# Verification of the Effects of the Harmonic Voltages in the Distribution System by Single-Phase SCs for Suppressing Voltage Unbalance.

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***Abstract*— Recently, since single phase loads and dispersed generators become widespread, unbalanced voltage in distribution line become an important problem for voltage management. One of them is that the control of a conventional voltage regulation device become difficult because of the difference of the magnitude of the line voltages, the other one is increase of 3rd harmonic voltages. The authors proposed an unbalanced voltage suppression system using static capacitors (SC system) in the past research. Hence, the effect of 3rd harmonic voltage should be verified under the conditions of harmonic resonance between reactance of line and capacitors. This paper presents analysis of the harmonic voltages in distribution systems with the unbalanced voltages. For the analysis, two distribution system models are configured, which is a model of a residential area and an industrial area. Harmonic voltages are calculated under the condition of SC system and evaluate the harmonic voltage level in the distribution line.**

***Keywords*: harmonics, voltage unbalance, distribution system, static capacitors.**

## I. Introduction

Recently, increasing of residential loads and distributed power generation systems such as single phase rooftop photovoltaic systems (PV), unbalanced voltage become large in distribution system. Furthermore, large number of electric vehicles (EV) and plug-in hybrid vehicles (PHV) which is large capacity of an electrical load connected to the distribution line in a single phase may expand the unbalanced voltage. Unbalanced voltage in distribution system may cause various problems. One of them is that voltage regulation in proper range become difficult in distribution system. In the conventional methods of voltage control, Load Ratio control Transformer (LRT) at a distribution substation and Step Voltage Regulators (SVR) in the line are used. These equipment control three-phase voltages simultaneously, unbalanced voltage can not be suppressed.

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The other problem caused by the unbalanced voltage is effect of 3rd harmonic voltages. In the past studies, as the harmonic voltage analysis is performed using the model of the balanced distribution system, the objective order of harmonic analysis is $5^{th}$ and $7^{th}$ harmonic voltage. In Japan, configuration of the distribution system is 3-phase 3-wire system without ground at neutral point, hence $3^{rd}$ harmonic voltage is not so large. However, in the unbalanced distribution system, $3^{rd}$ harmonic voltage become larger because of increasing residential nonlinear load. In order to suppress the unbalanced voltage, authors propose the unbalanced voltage suppression device using single-phase SCs (named SC system) in the past research. This system is operated as decreasing the difference between a maximum line voltage and minimum one.

On the other hand, some consumers in distribution system have static capacitors (SCs) for improving power factor and the some SC banks are switched with adjusting the reactive power of the load. Series reactors (SRs) are connected these SCs for suppressing inrush currents and harmonic currents. As the capacity of SR is 6% of SC, series harmonic resonance frequency between SC and SR is about 240Hz ($4^{th}$ ). Therefore the SC bank with SR has capacitive reactance at $3^{rd}$ harmonic and inductive reactance at 5th harmonic. The reactance of 3rd harmonic is small, the harmonic resonance between SC bank and the reactance of the line will be occurred and 3rd harmonic voltage will become large easily.

From these background, analysis of 3rd harmonic is required under the condition of voltage unbalance. This paper presents the relation between voltage unbalance rate and $3^{rd}$ harmonics voltage using simple distribution system model. Then, the effect of harmonic voltages in distribution system in case that SC system is connected in distribution system is analyzed. In this study, two type of simulation models are presented, one of them is the model of residential area which has large number of the single phase load. The other is the model of industrial area which has large number of SCs for improving the power factor.

Section II shows the configuration of SC system, the simulation model is presented in Section III and IV. Section V and VI shows the simulation results and discuss the effects of harmonic voltages in case that SC system is operated.

## II. SC system

### A. *Configuration of SC system*

Fig. 1 shows a circuit configuration of SC system. This circuit has 3 SCs and 6 mechanical switches. By this circuit, unbalanced voltage is able to be suppressed using minimum number of SCs. This system is low cost because the system is not used semiconductor switches such as IGBT and thyristor. SR is connected to SC to prevent harmonic current and suppress inrush currents, the capacity SR is 6% of SC. The objective of SC system is regulating the line voltages in adequate voltage range and suppressing unbalanced voltage.

