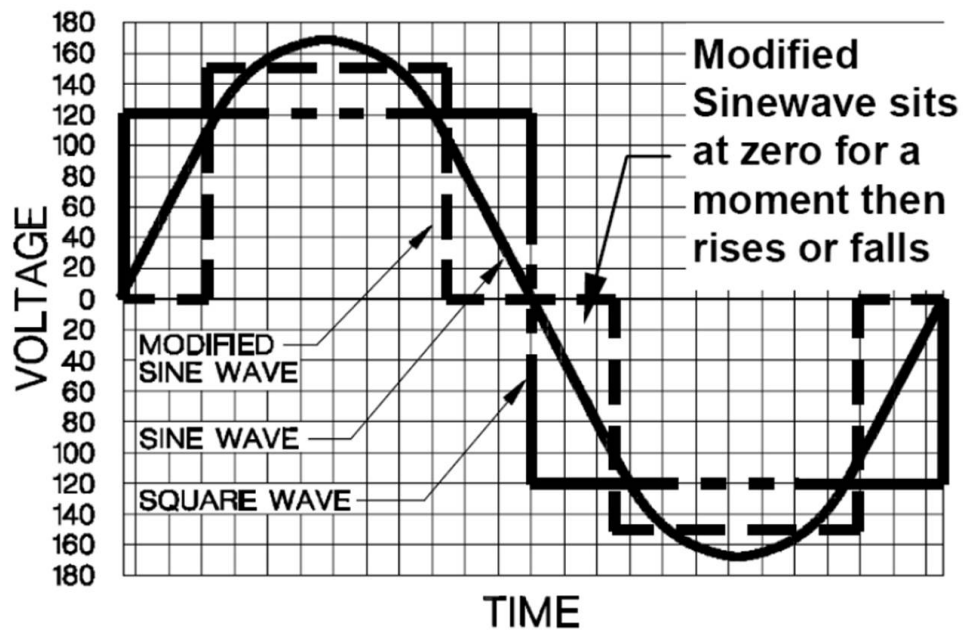
Figure 9. Comparisson between pure sine wave, modified sine wave and square wave.

As for instance, after going through filtering process, the square waveoutput signal is still consisting of higher order harmonics as shown on Fig 10, as following.
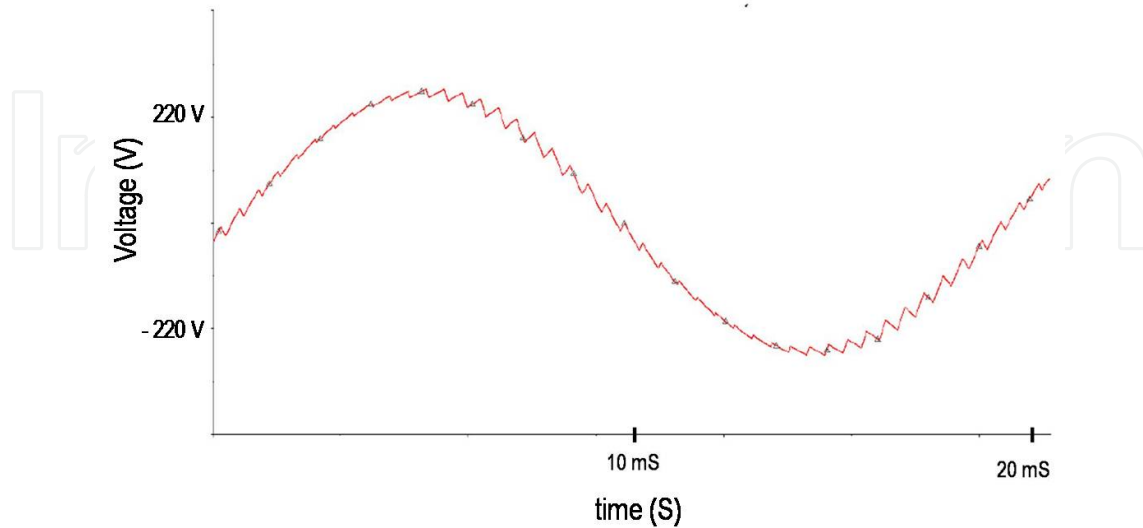
Figure 10. Output signal square wave as shown on Fig 6 and 7 (after filtered).

Eventhough modified-sine wave improves the output by suppressing the harmonics more than the square wave, however technically, it is too expensive, because conducting controls on two inputs: switching and Vcc. Furthermore, we will leave this modified-sine wave method.

The method that is proven good to improve output efficiency by suppressing higher order harmonics is pulse width modulation (PWM). In general PWM is the squential of discrete pulse, which is based on pulse width modulation. PWM technique becomes famous to generate pure sinusoidal wave, which is applied for DC to AC inverter and for controlling electrical motor.

