Renewable Energy Penetration Limits: Effect and Solution Issues for Interconnected Grid

アジアの豊かな再生可能エネルギーを利用するために、その電力供給源を電力系統に多数連系し、利用するための問題点と解決策。

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Abstract This paper deals with the quantity of renewable energy generation which can be introduced in Distribution Systems by using computer simulation which employs a model of the Distribution Systems containing a large-scale photovoltaic power generation (Mega Solar). From the viewpoint of the critical mass of the reverse power flow occurring in the Main Grid from the Mega Solar, the quantity of renewable energy generation which can be introduced was determined. When the amount of connected Mega Solar increased, as a result of the simulation, it became obvious that the reactive power of the Main Grid is consumed and the voltages rise at the connected bus. Furthermore, it was proved that the connectable quantity of the Mega Solar is restricted with 3-phase-short-circuit level at base voltage of the Main Grid. Then, by increasing 3-phase-short-circuit level at base voltage or connecting reactive power compensation equipment to the Distribution Systems, a connectable quantity of the Mega Solar has been increasingly introduced. In this study, for simulation of an actual power system, for the first time, a simulation model of the IEEE 30 Bus Test System on the MATLAB/Simulink environment is developed and its effectiveness is verified through various simulation results.

Keywords Photovoltaic power generation; Distribution systems; Penetration limit; Reactive power compensation; IEEE 30 Bus test system

Introduction

Recently, due to reformation of energy-oriented society independent of a fossil fuel or atomic power towards a reduction of greenhouse gas, or solution of a nuclear power generation problem, expectations are growing for extensive introduction of renewable energy, such as wind and solar power.

However, when they connect to a distribution system in large quantities as DG (Distributed Generation), they may oversupply. The generated output of DG flows into a higher level system as reverse power flow, and may have a negative impact on electric power quality such as raising the voltage of the distribution system, changing the allowable voltage range, or making reactive power insufficient.

In this research, penetration limits of DG when renewable energies are introduced is clarified. Our aim is to find the maximum limits of DG which can be introduced for the main grid.

Method of Research

If PV is expanded as a plant scale, it becomes very difficult to smooth by adjusting the balance of voltage variation and the amount demanded using electric-power-storage equipment.

Therefore, conventional research, as shown in Fig. 1,[1] has considered how to control reactive power and voltage before carrying out the penetration of the DG to the power system by using PCS (Power Conditioning Subsystem: It has a conversion function of DC and AC, and a voltage control function.).[2) 3)]

However, PCS is installed in a low rank rather than the transformer. A solar cell is connected according to the regulatory capacity of PCS. Therefore, the more it enlarges the scale of PV, the more PCS(s) have to be installed.

In this research, DG is directly connected to the distribution system without passing through a control device. Therefore, it is less of a need for electrical storage devices.

Moreover, raising the voltage of distribution system absorbs the reactive power of the distribution system. As a result, it is expected that the reactive power of distribution system will become insufficient. As shown in Fig. 2, equipment which can compensate for reactive power had to be collectively installed in the higher level of distribution system, and stabilization of distribution system had to be attained by supplying reactive power.

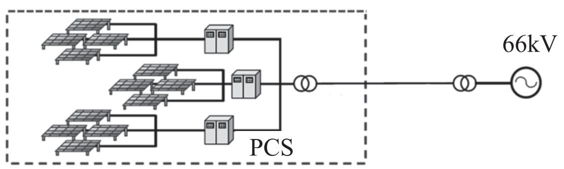

Fig. 1 Grid-connected Mega Solar System

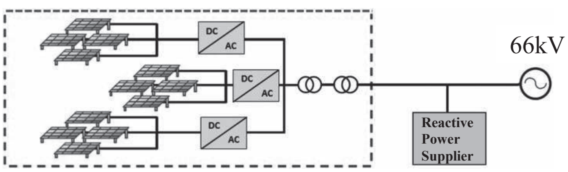

Fig. 2 Direct Connection of Mega Solar System to the Distribution System

Method of Simulation

Using MATLAB/Simulink, a 66kV electric power system was constructed in which a Mega Solar system is directly connected to a distribution system[4)].

Main Grid and load is connected to Bus 1. Mega Solar is connected to Bus 2. Bus 2 is also connected to Bus 1.[5)] The active power and reactive power of two power supplies are measured. In addition, frequency, voltage, and current of each bus are measured. The power consumption of load is supplied by the power supply of Main Grid and Mega Solar. By changing the supply rate of two power supplies gradually, it is possible to observe what kinds of effects occur in the Main Grid when the generated output of Mega Solar changes. When each measured value has been changed, if it is less than ±5% from standard value, we can judge that it is proper.[6)]

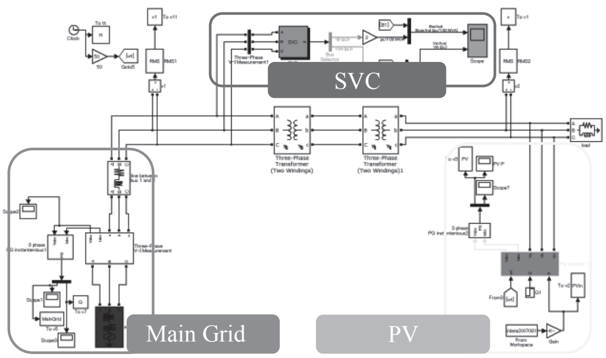

Fig. 3 The 66kV Electric Power System Simulation Model

Simulation Results 1

(1-1) *Influence which 3-phase-short-circuit level at base voltage causes to Main Grid (Mega Solar is not introduced)*

