

Verification of Cooperative Control Method for Voltage Control Equipment on Distribution Network Simulator Considering Interconnection of Wind Power Generators

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Abstract-- This paper verifies the developed cooperative control method for voltage control equipment on distribution network simulator considering interconnection of wind power generators. The authors have developed a cooperative control method for existing voltage control equipment and newly developed voltage compensating equipment applying power electronics technology. The developed control method can handle various steep voltage fluctuations such as large steep generating power fluctuations of wind power generators and electrical flickers such as little periodical fluctuation by a tower shadow effect of wind power generators. The developed method has been applied to typical distribution models on analog distribution network simulator (15kVA/200V). The results indicate that the proposed method can regulate the line voltage within the regulated voltage ranges and can reduce electrical flickers.

Index Terms--Cooperative Control Method, Distribution Network Simulator, Power Electronics Technology, Step Voltage Regulator, Wind Power Generator

I. INTRODUCTION

Transformer with automatic tap changer called step voltage regulator (SVR) is usually installed in distribution systems in Japan in order to regulate the line voltage. In recent years, wind power generator, which may have steep fluctuations of power generation, has been introduced in distribution systems. Therefore, it may cause steep voltage fluctuations in distribution systems. SVR has a dead band value for a target control voltage and time delay from a few seconds to a few minutes to avoid frequent tap changing. On the contrary, wind power generator may reach full power output from zero output within one minute, at which SVR cannot regulate because of the time delay. Therefore, it becomes difficult to regulate the line voltage within the

regulated voltage ranges with only existing SVR.

On the other hand, wind power generator may cause electrical flickers such as little periodical generating power fluctuations by "a tower shadow effect" [1]. It is impossible to reduce electrical flickers by using only existing SVR.

The voltage compensating equipment applying power electronics technology, called FACTS, is effective against steep voltage fluctuations, because the equipment can respond quickly to the fluctuations. The equipment is called static var compensator (SVC). However, if only the equipment is installed to regulate the line voltage, it requires large capacity to regulate the line voltage. Therefore, cooperative control method using both SVR and newly installed voltage compensating equipment applying power electronics technology has been eagerly awaited. The authors have already developed the cooperative control method by steady-state analysis based on power flow calculation and instantaneous analysis using EMTDC [2].

This paper verifies the developed cooperative control method for voltage control equipment on analog distribution network simulator (15kVA/200V) considering interconnection of wind power generators. The developed method can regulate the line voltage within the regulated voltage ranges against steep voltage fluctuations. The developed method requires little capacity and low cost of the voltage compensating equipment and can be effective to regulate the line voltage and to reduce electrical flickers. The developed method has features as follows:

- (a) Using the developed method, a gradual voltage fluctuation is compensated by SVR and a steep voltage fluctuation is compensated by SVC.
- (b) It can select a certain reference voltage value of SVC, which is appropriate to each voltage fluctuation condition. It allows regulating the line voltage within the regulated voltage ranges against steep voltage fluctuations by SVC with minimum capacity.
- (c) It can modify the reference voltage value of SVC. It allows regulating the line voltage with SVR by shifting voltage compensation form SVC to SVR.

The verification of the developed method is demonstrated on typical distribution system models on analog distribution

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network simulator. According to the results, the developed voltage control method can regulate the line voltage within the regulated voltage ranges and can reduce electrical flickers. Required SVC capacity is compared between the conventional voltage control method and the developed method. The conventional voltage control method using conventional SVC maintains the line voltage with the reference voltage of its installed point. The results indicate that the required capacity of SVC in the case of the developed method is about half compared with the conventional SVC

II. OVERVIEW OF VOLTAGE CONTROL METHOD

A. Characteristic of Voltage Control Equipment

Since SVR has a time delay from a few seconds to a few minutes to avoid frequent tap changing, it cannot handle steep voltage fluctuations. On the contrary, newly installed voltage control equipment can quickly respond to the voltage fluctuations compared with SVR and it may over-compensate voltages in which SVR should handle because of slow fluctuations. Therefore, there is no chance for SVR to operate against the fluctuations and large capacity of new voltage compensation equipment is required. Considering these characteristics, cooperative control between SVR and new voltage control equipment must decide their roles.

