VALIDATION OF A HARMONIC STATE ESTIMATION METHOD BASED ON FIFTH HARMONIC CURRENT CHARACTERISTIC OF UTILITY CUSTOMER USING TRANSIENT SIMULATION

Naotaka OKADA
CRIEPI – Japan
okada@criepi.denken.or.jp

Kenji YUKIHIRA
CRIEPI – Japan
yukihira@criepi.denken.or.jp

ABSTRACT

In the last decade, harmonic analysis of Japanese middle voltage (MV) customer and low voltage (LV) customer has been done, the distribution of the fifth harmonic current can be classified MV customer's single phase load, LV customer's three phase and single phase load named group A and MV three phase load named group B, and the amplitude per load kW has been investigated from sum of each current vector. By the application of this knowledge, there is a possibility to estimate the harmonic distribution with many harmonic source in the distribution network. We have proposed a harmonic state estimation method with limited measurement condition by using the fifth harmonic current phase angle classification model. Many demonstration cases are needed to support proposed method. In this paper, we demonstrate the harmonic state estimation method based on fifth harmonic current characteristic of utility customer using transient simulation.

INTRODUCTION

By the spray of power electronics technology, harmonic situation has changed to be generated from many utility customer. Reproductive simulation of the measurement data by the harmonic analyze is start point to understand harmonic voltage distortion mechanism. It is difficult to measure all utility customer in a distribution feeder at same time. Under the terms of low number of measurement, it is difficult to determine effectual harmonic current combination to conform calculation closely to measurement.

Due to high expense of harmonic measurement system, only limited number of harmonic meter are available in power transmission network. To solve this problem, optimal meter placement method has been developed [1], [2]. However, in case of the number of meter less than the harmonic sources, harmonic state estimation (HSE) cannot estimate harmonic sources. On the other hand, sparsity maximization method has been proposed to solve this estimation problem supposing spatial sparsity of harmonic current in power transmission network [3]. In case of distribution network with many harmonic source, there is possibility spatial evenness of harmonic current.

On the one hand, analysis of the middle voltage customer and low voltage customer has been done, the distribution of the fifth harmonic current can be classified two groups [4], [5]. By the application of this knowledge, there is a possibility to estimate the harmonic distribution with many harmonic source in the distribution network. We developed a harmonic state estimation method with limited measurement condition by using the fifth harmonic current phase angle classification model [8].

Many demonstration cases are needed to support proposed method. In this paper, we demonstrate the HSE method based on fifth harmonic current characteristic of utility customer using transient simulation of MATLAB Simulink. Numerical experiments are conducted in seven node distribution network to test the proposed method. The results show that the proposed harmonic state estimation by using the fifth harmonic current phase angle classification model approach can reliably identify harmonic distribution by using transient simulation.

ANALYSIS OF FIFTH HARMONIC CURRENT ON UTILITY CUSTOMERS IN JAPAN

The fifth harmonic mainly generate failure. Therefore, it is important to understand this mechanism. The fifth harmonic current of 81 single phase transformer and 87 three phase transformer in middle voltage (MV) utility customer have been analyzed in reference [4]. And also the fifth harmonic current of 30 single phase transformer in low voltage (LV) utility customer have been analyzed in reference [5].

Phase Angle

JIS C 4304-2005 "6 kV Oil-immersed distribution transformers" (Japanese Industrial Standards) specify the three phase transformer of the capacity from 75kVA to 500kVA Y-delta connection for primary-secondary. Therefore, the three phase load of the MV customer supplied from this Y-delta transformer. On the other hand, single phase loads and LV three phase loads were supplied form line-to-line single phase transformer and delta-delta transformer, as shown in figure 1.