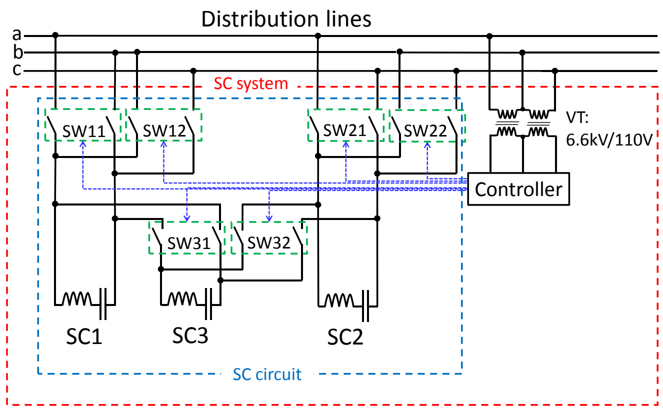



Fig. 1. A circuit of SC system(voltage unbalance suppression system using single-phase SCs)

### B. *Effects of harmonic voltage*

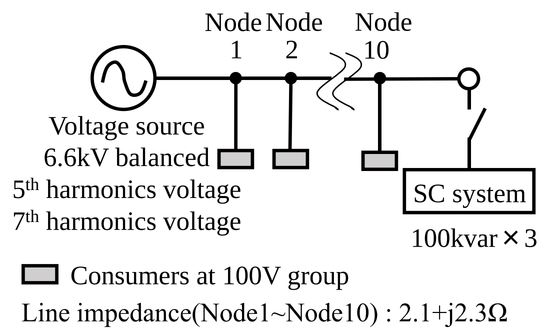
Consumers whose voltage levels are 6.6kV have 3-phase SCs for improving power factors. 3-phase SCs. Some large capacity consumers has plural SCs and they are switched according to the variation of reactive power of the load. Hence those SCs has SR in series to prevent the inrush current. Other small capacity consumer has SCs without SR. Those SCs are always connected to the line. Therefore, in the distribution line, there are SCs with SR and SCs without SR simultaneously, harmonic resonance frequency changes variously. As described above, resonant frequency of voltage at end of feeder are around 240Hz because of SC with SR (6% of SC capacity). Therefore, 3rd (180Hz) harmonic voltage is expand.

SC system are connected at end of feeder, 1 or 2 bank of single-phase SCs are connected in each phase to the line. Effects of 3rd harmonic voltage by SC system is complicated, harmonic voltage analysis is required to prevent a harmonic failure. So in Section 3, distribution line models are explained and effects of 3$^{rd}$ harmonic voltages are verified when SC installed at end of feeder in Section 4~6.

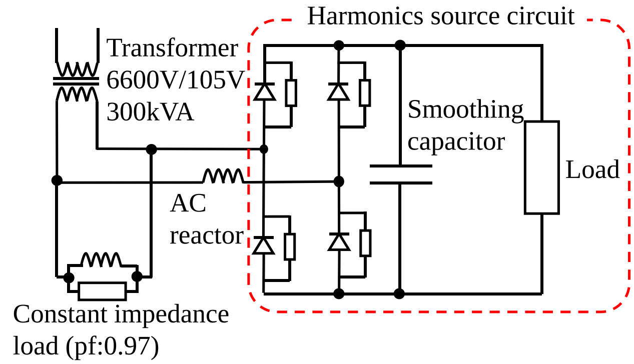
## III. Simulation Model

### A. *Residential area model*

2 models of the line are made for verification of harmonics voltage. Fig. 2 shows the distribution line model of residential area in rural district to simulate the large number of the single-phase loads. (a) shows distribution system model and (b) shoes detail of customer group load at 100V. Line impedance from voltage source to end of feeder is 2.1+j2.3Ω. Table 1 shows capacity of loads in each node based on representative feeder information. All loads are single-phase type. Capacity of the load connected between phase a-b are larger than the other loads to model the unbalanced distribution system. Single-phase loads are composed rectifier circuits and R-L loads like Fig. 2(b). Ratio of these loads are 50% of all loads to simulate the light load time. The capacity of each SC in SC system is 100kvar. Voltages at the source are balanced and the magnitudes are 6.6kV, 5th and 7th harmonic voltages are contained 0.72%, 0.55% respectively. These harmonic voltage distortion are maximum values of a representative actual data. 3$^{rd}$ harmonic voltage are output by rectifier circuit connected unbalance.




