CHARACTERISTICS OF FIFTH AND SEVENTH HARMONICS IN JAPANESE ELECTRIC POWER DISTRIBUTION SYSTEM

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ABSTRACT

Many transformers of customers such as buildings connected to medium voltage of distribution network in Japan mainly use Y - Δ transformers. On the other hand, low voltage single-phase load uses line to line voltage. From this fact, it is expected that the fifth and seventh harmonics generated from these customers will cancel each other, but these conditions have not been well understood so far. In this paper, characteristics of the fifth and seventh harmonics will be explained with reference to the literature on harmonics. In addition, from the realities of these fifth and seventh harmonic currents, a harmonic current model is created and the effect of the current harmonic limit value is considered.

INTRODUCTION

Although the number of pieces of load that emit harmonic currents has increased, harmonic voltages in Japan have gradually decreased since about 1999 [1]. Recently, although the slope of decreasing degree has become loose, the trend of decrease continues [2]. In addition, harmonic voltages are generally lower during the daytime when there is greater usage of different type of load that emit harmonic currents. Until now, why this happens was not known, but recently, these mechanisms have been clarified based on analysis of the fifth and seventh harmonic currents generated from customers [3-5]. In this paper, characteristics of the fifth and seventh harmonics of the first and second components based on a series of analyses are explained according to the literature.

MEASUREMENT OF HARMONIC CURRENT

According to JIS C 4304, many transformers of customers such as buildings connected to medium voltage of distribution network in Japan mainly use Y - Δ transformers. On the other hand, low voltage single-phase load uses line to line voltage. From this fact, it is expected that the fifth and seventh harmonics generated from these customers will cancel each other, but these conditions have not been well understood so far. Therefore, measurement conditions of middle voltage customers and low voltage customers will be described.

Middle voltage customers

Targeted middle-voltage customers are total of 86 with 37 factories and 49 buildings, sampled from 2 to 20 in each 10 electric power companies in Japan (Table 1).

Low voltage customers

Measurement of low-voltage customers was carried out in substation of condominiums in Tokyo, because it can measure many customers collectively. The measurements were carried out in 8 condominiums (Table 2).

Table 1 Area of measured consumers of 6.6kV or higher voltage power supply [4].

area	factory	building
Hokkaido	4	4
Tohoku	4	4
Tokyo	7	13
Chubu	6	11
Hokuriku	2	2
Kansai	5	8
Chugoku	2	1
Shikoku	1	1
Kyushu	4	4
Okinawa	2	1
Subtotal	37	49
Total	86	

Table 2 Transformers for consumers of 100V / 200V power supply [5].

	Transformer (kVA)	
	Single-phase	Three-phase (V connection)
A	75	25×2
B	100,100, 100,100	50×2
C	100,100	25×2
D	50, 70	30×2
E	50	30×2
F	50, 55	20×2
G	100	30×2
H	100,100	15×2

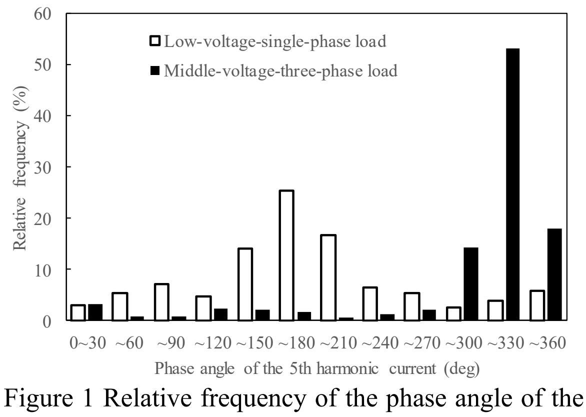


Figure 1 Relative frequency of the phase angle of the fifth harmonic current related to fundamental phase voltage [3].

ANALYSIS OF HARMONIC CURRENTS

Cancel of fifth harmonic currents

Since about 1999, Japanese harmonic voltage has been decreasing slightly. As a first step to elucidate this unnatural phenomenon, the loads are classified into two groups by transformer connection. In this way, it can be seen that harmonic currents from middle-voltage-three-phase load and low-voltage-single-phase load are cancelled each other in the entire power system (Figure 1).

