Comprehensive design of a residential PV system

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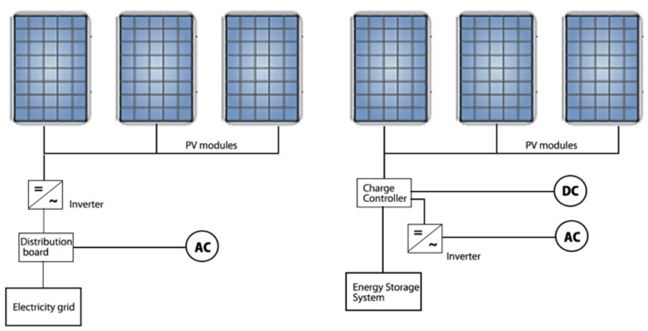
***Abstract*—This paper aims to give a comprehensive overview on the design of a residential solar system, also called photovoltaic(PV) system, in a practical scale. To balance the cost and efficiency, the choice on each electric component is considerate. A 30kW roof-mounted PV system at Hong Kong is discussed as an example model. The system is a grid-connected system with multi-string inverter topology. With an annual electricity generation of 42.8MWh, the electric power generated can provide power for around 4 classrooms and can save $20000 per year.**

I. Introduction

As the situation of the global warming is increasingly serious, developing renewable energy has raised more public awareness. Due to the abundance and easy accessibility of solar energy, PV systems have become a popular choice for the shift to renewable energy in residential scale. To start a PV system project, the first thing is to figure out the solar energy available at the target area. Though solar resource is abundant and free, the distribution of the solar insolation is not uniform. The distribution of the solar resource are determined by many environmental factors like altitude, landform and climate. As a intrinsic property of a district, the data of insolation can be looked up in some database like NASA Surface meteorology and Solar Energy Database(SSED). Once the location of the planned PV system is decided, all detailed design on different components needs to be taken into consideration based on the solar energy available. A residential PV system rated at 30kW located on the campus of the Chinse University of Hong Kong is referred as an example for more details. The average insolation incident in Hong Kong(HK) is 3.89 kWh/(m^2·day) as a 23-year average given by NASA SSED[1].

II. System Overview

A. Operating Mode



(a) (b)

Fig. 1. Schema of PV system in (a) grid-tied mode (b)stand-alone mode

Common residential PV systems have two kinds of operating modes, stand-alone and grid-tied. Stand-alone PV systems, as shown in the Fig. [1b], have become popular in applications at remote areas for local energy supply. Distributed energy systems can overcome the restriction of grid and realize entirely self-sufficiency in electrical power. Meanwhile most residential PV systems are grid-connected, similar to the schematic graph presented in Fig. [1a]. The system is connected to original electrical system and inconsumable electricity is transmitted into the grid for the supply of other users in the grid. Thus people can get profits from selling electricity besides subsidy for renewable energy from the government. An energy storage system(ESS) like batteries or capacitors can also be implemented in grid-tied systems.

B. Application Scope

The scope of the system depends on how many loads to supply. This is vital important for stand-alone systems since the output energy should be able to fulfill the local need. While for grid-tied systems, the power rating is not restricted due to the existence of grid but focusing on some specific occasions is helpful for judging the performance of the system. The example project was aimed to provide power supply for normal classrooms. Listing all load with power rating and their operating time is useful. A typical classroom has an average annual consumption of 11,000 kWh, details of modeling are shown in Appendix.

C. Site survey

Choosing an appropriate site is a solid basis for the good performance of the system since surrounding shading has detrimental effects on the efficiency of power output as well as the lifetime of PV modules.

