Estimation Method of Harmonic Sources on Distribution System and Experimental Verification

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***Abstract*—In recent years, the debasement of power quality of a distribution system such as the increase of power system harmonics has been apprehended. It is thought to be causally related to the diversification of loads by progress of power electronics technology and the increase of the number of interconnection of distributed generators for home use with the reduction of the effect on the environment. The harmonics cause not only deterioration of power quality but also further various problems. In this paper, the authors propose an estimation method of harmonic sources by separating the harmonic current flowing through the distribution lines. In addition, the authors carry out the numerical calculation and experiment in order to verify the validity of the proposed method.**

***Index Terms*--Distribution system, harmonic sources, interconnected inverter, power quality, power system harmonics**

I. Introduction

Recently, renewable energy sources such as photovoltaic (PV) generation and wind-power generation has been noticed in Japan in order to break away from dependent on nuclear power. Moreover, the total number of distributed generation (DG) which is interconnected to a distribution network has been increasing steadily. In the future, the DGs will further increase. Along with increase of DGs, the number of inverter and converter interconnected to the distribution system will also increase. Such a power electronics equipment generates various harmonics. In Japan, against the harmonics, 6.6 kV distribution system need to be kept the voltage total harmonic distortion (THD) under 5 % as the level of harmonic environmental target [1]. In addition, the harmonics generated form household appliances and interconnected inverters are regulated [2], [3]. Thus, the harmonics will increase in the distribution system, and then the voltage THD in the distribution system will exceed the specified value. Therefore, in the future, the harmonic countermeasure devices such as an active filter or STATCOM (static synchronous compensator) will need to interconnect more. However, the interconnection of those devices is not realistic since those are very expensive. It is necessary to install the minimum number of harmonic countermeasure devices at the point where harmonics are noticeable from a viewpoint of installation cost. The estimation method of harmonic sources in the distribution system is needed for this realization, however, the estimation of harmonic sources is very difficult itself.

On the other hand, the actual state of harmonics has been reveal nowadays by the previous research [4]. However, the study of harmonics by a detailed model of distribution system is very difficult, so a simplified model was mainly used [5]-[7].

In this study, the authors propose an estimation method of harmonic sources on the distribution system. In the proposed method, the harmonic current flowing through the distribution line is separated into a harmonic current flowing from the upper side of distribution line and a harmonic current flowing out from the lower side, in order to estimate the harmonic sources. The authors verify the validity of the proposed method from both sides of numerical calculation and experiment. The analytical model used for the numerical calculation includes interconnected inverters of PV system and non-linear loads which are the harmonic sources. The simulated distribution system equipment used for the experiment is composed of loads that generates harmonics, interconnected inverters of PV system, distribution lines, and so on. This experimental equipment is scaled-down 210V distribution system.

II. Estimation Method of Harmonic Sources

A. *Separating Method of Harmonic Currents*

This section describes the separating method of harmonic currents flowing through the distribution lines. In general, the harmonic current flowing through the distribution line is sum of a harmonic current flowing from the upper side of distribution line and a harmonic current flowing out from the lower side, and it is not possible to measure each harmonic current individually. However, if the specific information of distribution lines can be obtained, each harmonic current can be estimated and these currents can be separated [6]. The harmonic current flowing from the upper side of distribution line is obtained by (1).

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$$\hat{I}^{upper}_{h,Nk-N(k+1)}(t)$$

$$= \frac{E_{h,N(k-1)-Nk}(t)}{Z^{upper}_{h,S-N(k+1)} + 1/(\hat{Y}^{L}_{h,N(k+1)-Nend}(t) + \hat{Y}^{C}_{h,N(k+1)-Nend}(t))} \quad (1)$$

Where, $\hat{I}^{upper}_{h,Nk-N(k+1)}(t)$: estimation value of h-th harmonic current flowing from upper side of distribution line, N: node, k: node number, $E_{h,N(k-1)-Nk}(t)$: h-th harmonic voltage at upper side of distribution line, $Z^{upper}_{h,S-N(k+1)}$: h-th impedance at measurement point (S means voltage source), $\hat{Y}^{L}_{h,N(k+1)-Nend}(t)$: estimation value of h-th harmonic admittance of loads from measurement point to end of distribution line, $\hat{Y}^{C}_{h,N(k+1)-Nend}(t)$: estimation value of h-th harmonic admittance of static capacitor of utility customers from measurement point to end of distribution line.