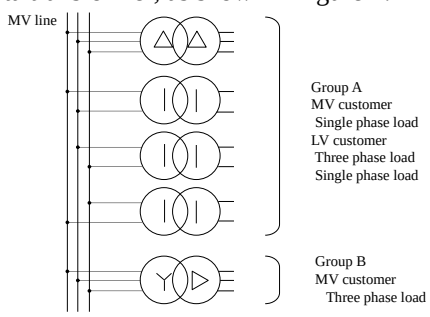

Figure 1 Transformer winding for single phase, LV three phase and MV three phase loads in Japan.

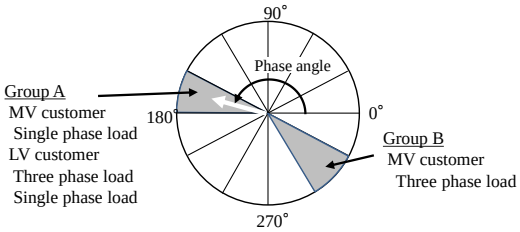

Figure 2 Distribution of two fifth harmonic current vector groups on utility customers.

For these reason, the distribution of fifth harmonic current vector in MV line, as shown in figure 2, can be classified MV customer's single phase load, LV customer's three phase and single phase load named group A (supplied by line-to-line single and delta-delta transformer) and MV three phase load named group B (supplied by Y-delta transformer) [4], [5].

Amplitude

Root mean square (RMS) currents of the fifth harmonic converted MV distribution line phase current are discussed here.

In MV utility customer, the RMS current per load kW has been investigated from sum of each current vector. RMS of fifth harmonic current per 1kW of load are 3.5 ~ 7.5mA/kW for single phase transformer and 5 ~ 11mA/kW for three phase transformer [4].

In LV utility customer, RMS of fifth harmonic current per 1kW of load are 4 ~ 8mA/kW for single phase load and 27.1mA/kW for three phase load [5]. The RMS harmonic current of three phase load in LV customer was 4.5 times for single phase load. This result may be caused by low load level for only three phase load of LV customer, in this investigation. An investigation of harmonics attenuation and diversity among distributed single-phase power electronic loads is shown in reference [6].

HARMONIC CURRENT OF ELECTRICAL APPLIANCE

Harmonic current of electrical appliances via line to line single phase transformer and three phase Y-delta transformer are discussed here. Figure 3 shows three line to line single phase transformer connected to single phase diode rectifier with smoothing capacitor. The voltage v_a and the current i_a are shown in figure 4. On the right shows the fundamental and fifth current vectors which are referenced to phase angle v_a. The phase angle of the fifth harmonic current vector is about 150 degree.

Figure 5 shows three phase Y-delta transformer connected to three phase diode rectifier with smoothing capacitor.

The waveform of the v_a and the i_a, the fundamental and fifth current vectors are shown in figure 6. The phase angle of the fifth harmonic current vector is about 310 degree.

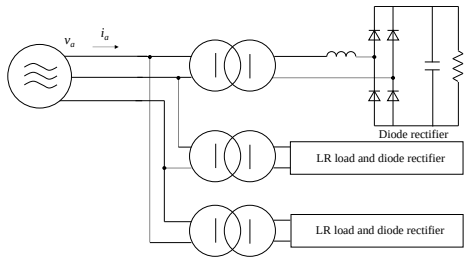

Figure 3 Three line to line single phase transformer connected to single phase diode rectifier with smoothing capacitor.

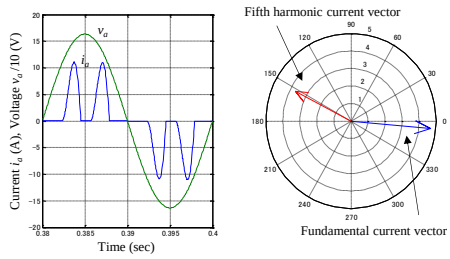

Figure 4 Current waveform and fifth harmonic current vector on three line to line single phase transformer connected to single phase diode rectifier with smoothing capacitor.

