SUMMARY

The New Energy and Industrial Technology Development Organization (NEDO) advertised for consignment research business called “Verification of Grid Stabilization with Large-scale Photovoltaic (PV) Power Generation Systems” in 2006. Two sites were selected to the verification test. They are Hokuto City in Yamanashi Prefecture and Wakkanai City in Hokkaido. Mega-solar system of about 2MW and about 5MW were constructed in Hokuto and Wakkanai, respectively. The outline of Hokuto Mega-solar system is introduced and some results are described and discussed in this paper.

In the first stage, we constructed the 600kW system consisting of 24 kinds of PV modules in 2006. The system was connected to 6.6kV distributed grid through 60 conventional 10kW PCSs (power conditioners). And their PV characteristics were evaluated. In the second stage which started from 2008, we constructed about 1200kW system consisting of 4 kinds of PV modules which were selected from the first stage evaluation. At that point, the total capacity of the system becomes about 1,800kW. They are connected to 66kV extra high voltage grid together with the first stage PV system. In the second stage, in order to connect the 1200kW system to the grid, we developed three 400kW large-scale PSCs (LS-PCSs) so as not to adversely affect it, too. The functions of the LS-PCSs are voltage fluctuation suppression due to solar generation fluctuations, harmonics current suppression and fault ride-through (FRT) in the grid faults. The confirmation tests of the LS-PCSs were carried out using a miniature model before put into verification test in the field. The test results in a factory provided expected results and were satisfactory. Verification test results in the field are provided, too and are discussed in the paper.

Verification tests of NEDO were finished in the last fiscal year. Although we transferred the system in the Hokuto city, we will continue to collect field data in cooperation with the city and to evaluate for the future.

KEYWORDS

Large-scale PV system, Grid stabilization, Power conditioner, Voltage fluctuation, Harmonics current, Fault-ride-through, MPPT, PV module, Performance ratio

INTRODUCTION

Photovoltaic generation systems are one of the promising measures for reducing global warming. It is also important for future energy resources, especially in Japan. An installed capacity target of PV system in our country is set to 28GW in 2020, but the cumulative installed capacity is still 4.24GW in 2021.
2009. About 80% of the capacity is mainly residential use such as roof-top types. They are 3 kW to 5 kW PV systems and very small size. Some large-scale photovoltaic (LSPV) systems should be constructed to attain the target. Moreover, intensive development of related technologies such as grid stabilization, high generation efficiency, and cost reduction is urgent concerns. The New Energy and Industrial Technology Development Organization (NEDO) advertised for consignment research business called "Verification of Grid Stabilization with Large-scale Photovoltaic Power Generation Systems" in 2006. The verification tests are carried out in two sites. They are Hokuto City, Yamanashi Prefecture and Wakkanai City, Hokkaido. Each installed capacity is about 2MW and about 5MW, respectively.

In this paper, the outline of Hokuto Mega-solar system is introduced and some results are described and discussed.

**HOKUTO MEGA-SOLAR PROJECT [1-2]**

24 kinds of PV modules provided from both inside and outside of Japan were constructed in the first stage which started from FY2006 and ended on FY2007. The capacity is 600kW at that time. They were connected to an AC grid through conventional 10kW power conditioners. Their data have been collected and evaluated for applicability to the future LSPV systems. In the second stage which started from FY2008 and ended on FY 2009, we constructed 1,200kW PV modules. We selected 4 kinds of PV modules from the first stage evaluation. For evaluating the 1200kW system, we developed a large-scale power conditioner (LS-PCS). In the final stage which is in FY2010, we constructed another 40 kW of future promising PV modules. AT the present, 1,840kW PV modules have been evaluated. Fig.1 shows the aerial photograph of the mega-solar system.

**DEVELOPMENT OF LS-PCS**

Generally, LSPV systems are connected to the power grids, and adverse influence on stabilized operation of power grids, which is power and voltage fluctuations caused by unsteady output of PV due to sunshine changes, is the most important concerns to be solved. For solving some of these, we have developed the LS-PCS with three functions: voltage fluctuation suppression (VFS) function, harmonic reduction function and fault ride-through (FRT) function [3].