In (1), the authors referred to [7] about calculation of $\hat{Y}^{C}_{h,N(k+1)-Nend}$. And then, the harmonic current flowing out from the lower side of distribution line is obtained by (2).

$$\hat{I}^{lower}_{h,Nk-N(k+1)}(t) = I_{h,Nk-N(k+1)}(t) - \hat{I}^{upper}_{h,Nk-N(k+1)}(t) \quad (2)$$

Where, $\hat{I}^{lower}_{h,Nk-N(k+1)}(t)$: estimation value of h-th harmonic current flowing out from lower side of distribution line, $I_{h,Nk-N(k+1)}(t)$: measured h-th harmonic current flowing through the distribution line.

B. *Evaluation Method for Estimation of Harmonic Sources*

Based on the results obtained from (1) and (2), the authors estimate where the generation of harmonic current is noticeable. In this study, the harmonic sources are estimated by calculating in plural time periods. Using the amount of change in the difference of harmonic currents which flow between nodes as an evaluation index, it is determined whether or not a large change appears with the loads as a boundary. The evaluation index for estimation of harmonic sources is shown in (3) and (4).

$$EHS_{h,Lk} = \left| \Delta(I\_\hat{I}_{upper})_{h,N(k-1)-Nk} - \Delta(I\_\hat{I}_{upper})_{h,Nk-N(k+1)} \right| \quad (3)$$

$$\Delta(I\_\hat{I}_{upper})_{h,Nk-N(k+1)} = \sum_{t=0}^{T} \left| I_{h,Nk-N(k+1)}(t) - \hat{I}^{upper}_{h,Nk-N(k+1)}(t) \right| \quad (4)$$

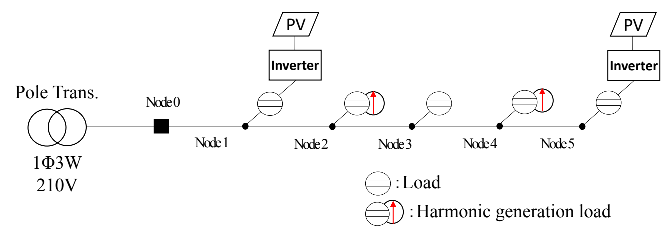
Where, in (3), L_k means a load at node k. $EHS_{h,Lk}$: evaluation index for estimation of harmonic sources, $\Delta(I\_\hat{I}_{upper})_{h,Nk-N(k+1)}$: integrated value of difference of $I_{h,Nk-N(k+1)}(t)$ and $\hat{I}^{upper}_{h,Nk-N(k+1)}(t)$ between node k and node (k+1).

III. VALIDATION BY NUMERICAL CALCULATIONS

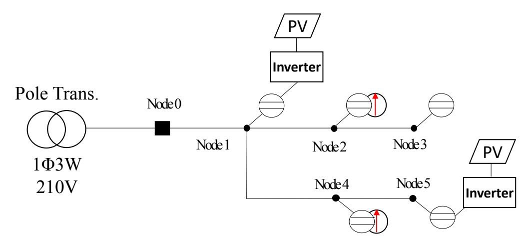
In order to verify the validity of the proposed method, the numerical calculations are carried out by using the analytical model of distribution system. In this study, only the 5th order is analyzed for the estimation.