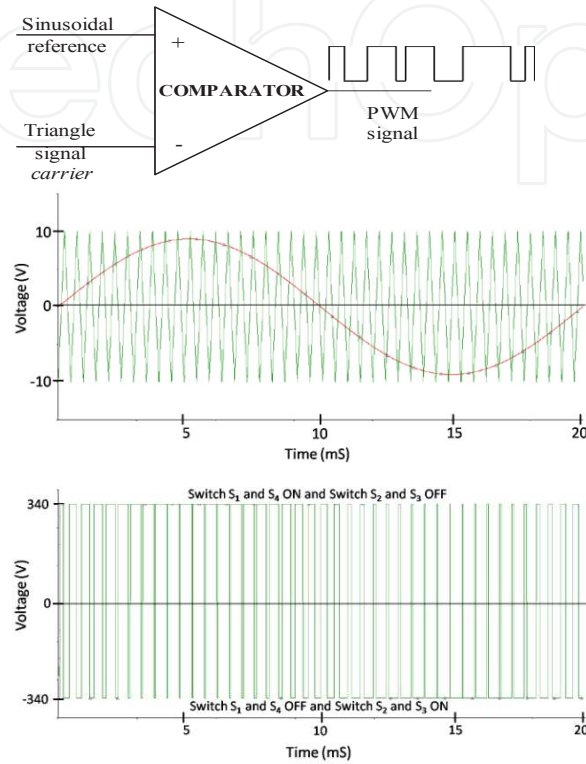### 4.2.1.3. Sinusoidal pulse wave modulation

The basic principal in forming PWM sine wave is by comparing two waves i.e. sinus wave as the reference and triangle wave as the carrier in real time. The sine wave has frequency f_r, which will be the inverter output frequency, i.e. 50 Hz or 60 Hz. The carrier signal has frequency f_c, which becomes switching frequency in inverter circuit. The ratio between f_c and f_r is called frequency modulation ratio, m_f, which is defined as:

$$m_f = \frac{fc}{fr} = \frac{ftri}{fsin} \tag{21}$$

The typical switching frequency is between 2 kHz – 15 kHz, and sufficient for power system applications. The higher carrier frequency, the easier conducting filtering that is separating fundamental frequency output from the carrier frequency and its higher harmonics. Howev-

er, the higher the switching or triangle frequency, it will increase interference effect to other electronics instruments (electromagnetic compatibility – EMC). Fig 11 below, shows the basic concept of signal comparisson between reference and carrier signals, or sometimes called as 2-level PWM.

Figure 11. Basic concept formation of 2-level sine wave PWM

The comparisson of two input signals (sinusoidal reference and triangle carrier) results in discrete signal that is called as pulse width modulation (PWM), as shown on Fig 11 above. Moreover, the ratio between reference signal and carrier amplitudes, is called as amplitude modulation ratio m_a, which is defined as:

$$m_a = \frac{Vm, \quad sinusoidal\ reference}{Vm, \quad triangle\ carrier} \tag{22}$$

Where :

$V_{m,\ sinusoidal\ reference}$: peak amplitude of reference wave

$V_{m,\ triangle\ carrrier}$: peak amplitude of carrier wave

The PWM output, as result of comparisson between sinusoidal reference signal and triangle carrier signal, can be represented in the form of *transcendental equation*. Later on m_a can be used to control the output amplitude of the PWM fundamental frequency. Moreover, the

value of m_a can be used to compensate the variation of DC input voltage, such that resulting in constant output AC voltage.