In a simulation, when the output of Mega Solar is set at 0 in the electric power system simulation model shown in Fig. 3, that is, there is no generated output from Mega Solar and electric power is supplied to load only by the power supply of the Main Grid. In this simulation, the 3-phase-short-circuit level at base voltage of the power supply of the Main Grid is

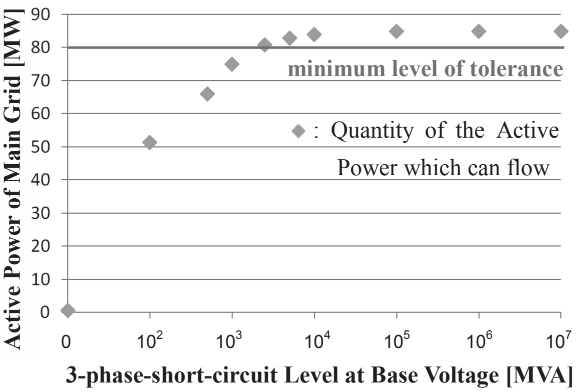

Fig. 4 3-phase-short-circuit Level at Base Voltage vs Active Power of Main Grid

changed from 10 MVA to 10^7 MVA to observe what kind of influence these changes would lead to in the active power of the Main Grid.

As a result, when 3-phase-short-circuit level at base voltage was changed, it turned out that the power flow of active power was restricted. The value for which active power converges was investigated. The results are shown in Fig. 4. Since the power consumption of load was set to 85 MW, the red line showed the minimum of the tolerance level of active power. According to Fig. 4, when 3-phase-short-circuit level at base voltage was more than $2.5*10^3$ MVA, the result was that the active power of the Main Grid took a proper value.

(1-2) ***Influence of 3-phase-short-circuit level at base voltage on the Main Grid (Mega Solar: 10 MW, 3-phase-short-circuit level at base voltage: 10^3MVA)***

In this simulation, electric power with Mega Solar connected to Bus 1 was performed. Load consumption is 85 MW. Main Grid supplies 75 MW and Mega Solar supplies 10 MW. 3-phase-short-circuit level at base voltage was set as 10^3 MVA according to Fig. 4 so that Main Grid might yield 75 MW output.

All the active power of Mega Solar was consumed by load, and the result revealed that the Main Grid was compensating the part in which Mega Solar was not able to cover the power consumption of load. However, the Main Grid supplied 65 MW supplied instead of 75 MW. Furthermore, the sum of the active power of two power supplies was set to 75 MW which is a preset value of Main Grid. This showed that 3-phase-short-circuit level at base voltage had restricted the power flow of all the buses.

(1-3) ***Influence of 3-phase-short-circuit level at base voltage on the Main Grid (Mega Solar: 10 MW, 3-phase-short-circuit level at base voltage: $3*10^3$ MVA)***

The power flow of the generated output of Mega Solar penetrated to Bus 1. Load consumption is 85 MW. Main Grid supplies 75 MW and Mega Solar supplies 10 MW. However, 3-phase-short-circuit level at base voltage was set at $3*10^3$ MVA because when 3-phase-short-circuit level at base voltage is more than $2.5*10^3$ MVA, the active power of Main Grid takes a proper value. When 3-phase-short-circuit level at base voltage is set at more than $2.5*10^3$ MVA, even when the sum total of the power flow of two buses was set to 85 MW, a power flow could be carried out without restriction. Moreover, since it was just below the minimum of the normal operation range when 3-phase-short-circuit level at base voltage is $2.5*10^3$ MVA, it set at $3*10^3$ MVA.

All the active power of the Mega Solar was consumed by load, and the Main Grid was compensating for what the Mega Solar was not able to cover in terms of power consumption of load. Moreover, since the Main Grid supplies the remaining 71.6 MW, it was clarified that mitigation of load flow restrictions was completed by making three-phase short circuit capacity increase. It can be said that the measured value of this simulation is within the limits of normal operation.

(1-4) ***Influence of 3-phase-short-circuit level at base voltage on the Main Grid (Mega Solar: 0-120 MW, 3-phase-short-circuit level at base voltage: $3*10^3$ MVA)***

The same simulation as the previous one was performed. When the electric power production of

Table 1 Operational status with Measured Values (3-phase-short-circuit Level at Base Voltage : $3*10^3$ MVA)

Mega Solar [MW]	Active Power [MW]	Bus Voltage [kV]	Reactive Power [MVAR]	Operational Status
0	81.6	64.7	50.7	usual
10	71.6	64.7	51.0	usual
30	51.7	64.7	51.3	usual
60	21.8	64.8	51.3	usual
90	-8.07	64.9	50.7	usual
100	-18.0	64.9	50.4	usual
105	-22.9	64.9	50.2	unusual
110	-27.9	65.0	50.0	unusual
120	-38.0	65.0	49.5	unusual

Mega Solar increases from 0 W to 120 MW, it is investigated what kind of influence it has on the active power and reactive power of Main Grid, and bus voltage. The result of this simulation is shown in Table 1 and Figs. 5 and 6. In addition, the red line in Figs. 5 shows the maximum and minimum of tolerance level. Only a minimum of tolerance level is shown in Fig. 6.