B. Role of Voltage Control Equipment

Considering difference of characteristics between SVR and SVC, SVR handle should slow voltage fluctuations and SVC should handle steep voltage fluctuations.

III. OVERVIEW OF THE DEVELOPED CONTROL METHOD [2]

A. Cooperative Control Method

Fig.1 shows a block diagram of the developed voltage

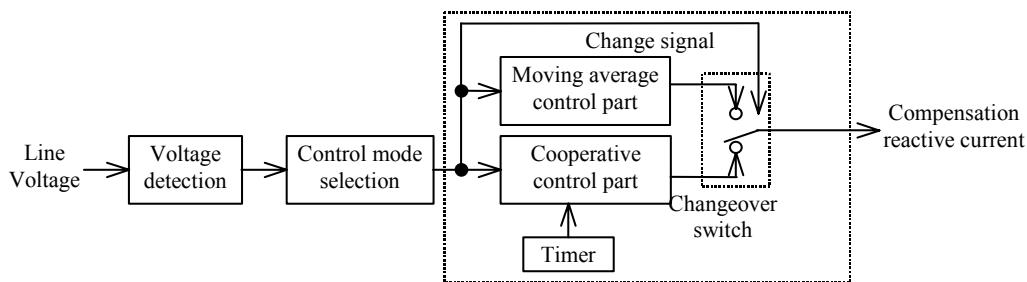
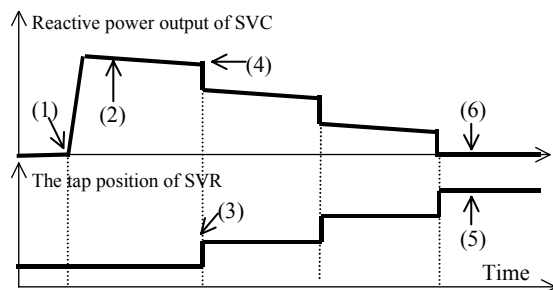


Fig. 1. A block diagram of the developed control method.



- (1) Generation of steep fluctuation of power output by wind power generator
- (2) At the beginning, voltage compensation of SVC
- (3) SVR changes its taps
- (4) Decrease of reactive power output of SVC
- (5) Total voltage compensation is moved from SVC to SVR
- (6) Compensation amount by SVC becomes about zero, and becomes standby mode

Fig. 2. Outline of the cooperative control method.

control method. SVC detects line voltage of installed point. When steep voltage fluctuations, which violate regulated voltage ranges, are appeared in the target distribution systems, SVC chooses the cooperative control mode by the operation mode selection. The cooperative control part chooses either reference voltages between upper and lower values. SVC gradually decreases reactive power output in order to move voltage compensation by SVC to SVR. Namely, when SVC compensates line voltage, the detected voltage of SVR is within its dead band. After the decrease of reactive power output of SVC, the detected voltage of SVR can move from the dead band and SVR can change tap to regulate the voltage. Consequently, while SVC compensates the steep voltage fluctuations at the beginning, after that, SVR changes taps and the main compensation role is moved to SVR. Therefore, voltage compensation by SVC does not maintain for a long time and SVC waits for the next steep voltage fluctuations. Fig.2 shows the outline of cooperative control method. The cooperative control method can be described as follows:

Step. 1 Quick voltage compensation by SVC

SVC compensates steep voltage fluctuations by sudden output changes of wind power generator.

Step. 2 Correction of reference voltage of SVC

The reference voltage value is gradually corrected and the compensation amount by SVC is gradually decreased.

Step. 3 Constant voltage compensation by SVR

The detected voltage value of SVR moves from the dead band by the decrease of compensation amount of SVC. The operated time of SVR outside the dead band reaches SVR's operation time, the tap of SVR is changed.