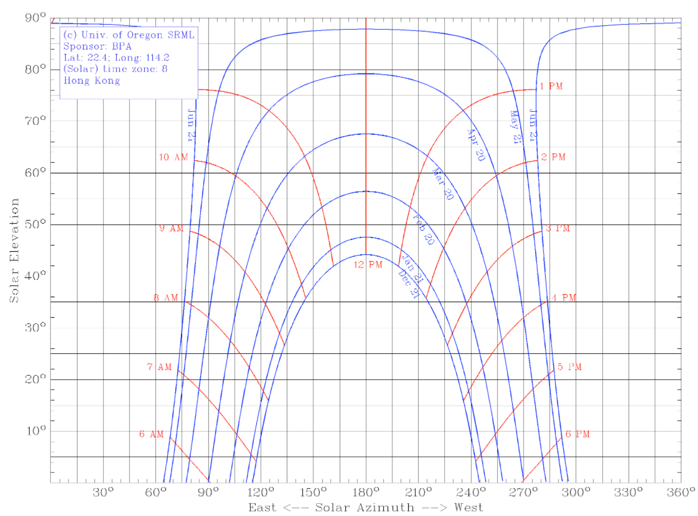


Fig. 2. Sun path diagram at 22.4°E, 114.2°N

The shading changes with the path of the sun, which also periodically changes in a year. The example system is located at 22.4°N, 114.2°E. Winter solstice is the worst case in a year, and meanwhile, the irradiance at winter is also weak compared to other parts of the year. Thus the period between the vernal equinox and autumnal equinox has higher insolation and would be attached with more importance. Sun path diagram shown in Fig.2 is useful in determining surrounding shading. It shows the location of the sun at different time in a day for different months of the year. The vertical axis shows the height of the sun in the sky, while the horizontal axis shows the azimuth angle of the sun(0° represents north and 90° is east.).

In Fig. 1, the red lines indicate the time of the day and the blue lines show the path of the sun across the sky for different dates in a year. The top blue line path is the path of the sun at the summer solstice, and the bottom blue line is at the winter solstice. Areas between these two blue lines can be considered as effective sunlight. Surrounding shading is represented as a rectangle drawn by an azimuth range and an elevation angle range. For instance, if there is a building with an elevation angle, the angle you look up to the top of it, of 30°, and it's located at southeast(around 130°~140°) to your site, then the area restricted by this two ranges can be deducted from the effective sunlight area as the effects of shading. Typically, a place with less than 10% shading would be a good choice.

The example PV system is set on the roof of the student dormitory. The rectangular roof is a 40m by 15m, with exterior walls on all sides. The exterior walls are 5 meters in height, which results in huge effects when considering shading. This roof is definitely not an perfect place to build PV systems. However, in practical design of residential PV systems, the conditions of the site are usually limited. This implies that the key is to utilize the area available and adjust the arrangement of PV cell, which will be discussed in following parts.

III. DETAILED DESIGN

When it comes to the choice of different components, the decision is always case-sensitive. Taking several factors into consideration, the final decision is always a compromise between cost and efficiency.

A. PV Module Selection

There are a variety kinds of PV modules available in the market. Different technology and materials enables different characteristics. . The technology of the wafer, the fill factor, the size of the module as well as the power rating will altogether be considered. The crystalline silicon(c-Si) is most widely used due its cheap price and mature manufacturing techniques. The final choice for example project is CIGS(CuInGaSe) PV modules for its superior temperature coefficient. The temperature in HK is high all over the year since it's at tropic. The surface temperature can be extremely high under direct sunlight in summer. Since the efficiency is negatively correlated to the module temperature, the temperature coefficient can be a determining factor in tropic area. Some important parameters are shown in Appendix.

B. PV Module Arrangement and Inverter Schema

Besides the shading from surroundings, the mutual shading with panels is also a problem. The length of the shadow of a module of length l is given by equation (1)[2],

$$d = l[\cos\theta_M + \sin\theta_M \cot a_s \cos(A_M - A_S)] \quad (1)$$

where θ_M is the tilt angle of the panel, A_M is azimuth angle of the panel, a_s is the altitude of the sun and A_S is the azimuth of the sun. As a rule of thumb, the distance between each row is larger than two times of the module length along that direction. For tropic areas, a tilt angle with the same value as the latitude would fully utilize the irradiance during the year[3].

Several PV modules in series connection is called a 'string' of PV modules. Basically each string is controlled by one inverter. The easiest way, also a popular way for grid tied system, is to connect all solar panels in series as a single string, then it's fed into a central inverter to the existing grid. This design is straight forward and simple to realize in practical system. The cost is minimized with only one converter and inverter needed. The single string produces a high voltage, which also decrease losses at the inverter.

The problem of this design is that the efficiency of each PV module is not guaranteed. Since the performance of a series of modules is limited by the worst one, shading would have strong effects on this design. Besides, the high voltage in DC wiring may raise some safety issues.

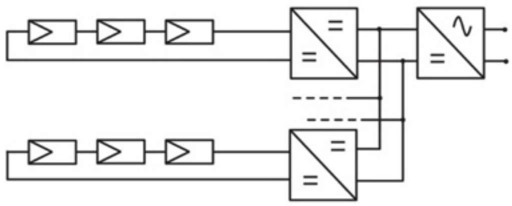


Fig. 3. Schema of multi-string inverter

The most effective as well as the most expensive framework is microinverter, in which each PV module or several modules are connected to an inverter. This architecture minimizes the mismatch losses and each modules can work at its maximum power point (MPP).