The developed target and specification of the LS-PCS is shown in Table 1. The capacity of the developed LS-PCS was decided as 400kW in consideration of cost, size, expandability to the future application, and so on. The VFS function by reactive power control of LS-PCS is focused on in this paper.

Voltage fluctuation Suppression function

In the developed method, the power factor of the PCS is adjusted automatically to the suitable value, which is related to the system conditions of the power grids, in order to reduce voltage fluctuations caused by the active power fluctuations due to PV generation. Specifically, reactive output power Q of the PCS for reducing voltage fluctuations is generated in proportion to the active output power P of the PCS using the calculated and estimated constant value α as shown in Eq. (1).
Suitable Var command calculation block

\[ Q = \alpha \cdot P \] ..........................(1)

\( \alpha \): Constant parameter related to transmission line impedance (=R/X)

R: Resistance of the transmission line (pu),
X: Reactance of the transmission line (pu)

Fig. 2 shows the VFS control block diagram. It consists of a suitable Var command calculation block and a Var offset control. In the suitable Var command calculation block, the estimation values of constant parameter \( \alpha \) (=\( \Delta Q/\Delta P \)) are calculated using a change of PV generation powers \( \Delta P \) and voltage fluctuations \( \Delta V_s \) so as to minimize the \( \Delta V_s \) due to the \( \Delta P \). For this purpose, the voltage of the grid \( V_s \) and the PV generation power \( P \) are detected, and the \( \Delta V_s \) and the \( \Delta P \) are calculated after passing through a band-pass filter (BPF). The \( \alpha \) is adjusted from its initial value \( \alpha_0 \) by integrating the product of \( \Delta V_s \) and \( \Delta P \) as shown in the figure. In the Var offset control, the amount of compensation of \( Q \) for reducing the voltage fluctuation without an excessive increase is adjusted by the offset of \( Q_{BASE} \). The behaviors and effects of the method were examined by numerical analysis with the detail VFS control models of the PCS.

Fig 3 shows the numerical analysis results of the VFS control. \( \Delta V_s \) are 1.6% against 100% PV generation fluctuations without the control, but with the control, they are suppressed within 0.2%. For suppressing them, the PCS output \( Q \) is changed from 0 to 0.35 pu. The value of \( \alpha \) (=R/X) at that time is 0.38.

A rough connecting diagram of the Hokuto mega-solar system is shown in Fig.4. The point for evaluating the VFS function was put at the secondary winding output of the 1200kW feeder transformer. Because larger voltage fluctuations occur due to the existing line impedance in comparison with at the PV system connecting point, where we should originally suppress the voltage fluctuations. The \( P \) and \( Q \) were measured at the output of PCS.

Fig. 4 shows measured data of voltage fluctuations due to the PV generation fluctuations in the field. They are less than 0.4% against 1 pu PV fluctuations. We verified that the voltage fluctuations caused by PV generation fluctuations at the connecting point could be reduced by controlling reactive powers of PCS in the suitable value responding to the grid conditions. And we confirmed that there is no need to increase the PCS capacity by adjusting the offset of the reactive power properly, too.

Harmonics suppression

Measured harmonics currents are shown in Fig 5. They indicate the harmonics currents at the connecting point A. The fundamental component of the current changes according to the PV generation but the low order harmonics is almost constant regardless of the PV generation. Therefore it can be considered that they are not generated by the PCS but from the grid. Anyway they are small enough compared to the values of the guide line and are no problem.
Continuous operation
No grid faults have occurred since the confirmation tests of LS-PCSs in the field have started, and the FRT function has not been confirmed yet.

**MPPT CONTROL**

The control algorithms were modified from a DC current control to a DC voltage control. At first, because it is easy to protect from over voltages and over currents in the faults, the chopper in the LS-PCS was operated with the DC current control. So the maximum power point of the PV arrays was searched through scanning the DC currents by the MPPT control of the chopper. We found that there is a fundamental problem described below.

When the shade occurs in some strings of the arrays, some PV modules of the strings are bypassed and operating points easily go to the direction of zero currents. Because the DC current control keeps the DC currents to a predetermined value and by lowering the DC voltage, the DC currents increase. So the bypass diodes conduct easily. When the chopper loses the maximum power point, it needs much time to return the following next maximum power point. Once the bypass diodes conduct, it needs to switch off the diode current in order to move to a following next maximum power point. This behavior sometimes occurs in the DC current control.