Interlocking of time trend of fifth harmonic current and voltage

As a second step, the different type of load was classified into six groups depending on the number of phases (i.e., single-phase or three-phase) and the users' supply voltage. The ratio of the contribution of each group to the fifth harmonic voltage was then quantitatively clarified. Figure 2 shows variation fifth harmonic voltage and vector sum of fifth harmonic current by all groups of loads. The time trend of fifth harmonic current and voltage are interlocking. The fifth harmonic voltage in the electric power distribution system in Japan is produced mainly by single-phase load. The harmonic current generated from the middle-voltage-three-phase load mainly cancel the harmonic current generated from the single-phase load in the daytime.

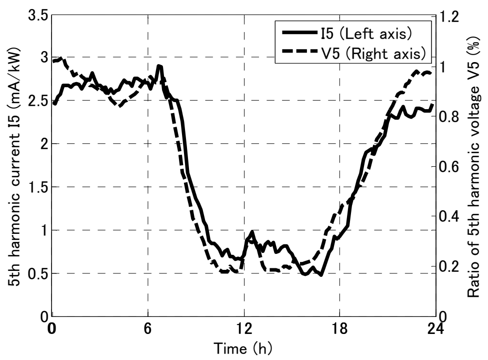


Figure 2 Variation fifth harmonic voltage and vector sum of fifth harmonic current by all groups of loads [4].

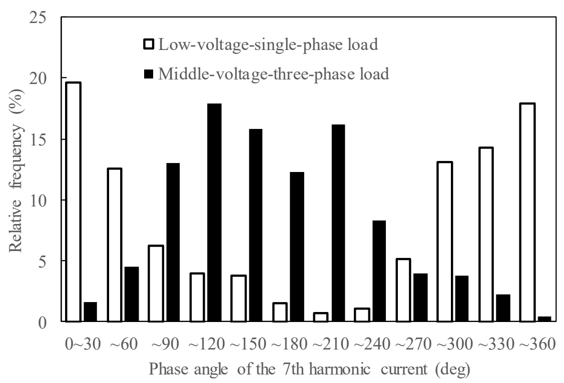


Figure 3 Relative frequency of the phase angle of the seventh harmonic current related to fundamental phase voltage [5].

Analysis of seventh harmonic

When the cancellation of the fifth harmonic in the entire system is correct, there should be a cancellation even at the seventh harmonic.

As a third step, the seventh harmonic current was analyzed in the same way as the fifth harmonic current. The existence of cancellation was confirmed also in seventh harmonic (Figure 3).

Time trends of the fifth and the seventh harmonic voltages are different (compare Figure 4 and Figure 2) but the estimated results of electric energy of each group were almost same (Table 3). The validity of the obtained group ratio can be confirmed [5].

Here, load group *j* shown in Table 3 means 1: middle-voltage-factory-three-phase load, 2: middle-voltage building-three-phase-load, 3: middle-voltage-factory single-phase load, 4: middle-voltage-building-single-phase load, 5: low-voltage-three-phase load and 6: low-voltage-single-phase load. In the next chapter, *Kr*(*j*) will be used as the reference electric energy ratio of each load group.

HARMONIC CURRENTS MODEL

In order to clarify the factor of forming the harmonic voltage of the distribution feeder, we estimate fifth and seventh harmonic currents according to the local load group configuration. In this paper, a calculation model was

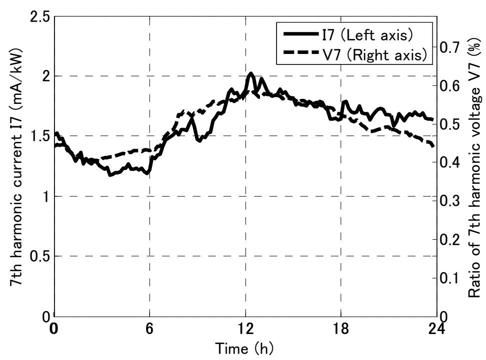


Figure 4 Estimated seventh harmonic current of each load group and seventh harmonic voltage [5].

Table 3 Estimated ratios of electric energy of each load group *j* [5].

Load group: *j*	Fifth		Seventh	
	Kr(*j*)	-	-	-
1	0.230	0.532	0.224	0.518
2	0.177		0.172	
3	0.036		0.035	
4	0.089		0.087	
5	0.037	0.468	0.039	0.482
6	0.431		0.443	

Table 4 Estimated ratios of electric energy of each load group j for each area i.