A. *Analytical Model*

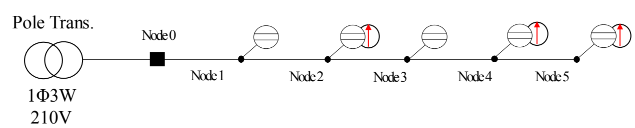
In this study, the analysis target for the estimation of harmonic sources is a low-voltage distribution system, in order to compare with the experimental results described in Chapter IV. The system configuration diagrams used for the estimation are shown in Fig. 1.



(a) Case 1 (with PV systems, single feeder)



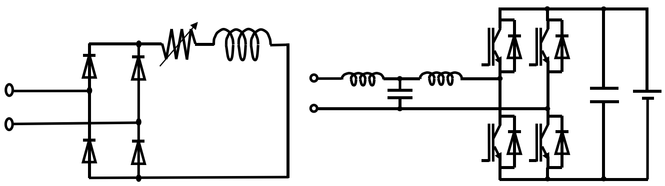
(b) Case 2 (with PV systems, branched feeders)



(c) Case 3 (with static capacitor)

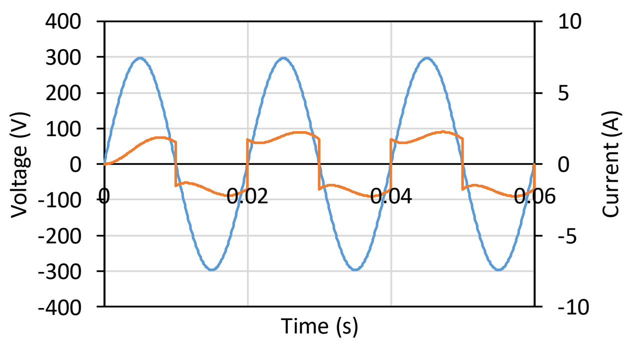
Figure 1. Analytical model of low-voltage system.

In these figures, the harmonic generation loads are single phase full-wave rectifier circuits with RL loads, and the loads are R loads (100 Ω). The pole transformers are simulated with voltage sources and included 5th harmonic voltage of 4 %. The phase of fundamental wave voltage is fixed at 0 degree and the phase shift of 5th harmonic voltage is set to four patterns of 0, 90, 180, and 270 degrees. In Case 1 and Case 2, RL values of the load at Node 2 is 100 Ω and 500 mH, RL values of the load at Node 4 is 140 Ω and 500 mH, respectively. And the capacity of PV system is 1 kW. Fig. 2 shows the harmonic generation load and inverter connected to the analytical model, and Fig. 3 shows the load current of harmonic generation load and the output of inverter.

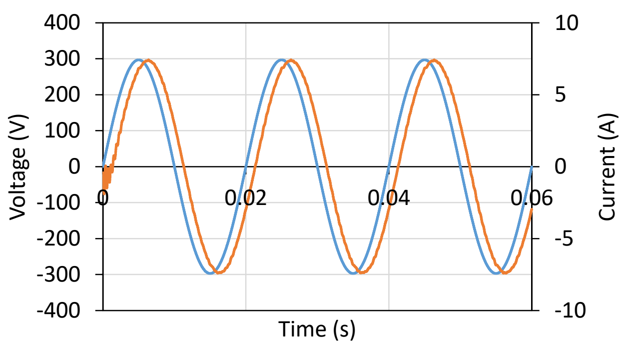


(a) Harmonic generation load (b) Interconnected inverter

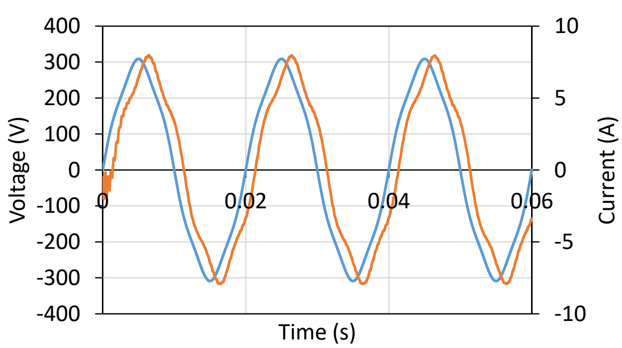
Figure 2. Harmonic generation load and inverter connected to analytical model.