As seen in Table 1, when Mega Solar increases gradually, the active power of Main Grid decreases gradually. On the other hand, as shown in Fig. 5, bus voltage has not reached a maximum or a minimum. However, it is expected that it will reach a maximum if Mega Solar further increases since the monotone increase of the bus-bar voltage is carried out with the increase in Mega Solar.

Moreover, from Fig. 6, with the increase in Mega Solar, once reactive power goes up, it is descending. The reason which went up once in the first stage is shown below. When Mega Solar is set at 0 W, output is not actually 0 W but several negative values of 100W. Since the active power from the power supply of the Main Grid passed along the Bus 2 and flowed into the Mega Solar, a measured reactive power is consumed. This is why the value of the reactive power was smaller than the value of the original. Reactive power is descending, after reaching at the

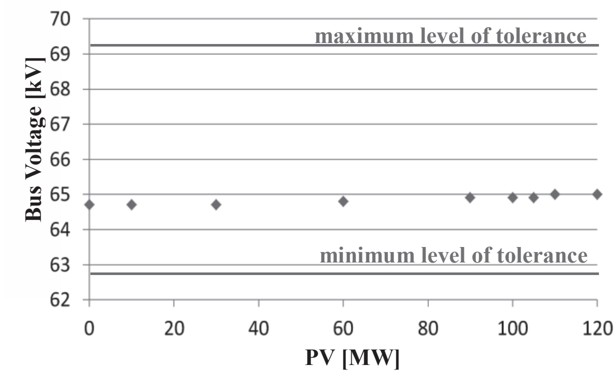

Fig. 5 Mega Solar vs Bus Voltage (3-phase-short-circuit Level at Base Voltage: $3*10^3$ MVA)

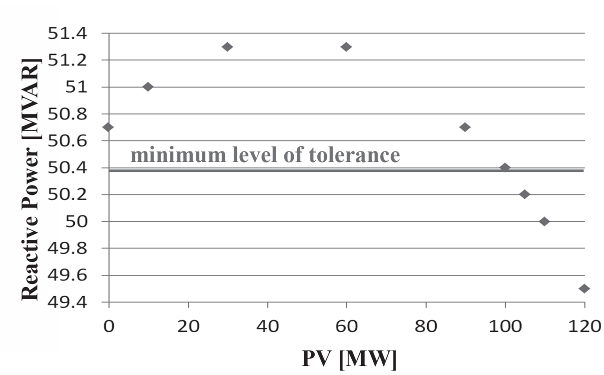

Fig. 6 Mega Solar vs Reactive Power (3-phase-short-circuit Level at Base Voltage: $3*10^3$ MVA)

peak in 51.3 MVAR. Reactive power reached 50.2 MVAR when the active power of Mega Solar was set at 105 MW. This is less than 50.35 MVAR of a tolerance level minimum. Therefore, it can be judged as an unusual operation.

In the setup of this research from these results, when 3-phase-short-circuit level at base voltage was 3000MVA, it turned out that the penetration limit of Mega Solar was 105 MW.

(1-5) *Influence which 3-phase-short-circuit level at base voltage causes to the Main Grid (Mega Solar: 0-300 MW, 3-phase-short-circuit level at base voltage: 10^5 MVA)*

From the result of the simulation (1-4), if 3-phase-short-circuit level at base voltage of the power supply is further increased, it can be expected that the penetration limit of Mega Solar will increase. Therefore, 3-phase-short-circuit level at base voltage was set at 10^5 MVA, and the same simulation was carried out as last time.

When the electric power production of Mega Solar increases from 0 W to 300 MW, what kind of influence it leads to is investigated in terms of the active power and reactive power of Main Grid, and bus voltage. The result of this simulation is shown in Table 2.

From Table 2, when Mega Solar increases gradually, the result is that the active power of Main Grid decreases gradually. On the other hand, the maximum and minimum of bus voltage are 69.3 kV and 62.7 kV, respectively. Although measured value has not been reached, bus voltage decreases with the increase in Mega Solar.

Furthermore, monotone decreasing of the reactive power is carried out with the increase in the Mega Solar. When the active power of the Mega Solar is set at 300 MW, reactive power rapidly decreases. Because of this result, furthermore, it will be expected that a limit is approached if the amount of introduction increases. In any case, it can be judged as normal operation.

From these results, it can be concluded that the more 3-phase-short-circuit level at base voltage increased, the more the penetration limit of the Mega Solar increases.

(1-6) *Influence of reactive power compensation on the Main Grid (Mega Solar: 0-120 MW, 3-phase-short-circuit level at base voltage: $3*10^3$MVA)*

In this simulation, the insufficiency from 53 MVAR which is a standard value of reactive power was compensated for by a VAR System which includes power capacitors. When the power production of the Mega Solar increases from 0 W to 120 MW, it shows what kind of influence it leads to in the active power and reactive power of the Main Grid, and bus voltage. The result of this simulation is shown in Table 3 and Figs. 7 and 8. In addition, the red line shows the maximum and minimum of tolerance level.