$K(i,j)$	j=1	j=2	j=3	j=4	j=5	j=6
i=1	0.381	0.244	0.060	0.122	0.015	0.178
i=2	0.000	0.428	0.000	0.215	0.028	0.329
i=3	0.183	0.130	0.029	0.065	0.047	0.546
i=4	0.346	0.124	0.054	0.063	0.033	0.380

Table 5 Estimated total electric energy ratio $Ka(j)$.

	j=1	j=2	j=3	j=4	j=5	j=6
$Ka(j)$	0.226	0.188	0.035	0.095	0.036	0.419

Table 6 Feeder number ratio $L(i)$ and feeder electric energy ratio $C(i)$ in each area i.

Area i	$L(i)$	$C(i)$
i=1	0.169	0.273
i=2	0.157	0.218
i=3	0.434	0.294
i=4	0.239	0.215

constructed by multiplying the harmonic current vector of each load group by the load group ratio of each area and the average power of distribution feeders in each area.

Estimation of electric energy ratios

Table 4 shows estimated ratios of electric energy of each load group j for each area i were obtained by the least squares method so that makes the load curve of each areal distribution feeder coincide with the survey report [6] of Electric Technology Research Association. Here, area i means 1: industrial, 2: commercial, 3: residential and 4: rural.

Table 5 shows estimated total electric energy ratio $Ka(j)$ obtained by weighting the electric energy ratio $K(i, j)$ of each area with the feeder number ratio $L(i)$ and feeder electric energy ratio $C(i)$ of each area. The ratios $L(i)$ and $C(i)$ were shown in Table 6.

$K(i,j)$ which show in Table 4 will be estimated. Following estimation model has been used in this paper.

The estimating ratio $Ka(j)$ of the total electric energy is set to

$$Ka(j)=\frac{\sum_{i=1}^{4} L(i)\cdot C(i)\cdot K(i,j)}{\sum_{k=1}^{4}\sum_{l=1}^{6} L(k)\cdot C(k)\cdot K(k,l)}, \tag{1}$$

where objective function J_1:

$$J_1=\sum_{j=1}^{6}\left(Ka(j)-Kr(j)\right)^2 \tag{2}$$

is minimised to make the $Ka(j)$ matches the estimated ratio $Kr(j)$ shown in Table 3.

$Pe(j, t)$: j=1, ..., 6 are the active power curves of the load groups j. By using the $Pe(j, t)$: j=1, ..., 6, active power curves $Pa(i, t)$: i=1, ..., 4 of each area are synthesized as shown in

$$Pa(i,t)=\sum_{j=1}^{6} K(i,j)\cdot Pe(j,t). \tag{3}$$

Secondly, objective function J_2:

$$J_2=\sum_{i=1}^{4}\sum_{t=0}^{24}\left(Pa(i,t)-Pr(i,t)\right)^2 \tag{4}$$

is used as a condition to make the synthesized active power Pa (i, t) coincide with the time change of the load of each area. Here, the load curve $Pr(i, t)$: i=1, ..., 4 of reference [6] is used as the time change of the load of each area. The $Pr(i, t)$: i=1, ..., 4 are load curves normalized by the average electric power $Pm(i)$: i=1, ..., 4 of distribution feeder in industrial: i=1, commercial: i=2, residential: i=3 and rural: i=4 area.

The two objective functions J_1 and J_2 of equation (2) and (4) are combined as

$$J=100\cdot J_1+J_2, \tag{5}$$

where coefficient 100 of J_1 is chosen to give appropriate results and finally J is minimized.

By using the ratios $K(i, j)$ for j=1, j=3, j=2, j=4, j=5 and j=6 configure the constraint condition of following:

$$\begin{aligned}
K(i,1)&=\frac{23}{23+3.6}Kv(i,1)\\
K(i,3)&=\frac{3.6}{23+3.6}Kv(i,1)\\
K(i,2)&=\frac{17.7}{17.7+8.9}Kv(i,2),\\
K(i,4)&=\frac{8.9}{17.7+8.9}Kv(i,2)\\
K(i,5)&=\frac{3.7}{3.7+43.1}Kv(i,3)\\
K(i,6)&=\frac{43.1}{3.7+43.1}Kv(i,3)
\end{aligned} \tag{6}$$

where auxiliary variables $Kv(i, 1)$, $Kv(i, 2)$ and $Kv(i, 3)$ mean relation of the $K(i,1)$ and the $K(i,3)$, the $K(i,2)$ and the $K(i,4)$, the $K(i,5)$ and the $K(i,6)$ ratio, respectively.

In addition, the constraint condition of

$$\sum_{j=1}^{3} Kv(i,j)=1 \tag{7}$$

is given to equation (6). In this way, the search variables for minimizing the objective function J are eight variables $Kv(i, 1)$ and $Kv(i, 2)$, i = 1 to 4. In addition, these variables take values of 0 or more and 1 or less.