4.2.2. 3-Level PWM realization

2-level PWM, which is illustrated on Fig 11, is successful to suppress the higher order harmonics, such that improving inverter efficiency close to 80%. In order to suppress more on higher order harmonics, it is proposed to use 3-level PWM. To realize the 3-level PWM concept, it is required a circuit that can control the synchronization of switch pairs: S_1 with S_4 and S_2 with S_3, which are represented by H-bridge on Fig 7. The circuit that realizes 3-level PWM is shown on Fig 12. It is the development of basic concept of 2-level as shown on Fig 11. The 3-level PWM requires 2 equal inputs of sine wave references with 180^0 phase different. The resulting 3-level PWM signal is shown on Fig. 12 below.
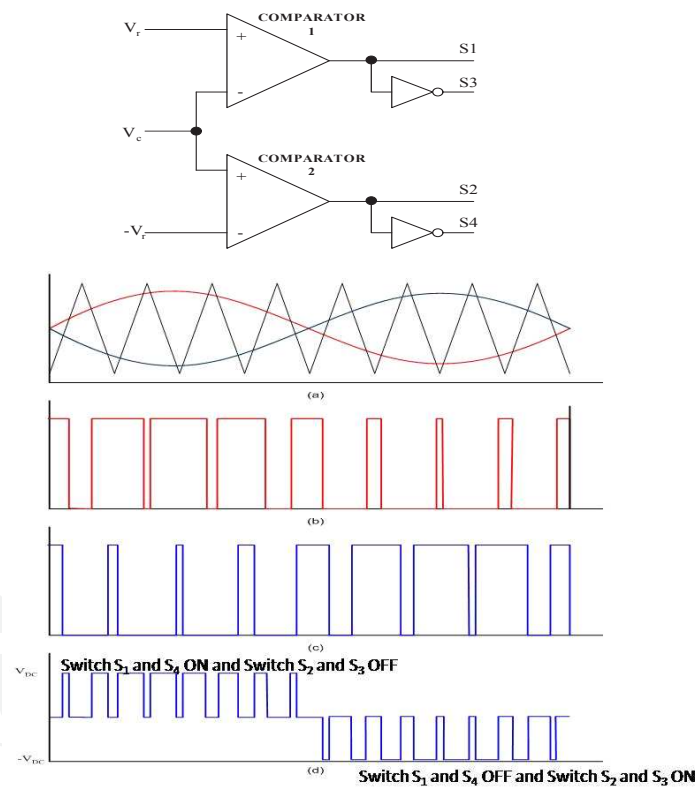
Figure 12. Illustration of 3-level PWMGenerator dan process generation of 3-level PWM [4,5]

a. Comparisson between 2 sine reference signals dan triangle carrier signal

b. Pulse for S1 and S4

c. Pulse for S2 san S3

d. Output wave

Fig 13 shows the output spectrum of 3-level PWM, which has output efficiency close to 85%, even one reports achieving 90%. If it is compared to the square wave spectrum, which is shown in Fig 8 and has output efficiency of 65-75%, then it can be concluded that 3-level PWM gives us a significant efficiency improvement.
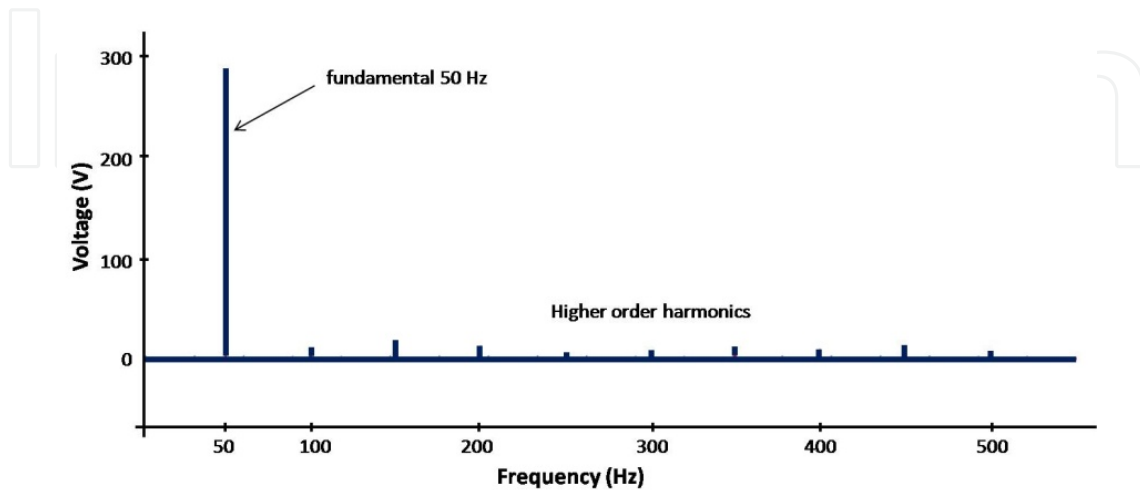