The framework of the example system is using multi-string inverter. The system consists of 150 CIGS PV panels in total. Each five panels are connected in series as a "string", producing a nominal voltage of 480V at MPPT. There are five strings in one row(along the long side of the roof) and six rows in total. The rows near the exterior will not influence the performance of others even when they are shaded by the wall.

C. Converter and Transformer

The voltage standard varies in different places. Appropriate converters are required to adjust the voltage. Moreover, galvanic isolation between DC and AC parts are required for safety issues. This can be implemented by adding transformer in between.

The standard voltage at HK is 220V at 50Hz. As mentioned before, the nominal voltage of each string is 480V, thus buck converters with duty cycle D=0.458 is adopted. And 1:1 transformer is added for galvanic isolation.

D. Controlling and maintainance

To achieve optimum performance of the system, controlling is necessary. There are mainly three controlling parts in a PV system. First is the Maximum Power Point Tracking (MPPT). Incremental conductance methods chosen for MPPT. This method compares incremental conductance and instantaneous conductance, with a flow chart shown in Fig. [4]. Second is the charge controller needed for PV systems with an ESS to avoid over-charge or over-discharge, which usually offered by manufacturer. Third is the control of the balance between generation and load at the grid side for grid-tied system. This is complicated since its related to the global control of the grid and is regulated by the grid company.

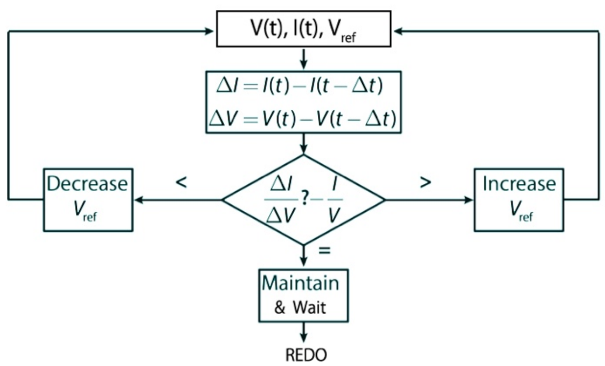


Fig. 4. Schema of string inverters

Design an efficient PV system is a comprehensive process, thus the timely maintenance is also important. Periodically check of the state of each electric components is necessary for the normal operation. Similar to the bad effects from shading, Since real time monitoring system are now available from PV module manufacturers. The condition of battery and other power electronics can be tracked at all times.

IV. Performance Judgement

A. Efficiency analysis

After the choosing main components in the PV system, the efficiency of the whole system can be figured out. The efficiencies of each components for the example system are shown in Table Ⅰ. The energy loss in circuit is assumed to be 5%.

TABLE I. EFFIECIENCY FOR EACH COMPONENT

Components	**Efficiency**
PV modules	16.3%
Inverters	98%
Converters&MPPT	92%
Others	95%
Overall	13.96%

B. Economic Analysis

1) Cost

Investment costs, or total system costs, represent the most important barrier to the PV deployment today. Total system costs consist of the sum of module costs including mounting structures, inverters, cabling and power management devices. The total costs can be further divided into three parts: direct capital cost, indirect capital cost and operation cost.

For direct capital cost, it is mainly the cost of modules and other electric components, which is listed in Table Ⅱ.

TABLE II. DIRECT CAPITAL COST OF A GRIED-TIED SYSTEM

Components	**Cost($)**
PV modules	21500
Inverters	2290
Converters	2850
Transformer	220
Cables & other components	500
Total	27360

a. Prices were recorded in 2016

For indirect capital cost, the cost of permitting and environmental studies, engineering and developer overhead and grid interconnection are considered. The details are listed in Table Ⅲ.

TABLE III. INDIRECT CAPITAL COST OF A GRIED-TIED SYSTEM

Components	**Cost($)**
Permitting and Environmental studies	1000
Engineering and Developing overhead	5000
Grid interconnection	2000
Total	8000

b. Rough estimation based on conditions in HK

And the operation cost is a fixed annual expense, rated at around 5% of the direct capital cost.