(a) Load current of harmonic generation load



(b) Output of inverter (without harmonic voltage from upper system)



(c) Output of inverter (with 5th harmonic voltage of 4% from upper system)

Figure 3. Load current of harmonic generation load and output of inverter.

In Case 3, each single phase full-wave rectifier circuit has a static capacitor (SC). The SC is inserted in parallel so as to the power factor of the load is one. And in Case 3, the active power and reactive power of the load at Node 2, Node 4, and Node 5 are varied in 24 hours as shown in Fig. 4, in order to obtain the admittance of SC: $\hat{Y}^{C}_{h,N(k+1)-Nend}(t)$. Fig. 5 shows the transition of the content rate of 5th harmonic current when the active power and reactive power vary as shown in Fig. 4.

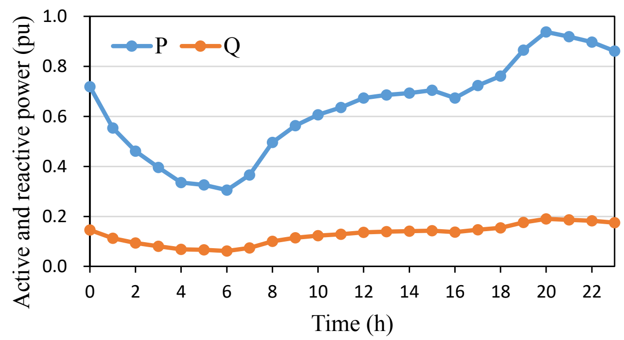


Figure 4. Load curve of feeder.

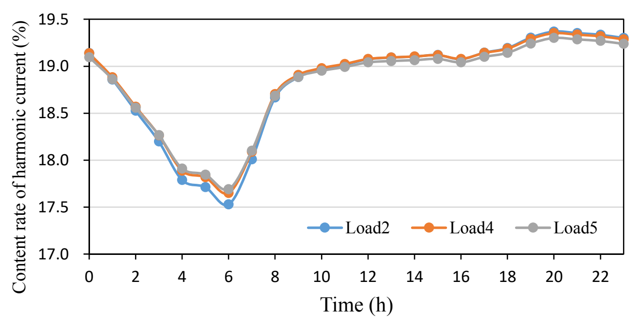
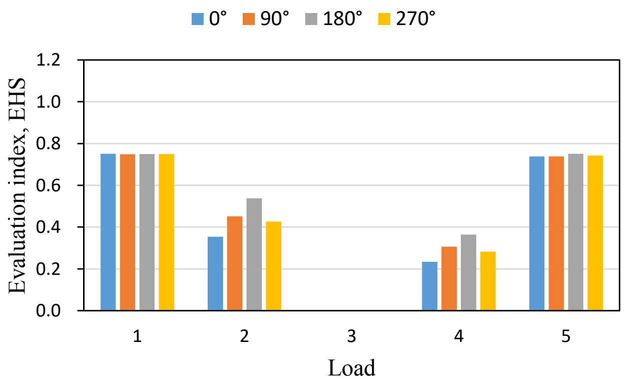


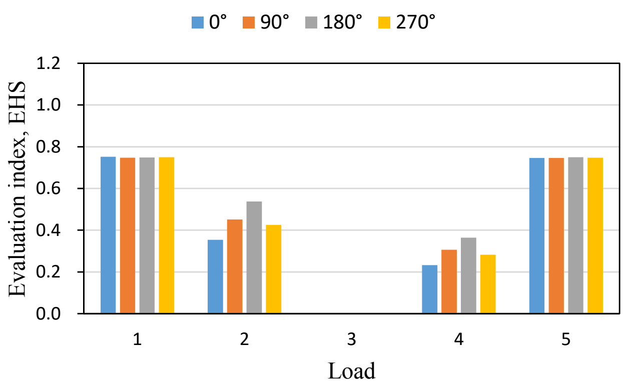
Figure 5. Transition of content rate of 5th harmonic current at Load 2, Load 4, and Load 5.