Figure 13. level PWM Harmonics Analysis of Unfiltered Output

4.3. Filter

Fig 13 shows that 3-level PWM suppresses higher order harmonics much better than square wave. However, the existing higher order harmonics are still able to annoy the performance of electro-mechanical systems. By this reason, those higher order harmonics must be sop-press more such that the harmonics becomes very low and not significant. We need a low-pass filter, which has a cut-off frequency $f_c < f_2$ (where: f_2 is second harmonic frequency). The filter is realized in the form of passive filter that consists of passive components L and C, as shown on Fig 14 below.
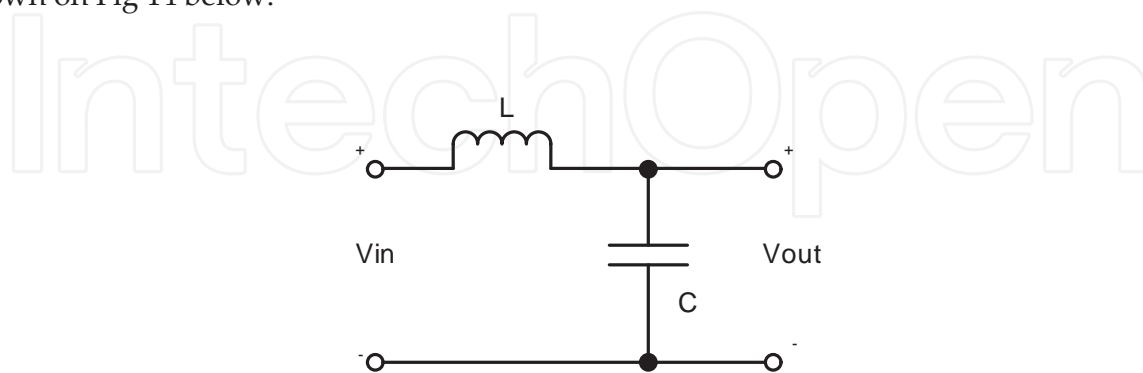

Figure 14. A simple low-pass L-C filter to filter out higher order harmonics of PWM.

The inductor value is designed such that the drop voltage on the inductor should be <3% of the inverter output voltage,

$$I_{load,max}.2.\pi.f.L < 0,03V_{ac} \tag{23}$$

Where:

$I_{load,max}$: maximum RMS load current

V_{ac} : RMS output voltage

f : output frequency

For a simple low-pass L-C filter, the cut-off frequency is[6]:

$$f_c = \frac{1}{2\pi\sqrt{LC}} \tag{24}$$

$$C = \frac{\left(\dfrac{1}{2 \times \pi \times f}\right)^2}{L} \tag{25}$$

However, sometimes, as a recommendation, the cut-off frequency should be set up on 1 or 2 octave above the fundamental frequency, i.e. 150 Hz, for 50 Hz system.

The big picture of 3-level PWM inverter 1-phase full-bridge is illustrated on Fig 15 below. Four op-amps that exist on Fig 15 function as combination of 2 NANDS logic circuits and 2 op-amps as shown
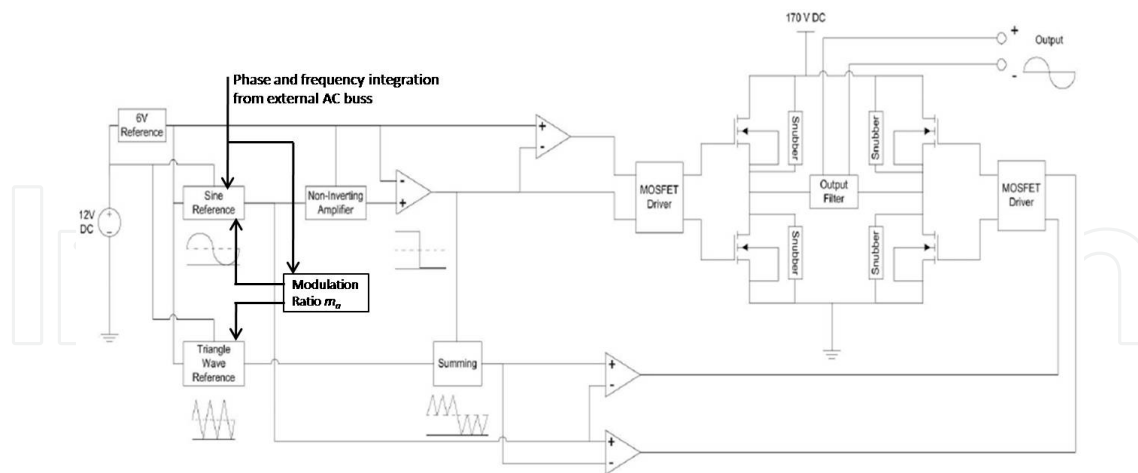
Figure 15. Comprehenssive 3-level PWM schematic blocks [4].

on Fig 12. For the sake of integration with external electrical AC buss, the system conducting synchronization of 3 main parameters: frequency (50 or 60 Hz), phase and voltage. To simplify synchronization process, the sensing (monitoring) and controlling those 3 parameters must be conducted by microprocessor system.