2) Profits and Return

Two different policies, net meter and fit-in tariff, are adopted in selling PV-generated electricity. Net meter means the amount of electricity you produced offsets equal amount of your consumption. Fees are decided on the net sum. While a feed-in tariff is a policy mechanism designed to accelerate investment in renewable energy technologies. It achieves this by offering long-term contracts to renewable energy producers, typically based on the cost of generation of each technology. The goal of feed-in tariffs is to offer cost-based compensation to renewable energy producers, providing price certainty and long-term contracts that help finance renewable energy investments.

According to the policy of Hong Kong Electric, feed-in tariff is adopted. Compared to the average electricity price of 0.15$/kWh, the fit-in tariff rate shown in Table Ⅳ is higher to encourage the shift to renewable energy system.

TABLE IV. FIT-IN TARIFF RATE BY HK ELECTRIC

Renewable Energy Power System Capacity(kW)	**Fit-in tariff rate($/kWh)**
<5	0.65
10~200	0.52
>200	0.39

Payback time is usually the standard of judging the feasibility of a PV system. The energy payback time of a power generating system is the time required to generate as much energy as is consumed during production and lifetime operation of the system. The energy payback time for solar PV systems has been greatly reduced in the past decade thanks to the rapid development of PV technologies. It's estimated to be around 1.5 years for c-Si PV systems. And the economic payback time shows the profitability of a system and is calculated by

$$\text{Economic Payback Time} = \frac{\mathit{Total\ cost}}{\mathit{Annual\ Return}} \tag{2}$$

Annual return is the net profits from electricity sales. Other fixed expenses like annual operating cost and depreciation needs to be deducted. Thus the annual net profit for the example system is around 20000$. The economic payback time of the system is 2.08 year, better than an average of 5 years for residential systems.

V. SIMULATION STUDY

Simulation of the system is conducted by Simulink in MATLAB. A buck converter is used to convert the string voltage from 480V to the standard 220 V_{rms} in HK. And an H-bridge inverter is utilized to transfer DC power to AC power with a PWM modulator. A 1:1 transformer is added to implement galvanic isolation. Specific schematic graphs are shown in Fig.[6]& Fig. [7] at last.

The output voltage is plotted as in Fig. [5], matching the required voltage standard.

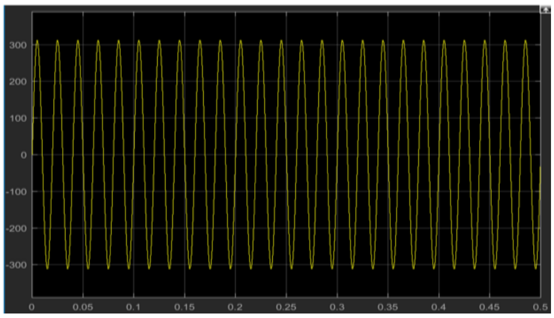


Fig. 5. Voltage output of the simulation

VI. CONCLUDING REMARKS

In conclusion, the design of a residential PV system is always finding the balance between cost and efficiency. The example project is not built on an ideal site but the performance is good. Finding the most suitable electronics and schema for the system is the key to achieve success. From May to August in 2017, 13.6 MWh electricity was produced by the system, roughly matches the expectation of an annual output of 42.8 MWh. In a word, solar power is an excellent and practical resource. The emergence of more and more residential PV systems is making a huge contribution to the transforming of power consumption structure.

APPENDIX

A. Some parameters of system compenents

TABLE V. PARAMETER OF LOADS IN A CLASSROOM

Load	***Number***	***Power Rating(W)***	***Total***
Air conditioner	4	1500	6000
Lamp Tube	32	30	960
Computer	1	340	340
Projector	2	320	640
TV	4	150	600
Others	1	50	50

TABLE VI. WORKSHEET OF LOADS IN A CLASSROOM

Time Period	***Load***	***Power (W)***	***Working Hours (h)***
Summer weekday(149 day)	All	8590	8
Holiday(166 days)	All	8590	0
Winter weekdays(50 days)	Air conditioner	6000	0
	other	2590	8
Total Annual Power Comsumption(kWh)			11276

TABLE VII. PARAMETER FOR PV INVERTER

Parameter	Data
Maximum Input DC Power	16.30%
Maximum DC Voltage	208.85 W
Output AC Voltage Range	148.0 W
Efficiency	98%

TABLE VIII. PARAMETER FOT PV MODULE (BY LOCAL PRODUCER)

Components	Cost
Nominal efficiency	16.30%
Maximum Power (P_{mpp})(± 5%)@STC	208.85 W
Maximum Power Voltage (V_{mpp})	94.93V
Maximum Power Current (I_{mpp})	2.20A
Open Circuit Voltage (Voc)	117.6V
Short Circuit Current (Isc)	2.386V
Temperature Coefficient of P_{MPP}	-0.24%/°C

