A new type of scaled-down network simulator for testing PV inverters

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This paper describes to design and build the ultra scaled-down network simulator. It is composed of the ultra scaled-down network simulator with electronic circuits and an active power interface (API). The component of the ultra scaled-down network simulator and its fundamental characteristics are described in detail. The simulator can imitate the distribution grid which a lot of distribution generators connected with. Islanding and voltage arising can be tested using the simulator.

Keywords: PV inverter, scaled-down network simulator, distribution generator

1. Introduction

Recently, a number of grid-connected photovoltaic (PV) systems have been rapidly increasing. Moreover, in view of diffusion PV system, a great number of PV systems will be connected to the distribution grid intensively. In addition, a lot of distribution generators as well as PV systems are connected. To test the functions of PV system in such a condition, it is necessary to enlarge experimental equipment, which leads to high construction cost and large space to install.

The purpose of this study is to develop a new scaled-down network simulator which has advantages in size and cost for expanding. In the previous study, the ultra scaled-down network simulator with electronic circuits and an Active Power Interface (API) [1] is proposed. That includes resistance, capacitance and inductance composed with electronic circuit. Using the API, it is possible to connect actual PV inverters to electronic circuit directly.

2. Ultra scaled-down network simulator

2.1 Basic design

An ultra scaled-down network simulator is composed of electronic circuits. The advantage is the flexibility in the expanding and the replacement. In addition, it makes the space and cost reduced. However, it is impossible to connect the actual PV inverters for grid connection with the electronic circuits, because there is a serious difference in the power levels between PV inverters and electronic circuits. A solution is inserting an API between a PV inverter and an ultra scaled-down network simulator.

A basic design of such a simulator is shown in Fig.1. It consists of the ultra scaled-down network simulator and the API. The most significant component in this system is the API, which makes it possible to be connected with actual scale power sources such as a PV inverter.

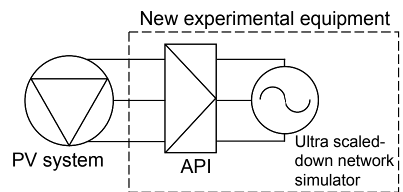


Fig.1.Composition of ultra scaled-down distribution grid simulator.

2.2 Composition of the proposed simulator

A model diagram of the ultra scaled-down network simulator is shown in Fig.2. It is based on the average distribution system in Japan. It is modeled on residential area; low voltage system is 100/200V, single-phase three wire type, and the capacity of transformer is 30kVA. To design a scaled-down model, the capacity and voltage of the distribution system are respectively reduced from 30kVA to 10VA and from 100/200V to 5/10V. Using these scale-factors, impedance, connected loads, and PV output power are calculated by the p.u. method.

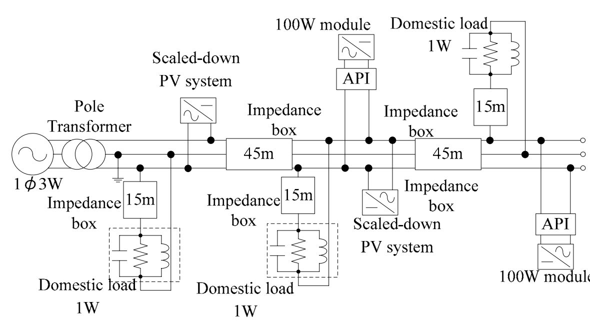
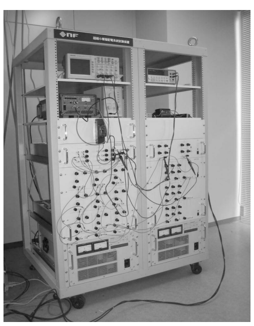


Fig.2. A model diagram of the ultra scaled-down network simulator.

The Ultra scaled-down network simulator includes an AC power supply, pole transformers, low voltage distribution lines, incoming lines, and low voltage loads. The AC power supply is a bipolar power supply which can absorb the reverse power flow from the PV systems. Pole transformer includes resistances and inductances. It is designed from an equivalent circuit of a transformer. Low voltage distribution line consists of resistance and inductance which are connected in series. The impedance is calculated from ACSR-OW120mm^2, and it is assumed up to 90m. Incoming line is consists of resistance and inductance which are connected in series. The impedance is calculated from 3DV3.2mm, and it is assumed 15m. Low voltage load consists of resistance, inductance and capacitance which are connected in parallel. The impedance can be changed by sequential change of the resistance and the inductance. The capacitance is changed in 1μF step. Active power and reactive power are able to be changed variously by adjusting the resistance and the inductance. The all inductances are included in the ultra scaled-down network simulator consist of electric circuit.