5. Energy management: Energy flow-in, flow-out and monitoring energy in the baterrays

The keyword for energy management in solar cell system is sustainability. The main rule, if the total electrical energy supply from solar cells to the batteries is less than the total used energy, then to maintain the sustainabilty, there must be energy supply from the external energy resource(s). Moreover, if the total electrical energy supply from solar cells to the batteries is more than the total used energy, then the collected energy from the solar cells must be stored to the batteries, if full, then must be delivered to the external AC buss. This purpose is that the excess of supply energy can be utilized by other outside consumers that connected to common external AC buss. If there exist many autonomy renewable energy system, then they can be coordinated to build an energy grid system, which makes possible to collaborate each other to maintain sustainability altogether. By the existence of a grid system, then a business concept of buying-selling electrical energy supply between autonomy renewable energy systems can be realized.

In order such that Solar cell system can function as autonomy energy system, then it must has an energy management system in the form of an electronic control system, supported by microprocessor circuit or computer system, which monitors the total IN and OUT of electric energy on battery storage. Moreover, at the same time, it monitors the number of available energy in the storage and controlling the flow and contingency electric energy in the system. By monitoring IN and OUT energy and the availability energy in the storage, it is expected that the total energy available in the storage can always be monitored real time accurately. The core components of energy management in solar cell system are batteries and processor system. The following is brief explanation regarding to both components.

5.1. Batteray analysis

Electric energy storage is used to store the received energy from solar cells (at noon), in order to be utilized at the time when there is no available electrical energy supply from the solar cell (at night). In general, electric energy storage can be realized in the form of wet and dry batteries, super capacitors and even carrier energy storage in the form of hydrogen gas storage. Priambodo et al [7], have shown that electrical energy received from solar cell array can be stored by converting it into energy carrier in the form of H_2 gas by using electrolysis method. Furthermore, the stored H_2 gas can be used when there is no available supply electric energy from solar cells, by using fuel cell system. In this chapter, we will limit discussion to battery storage only.
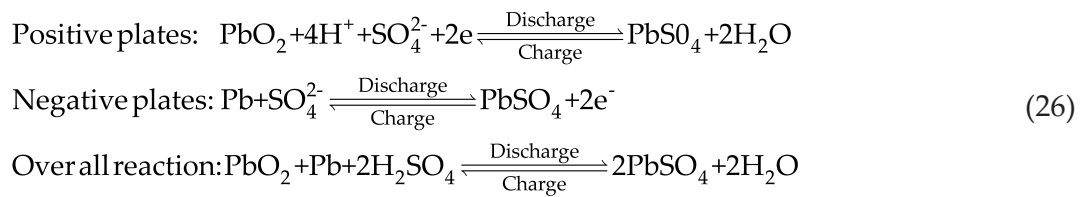
Solar cell system needs battery bank to store the electric energy that collected in at noon. In general, there are two kinds of batteries, wet and dry. The wet battery uses electrolysis method, where it requires a sealed box to keep two plates anode and cathode, which are connected by wet electrolyte which can be base or acid. During charging time, there exists ionization process in electrolyte liquid, while during discharging process, there exists deionization process. The dry battery, actually is not really dry. The dry battery working concept

is still the same with the wet one, however, the dry battery uses electrolyte gel, such that looks more dry. The components of battery are illustrated in Fig 16, as follows.
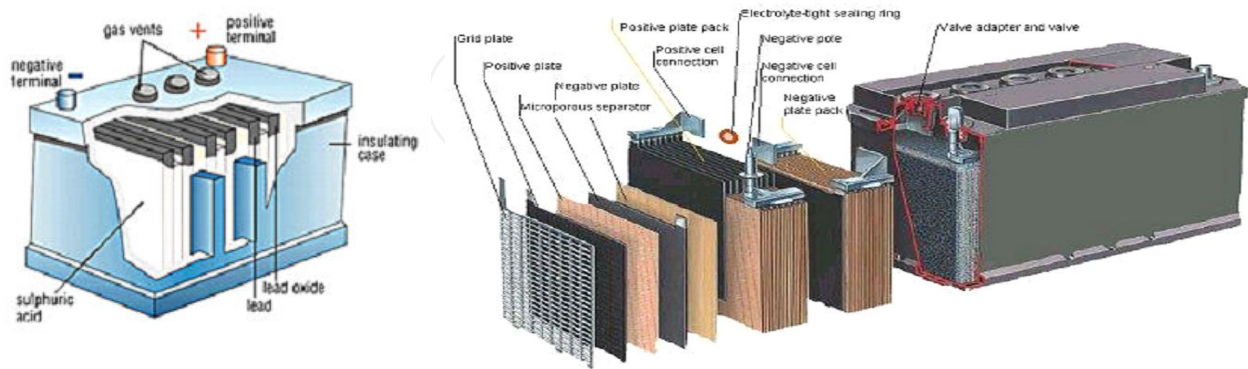
Figure 16. Component parts of a batteray