Step. 4 Standby condition of SVC

The compensation amount by SVC changes to the steady state amount by the tap change of SVR. Then, SVC becomes a standby condition at which SVC can handle the next steep voltage fluctuations.

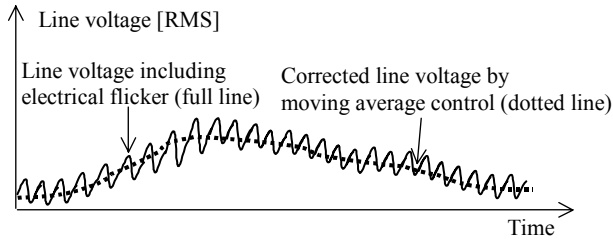


Fig. 3. Outline of the moving average control method.

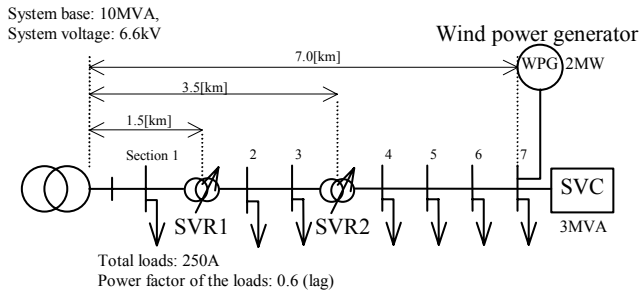


Fig. 4. A distribution model.

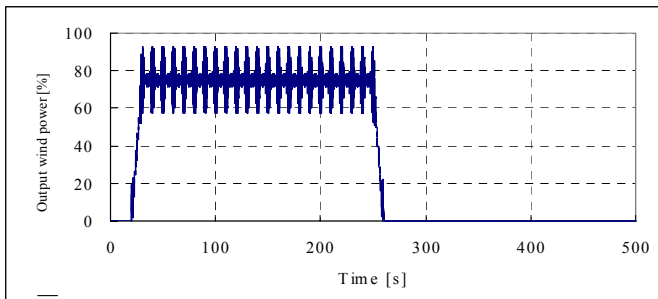


Fig. 5. A wind power output.

B. Moving Average Value Control Method

Wind power generator is said that output fluctuations by “tower shadow phenomena” [1] are more little than output fluctuations by change of wind velocity. Frequency of the fluctuations is about 1 [Hz], magnitude is about 20 [%] of the rated output. The fluctuation may cause line voltage fluctuation. Namely, generator output fluctuation may cause electrical flickers. This kind of little line voltage fluctuations is removed by operation of the moving average control, which has no relation with SVR. Fig.3 shows the outline of the moving average control method. The moving average value control is operated for 1 [Hz] or less order fluctuation like electrical flickers. Therefore, the moving average control does not compensate a long periodic fluctuation like load fluctuation. This kind of the long periodic fluctuation is compensated by SVR.

IV. VERIFICATION OF THE DEVELOPED METHOD ON ANALOG DISTRIBUTION NETWORK SIMULATOR

A. Distribution Network Simulator

Distribution network simulator is experimental equipment, which scales down the line voltage from actual 6 [kV] system

COMPARISON OF VARIOUS PARAMETERS BETWEEN ACTUAL 6kV AND DISTRIBUTION NETWORK SIMULATOR.

Circuit constants		Actual 6kV	Simulator
Base capacity		10MVA	15kVA
Base voltage		6.6kV	200V
Base current		875A	43.3A
Base impedance		4.36	2.67
Short impedance of transformer		0.33 (7.5%)	0.20 (7.5%)
Line impedance	X1	1.00mH/km (8.6%)	0.61mH/Set (8.6%)
	R1	0.296 /km (6.8%)	0.18 /km (6.8%)
Load register		100kW/km	150W/Set
Load reactor		133kVA/km	200VA/Set

TABLE II
SETTING VALUE OF VOLTAGE CONTROL EQUIPMENTS.
(A) SVR

Setting value	SVR1	SVR2
Reference voltage	6550V	6550V
Impedance setting value (R)	3%	4%
Impedance setting value (X)	2%	2%
Dead band	± 1%	± 1%
Operation time	45s	60s