From the results in Table 3, we see that when the Mega Solar increases gradually, the active power of the Main Grid decreases gradually. On the other hand, the maximum and minimum of bus voltage are 69.3 kV and 62.7 kV, respectively. Measured value has not reached the maximum and minimum levels. Although reactive power decreases with the increase

Table 2 Operational Status with Measured Values (3-phase-short-circuit Level at Base Voltage: 10^5 MVA)

Mega Solar [MW]	Active Power [MW]	Bus Voltage [kV]	Reactive Power [MVAR]	Operational Status
0	84.9	66.0	52.8	usual
10	75.0	66.0	52.8	usual
30	55.0	66.0	52.8	usual
60	25.0	65.9	52.8	usual
90	-5.00	65.9	52.8	usual
100	-15.0	65.9	52.8	usual
120	-35.0	66.0	52.8	usual
140	-55.0	65.8	52.7	usual
160	-75.0	65.8	52.7	usual
300	-215	65.6	52.1	usual

Table 3 Each Measured Value (3-phase-short-circuit Level at Base Voltage : $3*10^3$ MVA, with Reactive Power Compensation)

Mega Solar [MW]	Active Power [MW]	Bus Voltage [kV]	Reactive Power [MVAR]	Operational Status
0	81.4	64.7	52.9	usual
10	71.5	64.6	52.9	usual
30	51.6	64.7	52.9	usual
60	21.7	64.7	52.9	usual
90	-8.2	64.8	52.8	usual
100	-18.2	64.8	52.8	usual
105	-23.2	64.8	52.8	usual
110	-28.2	64.8	52.7	usual
120	-38.2	64.9	52.7	usual

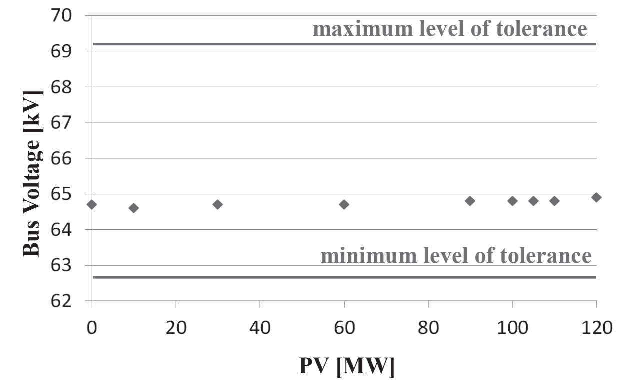

Fig. 7 Mega Solar vs Bus Voltage
(3-phase-short-circuit Level at Base Voltage: 3*10^3 MVA, with Reactive Power Compensation)

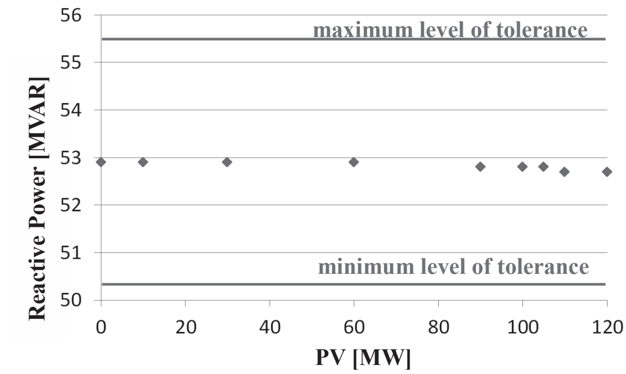

Fig. 8 Mega Solar vs Reactive Power
(3-phase-short-circuit Level at Base Voltage: 3*10^3 MVA, with Reactive Power Compensation)

in the Mega Solar, it is almost fixed at a standard value. In any case, in the simulation under these conditions, it can be judged as normal operation.

From these results, it is possible to install reactive-power-compensation equipment in the higher rank of an electric power system collectively, and to keep the state of an electric power system stable by supplying reactive power, and also to make the amount of introduction of the Mega Solar increase without increasing of 3-phase-short-circuit level at base voltage of the power supply contained in the Main Grid.

IEEE 30 Bus Test System

The IEEE 30 Bus Test System represents a portion of the American Electric Power System (in the Midwestern US) as of December, 1961. This model of IEEE is officially recognized as a benchmark. It was recommended to the power system research as a standard model system, therefore the obtained results of the similar simulations could be compared together. Since 1961 it has been used as a general model system for power system simulation. In this study, we also used this IEEE 30 Bus Test System. However, we went further and designed this model system on the MATLAB/Simulink. Thus, by performing the simulation close to the actual power system, we can assume that our research subject on penetration limits of a Mega Solar connected to metropolitan area power grid is close to the real conditions. It should be noted that the original total installed capacity of the IEEE 30 Bus Test System is about 189.2MW, so in order to use this model system, we should modify the total capacity adjusted to the subject or our study.

Recently, much research is done using MATLAB/Simulink, so we thought of developing an IEEE 30 Bus Test System which can be run on MATLAB/Simulink so that the results could be seen graphically with great flexibility. So far, there is no such model on the MATLAB/Simulink and the authors believe this is the first one developed so far. In this research, we could successfully and newly develop the model and connect the Mega Solar for further simulation. Through this simulation, we investigated the penetration limits of a Mega Solar connected to power grid. The benefits of using this model on the Simulink are that it consists of various elements such as power supply, bus, transformer, loads and many modules that can be combined freely and easily. It became possible to observe in detail the state of any element. Also, many states such as failures and other phenomena which may happen in the large-scale power system with large interconnected PV and other renewable energies can be analyzed. Using this model, we can increase the penetration limits of a Mega Solar by removing the causes.

Currently, the development of IEEE 30 Bus Test System simulation model[7] has been completed. Fig. 9 shows the complete developed IEEE 30 Bus Test System operating on MATLA /Simulink.