B. Calculation Results

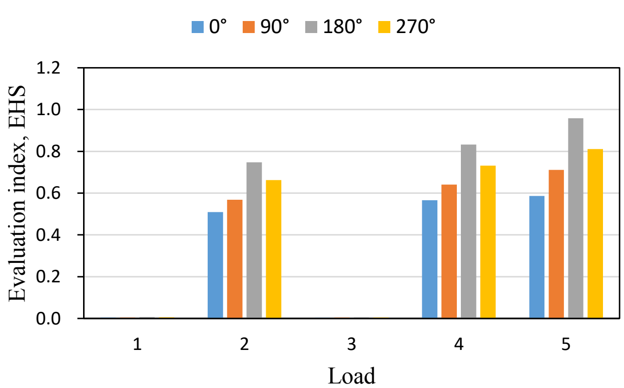
Fig. 6 shows the analysis results of each case. As shown in Fig. 6 (a), (b), in Case 1 and Case 2, the harmonic sources could be clearly estimated regardless of the presence or absence of branching of the feeder. In addition, it is considered that the loads with the large evaluation index have high harmonic content. In Case 3, as shown in Fig. 6 (c), the harmonic sources could be clearly estimated even when SC exists. From these results, it is considered that there is no influence of SC in the estimation of the harmonic sources by the proposed method. Throughout the obtained results, it was confirmed that the harmonic generation amount varies depending on the phase of harmonic voltage.



(a) Case 1 (with PV systems, single feeder)



(b) Case 2 (with PV systems, branched feeders)



(c) Case 3 (with static capacitor)

Figure 6. Calculation results of each case.

IV. Validation by Experiment

The validity of the proposed method is also verified from a viewpoint of experiment by using the simulated distribution system equipment.

A. Simulated Distribution System Equipment

The simulated distribution system equipment is shown in Fig. 7. The system configuration of experimental equipment is the same as in Fig. 1 (a), (b), and the value of each load is the same as the value of analytical model described in Chapter III. Two types of inverters are used for PV systems, and each rated capacity is 1 kW and 5.5 kW. The pole transformer is simulated with a programmable AC power supply and the AC power supply generates 5th harmonic voltage of 4 %. For Case 3 in Fig. 1 (c), the authors have not verified in this paper since there is no SC in the experimental equipment.

