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Energy Reports

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Suggested Citation: Huang, Bin-Juine et al. (2020) : Study of power dispatching control scheme in pyramid solar micro-grid, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 6, Iss. 2, pp. 107-113,
<https://doi.org/10.1016/j.egyr.2019.11.049>

This Version is available at:

<https://hdl.handle.net/10419/243865>

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The 6th International Conference on Power and Energy Systems Engineering (CPESE 2019),
September 20–23, 2019, Okinawa, Japan

Study of power dispatching control scheme in pyramid solar micro-grid

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Received 2 October 2019; accepted 22 November 2019

Abstract

High penetration of solar PV systems will cause grid instability and requires storage and micro-grid. Pyramid solar micro-grid which consists of many solar home systems with storage was thus proposed. The reliability of solar micro-grid is an important issue. In the present study, we develop an advanced power dispatching control for pyramid solar micro-grid. A 4+4 solar micro-grid was built and tested. It is experimentally shown that the power dispatching control of the pyramid solar micro-grid using cascaded scheme is much reliable than the mobile-commander scheme. The data loss is near zero (0.002%). © 2019 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of the scientific committee of the 6th International Conference on Power and Energy Systems Engineering (CPESE 2019).

Keywords: Micro-grid; Solar micro-grid; Solar PV power

1. Introduction

Solar PV energy disseminates very fast through FIT (feed-in-tariff) policy and may cause grid instability if the penetration is very high. Solar PV generation for self-consumption with micro-grid is a promising solution. Micro-grid in different structure was proposed and studied [1–7]. The conventional solar micro-grid was designed usually based on the concept of centralized power system with smaller scale. Solar panels, power control system, battery bank, and charger/discharger, inverter etc. are put together to build a small centralized power plant. The generated power is then transmitted to many users. Such kind of solar micro-grid is expensive and has high maintenance/operation cost. It is also difficult to build and not reliable. A solar home system called “hybrid solar PV (HyPV)” was developed by National Taiwan University (NTU) [8], as shown in Fig. 1. HyPV is a solar PV system with energy storage. HyPV operates at stand-alone PV mode or grid mode by switching technique using ATS (automatic transfer switch) and does not feed solar power into grid. It operates at PV mode when solar PV

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<https://doi.org/10.1016/j.egy.2019.11.049>

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Nomenclature

n_{HyPV}	Total number of HyPVs in the micro-grid
n_I	Number of steps in power dispatching operation
n_L	Number of micro-grid cascaded layers
N_s	Total number of successive data transmission upward to the top level CCU in each time interval
n_{CCU}	Total number of CCUs in the micro-grid
t_{exe}	Executing time of completing a power dispatch from command release, s
t_{day}	Daily operation time of micro-grid, s
t_{sun}	Running time of micro-grid in daytime, s
Δt_s	Time interval of data transmission, s

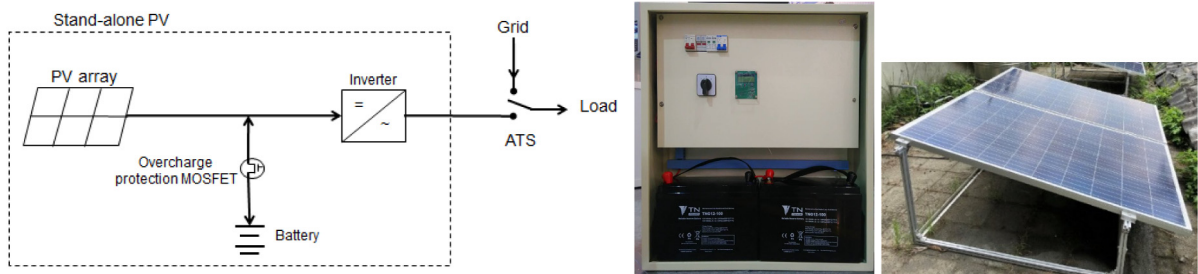


Fig. 1. Hybrid PV system (HyPV).

power generation or battery storage is high enough and switches to grid mode when battery storage is low. HyPV can be treated as a home appliance, easy to install and free of maintenance.