(B) CONVENTIONAL SVC

Setting value	Conventional SVC
Reference voltage	6600V

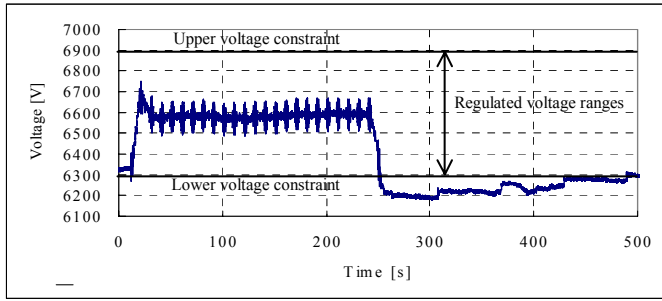
(C) NEWLY DEVELOPED SVC

Setting value	Conventional SVC
Threshold voltage between cooperative control mode and moving average mode	Upper : 6830V Lower : 6370V
Initial value of upper target voltage	6730V
Initial value of lower target voltage	6470V
Final value of upper target voltage	6800V
Final value of lower target voltage	6400V

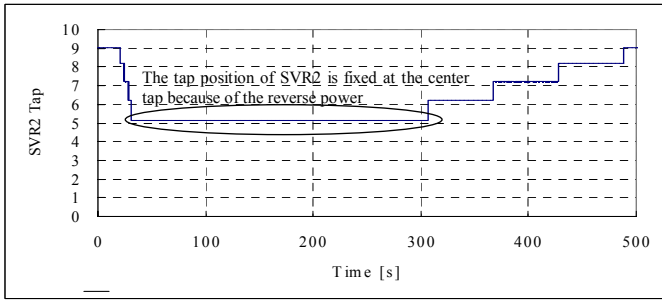
to 200 [V]. It has fundamental equipments such as transformer model, line model, and load model. Distribution network simulator can verify and analyze various phenomena in actual 6 [kV] distribution systems. Table.1 shows the comparison of various parameters between actual 6 [kV] and distribution network simulator. It also has equipments such as distributed generator model (synchronous generator, rated capacity is 3 [kW]), voltage compensating equipment model applying power electronics technology (rated capacity is 4.5 [kVA]), and SVR model (rated capacity is 4.5 [kVA]).

B. Experimental Conditions

Fig.4 shows a distribution model for experiment. It is noted that system parameters in Fig.4 are converted from 15kVA/200V to 10MVA/6.6kV distribution systems. Experimental conditions are as follows. Total line length of the distribution model is 7 [km]. Two SVRs are installed in



(a) Voltage at the end of the feeder.



(b) The tap position of SVR2.

Fig. 6. Voltage at the end of the feeder and SVR2 tap transition in case No.1.

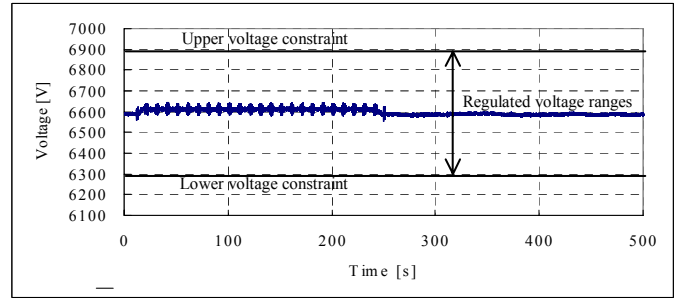
distribution model. One is installed at 1.5 [km] point (SVR1) and another is installed at 3.5 [km] point (SVR2) from the substation. The wind power generator and SVC are installed at the end of the feeder. Table.2 shows the setting value of voltage control equipments. Total loads in the system are 250 [A] assuming heavy loads, and power factor of the loads are 0.6 (lag). The regulated voltage ranges are assumed to be between 6300 [V] and 6900 [V]. At the distribution model, step power output change of the wind power generator and little fluctuation (about 1.6 [Hz]) of the power output is assumed. Namely, it is assumed that the wind power output is firstly zero output. At 20 [s], the wind power output is changed from zero output to about 75 [%] output of the rated output. At 250 [s], wind power output is changed from 75 [%] output of the rated output to zero output. Finally, the power output is maintained zero output until 500 [s]. While the wind power output is not zero, little fluctuation is overlapped the power output. The magnitude of little fluctuation is about 20 [%] of the rated output. The frequency of little fluctuation is about 1.6 [Hz]. Fig.5 shows the wind power output. The frequency of little fluctuation (about 1.6[Hz]) for the power output of wind power generators is actually measured in Japan. Therefore, the output in fig.5 has the same characteristics of little fluctuation as tower shadow phenomena. The following three cases are compared in experiments.