On the other hand, in the DC voltage control, the operating points move to the point according to the size of the shade. Because the voltage control keeps DC voltages to a predetermined value and bypass diodes will not conduct. The strings which were not able to output the voltage are separated from the MPPT control. So it is easy to return the following next maximum power point.

By this reason, we modified the control algorithms from the DC current control to the DC voltage control. When the faults occur in the AC grid, the control system is changed to the DC current control for easy protection.

**PERFORMANCE OF PV MODULES**

The LS-PCS consists of a 400kW inverter and two 200kW choppers. 4 kinds of PV modules were selected from 24 kinds of PV modules of the first stage. The selection was done in consideration of cost [yen/W], generation efficiency [Wh/W], compactness [m²/W], gentleness for the environment.
[J/w], productivity ability of the makers, and so on. Each 200kW array is connected to the 6 choppers each. Two 200kW hybrid arrays consisted of single crystalline Si and amorphous Si, are connected to LS-PCS_1 through chopper_11 (CH_{11}) and chopper_12 (CH_{12}). Both 200kW single crystalline Si arrays and 200kW CIGS arrays are connected to LS-PCS_2 through chopper_21 (CH_{21}) and chopper_22 (CH_{22}), respectively. The rest of two 200kW multi-crystalline Si arrays are connected to LS-PCS_3 through chopper_31 (CH_{31}) and chopper_32 (CH_{32}). The performance ratios (PRs) of six 200 kW arrays are shown in Fig. 6. The PRs of DC-side (CH_{11}-CH_{32}, chopper input) are high enough and they are between 95.9% and 92.1%. On the other hand, the PRs of AC-side (INV_{1}-INV_{3}; Inverter output) are between 91.7% and 88.4%. They are about 4% low compared to those of DC side. The difference is considered losses due to PCS, DC circuit, and others. Here, the array's direction is south and the tilt angle is 30 deg. The data were measured from January 8th to 21st in 2011. Usually, it is said that the PRs at AC-side are 70% to 80%. We continue measuring after this for the long term evaluations.

CONCLUSION

About 2MW PV system has been constructed in Hokuto to verify grid stabilization with a large-scale PV system. In order to connect it to an existing extra-high voltage AC grid effectively and operate stably, the 400kW large-scale power conditioner (LS-PCS) has been developed. In this paper, the project outline and the test results are shown and discussed. A modification of key control systems of the LS-PCS were carried out to get PV generation power with high efficiency. They are also discussed. Although the verification tests have been finished last fiscal year, data collecting and their evaluation will be continued.

BIBLIOGRAPHY


Short Bio-data of Main Author

Hiroo Konishi received M.S. degree from Osaka University in 1972. He joined Hitachi Research Laboratory and worked in R&D of HVDC. Since 2006, he has been working in R&D of large-scale solar system in NTT Facilities Inc. He received Ph.D degree from Osaka University in 1989. He is a senior member of IEEJ.
VERIFICATION TEST RESULT
IN HOKUTO MEGA-SOLAR SYSTEM

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INTRODUCTION

- Solar generation systems are one of the measures for reducing global warming and are important as countermeasures for drying up of resources.

- An installed capacity target of solar generation systems in our country will be set 28GW in 2020, however construction is still 4.24GW in 2009.


- The verification tests are carried out in two sites of Hokuto City, Yamanashi Prefecture and Wakkanai City, Hokkaido.

- The outlines and the developing targets and studying/measured results of the Hokuto Mega-solar project (HMP) are introduced.
PV Installed capacity and target

Cumulative installed capacity (GW)

Year:
- '99
- '00
- '01
- '02
- '03
- '04
- '05
- '06
- '07
- '08
- '09
- '10
- '11
- '12
- '13
- '14
- '15
- '16
- '17
- '18
- '19
- '20

Targets:
- 2.14 GW
- 4.24 GW
- 28 GW

Ref.: http://www.fepc.or.jp/future/new_energy/jisseki/index.html
System configuration of Hokuto

1st stage (600kW) 2006-2007

2nd stage (1,200kW) 2008-2009

3rd stage (40kW) 2009

PV system

Conv. PCS (10kW × 60)

Conv. PCS (10kW × 4)