In order to reduce PV generation loss due to improper match between load and sizes of battery and PV modules, NTU further proposed a networking technique, called “pyramid solar micro-grid”, which connects individual HyPVs together and shares solar PV energy each other through a power dispatching control [9,10]. A 4 + 4 pyramid solar micro-grid constructed based on the binary connection of HYPVs at 3 levels is schematically shown in Fig. 2. Solar power of eight HyPV units can be shared each other through a smart power dispatching control. Two 1 + 1 pyramid solar micro-grids using RS485 for data transmission and communication were built [9,10]. The long-term field test shows that data transmission and signal communication fault could cause system breakdown occasionally.

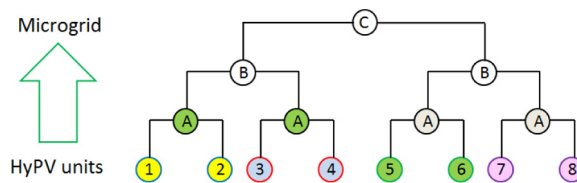


Fig. 2. Pyramid solar micro-grid based on binary connections.

NTU further modified the data transmission and communication using MODbus and CANbus protocols to improve system performance in a 2 + 2 pyramid solar micro-grid (Fig. 3) [11]. The long-term test shows that the power dispatching performance is free of system breakdown. However, signal loss in MODbus and CANbus is 37 and 4 times per day, respectively. The system reliability still needs to be improved. In the present study, we further investigate the effect of dispatching control scheme on the reliability of a larger pyramid solar micro-grid.

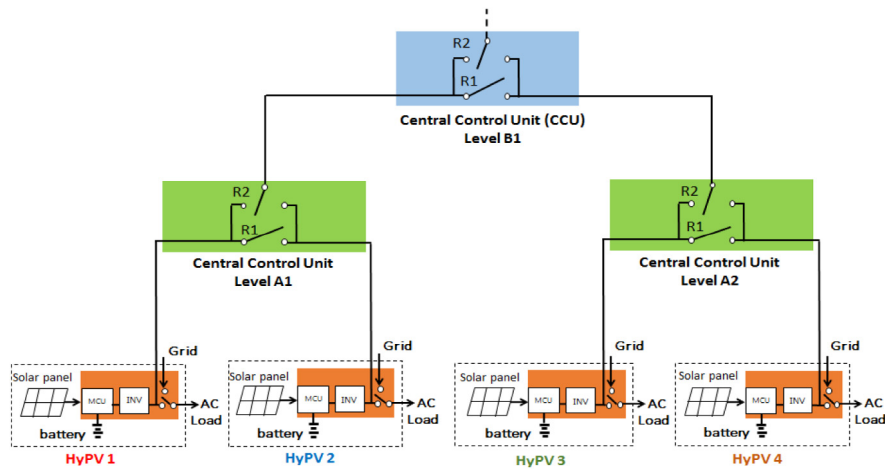


Fig. 3. 2 + 2 pyramid solar micro-grid.

2. Experimental setup of 4 + 4 pyramid solar micro-grid

To study the power dispatching control in a larger pyramid solar micro-grid, a 4 + 4 micro-grid (Fig. 2) was built.

2.1. CCU design

The central-control-unit (CCU) is used to connect the HyPV's in binary hierarchical form which divides the micro-grid into several cascaded layers, noted as "Level-A, Level-B, Level-C..." etc. as shown in Fig. 3. Each CCU consists of two relays to connect upward and downward for power flow. CCU was designed using PIC18F25K80 microprocessor, RS485 circuits, and CAN transceiver etc. MODbus and CANbus protocols are used at different levels. MODbus protocol is used for the communication below Level-A (to two individual HyPVs). For data transmission between the CCUs of Level-A, Level-B, and the above, CANbus protocol is used [11].

2.2. Electronic HyPV simulator

It is quite expensive and time consuming to build a 4 + 4 pyramid solar micro-grid with 8 units of HyPV for studying the power dispatching control. We designed an electronic HyPV simulator (SIM) to simulate the real performance of HyPV using physical model and input data (weather conditions, load pattern, PV module properties, battery design etc.). Each electronic simulator can simulate two HyPVs and output the data of solar power generation, load, battery state of charge (SOC) and voltage etc. to Level-A CCU.