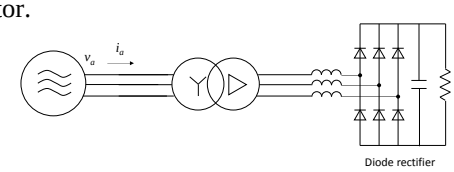

Figure 5 Three phase Y-delta transformer connected to three phase diode rectifier with smoothing capacitor.

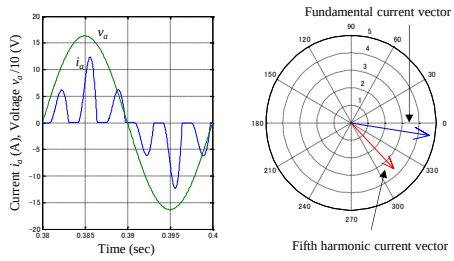

Figure 6 Current waveform and fifth harmonic current vector on three phase Y-delta transformer connected to three phase diode rectifier with smoothing capacitor.

PROPOSED FIFTH CURRENT MODEL

The weighted least squares (WLS) method is a powerful tool to determine most probably system state from measurement data with random noise. We use the WLS method for state estimation of distribution network. Fundamental and fifth harmonic model of utility customer are described here.

Power and Reactive Power Model of Utility Customer

To compensate for the lack of measurement data, pseudo measurement data has been used in state estimation of distribution system. The pseudo measurement data of

customer load is based on customer monthly kWh, kW rating, load type and so on. In this paper, we try to estimate fundamental phase angle of nodes in a way that sets the pseudo measurement data based on a simple assumption.

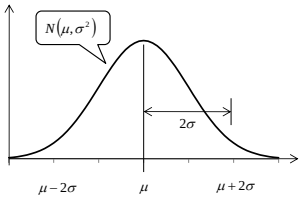

Figure 7 Normal distribution model for State Estimation.

As shown in figure 7, we assume a normal distribution of average demand μP_i and standard deviation σP_i as demand data for each node i in the distribution feeder. The μP_i is used as measurement data for the lack of demand measurement data. And the σP_i is set as weight of the WLS method [7].

Concretely, average power μP_i and standard deviation σP_i of node i is given by the following.

$$\mu P_i = \frac{(P\max_i + P\min_i)}{2},\quad \sigma P_i = \frac{(P\max_i - P\min_i)}{4} \qquad (1)$$

Where, $P\max_i$ set based on maximum or contract capacity of customer for each harmonic current group at node i. Similarly, $P\min_i$ set zero or minimum capacity of customer for each harmonic current group at node i. Average reactive power μQ_i and standard deviation σQ_i of node i are obtained as multiply (1) by power factor of utility customers.

Fifth Harmonic Current Model of Utility Customer

Normal distribution model, shown in figure 7, apply to fifth harmonic current phase angle and RMS of amplitude. The fifth harmonic current angle characteristic at node i utility customer in the distribution network modelled average $\mu\theta 5_i$ and standard deviation $\sigma\theta 5_i$ by reference to [4] and [5].

Similarly, the RMS of harmonic current amplitude modelled average $\mu A5_i$ and standard deviation $\sigma A5_i$.

$$\mu A5_i = K5_i \cdot \mu P_i,\quad \sigma A5_i = K5_i \cdot \sigma P_i \qquad (2)$$

Where, $K5_i$ is harmonic current per load kW.

Harmonic State Estimation

By the component of line inductive reactance, when increase of load flow, the voltage phase angle of fundamental at end of feeder lag to norm bus voltage. Because of non-linear load generate harmonic current for voltage at connection node, fifth harmonic current shift 5 times for fundamental voltage angle shifting in fifth harmonic space.

This phase shift of fundamental voltage make influence for estimation result of harmonic when unconsidered this phase shift. HSE in combination with fundamental state estimation (FSE) method are described here. Figure 8 shows calculation flow of HSE in combination with FSE.