(a) A distribution line model of residential area.




(b) Detail of customer group load at 100V (3$^{rd}$ harmonics voltage source).

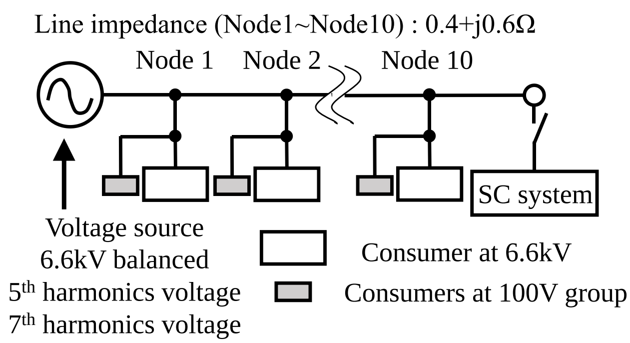
Fig. 2. A simulation model of residential area.

TABLE I
Detail of Loads at Residential Area Model [Unit of Load: kW]

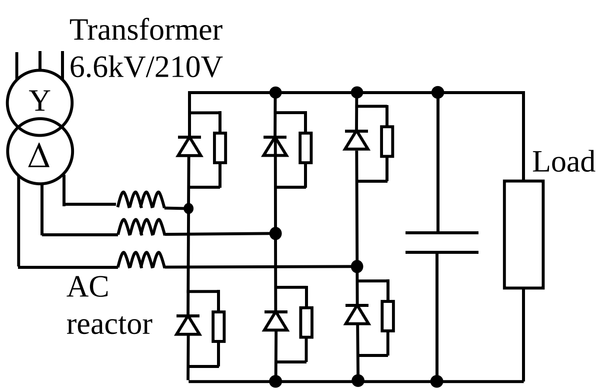
| Node | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Load capacities(unbalanced) | 50 | 88 | 145 | 135 | 135 |
| Node | 6 | 7 | 8 | 9 | 10 |
| Load capacities(unbalanced) | 142 | 142 | 135 | 142 | 43 |

### B. *Industrial area model*

Another model is a distribution line of industrial area. In this model, consumers are buildings and factories, the loads are modeled 6.6kV 3-phase balanced loads that have 3-phase R-L loads, SCs and 3-phase rectifier circuits as harmonic voltage sources. Low voltage (100V) single-phase loads are connected in parallel via a pole transformer. Line impedance is 0.4+j0.6Ω, it is smaller than the residential area model. In this model, voltage unbalance rate is about 1.5% at end of line. Table 2 shows capacity of each loads based on that total load capacities 6.6kV consumers and low voltage consumers from a representative feeder information. Low voltage consumers are single-phase loads and the capacity of them in phase a-b is larger than the other loads to simulate the unbalanced distribution system. 6.6kV consumers are constructed equivalent impedance load whose power factors are 0.85(lagging) and 3-phase rectifier circuits. Ratio of these loads are 50% of all loads to simulate the light load time. Low voltage consumers are modeled to single-phase rectifier circuits like Fig. 2(b) and R-L loads whose power factors are 0.97(lagging). Capacities of rectifier circuits is twice as capacity of R-L loads. Voltages at source are balanced and the magnitudes are 6.6kV, 5th and 7th harmonic voltage distortions are contained 0.72%, 0.55% respectively. 6.6kV consumers have three-phase SCs for improving power factor, SCs in some consumers have SR and the other have no SR.. The capacity of each SC in SC system is 100kvar.




(a) Distribution line model of industrial area.




(b) Model of 3-phase rectifier circuits (harmonic voltage source).