2.3. Construction of 4 + 4 pyramid solar micro-grid using HyPV simulator

A Level-A CCU connects one electronic HyPV simulator which simulates the performance of two HyPVs. Four HyPV simulators (Fig. 4) were built to simulate the performance of 8 HyPVs (4 + 4). The micro-grid power dispatching controller is made of all the CCUs (Fig. 4). The power dispatching process was monitored and recorded.

2.4. Data input of HyPV simulator

Weather data are loaded into the simulator. To reduce the simulation time, 16 representative days of a year was generated from statistical analysis of local hourly meteorological data, including 6 sunny days (solar radiation >15 MJ/m² day), 3 mostly-cloudy days (10~15 MJ/m² day) and 7 cloudy/rainy days (<10 MJ/m² day). Solar PV power generation is simulated using the physical model in [8], which has been verified experimentally [8,10]. The

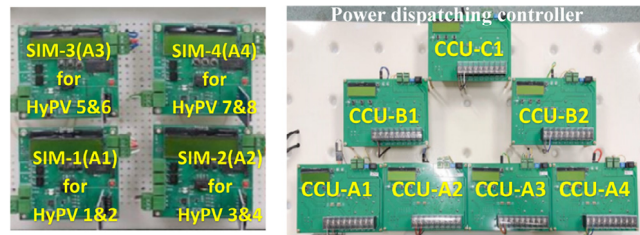


Fig. 4. 4 + 4 pyramid solar micro-grid using electronic HyPV simulators.

Table 1. Load combinations in electronic HyPV simulator.

System combination	Monthly electrical energy consumption (kWh/month)				
	Load pattern	HyPV-A1	HyPV-A2	HyPV-A3	HyPV-A4
1	Load B	300	300	500	500
	Load D	300	300	500	500
2	Load B	300	500	300	500
	Load D	300	500	300	500
3	Load B	300	300	500	500
	Load D	500	500	300	300
4	Load B	300	500	300	500
	Load D	500	300	500	300
5	Load B	300	300	500	500
	Load D	300	500	300	500
6	Load B	300	500	300	500
	Load D	300	300	500	500
7	Load B	300	500	300	500
	Load D	300	500	500	300

solar PV module installed is assumed 1380 Wp and the battery capacity is 4800 Wh. Two load patterns are used in the present study: Load B (75% energy used in daytime 6:00–18:00) and Load D (25%). The total number of system combinations provided by the simulators is 14, according to different load capacity and monthly energy consumption (Table 1).

2.5. Dispatching control scheme

Two kinds of power dispatching schemes are studied: (1) Mobile-commander scheme; and (2) Cascaded scheme. *Mobile-commander scheme*. In this scheme, Level-A CCU performs the power dispatching between two identified individual HyPVs (Buyer and Seller). Each HyPV monitors the following parameters and determines the status as a buyer or seller: V_H (battery voltage at full charging), V_L (battery voltage at full discharging), and D_B (battery discharge limit for selling energy). Each HyPV regularly transmits their status (qualified as a buyer or a seller or none) to all the CCUs which are connected using MODbus and CANbus. CANbus will chose one of the Level-A CCUs with buyer status as the commander (Master) for power dispatching control. The chosen Master CCU (A2 in Fig. 5) will find the optimal path for power dispatching. The master will be changed after executing a power dispatching command. This is called “mobile-commander power dispatching control” (Fig. 5). The total number of data transmission can be divided into two parts: one is the transmission between HyPV and CCU (RS485) and the other is transmission between CCUs (CANBus). The total number of data transmission between CCUs is negligible in Mobile-commander scheme because it is much less than the total number of data transmission between CCU and HyPV. The total number of data transmission between HyPV and CCU per day is