(a) Case No.1

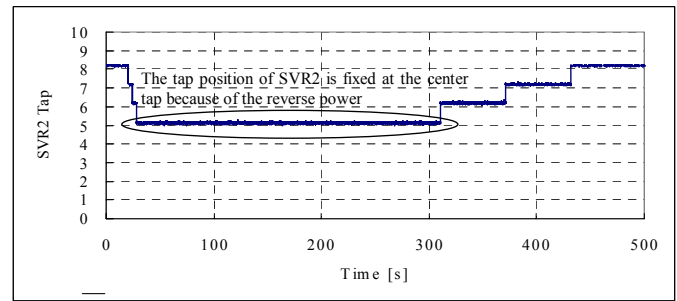
Only existing SVRs are utilized. Existing SVR will be fixed at its center tap, No.5 if reverse power from the wind power generator flows at the SVR.

(b) Case No.2

Existing SVRs and a conventional SVC, which are controlled by the conventional voltage control method, are

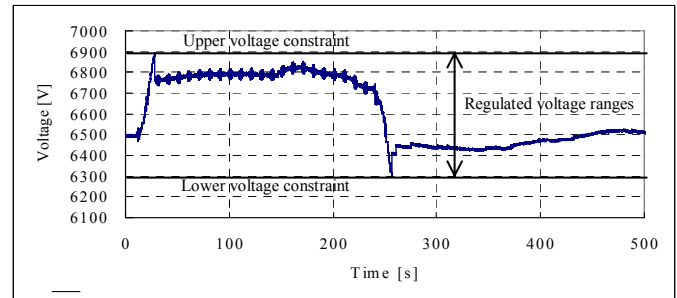


(a) Voltage at the end of the feeder.

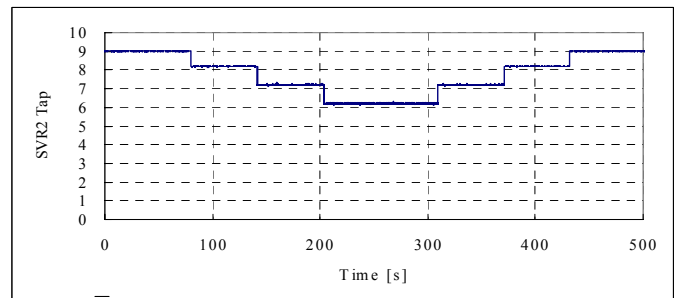


(b) The tap position of SVR2.

Fig. 7. Voltage at the end of the feeder and SVR2 tap transition in case No.2.



(a) Voltage at the end of the feeder.



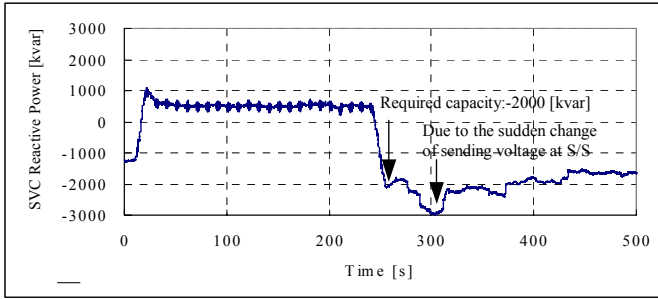
(b) The tap position of SVR2.