Fig. 3. A simulation model of industrial area

TABLE II

DETAIL OF LOADS AT INDUSTRIAL AREA MODEL

| Node | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 100V loads (Unbalanced) | 15 | 21 | 41 | 33 | 33 |
| 6.6kV load capacities | 35 | 77 | 108 | 127 | 127 |
| SC capacities [kvar] | 20 | 40 | 60 | 65 | 65 |
| Node | 6 | 7 | 8 | 9 | 10 |
| 100V loads(Unbalanced) | 39 | 39 | 33 | 61 | 9 |
| 6.6kV load capacities [kW] | 123 | 123 | 113 | 48 | 39 |
| SC capacities [kvar] | 66 | 66 | 60 | 44 | 20 |

## IV. SIMULATION RESULTS

### A. RELATION OF VOLTAGE UNBALANCE AND 3RD HARMONICS VOLTAGES

This section shows relation between voltage unbalance rate and 3rd harmonic voltage distortions. Fig. 4 and Fig. 5 show relation between voltage unbalance rate and 3rd harmonic voltage distortions at the end of line. Fig. 4 shows the results of residential area model, Fig. 5 shows the results of industrial area model. Horizontal axes in Fig. 4 and Fig. 5 are voltage unbalance rate at end of feeder. Vertical axis shows a content rate of 3rd harmonic voltage. Solid lines are result when harmonic sources are unbalanced, broken lines shows the results in case that harmonic source are balanced and equivalent loads are unbalanced. From these results, 3rd harmonic voltages are occurred by unbalanced harmonic sources. Because more capacities of harmonic sources are connected phase a-b, harmonic voltages at phase a-b are the most of harmonic voltages. The threshold level of harmonic management is 5%, 3rd harmonic voltage come to this level when unbalance harmonic sources are connected and voltage unbalance rate at end of feeder is more 2%. In industrial area, because capacities of each loads are more than in residential area, 3rd harmonic voltage distortions are larger than that in residential area at same voltage unbalance rates. Form the result, 3rd harmonic voltage rates are increased according to increasing voltage unbalance rates. Magnitude of 3rd harmonics voltage distortions depend on characteristic of line. Simulation uses MATLAB/Simulink, composing distribution model like Fig.2 or Fig. 3.

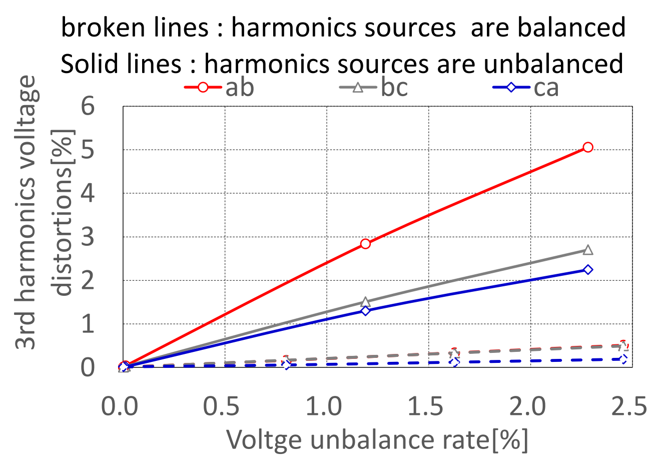



Fig. 4. Voltage unbalance rate and 3rd harmonics voltage in residential area.

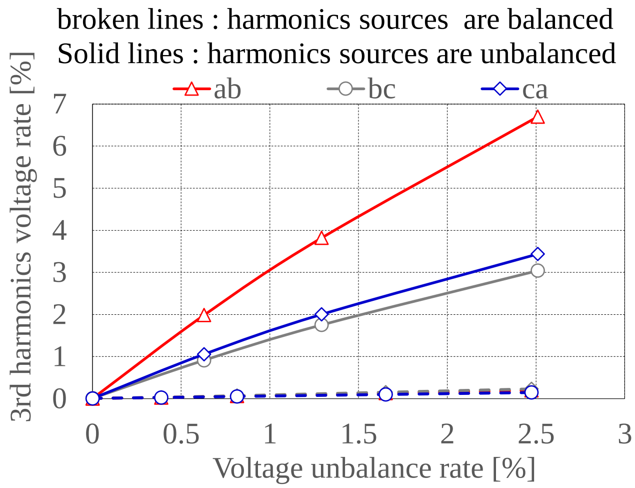
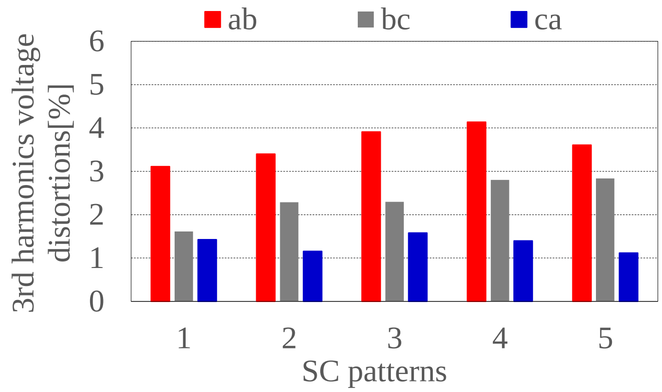