$$N_{mobile} = n_{HyPV} t_{day} / \Delta t_s \quad (1)$$

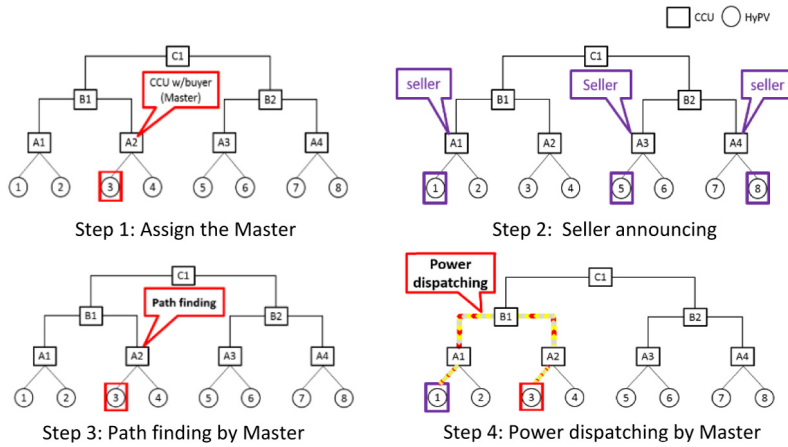


Fig. 5. Mobile-commander scheme in power dispatching control of 4 + 4 pyramid micro-grid.

where n_{HyPV} is the number of HyPVs in the micro-grid, t_{day} is the time length for the entire day, Δt_s is the time interval of data transmission. $N_{mobile} = 138,240$ for $n_{HyPV} = 8$ for 4 + 4 micro-grid, $t_{day} = 86,400$ s and $\Delta t_s = 5$ s. No matter what scheme we use, the total number of data transmission between HyPV Simulator and CCU are the same (138,240). The power dispatching flow is activated according to the following steps [11]:

- Step I: Searching the seller and the buyer for PV energy sharing by assigning the HyPV with high voltage V_H as a seller and the HyPV with low voltage V_L as a buyer. Pick one of the buyers as the Master.
- Step II: The Master will find the path of power dispatching flow and activate PV sharing when buyer and seller co-exists (R1 ON in Fig. 3) and monitoring the battery discharge of the seller.
- Step III: Stopping PV sharing (R1 OFF in Fig. 3) when the seller’s battery has discharged an amount of energy D_B and the PV sharing operation is terminated. The system returns to State I. A new master will be assigned if available.

Cascaded power dispatching scheme. The power dispatching follows the cascaded structure. Every CCU in different levels continues sending the data containing the HyPV status upward successively through CCUs of all levels. The highest level CCU (Level-C in 4 + 4 micro-grid) is the commander who chooses the seller and the buyer and decides the path of power dispatching (Fig. 6). The number of data transmission is larger than the mobile-commander scheme in which data is sent only from all HyPVs to CCUs in CANbus.

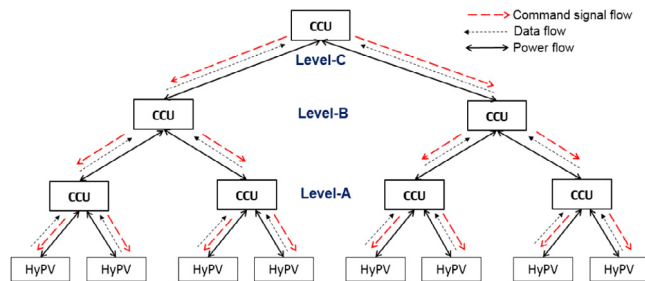


Fig. 6. Signal/data and power flow in cascaded power dispatching scheme.

In the cascaded scheme, the power dispatching decision is made by the Master only after all the data representing HyPV status are transmitted successively upward to the top level CCU. The total number of successive data transmission upward to the top level CCU in each time interval is

$$N_s = n_{CCU} - 1 \tag{2}$$

where n_{CCU} is the total number of CCUs in the micro-grid. $N_s = 6$ for three-level micro-grid (4 + 4) with $n_{CCU} = 7$.

The top-level CCU will be the master in the cascaded scheme, and it will transmit the command instructions to Level-A CCU for power dispatching. In order to complete the dispatch, four steps with four command signal transmission regarding to the connection of load to the power source (PV or grid) need to be carried out between two HyPVs (seller and buyer) [11]. The “executing time” from a command release for activating dispatch to completing actual dispatch, or from a command release for de-activating power dispatch, will be

$$t_{exe} = n_I(n_L - 1)\Delta t_s \quad (3)$$

where n_I is the number of commands signals in each buying and selling operation including load power source switching [11] (for pyramid solar micro-grid $n_I = 4$), and Δt_s is the time interval of regular data transmission. For example, it will take 60 s (t_{exe}) for $\Delta t_s = 5$ s in a 4 + 4 micro-grid. This is the “executing time” from a command release for activating dispatch to completing actual dispatch, or from a command release for de-activating power dispatch.