Regarding the state of the individual operation, the IEEE 30 Bus Test System we developed is operating normally. In terms of voltage, as an example, the error between the ideal values and our simulation result is about 0.41% at the maximum point.

In addition, voltage, current, active power, reactive power, frequency can be measured at any point. Table 4 shows an example of system voltage simulation results which is compared with the traditional Newton Raphson result.[8] The low error between the traditional Newton Raphson and our proposed model demonstrates the effectiveness of the model we developed. The details of the IEEE 30 Bus Test System components are shown in Fig. 9.

The “Red blocks” are the generators. In an actual power system, it is equivalent to a large-scale power plants. It implements a 3-phase simplified synchronous machine. The machine is modeled as an internal voltage behind the R-L impedance. Stator windings are connected in Wye to an internal neutral point. In this model, there are six power generations, G1 through G6. Swing type G1 can change its power output to keep the balance of supply and demand. However, the output values of G2 to G6 are kept fixed. The generator outputs are presented in Table 5.

There are 31 buses in this model. Bus 1 to Bus 30 are higher-level system buses (all 135kV). Bus 31 to which the Mega Solar is connected is called a Mega Solar bus. The output voltage of the Mega Solar bus is boosted to 135kV by the transformer.

The “Purple blocks” are the transformers. This block implements a three-phase transformer composed of three single-phase transformers. We can set the winding connection to ‘Yn’ when we want to access the neutral point of the Wye. It should be noted that in this simulation model, only the higher level system is represented and the lower level system is omitted. That is the reason why all buses are boosted to 135kV by the transformer.

Table 4 Simulation of the System Voltage and the Error Before Mega Solar Interconnection

Bus #	Demand		Voltage Magnitude		
	P [MW]	Q [MVAR]	Newton Raphson Result [pu]	Proposed Model Result [pu]	Relative Error [pu]
1	-	-	1.000	1.000	0.000
2	21.70	12.70	1.000	1.000	0.000
3	2.40	1.20	0.983	0.984	0.102
4	7.60	1.60	0.980	0.981	0.102
5	-	-	0.982	0.982	0.000
6	-	-	0.973	0.973	0.000
7	22.80	10.90	0.967	0.967	0.000
8	30.00	30.00	0.961	0.961	0.000
9	-	-	0.981	0.982	0.102
10	5.80	2.00	0.984	0.982	0.203
11	-	-	0.982	0.982	0.102
12	11.20	7.50	0.981	0.981	0.406
13	-	-	1.000	1.000	0.000
14	6.20	1.60	0.977	0.973	0.409
15	8.20	2.50	0.980	0.979	0.102
16	3.50	1.80	0.977	0.975	0.205
17	9.00	5.80	0.977	0.975	0.205
18	3.20	0.90	0.968	0.968	0.000
19	9.50	3.40	0.965	0.964	0.104
20	2.20	0.70	0.969	0.968	0.103
21	17.50	11.20	0.993	0.993	0.000
22	-	-	1.000	1.000	0.000
23	3.20	1.60	1.000	1.000	0.000
24	8.70	6.70	0.989	0.988	0.101
25	-	-	0.990	0.990	0.000
26	3.50	2.30	0.972	0.972	0.000
27	-	-	1.000	1.000	0.000
28	-	-	0.975	0.976	0.103
29	2.40	0.90	0.980	0.980	0.000
30	10.60	1.90	0.968	0.968	0.000