The illustration of chemical process in wet battery is shown in the following equations:

$$Positive\,plates:\ \ PbO_2 + 4H^+ + SO_4^{2-} + 2e \xrightleftharpoons[\text{Charge}]{\text{Discharge}} PbS0_4 + 2H_2O$$

$$Negative\,plates: Pb + SO_4^{2-} \xrightleftharpoons[\text{Charge}]{\text{Discharge}} PbSO_4 + 2e^- \tag{26}$$

$$Over\,all\,reaction: PbO_2 + Pb + 2H_2SO_4 \xrightleftharpoons[\text{Charge}]{\text{Discharge}} 2PbSO_4 + 2H_2O$$

The battery perfomance is determined by at least 5 parameters: (1) the speed to store electric energy in charging process; (2) the battery capacity; (3) battery leak; (4) energy dissipation; and (5) the speed of capability for discharging to the loads. The following is discussion according the analysis methods for those 5 parameters. There are 2 (two) conditions, i.e. charging and discharging, which requires different modelling. The reason to have different models for charging and discharging is to have a simplification, because the whole analysis components are related each other, in complex relation.

5.1.1. Batteray charging model

Charging process can be approximated by capacitance circuit model that is illustrated on Fig 17 below. Capacitance C models and illustrates the capacity of the battery, while Resistance R(V,i) models and illustrates the speed of battery charging and charging dissipation. For the sake of simplification, we assume that R is always constant. The lower R, then the faster battery charging process, at the same time it has lower dissipation. The main point, the good battery should has lower R.
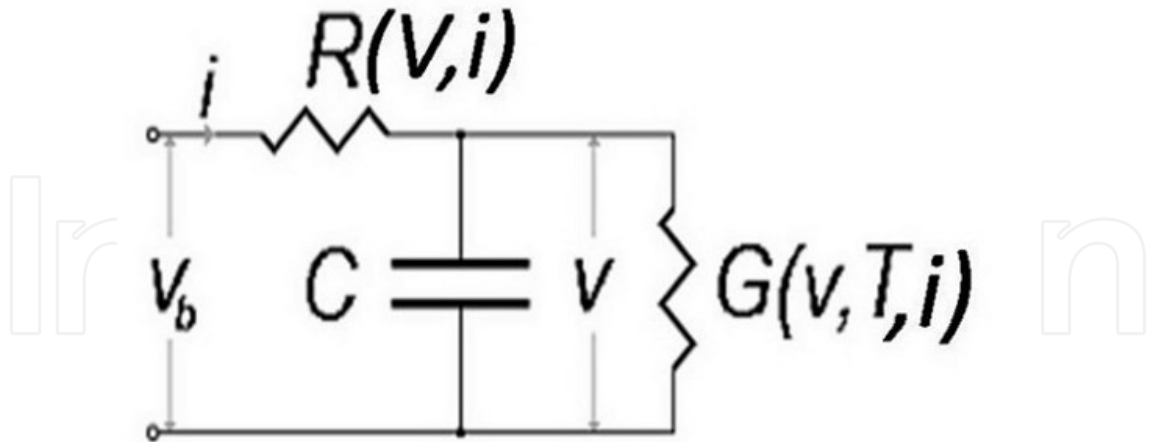
Figure 17. Batteray charging model [8].

Current equation for charging model based on the capacitance circuit is:

$$i = C\frac{dv}{dt} + G(V, T, i)V \qquad (27)$$

Battery charging cycle on this model, has characteristic graph, which is shown on Fig 18, below.
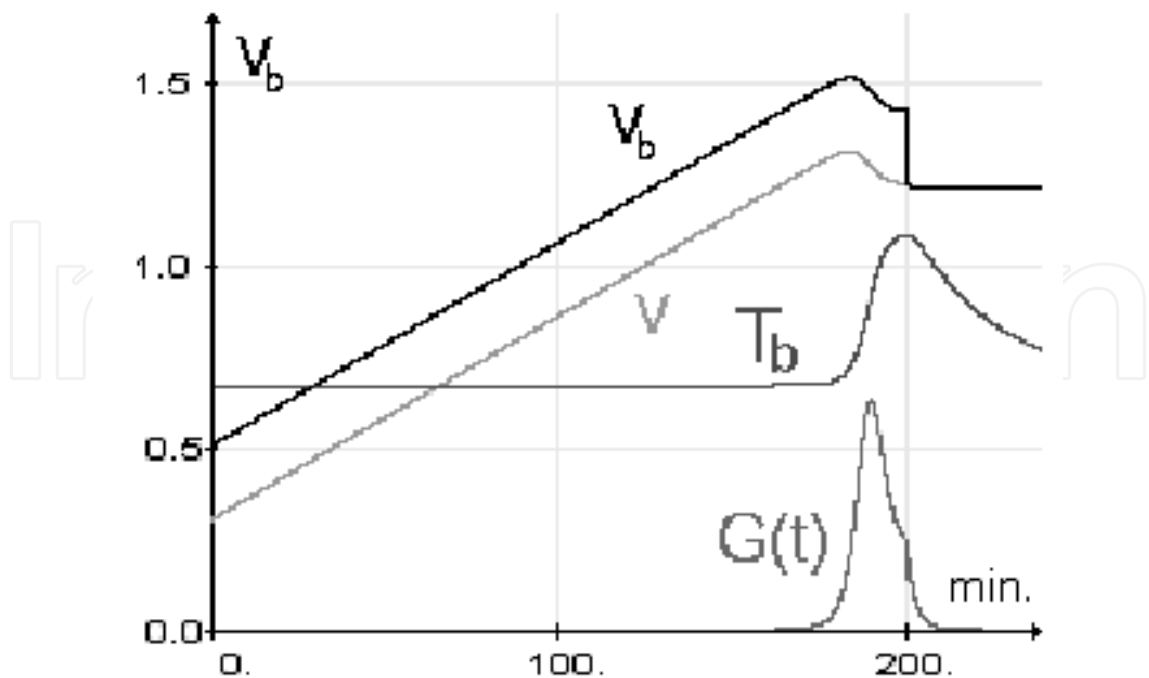