PV inverters are connected through the APIs. Instead of a real array, a PV array simulator is used [2]. Scaled-down PV systems will be the ac current sources which perform as PV inverters. They output higher harmonics like PV inverters and have islanding protections.



The view of the installed simulator in our laboratory is shown in Fig.3. The simulator can be set as arbitrary experimental circuits by wiring with jumper leads. The specifications of the ultra scaled-down network simulator compared with the actual scale [3] are shown in Table 1.

Fig.3. Installation situation of the simulator.

Table 1. Specifications of simulator and comparison with actual scale.

	Simulator	Actual scale
Capacity (VA)	10	30k
Voltage (V)	5/10	100/200
Low voltage distribution line (Ω/km)	1.87+j2.18	0.25+j0.29
Incoming line (Ω/km)	17+j0.77	2.3+j0.1
Maximum low voltage load (W)	2.5	7500

2.3 Expansion of ultra scaled-down network simulator

It is easy to expand the proposed simulator because it is composed the electronic circuits. At the present stage it is designed from pole transformer to low voltage loads. For the future, the simulator is to be expanded, which can be applied for various kinds of distribution generators. They may include wind turbines, gas generators, fuel cells etc. as well as PV systems. Those can be scaled down using the scale-factors described in chapter 2.2.

3. Fundamental characteristics of the API

The composition of the API is shown in Fig.4. Fundamental functions of the API are to transfer electrical properties, voltage and current from Terminal 1 to Terminal 2 and vice versa. These two Terminals have different power scale. A PV inverter is connected with Terminal 1, and the ultra scaled-down network simulator is connected with Terminal 2. The voltage V_1 and the current I_1 at Terminal 1 are transferred to Terminal 2 by multiplying factors of $1/n$ and $1/m$, respectively. At the same time, voltage V_2 and current I_2 at Terminal 2 are transferred to Terminal 1 by multiplying factors of n and m, respectively.

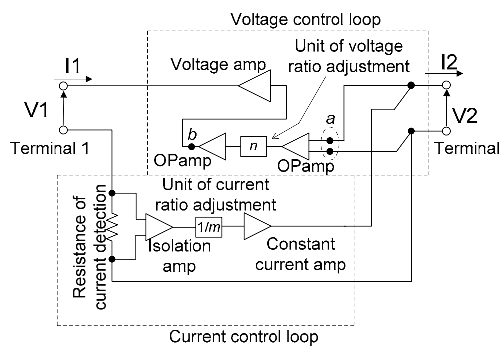


Fig.4. Composition of the API.

3.1 The accuracy of setting voltage ratio and current ratio

The accuracy which the voltage ratio is decided by is examined. An AC voltage source with 0.1V$_{peak}$ is connected with Terminal 2. The voltage ratio n is set by the unit of voltage ratio adjustment. It is set from 1 to 60 discretely and the V_1 is measured. The two APIs, API 1 and API 2, are measured. The voltage ratio R_v is calculated from V_1/V_2, the calculation results are shown in Table 2. The error E_{rv} between n and R_v is calculated by $E_{rv}=(n- R_v)/n$. As the results of the calculation, the Erv is within 4.6%.

Table.2 The calculation results V_1/V_2.

Setting	1	2	5	10	20	50	60
API 1	1.0	2.0	5.0	10.0	19.9	47.7	59.6
API 2	1.0	2.0	5.0	10.0	20.0	49.9	59.9

The accuracy which the current ratio is decided is examined. An AC current source with 10mA$_{peak}$ is connected with Terminal 1. The current ratio m is set by the unit of current ratio adjustment. It is set from 1 to 40 discretely and the I_2 is measured. The two APIs are measured. The current ratio R_i is calculated from I_1/I_2, and the calculation results are shown in Table 3. The error E_{ri} between m and R_i is calculated by $E_{ri}=(m-R_i)/m$. As the results of the calculation, the Eri is within 5.0%.