Calculation of harmonic current

The harmonic current vectors $Ih(i, t)$ in each area i is calculated by equation (8), where $Ihe(i, t)$ means harmonic current vector per kW of each load group. For fifth harmonic, $Ih(i, t)$ and $Ihe(i, t)$ in equation (8) replaced by $I5(i, t)$ and $I5e$ (i, t), respectively.

$$Ih(i,t)=Pm(i)\cdot\sum_{j=1}^{6} K(i,j)\cdot Pe(j,t)\cdot Ihe(j,t) \tag{8}$$

In equation (8), if j = 1 to 2, $Ih(i, t)$ means the middle-

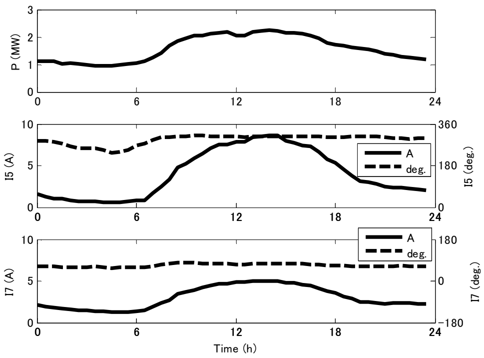


Figure 5 Feeder power, fifth and seventh harmonic currents of an industrial area.

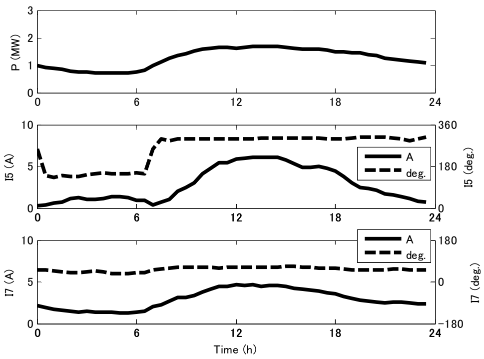


Figure 6 Feeder power, fifth and seventh harmonic currents of a commercial area.

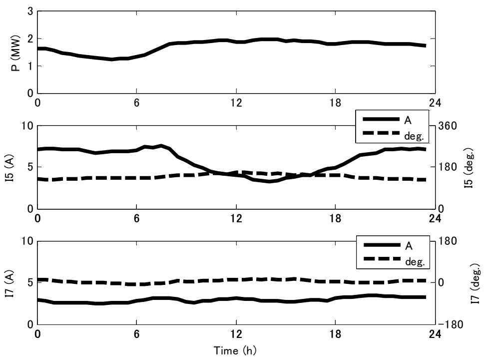


Figure 7 Feeder power, fifth and seventh harmonic currents of a residential area.

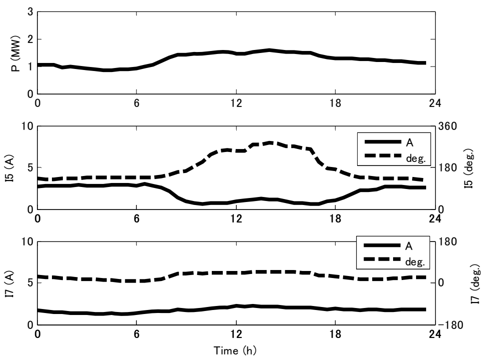
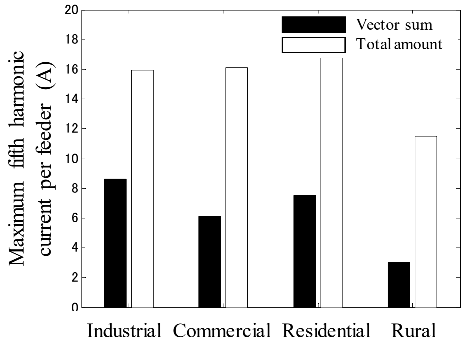
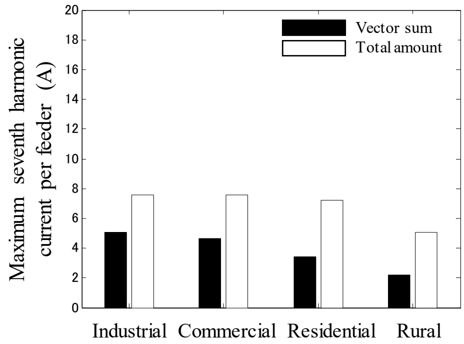


Figure 8 Feeder power, fifth and seventh harmonic currents of a rural area.