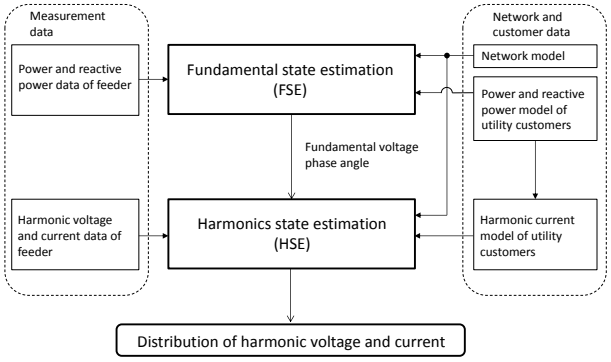

Figure 8 Calculation flow of harmonic distribution by HSE in combination with FSE.

Estimation by the WLS

Generally, the relation with measurement z, power system or measurement equation $h(x)$, state variables x and random noise n are shown as the following.

$$z = h(x) + n \qquad (3)$$

Estimated state variables xe are given by the state x which minimize the following equation J.

$$J = [z - h(x)]^T R^{-1} [z - h(x)] \qquad (4)$$

R is noise covariance matrix. Here, the diagonal elements R_{ii} set to σ_i^2. The σ_i is standard deviation of noise for measurement z_i. For example, we assumed deviation $2\sigma_i$ as maximum error guaranteed by measurement z_i.

In convergence calculation, state variable x is updated under the condition of $\partial J / \partial x = 0$.

SIMULATION AND RESULT

Numerical experiments are conducted in seven node distribution network model to test the proposed method by using transient simulation with MATLAB Simulink.

A Distribution Network Model

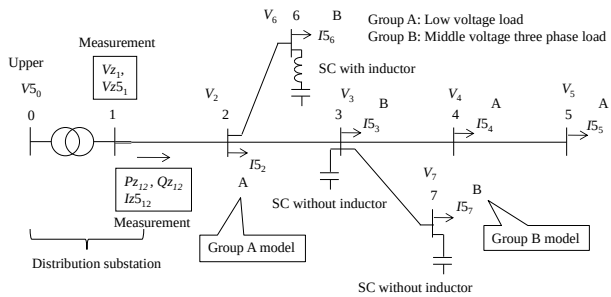

Figure 9 A distribution network model.

Medium voltage distribution feeders are mainly constructed by overhead 6.6kV distribution network, in Japan. Figure 9 shows a simple overhead 6.6kV distribution network model which feeds six areas by one feeder. And the feeder operation and maximum capacity are assumed 3MVA and 4MVA, respectively.

Voltage measurement Vz_1 and $Vz5_1$ are obtained at secondary bus of distribution substation transformer. Line power flow and current measurement Pz_{12}, Qz_{12}, and $Iz5_{12}$

are obtained at feeder from the bus.

Condition of Utility Customer

In this simulation model, group A customer assume node 2, 4 and 5. And group B customer assume node 3, 6 and 7. To compensate reactive power of load, shunt capacitor (SC) are installed mainly MV customer in Japanese distribution network. SC of MV customer were set at node 3, 6 and 7.

Line impedances of the distribution network, characteristics of fifth harmonic current of group A and group B, setting of customer capacity, and SC capacity of MV customer are set up by reference to [8].

Harmonics load model for Transient Simulation

Harmonic loads were modeled by diode rectifier and parallel resistor-inductor (RL) load. For group A, single phase diode rectifier as shown in figure 3 and parallel RL load were placed each phase to phase by single phase transformer. For group B, three phase diode rectifier as shown in figure 5 and parallel RL load was connected by Y-delta transformer.