Figure 18. Charging Process [8]

When the battery is not full yet, if there is no charging current (*i = 0*), then *G(V,T,i=0)* illustrates leak conductance (coefficient *c*), which exist on battery system in passive condition (recall Eq-1). When at *i ≠ 0*, then *i²R* is dissipation in charging process and *G(V,T,i ≠ 0)* is leak conductance at charging time. If the battery has already been full, then the battery voltage will be constant and the energy charging excess in charging process will change to heat dissipation, which shown by the leak conductance of *G(V,T,i=0)* function. R and G values show the degree of dis-efficiency of the battery. For the sake of electric management, it is requires accurate information according to R, C and G(V,T,i) function of baterry. The information of those 3 values can be obtained by careful measurements.

5.1.2. Batteray discharging model

Discharging process can approximated by using a Constant Voltage Source Circuit Model as illustrated on Fig 19 below. The reason we use Constant Voltage Source circuit model, because there is a fact that at condition of near to empty, the battery (without load) still has voltage that close to peak voltage when battery at the full condition. Based on this fact, it is difficult to use capacitance model for discharging process. At Constant Voltage Source Circuit Model, V_{DC} models Constant Voltage Source of the battery, while Resistance Rs models and represents the battery energy content. Gp represents the battery leak, which is quitely equal to G(V,T,i) function on battery charging model.
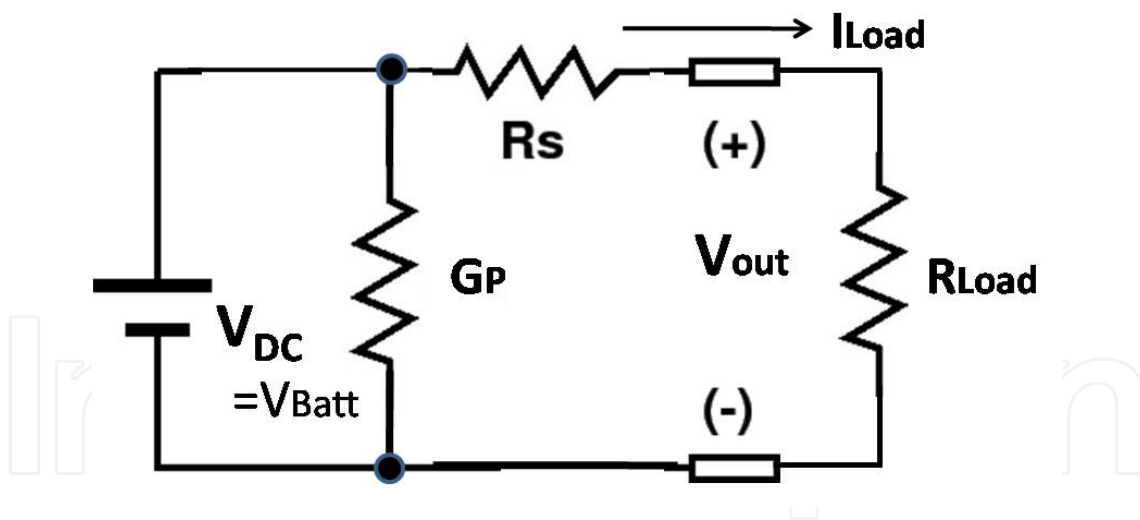

Figure 19. Baterry discharging model, Rs represents the battery energy content and Gp represents the battery leak.