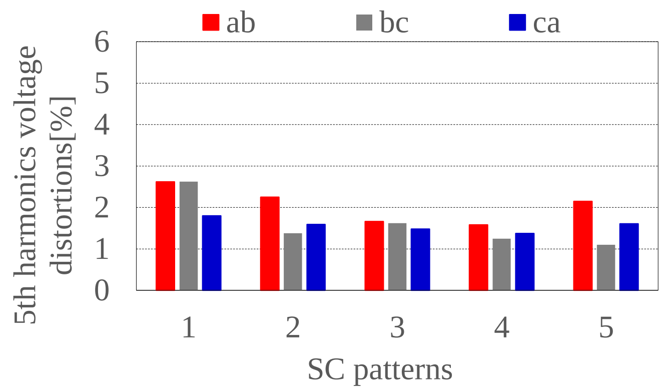

Fig. 5. Voltage unbalance rate and 3rd harmonics voltage in industrial area.

### *B. Analysis of residential area model*

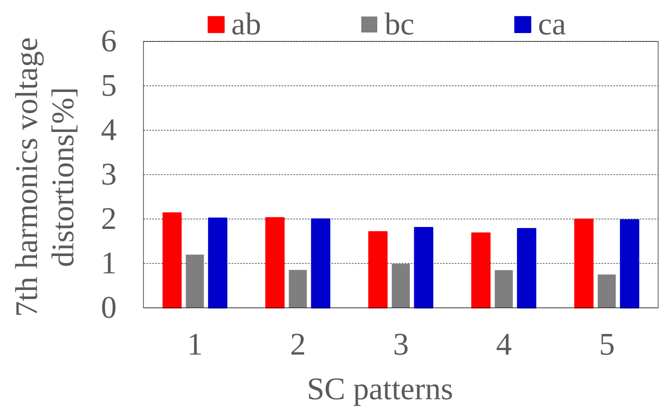
This section shows results of simulation using residential area model. Fig. 6 shows results of harmonic voltage distortions when SC system installed at end of feeder and single-phase SC connected according to SC connecting pattern for suppressing voltage unbalance. Table 3 shows SC connecting pattern for suppressing voltage unbalance and voltage unbalance rate at end of feeder. Pattern 1 in Table 3 is no SCs connected, voltage unbalance rate at end of feeder is 2.28% in this case. Horizontal axis in Fig. 6 are SC connecting pattern according to Table 3, and vertical axis are harmonic voltage rate. Fig. 6(a) shows 3rd harmonic voltage distortions, Fig. 6(b) shows 5th one, Fig. 6(c) shows 7th one and Fig. 7 shows total harmonic voltage distortions. In this figure, the magnitude of harmonic voltage at a-b phase is the largest because of that the capacity of single-phase load in a-b phase is the largest, harmonic currents from the load in a-b phase is the largest. From these results, harmonic voltages at phase a-b are not increased by controlling SC systems compared with Pattern 1. The harmonic voltage distortion rates are less than 5% that is threshold level value of harmonic voltage management. Fig. 8 shows relation between capacities of single-phase SCs that are installed at end of feeder and resonant frequencies of the line. In the range of the capacity of SC which is from100kvar to 300kvar, resonant frequencies of the line are almost constant around 180Hz. Although, this case is severe condition for 3rd harmonic voltages, 3rd harmonic voltages are not increased by controlling SC system compared with Pattern 1. The reason is that the unbalanced voltage is suppressed properly by SC system, 3rd harmonic voltage are canceled at phase to phase under the condition.