Result of FSE and Fifth HSE

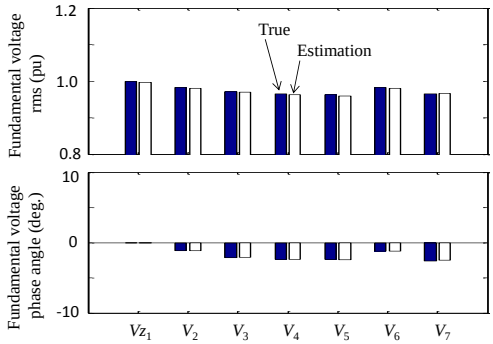

Figure 10 Comparison of true with fundamental voltage of FSE.

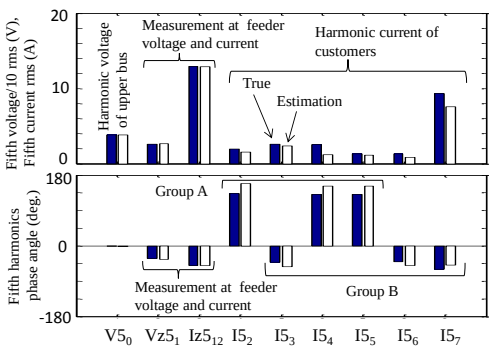

Figure 11 Comparison of true with fifth harmonic of HSE.

For true value calculation, numerical experiments are conducted by using transient simulation with fifth harmonic voltage distortion of upper back network voltage distortion of 1.0% and phase angle of 0 degree and distributed customer load condition. After true value calculation, FSE and HSE are conducted by using Vz_1, Pz_{12}, Qz_{12}, $Vz5_1$, and $Iz5_1$ as measurement value.

Figure 10 shows comparison of true with fundamental voltage of FSE result.

Figure 11 shows comparison of true with fifth harmonic of HSE result.

The results show that the proposed approach can reliably identify fundamental voltage and fifth harmonic distribution.

CONCLUTION

In this paper, we demonstrate that the proposed utility customer model approach for fifth HSE in combination with FSE in distribution network can reliably identify harmonic distribution by using transient simulation.

REFERENCES

[1] J.E. Farach, W.M. Grady, A. Arapostathis, "An optimal procedure for placing sensors and estimating the locations of harmonic sources in power systems", IEEE Transactions on Power Delivery, Vol. 8, No. 3, 1993, pp. 1303-1310.

[2] A. Kumar, B. Das, Jaydev Sharma, "Genetic algorithm-based meter placement for static estimation of harmonic sources", IEEE Transactions on Power Delivery, Vol. 20, No. 2, Part 1, 2005, pp. 1088-1096.

[3] Huaiwei Liao, "Power System Harmonic State Estimation and Observability Analysis via Sparsity Maximization", IEEE Transactions on Power Systems, Vol. 22, No. 1, 2007, pp. 15-23.

[4] K. Yukihira, N. Okada, “The Suppressing Effect of Voltage Distortions in Electric Power Systems by Harmonic Currents Emitted by Customers with High Voltage Power Supply”, CRIEPI Report, R11003, Oct. 2011.

[5] K. Yukihira, N. Okada, K. Ishibashi, “Characteristics of harmonic currents emitted by customers with low-voltage power supplies - Analysis of data measured in the metropolitan area in winter heavy-load season -”, CRIEPI Report, R13004, Feb. 2014.

[6] A. Mansoor, W.M. Grady, A.H. Chowdhury, M.J. Samotyi, "An investigation of harmonics attenuation and diversity among distributed single-phase power electronic loads", IEEE Transactions on Power Delivery, Vol. 10, Issue 1, 1995, pp. 467-473.

[7] N. Okada, M. Takasaki, K. Tanaka, "A case study of bad data detection for distribution feeder voltage measurement", ISGT Europe, 2012. pp. 1-6.

[8] N. Okada, K. Yukihira, “Harmonic State Estimation in Distribution Network Based on Fifth Harmonic Current Characteristic”, ICHQP 2014, The 16th International Conference on Harmonics and Quality of Power.