By assumption that V_{DC} is constant, then the battery energy E_{batt} can be represented by the value of R_S, which represents internal series resistance of the battery at discharging process. R_S can be calculated by the following simple formula:

$$R_s = \frac{V_{Batt} - V_{out}}{I_{load}} \qquad (28)$$

It is requires an algorithm to calculate R_S as representation of battery stored energy at real time condition. It is for reader exercise to develop thus R_s as a function of battery stored energy. The illustration of stored energy vs R_s is shown on Fig 20, below:
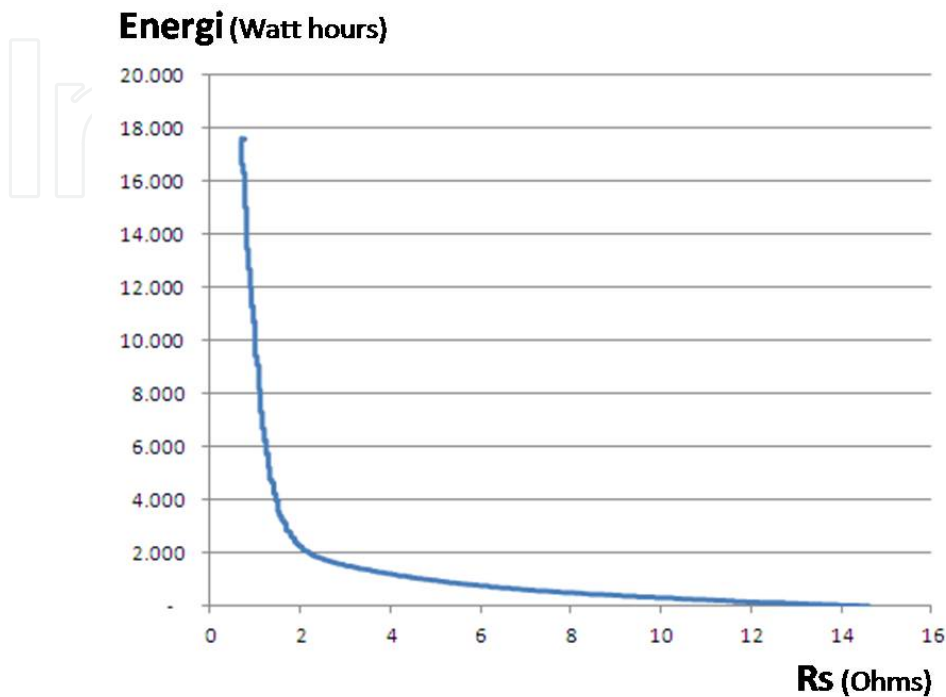
Figure 20. Illustration of stored energy vs Rs [9]

By understanding the information in this Chapter, the available information can be used to develop energy management concept for solar cell system. The main point is monitoring flow-in current to and flow-out current from batteries, which then combined with the information according to available energy in batteries, will give accurate information regarding to the energy in the system. The accurate information is required by the system when deciding integration process to keep maintain sustainability and also to conduct the business of selling and buying electric energy in the grid system.

5.2. Electronics energy management system

There are many tasks, which have to be done, such that energy management can be conducted accurately. The following, we list the mandatory tasks required in energy management for solar cell system. First of all is current monitoring flow-in to and flow-out from the battery bank. The second one is measuring electrical energy content inside batteray bank by using algorithm of stored energy vs Rs. The third one is an evaluation of the internal energy condition and based on the sustanainability criteria, conducting decission process to do integration with external system (grid). The fourth one, when integration is decided, then synchronization of frequency, phase and voltage must be conducted soon. Those four tasks require algorithms or procedures, which can be very complex for electronic analog circuits.

Hence, the only way is by utilizing microprocessor circuit or even computer system to conduct energy management tasks. The comprehenssive block diagram of Solar Cell Based Renewable Energy Unit System has been already shown on Fig 1. The detail of the circuitries are for the reader exercise to give contributions to realize an electrical energy management for solar cell system.

6. Conclusion

Electrical energy management and engineering for solar cell system is started by designing electrical energy requirements, technical specifications of solar cells and batteries, also information of zone latitude and statistical weather of the location. The characterizations to obtain information of solar cell and batteries efficiency are very important to support in designing the system. Furthermore, electrical energy management and engineering for solar cell system, must deal with 4 tasks listed in sub-chapter 5.2. To cover those 4 tasks, then it has to be developed a processing system based on microprocessor or even computer system. If there exist several units of autonomy solar cell systems, then they can be coordinated to build a grid energy system, which can support each other to keep maintain sustainability service. Ultimately, it can be established independent electric energy collaboration and totally eco-friendly.

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