For Level-C power dispatching in a 4 + 4 micro-grid, the daily total number of data transmission in the grid N_{tot} will be the sum of upward data transmission between CCU above level-A and downward data transmission below A-level which is data transmission in Mobile Scheme (N_{mobile}):

$$N_{tot} = (n_{CCU} - 1)t_{sun}/\Delta t_s + N_{mobile} \quad (4)$$

That is, $N_{tot} = 56,160 + 138,240 = 194,400$ data per day for $t_{sun} = 3600 \times 13 = 46,800$ s (13 h 6:00~18:59) and $\Delta t_s = 5$ s, larger than mobile-commander scheme (34,560). The amount of command signal transmission downward for power dispatching is much less than the data transmission upward for monitoring information collection and can be negligible since the power dispatching happens not very often.

3. Test results

Two parameters are used to evaluate the performance of power dispatching: (1) executing time from command release to actual execution in activating or de-activating power dispatching t_{exe} ; (2) signal or data loss. The experiments were carried out for 16 days performance using $\Delta t_s = 5$ s ($N_{tot} = 90,720$ per day) in 14 system combinations (Table 1). Table 2 shows the maximum executing time comparison. The average executing time for the cascaded scheme is 60 s and 30 s for Level-C and Level-B dispatching, respectively. For mobile-commander scheme, the executing time is shorter since no successive data transmission through all CCUs is required.

Table 2. Comparison of measured executing time.

Test run	Executing time t_{exe} (s)	Cascaded scheme	
		Level-C dispatching	Level-B Dispatching
	Activating/De-activating	Activating/De-activating	Activating De-activating
1	20	60	30
2	20	60	30
3	20	60	30

As shown in Table 3, the daily total number of data loss using cascaded scheme is near zero, much less than the mobile-commander scheme. This indicates that although the total number of data transmission in cascaded scheme is larger, the data transmission loss is 0.002%, much less than mobile-commander scheme (0.09%). This is caused by three facts: (1) MODbus and CANbus is quite reliable; (2) CANbus data transmission can be interrupted easier in mobile-commander scheme; (3) CANbus data transmission has priority in cascaded scheme.

4. Discussion and conclusion

In the present study, we develop a new power dispatching control in the pyramid solar micro-grid. A 4 + 4 solar micro-grid was built using an electronic HyPV simulator and run with a micro-grid control system consisting of all CCUs. It is experimentally shown from 16 days performance test using 14 system combinations that, the power

Table 3. Measured data transmission loss.

System combination	Average daily total number of data loss, times/day									
	Mobile-commander scheme					Cascaded power dispatching scheme				
	HyPV-A1	HyPV-A2	HyPV-A3	HyPV-A4	average	HyPV-A1	HyPV-A2	HyPV-A3	HyPV-A4	average
1	33	36	36	39	36	1	1	5	4	2
2	29	36	32	38	34	0	0	0	0	0
3	38	38	39	44	40	0	0	1	2	1
4	32	35	34	39	35	0	0	0	1	0
5	25	27	26	31	27	1	0	1	5	2
6	21	27	24	28	25	1	0	1	5	2
7	23	28	28	33	28	0	0	0	0	0
Average	29	32	31	36	32	0	0	1	2	1
Daily data transmission	34,560 × 4 = 138,240					56,160 + 138,240 = 194,400				
Data loss ratio	(32 × 4)/138,240 = 0.090%					(1 × 4)/194,400 = 0.002%				

dispatching control using cascaded scheme is much reliable than the mobile-commander scheme. The data loss is near zero for cascaded scheme although the amount of data transmission is larger than the mobile-commander scheme.

The waiting time (t_{exe}) for power dispatching is longer for cascaded scheme. This can be improved by bypassing some successive upward data transmission through CCUs at different levels or reducing the data transmission time interval (Δt_s). This can be optimized too.

It is noticeable that the present pyramid solar micro-grid consists of many HyPVs which can be treated as a home appliance free of maintenance. The construction of the pyramid micro-grid requires to install HyPVs and additional CCUs associated with wiring of a power line and a signal line between HyPVs and CCUs. The construction can be very fast and cheap.

Acknowledgments

This study was supported by National Energy Program II, MOST 107-3113-E-002-001-CC2, made by Ministry of Science and Technology, Taiwan.

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