Table.3 The calculation results I_1/I_2.

Setting	1	2	5	10	20	40
API 1	1.0	2.0	4.9	9.9	20.0	40.0
API 2	1.0	1.9	5.0	10.0	20.0	40.0

3.2 Frequency characteristics

The frequency characteristics of the voltage control loop from the point *a* to the point *b* in the Fig.4 are measured. The measured results are shown in Fig.5. The gain characteristic is maintained constant gain up to 100kHz, and the phase characteristic is maintained constant phase up to 25kHz. However, if the voltage amplifier is connected, the frequency is limited to 20kHz because of the frequency limitation of the amplifier.

Therefore, the voltage fluctuation up to 20kHz is transferred between Terminal 1 and Terminal 2.

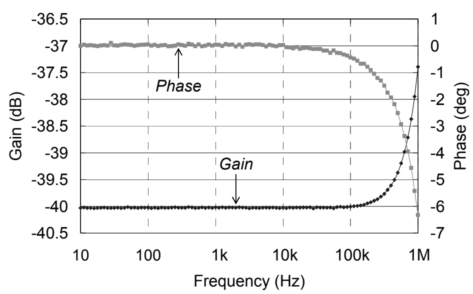


Fig5. The frequency characteristics of the voltage control loop from the point *a* to the point *b* in Fig.4.

The frequency characteristics of the current control loop are measured and the results are shown in Fig.6.

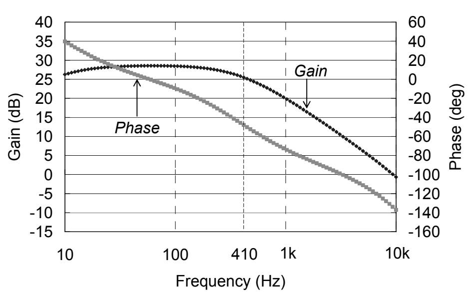


Fig.6 The frequency characteristics of current control loop.

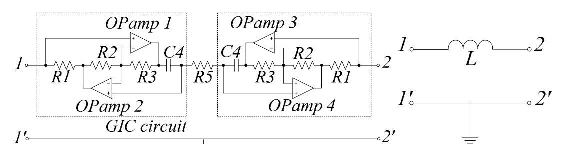
The gain characteristic drops by 3dB at 410Hz. The gain characteristic keeps dropping over 410Hz, which is affected by a low pass filter. If a spike is generated at Terminal 2, the harmonic components flow into positive feedback by the voltage control loop and the current control loop. If an over voltage is output to Terminal 1, PV inverters may be broke down. Thus, the low pass filter is included in the current control loop. The spikes may be generated at turning off of a circuit breaker in islanding tests.

Therefore, the current fluctuation up to 410Hz is transferred between Terminal 1 and Terminal 2.

4. Fundamental characteristics of the inductance [4]

The resistance and the capacitance in the ultra scaled-down network simulator are passive elements. On the other hand, the inductance components are built as electronic circuits by using the Generalized Impedance Converter (GIC) circuit with OP amps. As shown in Fig.7, all inductances in the simulator are the floating inductance; thus neither terminal voltage is connected to ground. It is used for the components of the pole transformers, line impedances and loads.

The circuit diagram is shown in Fig.7 (a), and the equivalent circuit of Fig.7 (a) is shown in Fig.7 (b). The R_5 in Fig.7 (a) is behaved as a inductance L in Fig.7 (b), and given by $L=(C_4 \cdot R_1 \cdot R_3 \cdot R_5)/R_2$.



(a) The circuit diagram (b) Equivalent circuit

Fig.7 The floating inductance

The frequency characteristics of the inductance are measured at 1.59, 585, and 1000mH. The measured results are shown in Fig.8 to 10. The phase at 50Hz is 83.5deg, 89.6deg, 88.1deg. The gain characteristic is increased as the frequency is increased up to 400kHz, 18kHz, 3.2kHz. The phase characteristic is maintained 85deg or more up to 12.6kHz, 18kHz, 126Hz. It becomes 0deg at 400kHz, 18kHz, 12.6kHz.