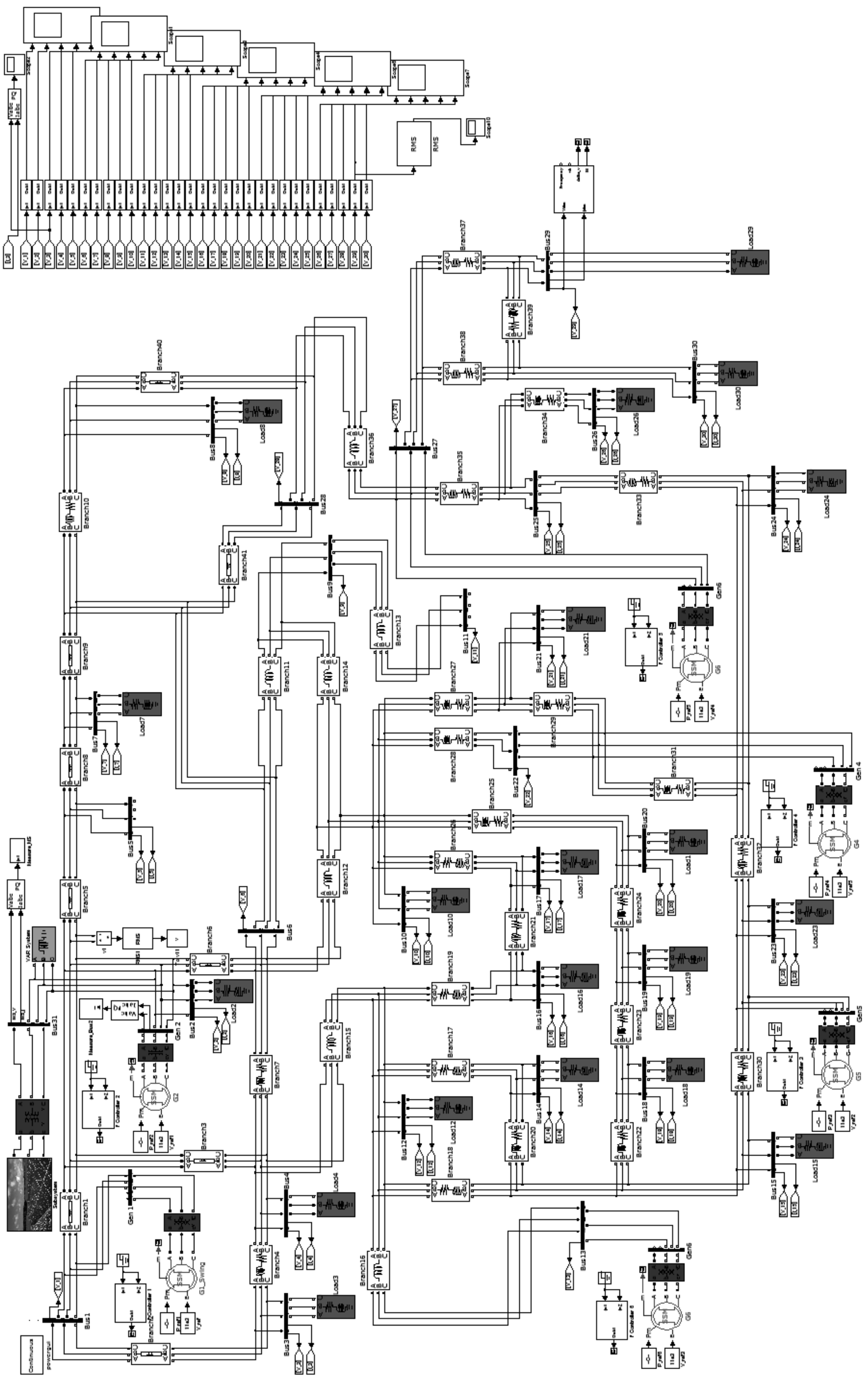

Fig. 9 Designed IEEE 30 Bus Test System on Simulink

Table 5 The Generator Outputs

Bus #	Pg [MW]	Qg [MVAR]	Qmax [MVAR]	Qmin [MVAR]
1	23.54	0	150	-20
2	60.97	0	60	-20
13	37	0	44.7	-15
22	21.59	0	62.5	-15
23	19.2	0	40	-10
27	26.91	0	48.7	-15

The "Gray blocks" are the loads. Loads are the large-scale factories and a set of houses. For each, a three-phase series RLC load is implemented. In this model, there are 20 loads (load 1 to load 20) in which they do not change and are kept fixed. The load consumptions are shown in Table 4 as demand.

The block that appears in the image of the PV is a Mega Solar. It can provide any output. Solar power output is varied by the irradiation and temperature. Fluctuations of Mega Solar over the model system can be observed and measured. Regarding the measured data for this Mega Solar, the values were actually measured at approximately noon on August 15, 2007, from an actual 20kW photovoltaic system installed at Tokyo University of Agriculture and Technology, Koganei-city, Tokyo, Japan.

For voltage and frequency, the quality of power flow of the Mega Solar and power system is consistent by adjusting the inverter. Parameters required in the design of the transmission line are mainly resistance, reactance, and capacitance. By reference to the value at 1 km, it is possible to set the values for any length.

Regarding the data, we referred to the parameter data of generators, loads, and branches provided by Iraj Dabbagchi of AEP and entered in IEEE Common Data Format by Rich Christie at the University of Washington.[9)] However, it has been published from the same research team that the line impedances were incorrect and the data has not been run through a power flow to check the answers. Therefore, in this study, we have adopted the set value in MATPOWER which is the embedded power flow calculation software of MATLAB.

MATPOWER data is based on two papers.[10) 11)] According to this data, generator locations and bus areas were improved from the IEEE 30 Bus Test System. Branch parameters were rounded to the nearest 0.01. Shunt values were divided by 100. Shunt on Bus 10 was moved to Bus 5. Load at Bus 5 was zeroed out.

Simulation Results 2

In this study, a Mega Solar is connected to Bus 2, where the generator G2 is also connected. As G2 is generating its maximum output, with the exception of G1 as the swing type, the power system may absorb the changes caused by the Mega Solar through the Bus 2. Fig.10 shows an enlarged view of the vicinity of the Mega Solar.

(2-1) *Influence of Mega solar on the Main Grid (Mega Solar: 0-10 MW, No reactive power compensation)*

In this simulation, the electric power with a Mega Solar connected to the Bus 1 was performed. Main Grid together with the Mega Solar supply power to the Load 2 and other loads. In this simulation, one of our main objectives was to investigate what impact it may have on the active and reactive power of the Main Grid as well as the bus voltage when the electric power from the Mega Solar increases from 0 to 10 MW. The obtained results of this simulation are shown in Table 6 and Fig. 11. In addition, the red line in Fig. 11 shows the minimum of tolerance level.

Table 6 clearly shows that the active power of the Main Grid decreases gradually in proportion to the increase of the Mega Solar. On the other hand, the bus voltage remained unchanged at 135kV and did not reach the maximum or minimum levels. Interestingly enough, it was anticipated that it would reach the maximum when the Mega Solar increased, since the monotone increase of the bus voltage is carried out with the increase in the Mega Solar.