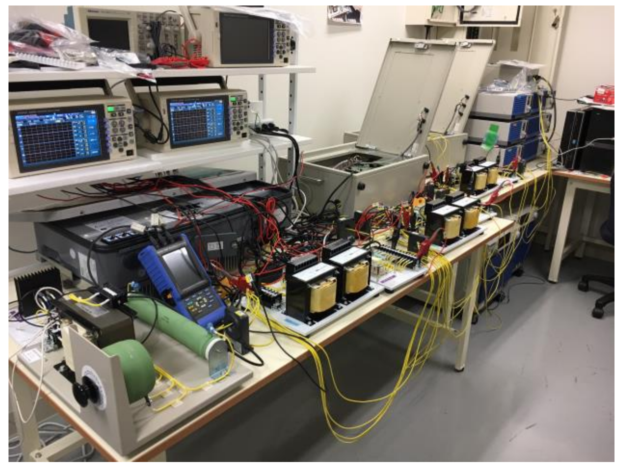
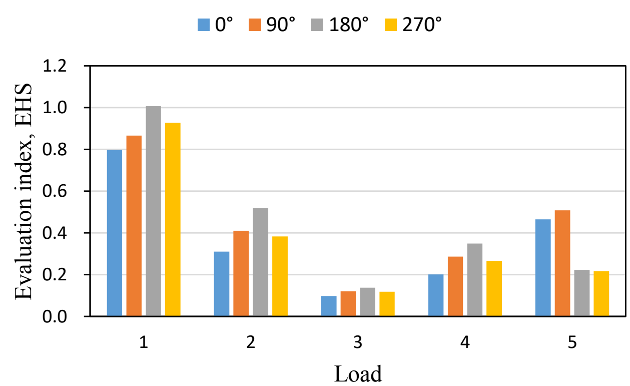
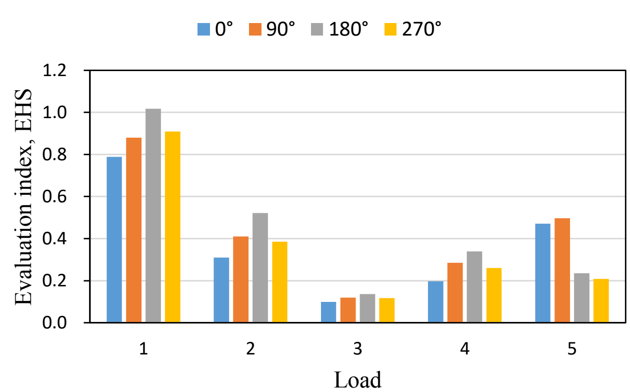


Figure 7. Simulated distribution system equipment.



(a) Case 1 (with PV systems, single feeder)



(b) Case 2 (with PV systems, branched feeders)

Figure 8. Experimental results of each case.

B. *Experimental Results*

The results of estimation of the harmonic sources obtained by analyzing the waveform data of voltages and currents measured at each node are shown in Fig. 8. As shown in Fig. 8, although harmonics were detected from Load 3, which is not a harmonic source, but since it is a relatively small amount, it was confirmed that the harmonic sources can be estimated regardless of whether there is no branch. Also in the experiment, it was confirmed that the amount of harmonic generation varies depending on the difference in phase shift of harmonic voltage from the upper system.

Fig. 9 shows the experimental results of Case 1 in the absence of harmonic voltage from the upper system. As can be seen from a comparison of Fig. 8 (a) and Fig. 9, the evaluation index of the inverter connected to the Load 1 is particularly different. From these results, it is considered that the influence of the harmonic voltage from the upper system is large.

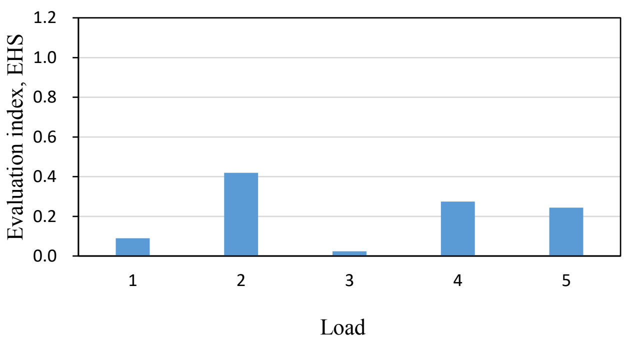


Figure 9. Experimental results of Case 1 (without harmonic voltage from upper system).

V. CONCLUSION

In this study, the authors proposed the estimation method of harmonic sources on distribution system. In the proposed method, the harmonic sources are estimated by separating the harmonic current flowing through the distribution line into the harmonic current flowing from the upper side and the harmonic current flowing out from the lower side. Then, it is possible to estimate the location where the value of the defined evaluation index is remarkable as the harmonic sources. The authors verified the validity of the proposed method by numerical calculation and experiment, and showed the possibility of the estimation of harmonic sources.

The future work is as follows.

- Verification in high-voltage distribution system
- Verification in more complex large-scale distribution system
- Analyses of influence by SC on estimation accuracy
- Development of harmonic suppression method

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