Fig. 8. Voltage at the end of the feeder and SVR2 tap transition in case No.3.

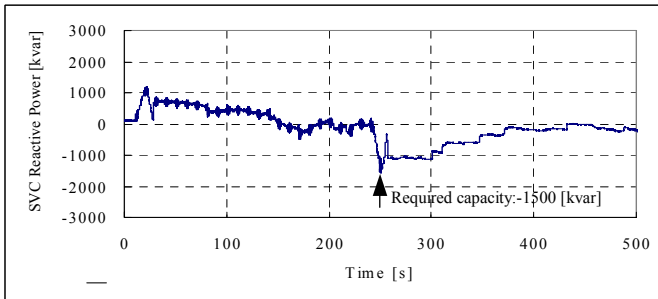
utilized. The conventional SVC maintains the line voltage with the reference voltage of its installed point.

(c) Case No.3

The developed method by improved SVRs and newly developed SVC are utilized. The improved SVRs can change their taps to bring the detected voltages near the reference voltages for cooperative control method, even though power flow at the SVRs becomes reverse power caused the wind power generator. Newly developed SVC



(a) SVC capacity by existing conventional SVC.



(b) SVC capacity by developed method.

Fig. 9. Comparison of SVC capacity by conventional method and developed method.

TABLE III
COMPARISON OF THE ELECTRICAL FLICKERS IN CASE NO.1 TO 3.

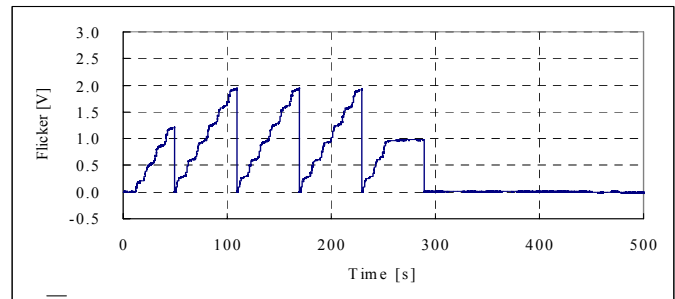
Case No.	Flicker[V]	Percentage[%]
No.1	1.93	100.0
No.2	0.52	27.0
No.3	0.50	25.8

contains a cooperative and moving average control method.

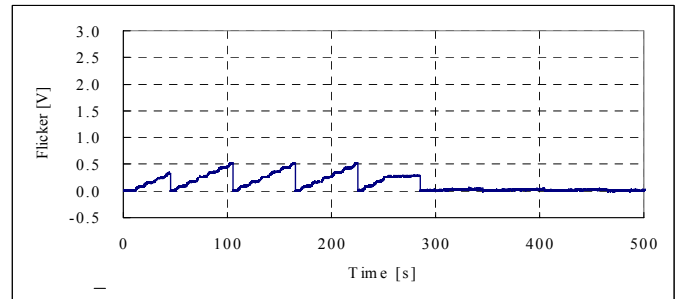
C. Experimental Results

Fig.6 (a) and (b) show the experimental results of the voltage at the end of the feeder and the tap position of SVR2, respectively in case No.1. Fig.6 (a) shows that only existing SVRs cannot maintain the line voltage within the regulated voltage ranges against steep voltage fluctuation. Due to the step power output change of the wind power generator from zero output to 75 [%] output of the rated output, the reverse power from the wind power generator flows at the SVR2. On the contrary, the reverse power does not flow at the SVR1. Therefore, a tap position of SVR2 is fixed at the center tap, No.5. After that, due to the step power output change of the wind power generator from 75 [%] output of the rated output to zero output, the reverse power from the wind power generator disappears and the tap position of SVR2 is changed at previous tap position. However, since SVR tap operation has a time delay, only existing SVRs cannot maintain the line voltage within the regulated voltage ranges.