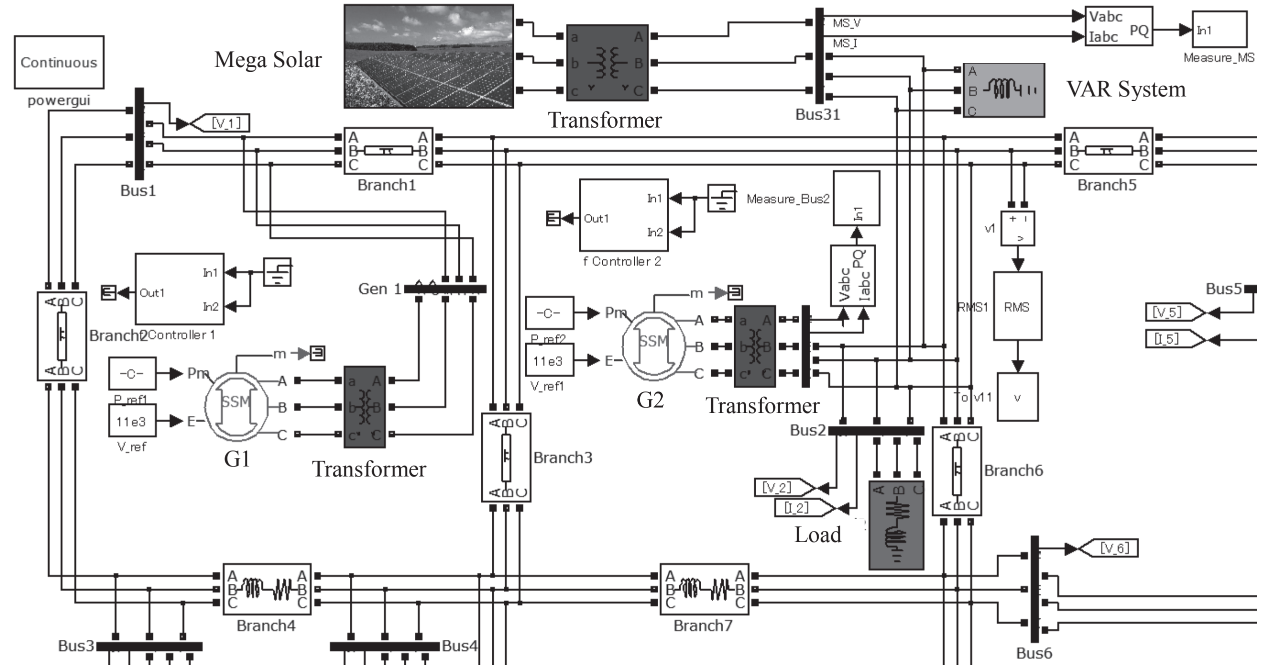

Fig. 10 Enlarged View of the Vicinity of the Mega Solar

Table 6 Influence of the Mega Solar Change on the Main Grid Active, Reactive Power and Voltage (No Reactive Power Compensation)

Mega Solar [MW]	Active Power [MW]	Bus Voltage [kV]	Reactive Power [MVAR]	Operational Status
0	68.73	135	96.33	usual
1	67.24	135	95.46	usual
2	65.74	135	94.6	usual
3	64.25	135	93.73	usual
4	62.75	135	92.87	usual
5	61.26	135	92	usual
5.5	60.51	135	91.57	usual
5.57	60.41	135	91.51	usual
5.6	60.37	135	91.48	unusual
6	59.77	135	91.14	unusual
8	56.78	135	89.41	unusual
10	53.79	135	87.68	unusual

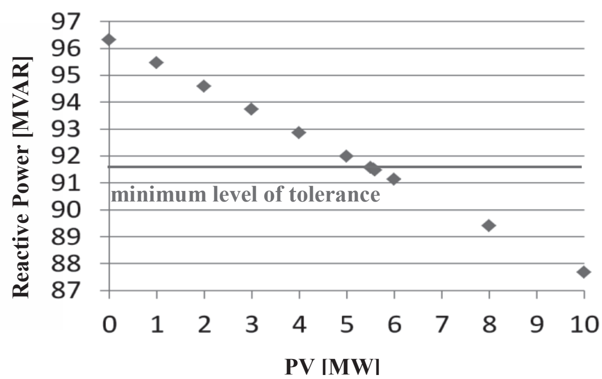

Fig. 11 Mega Solar vs Reactive Power (No Reactive Power Compensation)

Moreover, from Fig. 11, the reactive power of the Main Grid descreases with the increase of the Mega Solar. Reactive power was reached at 91.51 MVAR when the active power of the Mega Solar was set at 5.57 MW. This is just a minimum tolerance level.

On the other hand, with the exception of Bus 2, the changes in the other buses did not exceeded the limit. Based on the obtained results, it was obvious that the penetration limit of the Mega Solar introduced in the IEEE 30 Bus Test System is 5.57 MW. This value is almost 3% of the total installed capacity (189.2 MW).

(2-2) ***Influence of Mega Solar on the Main Grid (Mega Solar: 0–10 MW, with reactive power compensation)***

The insufficiency from 96.33 MVAR, which is a standard value of reactive power, was compensated for by a VAR System which includes power capacitors. Derived from the results of a simulation (2-1), the output value of VAR System is shown in the following equation (1):

$$\frac{96.33-Qm}{1.54} = Qvar\ system \quad (1)$$

Where, *Qm* is a measured value of reactive power in previous simulation and *Qvar* system is a reactive power which is compensated by the VAR System.