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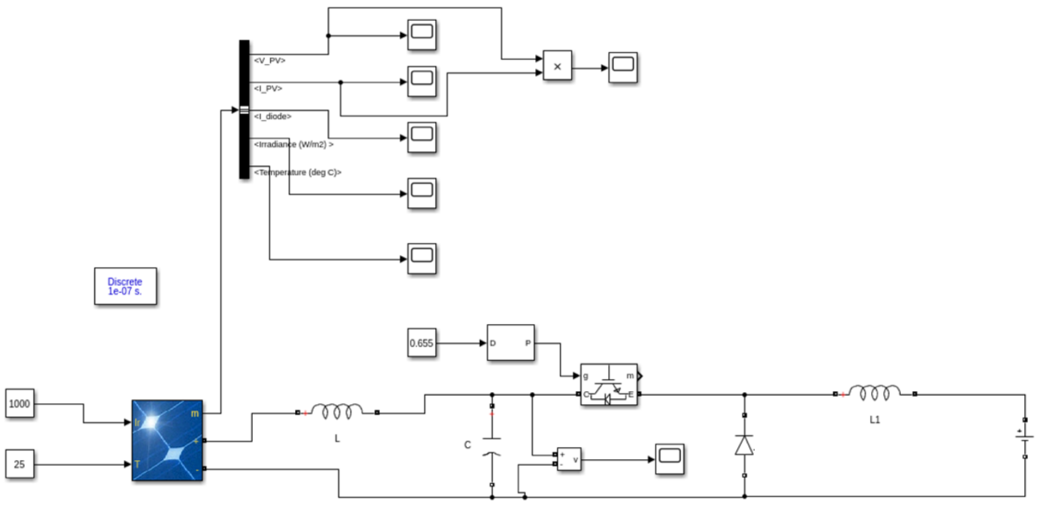

Fig. 6. Schema of modeling the buck converter part

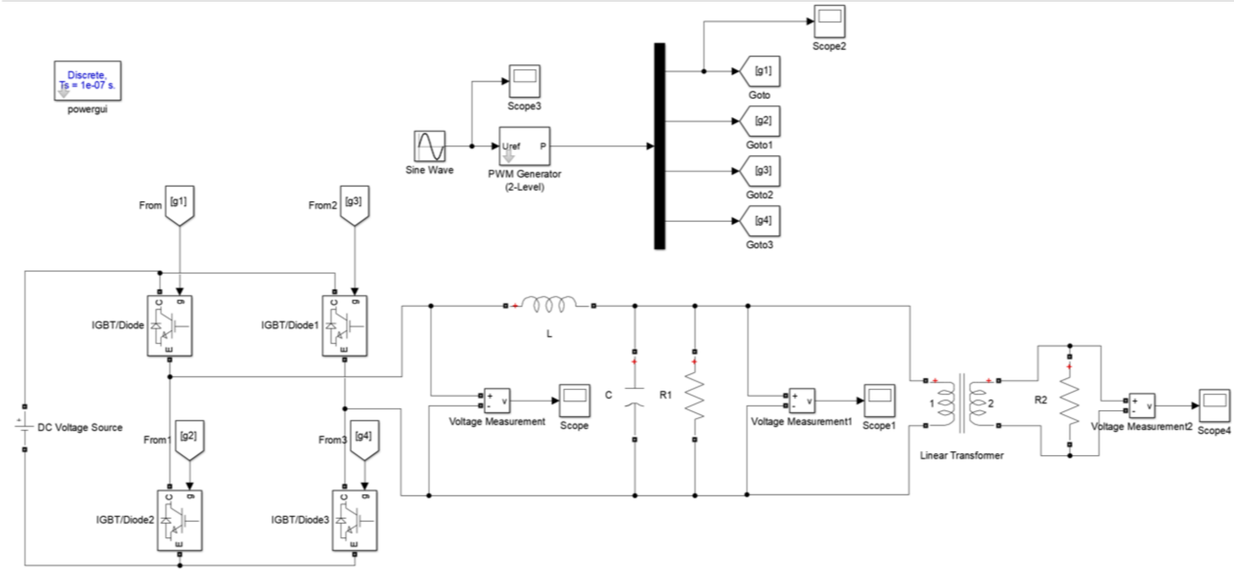

Fig. 7. Schema of modeling the H-bridge inverter part