(a) 3rd harmonic voltage distortions




(b) 5th harmonic voltage distortions




(c) 7th harmonic voltage distortions

Fig. 6 Result of harmonics voltage distortions when SC system is installed

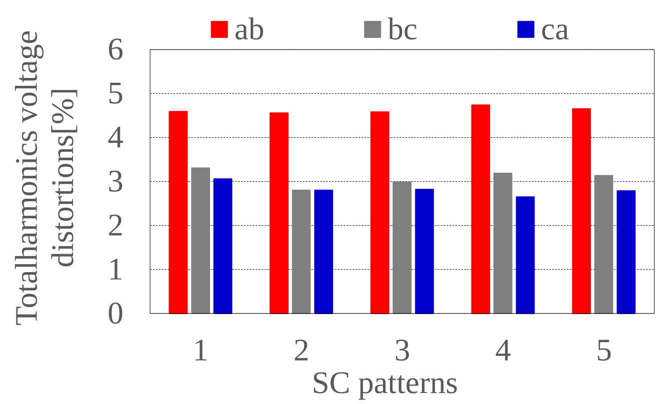



Fig.7 Total harmonic voltage distortions

TABLE Ⅲ

SC CONNECTING PATTERNS AND VOLTAGE UNBALANCE RATES

| SC patterns | The number of SCs connection | | | Voltage unbalance rate[%] |
|---|---|---|---|---|
| | a-b | b-c | c-a | |
| 1 | 0 | 0 | 0 | 2.28 |
| 2 | 0 | 2 | 0 | 1.62 |
| 3 | 1 | 1 | 0 | 1.64 |
| 4 | 2 | 1 | 0 | 1.72 |
| 5 | 1 | 2 | 0 | 1.17 |

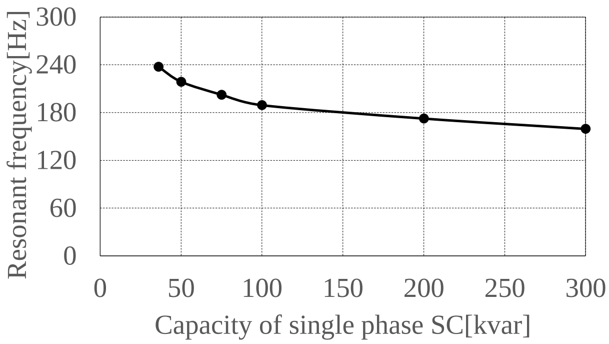


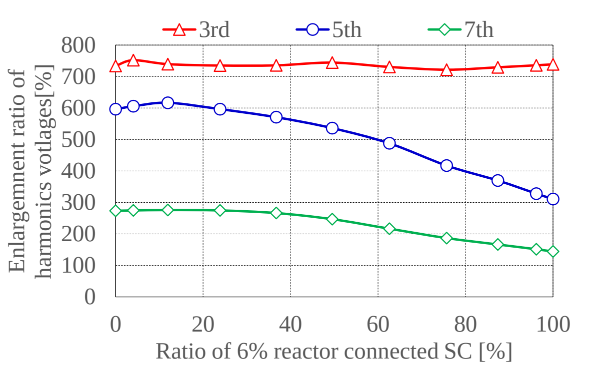

Fig. 8 connection of capacity of single phase SC and resonant frequency

### C. *Result of simulation using industrial area model*

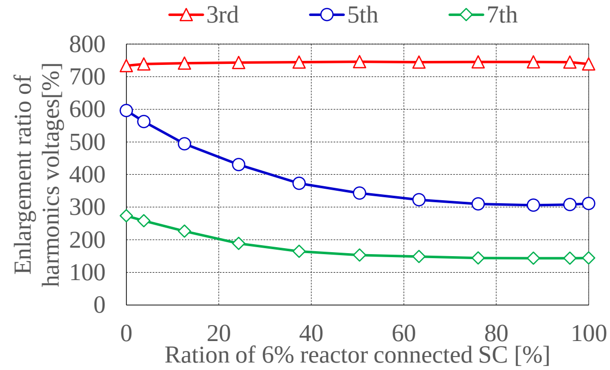
(1) Relation of rate of SC with SR and harmonics voltage

Effects of harmonic voltages are verified using industrial area model. This section shows relation between the capacity rate of SCs with SR against total capacity of SCs and harmonic voltage enlargement ratio. The harmonic voltage enlargement ratio is defined as the ratio of harmonic voltage at end of the line against the harmonic voltage at the voltage sources.