In this simulation, one of our main objectives was to investigate what influences it might have on the active and reactive power of the Main Grid as well as the bus voltage when the electric power from the Mega Solar increases from 0 to 10 MW. The obtained results are shown in Table 7 and Fig. 12. In addition, the red lines in Fig. 12 show the maximum and minimum of tolerance levels.

Table 7 clearly shows that the active power of the Main Grid decreases gradually in correlation with the increase of the Mega Solar. On the other hand, the maximum and minimum of bus voltage are 128.25 kV and 141.75 kV, respectively. Measured values did not reach the maximum or the minimum levels. The maximum and minimum of bus reactive power are 91.51 MW and 101.15 MW, respectively. Reactive power is almost fixed at a standard value. In any case, in the simulation under these conditions, it can be judged as normal operation.

From the obtained results, it is obvious that our developed IEEE 30 Bus Test System is successfully designed. Therefore, it is possible to install the reactive power compensation equipment at the higher

Table 7 Influence of the Mega Solar Change on the Main Grid Active, Reactive Power and Voltage (with Reactive Power Compensation)

Mega Solar [MW]	Active Power [MW]	Bus Voltage [kV]	Reactive Power [MVAR]	Operational Status
0	68.73	135	96.33	usual
2	64.79	135	96.29	usual
4	60.88	135	96.27	usual
6	57.01	135	96.26	usual
8	53.19	135	96.27	usual
10	49.43	135	96.30	usual

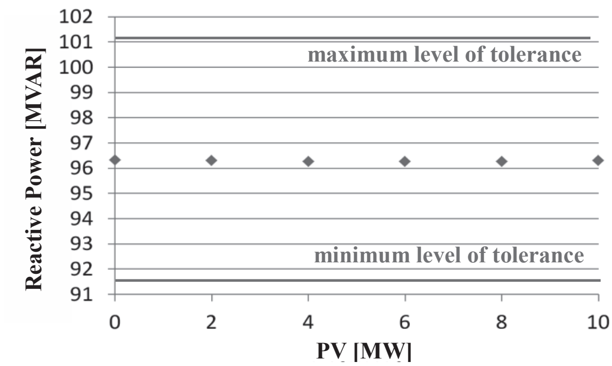

Fig.12 Mega Solar vs Reactive Power (with Reactive Power Compensation)

rank of a power system. Also it is possible to keep the state of a power system stable by supplying reactive power while the amount of the Mega Solar is increased.

Conclusions

In this research, in order to solve the problem of a bus voltage surge of distribution systems which may arise and when reactive power is insufficient, when a PV is connected and expanded to a plant scale, the technique of attaining stabilization of an electric power system was proposed. Installing reactive power compensation equipment in the higher rank of a power system enables the Mega Solar to connect to the power systems without passing a control device. From the results obtained from these simulations, it was shown that when the amount of Mega Solar introduction is increased, it does not make the 3-phase-short-circuit level at base voltage when the power supply of Main Grid increases. In this case, by installing reactive power compensation equipment, it is possible to stabilize the power system.

Moreover, in order to simulate the actual power system, we constructed a simulation model of the IEEE 30 Bus Test System on the MATLAB/Simulink environment. Simulation results showed the effectiveness of our proposed connection system to control the power quality in the actual power system.

There is still room for further study, such as considering a way to increase the amount of the penetration limit of the Mega Solar. Also, certain economy constraints should be taken into account.

Furthermore, in addition to the Mega Solar, we would like to consider other renewable energies such as wind power and geothermal power and develop an optimum mixture of renewable energies and existing electric power.

References

1) NTT Facilities. (2010) NEDO Mega Solar Project Hokuto Site ni okeru Jissho-Jikken

2) Yamaguchi, K. (2009) Study on voltage regulation method of a distribution network with a number of connected photovoltaic systems. Master's thesis, Tokyo University of Agriculture and Technology

3) Dohzono, T. (2007) Research on reliability of power generation system using renewable energies. Master's thesis, Tokyo University of Agriculture and Technology

4) Mori, H. and Nagasaka, K. (2007) Construction and Control of a Laboratory-based Micro-grid. Japan Society of Energy and Resources 26, 331-332

5) Shayani, R.A. and de Oliveira, M.A.G. (2010) Photovoltaic Generation Penetration Limits in Radial Distribution Systems. Journal of IEEE Transactions on Power Systems, 26 (3), 1625-1631

6) Law of Japan. (1964) Denki-Jigyo-ho

7) Kannan, P. et al. (2011) Voltage Sag Compensation of Thirty Bus System Using Unified Power Flow Controller. European Journal of Scientific Research, 51 (3), 372-382

8) Hayashi, Y. et al. (2013) Design and Simulation of Transmission Grid Inter-connected Off-Shore Wind Power. Japan Society of Energy and Resources 29

9) Christie, R. D. (1993) Power Systems Test Case Archive. http://www.ee.washington.edu/research/pstca/pf30/pg_tca30bus.htm (Last access: Dec. 31, 2012)

10) Alsac, O. and Stott, B. (1974) Optimal Load Flow with Steady State Security. IEEE Transactions on Power Apparatus and Systems, 93 (3), 745-751

11) Ferrero, R. W. et al. (1997) Transaction analysis in deregulated power systems using game theory. IEEE Transactions on Power Systems, 12 (3), 1340-1347