As the results, the phase characteristic of each measured value is 83.5deg or more at 50Hz. And they are maintained 85deg or more up to 126Hz.

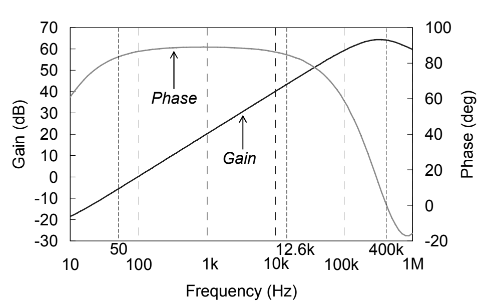


Fig.8 The frequency characteristics of the inductance at 1.59mH.

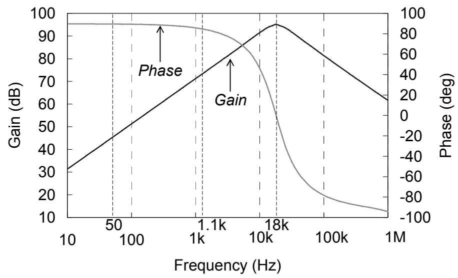


Fig.9 The frequency characteristics of the inductance at 585mH.

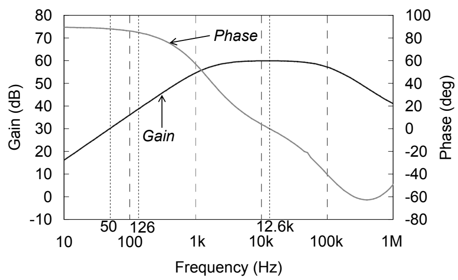


Fig.10 The frequency characteristics of the inductance at 1H.

5. Experimental Results of islanding test

An experimental circuit is shown in Fig.11. It is imitated a distribution system which is the single-phase two-wire type. The AC power supply outputs 5V, 50Hz. The line impedance is set to 0.1+j0.01Ω. The load is set to 0.31 W. The inductance is set to 0.27Var, the capacitance is set to 0.24Var, they are connected in parallel. PV inverters are European AC module (90W). In the both APIs, the voltage ratio is set to 1/46, and the current ratio is 1/20; thus the power ratio is 1/920. In this experiment, one PV inverter is considered as concentration of three PV inverters.

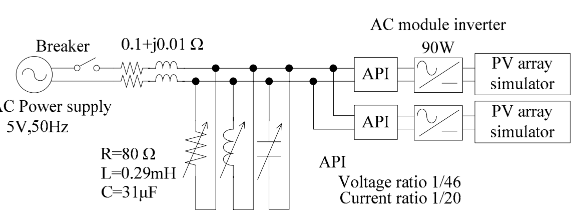


Fig.11 A circuit model for islanding tests.

The experimental wave forms are shown in Fig.12. The grid current is expanded to 10 times and displayed. The power supply from AC power supply stopped at the cutting off point. However, both the inverter 1 and the inverter 2 didn't stop. The islanding operation kept up to 8.5 seconds.

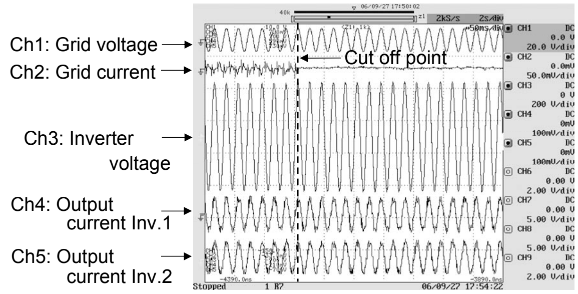


Fig.12 Observed waveforms in the islanding phenomenon. Horizontal: 50msec/div., Vertical: Ch1: 20V/div, Ch2: 500mA/div, Ch3: 200V/div, Ch4: 1A/div, Ch5: 1A/div

6. Conclusion

A new experimental equipment for PV inverters has been designed and built. Fundamental characteristics of the API and the inductance have been confirmed. Islanding phenomena have been observed with the proposed system. For the future, islanding and voltage arising will be tested in various experimental circuits. And the simulator is to be expanded, which can be applied for various kinds of distribution generators.

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