First case is that all three-phase SCs have no SR, then the SCs without SR are changed to SCs with SR from consumers near the voltage source. This simulation results shows in Fig. 9 (a). On the other hand, SCs without SR are changed to SCs with SR from consumers near the voltage source from consumers at end of the line. Fig. 9 (b) shows relation between the capacity rate of SCs with SR against total capacity of SCs and harmonic voltage enlargement ratio. From Fig. 9, 3$^{rd}$ harmonic voltages are not depend on reactor connected SCs position and it's capacities. 5$^{th}$ and 7$^{th}$ harmonic voltages has same tendency. From these result, the most serious condition is when consumer at Node1 has series reactor connected SC and consumers at node 2~10 have no reactor SCs.




(a) Connecting reactor connected SC from consumer at voltage source.

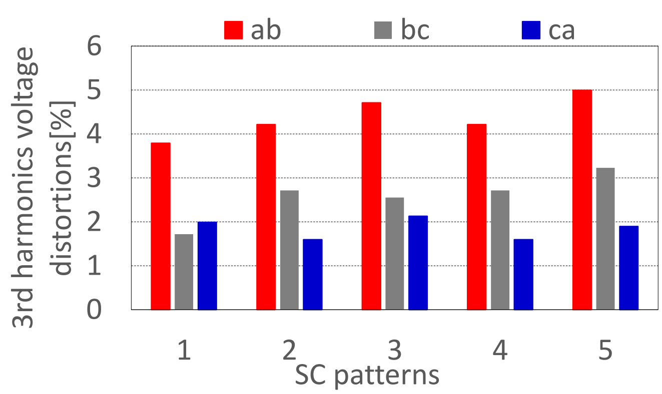



(b) Connecting reactor connected SC from consumer at end of feeder.

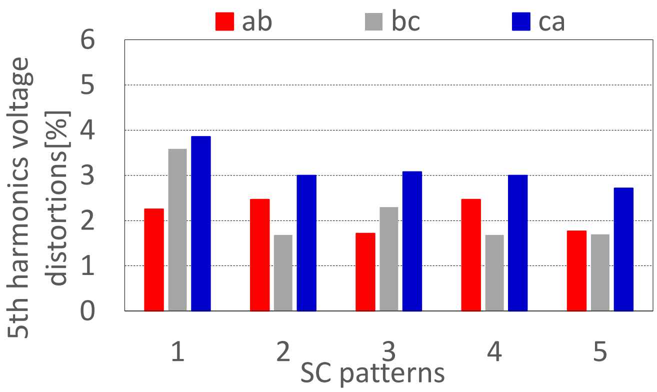
Fig. 9 Connections of reactor connected SCs and enlargement of harmonics