6.6kV/210V

AC Grid

Connecting point

Inverter (400kW)

Chopper (200kW)

Chopper (200kW)

66kV/6.6kV 6.6kV/420V

6.6kV/210V

6.6kV/210V

PCS-1

PCS-2

PCS-3
★ Installed capacity: nearly 2MW
★ Area: 6 ha
★ Developing period: 2006-2010
★ Location: Hokuto city, Yamanashi Prefecture
★ Sunshine hours are the longest in Japan

Hokuto, Yamanashi

Aerial photo of the site

Photo by SANNICHI PRINTING
2009.12
### Specifications and developing targets of 400kW PCS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value / Details</th>
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<tbody>
<tr>
<td>Capacity</td>
<td>420kVA/400kW</td>
</tr>
<tr>
<td>AC voltage</td>
<td>420Vac ± 10%</td>
</tr>
<tr>
<td>Insulation</td>
<td>Transformerless (Non-insulation)</td>
</tr>
<tr>
<td>DC voltage</td>
<td>400Vdc</td>
</tr>
<tr>
<td>Input DC voltage</td>
<td>230-600Vdc</td>
</tr>
<tr>
<td>Switching freq.</td>
<td>4 kHz</td>
</tr>
<tr>
<td>Conversion efficiency</td>
<td>&gt; 95 % from 30-100% output</td>
</tr>
<tr>
<td>Control functions</td>
<td>/ MPPT by choppers</td>
</tr>
<tr>
<td></td>
<td>/ Suppression of Δ Vac ≤ 2%</td>
</tr>
<tr>
<td></td>
<td>/ Low voltage ride-through ≥ 60%, within 200ms</td>
</tr>
<tr>
<td></td>
<td>/ Suppression of low-order harmonics ≤ 80% of the guide-line</td>
</tr>
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</table>
Voltage Fluctuation Suppression

Fig. 2 Developed VFS control block diagram

Suitable Var command calculation block

Var offset block

Fig. 3 Simulation result of VFS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>P [pu]</td>
<td>0.016pu</td>
</tr>
<tr>
<td>Q [pu]</td>
<td>0.002pu</td>
</tr>
<tr>
<td>ΔVs [pu]</td>
<td>0.35pu</td>
</tr>
<tr>
<td>α</td>
<td>0.38</td>
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</table>

Control start
Voltage fluctuation suppression

Measured points of P, Q, V

AC grid

Connecting point

66kV/6.6kV

1200kW feeder

M/M system

6.6kV/420V

Power meter

Evaluating point

640kW feeder

640kW PV system
(10kW PCS×64)

1200kW PV system
(400kW PCS×3)

PV fluctuation

ΔP=55%

/ Sampling time: every 1s
/M/M: Measuring/Monitoring system

Measured: 18 Feb. 2010
No harmonics current occurrence can be seen from the PCS
Grid code of each country

- HMS (Japan)
- REE (Spain)
- UK
- E.ON 2006 (USA)
- E.ON (USA)

Grid code in Fault-ride Through

Cited: wpa.jp/pdf/50-05spain090130.pdf
Performance ratio of 1,200kW system
(Each array is 200kW, Measured: 8\textsuperscript{th}-21\textsuperscript{st}, Jan., 2011)
Electric field strength of EMC is small enough and might rise no problems

Extending to a wide frequency region
Less than the signals of AM/FM radio, TV, and Cellular phone
In many PV systems, DC cables are generally used and PCSs are usually installed in the center of the site, and housed in the container

Characteristics of EMC noise in PV system

Cited: NTT Advanced Technology Inc., Research report on EMC from Large-scale PV system (11, 2008)
CONCLUSIONS

- The outline and the development target of the Hokuto mega-solar project are introduced.
- Some results, especially grid stabilization issues are discussed.
- PV performance shows good

Although the verification tests have been finished last fiscal year, data collecting and their evaluation will be continued.

We thank NEDO for R&D support.
Promotion of installation of PV system

- FIT, Government subsidy
- Reduction of PV system cost
- Improvement of PV module efficiency
- Grid stabilization
  - Smoothing of output energy
  - Development of large scale storage system
  - Adjustment of power by existing generation plants
  - Adjustment of generation and demand by ICT
  - PV output limits of the long vacation
  - Prediction of weather conditions