Pyramid solar micro-grid

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Abstract. A novel pyramid solar micro-grid is proposed in the present study. All the members within the micro-grid can mutually share excess solar PV power each other through a binary-connection hierarchy. The test results of a 2+2 pyramid solar micro-grid consisting of 4 individual solar PV systems for self-consumption are reported.

1. Introduction

Some studies have shown that there is a limit in solar PV penetration if all relies on feed-in solar PV system. Solar PV for self-consumption and with storage will be very important in high penetration of solar energy [1-2]. Many micro-grids in different structure have been studied to try to cope with the problem of power transmission due to high penetration of solar PV systems [3-7]. The New Energy Center at National Taiwan University has been devoted to the development of hybrid PV system (HyPV), Figure 1, which a solar PV system for self-consumption operating at stand-alone PV mode or grid mode without feeding access PV power into grid [8]. HyPV operates at PV mode when solar radiation or battery energy is high enough. It switches automatically to grid mode when battery storage is low. There may be a PV generation loss if the system match between load and sizes of battery and PV modules is not proper. To cope with this problem, we proposed a networking technique, called “pyramid solar micro-grid”, which connects neighbor HyPVs and shares solar PV power each other through a switching control device. Pyramid solar micro-grid constructed based on binary connection of HYPVs at 3 levels is shown in Figure 2. Solar power from eight HyPVs can be shared each other through a smart control. The binary connection of two HyPV systems at A-level (called “Hynet-2A”) was built and tested [9]. The long-term solar PV energy generation of Hynet-2A is close to that of grid-tied solar PV systems [4].

In the present study, the binary connection of four HyPV systems at B-level (called “Hynet-2B”) was built and tested.

2. Design of 2+2 pyramid solar micro-grid

The individual HyPVs can be connected in a binary structure (A-level) in order to share the solar PV power each other when one of the HyPVs is at low load and its battery storage is full. Two pairs of HyPVs can be further connected in binary form as B-level for 4 individual HyPVs to share excess solar power each other. See Figure 3.
The central control unit (CCU) for connection of each pair of HyPV at A-level and B-level are the same in hardware, but with different control logic. Hynet-2B consists of two pairs of 1+1 HyPV systems, A1 and A2. The design specifications of Hynet-2B is shown in Table 1. Figure 4 shows the concept of B-level connection.

| Table 1. Design of 2×2 pyramid solar micro-grid (Hynet-2B). |
|----------------------------------------------------------|
| Top level (B-level) | Bottom level (A-level) | A1   | B1   | A2   |
| HyPV ID           | D0  | D2  | T1   | T2   |
| PV size, kWp      | 1.47| 0.49| 1.47 | 1.47 |
| Battery type      | LA  | Li  | LA   | LA   |
| capacity, kWh     | 2.4 | 1.44| 4.8  | 1.824|
| Load type         | cooling and lighting | lighting | lighting |
| load power, kW    | 0.1–0.7 | 0.15–0.25 | 0.2–0.5 | 0.2–0.5 |
| load pattern      | daytime | 24 h a day | 24 h a day | 24 h a day |

A1 is made of 1+1 HyPV (D0+D1) and A2 is made of another 1+1 HyPV (T1+T2). The control logic for a pair of HyPVs consists of three control states [4]:

State I: Searching the donor system for PV energy sharing

1. Measure the battery voltage of D0 and D2
2. Choose the HyPV with full-charge voltage \( V_{H} \) as the donor and the other as the receptor.

State II: Starting PV sharing (R1 ON)
When battery voltage of the receptor is lower than $V_{th} - dV_r$, relay R1 is activated and PV sharing is started. $V_{th}$ is the high battery voltage limit, $dV_r$ is the voltage margin of the receptor. The battery discharge energy $E_d$ in the donor is measured right after the start of PV sharing.  

State III: Stopping PV sharing (R1 OFF)

(1) When the donor battery discharged energy $E_d$ reached $S_D$, the PV sharing operation is terminated. (2) The system returns to State I.

Figure 5 is the experimental setup of Level A1. Figure 6 shows the controller of Level A and Level B.

### Test results

#### 3.1 Day performance

Figure 7 shows the performance on 2016/10/06 with solar PV power sharing within B1 level. The excess solar power in A2 (HyPV T1) is used to support the load power need in A1 (D0). The CCU of A1, A2 and B1 are activated and T1 shares its excess PV power to D0 for 635 minutes with total energy 3,343 Wh. The increase of PV energy generation in T1 thus increases 2,490Wh. Figure 8 shows the performance of solar PV power sharing within B1 level (from A1 to A2). Since the load of T1 is zero, excess solar power is used to supply the load demand of T2 around 15:00 for 74 minutes with 280Wh. At 16:00, the load of D0 decreases and its excess PV power is used to supply the load demand of T2 for 89 minutes with 322Wh. Table 2 shows the performance of 2016/11/29.

#### Table 2. Performance of PV power sharing

| HyPV  | PV power sharing (2016/11/29) |
|-------|-----------------------------|
| T1    | PV generation: 1,029 Wh     |
|       | Feeding T2: 280 Wh          |
|       | Load: 0                      |
| D0    | PV generation: 816 Wh       |
|       | Feeding T2: 322 Wh          |
|       | Load: 229 Wh                |
| T2    | PV generation: 543 Wh       |
|       | Load: 1,056 Wh              |

#### 3.2 Long-term performance

The 2+2 pyramid solar micro-grid was test outdoor continuously. Figure 9 shows the long-term average PV power sharing at different levels. The average PV power sharing time is 84 min/day.
within A1 group (D0+D2) and 206 min/day within A2 group (T1+T2). The average PV power sharing time at B1-level (A1+A2) is 54 min/day.

Figure 10 to 13 shows the load consumption and output energy of individual HyPVs, D0, D2, T1 and T2. It is seen that D2 has a stable load which is much higher than PV energy generation. D2 is thus not able to output excess solar energy to its neighbor.

Figure 9. PV power sharing time.

Figure 10. Load consumption and output energy of D0.

Figure 11. Load and output energy of D2.

Figure 12. Load and output energy of T1.

Figure 13. Load consumption and output energy of T2.

Figure 14. PV generation efficiency of pyramid solar micro-grid (1 month).

Figure 14 shows the solar PV generation efficiency of 2+2 pyramid solar micro-grid in September, 2016. It is seen that the overall PV energy generation efficiency is 2.49 kWh/day per kWp of PV installation, which is very close to that of FIT system in Taipei (2.47).

The overall PV energy generation efficiency of the 2+2 pyramid solar micro-grid reaches 2.89 kWh/day per kWp of PV installation for 4 month operation (Figure 15) which is close to that of FIT system in Taipei in summer (2.47), about 17% increase.
Figure 15. PV generation efficiency of pyramid solar micro-grid (4 months)

4. Conclusion
In the present study, the binary connection of four HyPV systems at B-level ("Hynet-2B") was built and tested. It is shown that the excess PV power sharing within A-level or B-level can be effectively performed. The long-term test results show that the solar PV generation of the 2+2 pyramid solar micro-grid is very close to that of FIT system. The pyramid solar micro-grid is built bottom up from individual HyPVs by connecting in binary form. The controller (CCU) for solar PV power sharing control is simple and easy to be implemented. The time for building a pyramid solar micro-grid is very short and much cheaper than conventional micro-grid based on the concept of centralized grid.

5. References
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