### D. *Effects of harmonics voltages when SC systems are used in distribution system that have voltage unbalance*

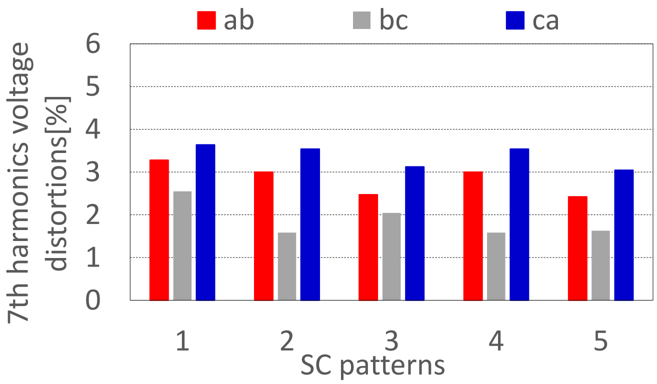
This section shows effects of harmonic voltages when SC system installed at end of the line. Fig. 10 shows the relation between voltage unbalance rates and harmonic voltage distortions. The horizontal axis in Fig. 10 is SC connecting patterns of SC system and the vertical axis is harmonic voltage distortions. SC connecting patterns are according to suppressing voltage unbalance to less than about 1% like Table 4. Fig. 10(a) shows 3$^{rd}$ harmonic voltage distortions, (b) shows 5$^{th}$ harmonic voltage distortions, (c) shows 7$^{th}$ harmonic voltage distortions and Fig.11 shows total harmonic voltage distortions. From Fig. 10, 3$^{rd}$ harmonic voltage distortions at end of the line is increased compared with Pattern 1, 5th and 7th harmonic voltages are decreased by controlling SC system. The reason is that SC has SR in SC system, 5th and 7th harmonic currents are absorbed in SCs. Therefore, the total harmonic voltage distortions are not enlarged in comparison with Pattern 1.




(a) 3$^{rd}$ harmonic voltage distortions




(b) 5th harmonic voltage distortions




(c) 7th harmonic voltage distortions

Fig. 10 Result of harmonics voltage distortions when SC system is installed

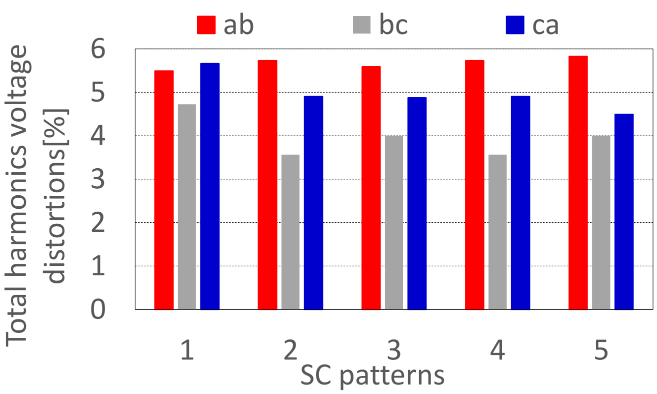



Fig.11 Total harmonic voltage distortions

TABLE IV
SC CONNECTING PATTERNS AND VOLTAGE UNBALANCE RATES

| SC patterns | The number of SCs connection | | | Voltage unbalance rate[%] |
|---|---|---|---|---|
| | ab | bc | ca | |
| 1 | 0 | 0 | 0 | 1.67 |
| 2 | 0 | 2 | 0 | 1.16 |
| 3 | 1 | 1 | 0 | 1.03 |
| 4 | 0 | 1 | 1 | 1.16 |
| 5 | 1 | 2 | 0 | 0.56 |

## V. CONCLUSION

This paper presents the effect of harmonic voltages when SC system is installed at end of the distribution line using residential area model and industrial area model.

From the numerical simulation results using the residential area model, 3rd harmonic voltage distortions increase depend on voltage unbalance rates. However, magnitudes of 3rd harmonic voltage distortions are depend on frequency characteristics of the line that depends on three-phase SCs installed in consumers at 6.6kV. By the results using residential area model, harmonic voltage distortions at end of feeder didn't increase when the unbalanced voltage is suppressed by SC system and total harmonic voltage distortion rates are less 5%. This value is less than the threshold level of harmonic voltage management.

From the numerical simulation results using the industrial area model, harmonic voltage distortions deviate from the threshold level of harmonic management regardless voltage unbalance suppression. This reason is that harmonic voltage depends on the conditions of the SCs for power factor improving in the 6.6kV consumers and the harmonic current of the load is severe condition compared with the residential area model. However, the harmonic voltage is not enlarged by controlling SC system compared with Pattern 1. From these result, risk of enlarging harmonic voltages is small under the condition that resonant frequency is around 3rd harmonic.

In the future works, the relation between voltage unbalance rate and 3rd harmonic voltage distortions should be verified under various conditions, and the optimum level of the voltage unbalance suppression in consideration of harmonic voltage distortions should be derived.

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