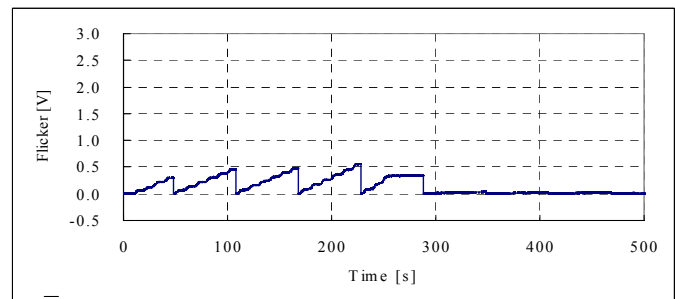
Fig. 7 (a) and (b) show the experimental results of the voltage at the end of the feeder and the tap position of SVR2, respectively in case No.2. For the same reason in case No.1, the tap position of SVR2 is fixed at the center tap. Since conventional SVC maintains voltage with reference voltage of



(a) The measured electrical flickers in case No.1.



(b) The measured electrical flickers in case No.2.



(c) The measured electrical flickers in case No.3.

Fig. 10. The results of the measured electrical flickers.

its installed point, no voltage constraint violation occurs.

Fig.8 (a) and (b) show the experimental results of the voltage at the end of the feeder and the tap position of SVR2, respectively in case No.3. According to the results, the developed method can maintain the line voltage within the regulated voltage ranges against steep voltage fluctuations.

Fig.9 (a) and (b) shows the comparison of SVC reactive power by the conventional method and the developed method. The maximum required capacity of conventional SVC is about -3000 [kvar] at 300 [s] in Fig.9 (a). However, the maximum capacity is due to the sudden change of sending voltage at S/S. The target fluctuation by the sudden power output change of wind power generator is occurred at 250 [s]. Therefore, the required SVC capacity of conventional method is about -2000 [kvar]. On the contrary, the developed method requires about -1500 [kvar] SVC capacity as shown in fig.9 (b). The results indicate that required SVC capacity of the developed method is about 3/4 times of that of the conventional SVC. Namely, the developed method can reduce SVC capacity compared with the conventional SVC and sustain the margin for flicker compensation. Namely, it indicates the cost effectiveness of the developed method.

Table.3 shows the comparison of electrical flickers and fig.10 shows the results of measured electrical flickers in case No.1 to 3. The electrical flickers are evaluated using ΔV_{10} flicker meter, which is widely used in Japan. Statistically, it is said that human being feels lighting flickers more than $\Delta V_{10} = 0.45$ [V]. The electrical flickers observed in case of No.1 are reduced to about four times larger than that of the voltage deviation. On the contrary, in case No.2 and 3, the electrical flickers are about as same as the voltage deviation (≈ 0.45 [V]). These results indicate effectiveness of SVC for reduction of the electrical flickers.

V. CONCLUSIONS

This paper verifies the developed cooperative control method for voltage control equipment on analog distribution network simulator (15kVA/200V) considering interconnection of wind power generators. Experiments are performed in three cases; by only existing SVRs, existing SVRs and conventional SVC, and the developed cooperative control method. The results are as follows:

- (a) Using only existing SVRs cannot maintain the line voltage within the regulated voltage ranges against steep voltage fluctuation.
- (b) Using existing SVRs and conventional SVC or the developed cooperative control method can maintain the line voltage within the regulated voltage ranges.
- (c) Required SVC capacity of the developed method is about 3/4 times compared with the conventional SVC. Namely, it indicates the cost effectiveness of the developed method.
- (d) Using SVC can reduce the electrical flickers and reduction ratios of the flickers of 1.6 [Hz] fluctuations are about 25 [%] compared with only SVRs.

The practical application of the developed method to actual distribution systems is considered as future works.

VI. REFERENCES

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VII. BIOGRAPHIES

Yoshiyuki Kubota received B.S. and M.S. degrees in Physics in 1992 and 1994, respectively, from Osaka University, Osaka, Japan. He joined Kansai Electric Power Co., in 1994 and has been working at Technical Research Center from 2001. His research interests include influence of a wind power generator in the distribution systems. He is a member of IEE of Japan.

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