(a) Fifth



(b) Seventh

Figure 9 Vector sum and total amount of harmonic currents generated from each load group.

voltage-three-phase harmonic current vector. Similarly, if j = 3 to 6 in equation (8), $Ih(i, t)$ means harmonic current vector other than three phases of middle voltage.

Harmonic currents in the each area of the industrial, the commercial, the residential and the rural areas are calculated by using equation (8). Figure 5 shows feeder power, fifth and seventh harmonic currents of an industrial area. Similarly, Figure 6, 7 and 8 show a commercial area, a residential area and a rural area.

By comparing the calculated a vector sum of the fifth harmonic currents and a total amount of harmonic currents generated from the load, it is found that there are cancellation effects of 0.26 times (rural area) to 0.54 times (industrial area) depending on the area (Figure 9 (a)).

The ratio of the calculated a vector sum of the seventh harmonic currents to the total amount of harmonic current generated from the load is 0.43 (rural area) to 0.67 (industrial area) depending on the area, and cancellation effect can be confirmed (Figure 9 (b)). However, the cancellation effect of the seventh harmonic in each area is small against the fifth harmonic 0.26 (rural area) to 0.54 (industrial area). This is because the difference between the phase angle of the middle-voltage-three-phase load and the phase angle of the harmonic current generated from others is as small as about 120 degrees in the seventh harmonic, compared to the fifth harmonic of about 180 degrees.

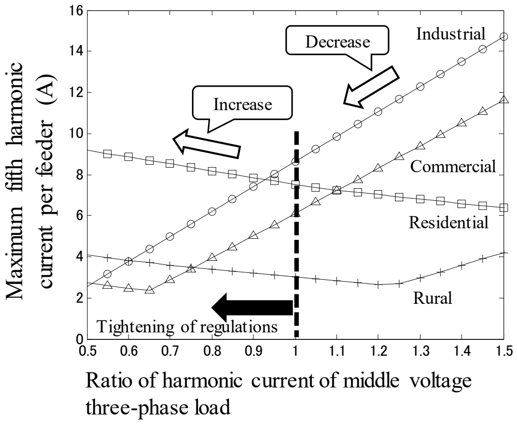


Figure 10 Fifth harmonic current of each areal distribution feeder.

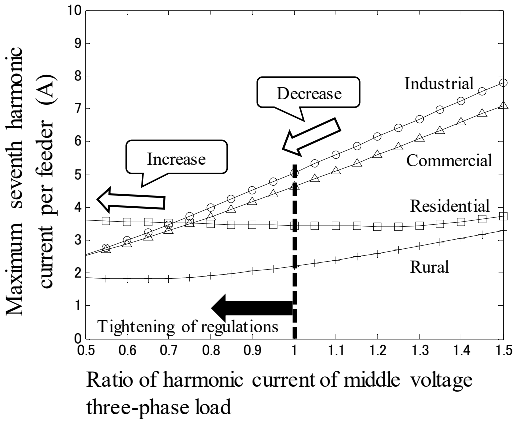


Figure 11 Seventh harmonic current of each areal distribution feeder.

CONSIDERATION OF HARMONICS LIMIT

In the fifth harmonic, when harmonic current is suppressed for middle-voltage-three-phase load, the harmonic current decreases in the industrial and commercial area. The cancellation effect decreases in the residential area and the rural area, resulting in this, it was found that the harmonic current increased (Figure 10).

Similarly, even at the seventh harmonic, suppression of the harmonic current with respect to the middle-voltage-three-phase load reduces the harmonic current in the industrial and commercial areas. The cancellation effect decreases in the residential area and the harmonic current increases (Figure 11). However, for the seventh harmonic, the increase of the harmonic current in the residential area was smaller compared with the fifth. For the rural area, there was a different trend in the fifth and seventh harmonics.

CONCLUSIONS

Fifth harmonic voltage in Japanese electric power distribution system is produced mainly by the single-phase load.

Fifth harmonic current generated by the middle-voltage-three-phase load reduces the fifth harmonic voltage.

At seventh harmonic, the harmonic current generated from the middle-voltage-three-phase load and harmonic current generated from the single-phase load also cancel each other. However, its cancel effect is smaller than the fifth harmonic.

The fifth and seventh harmonic, when harmonic current is suppressed for middle-voltage-three-phase load, the harmonic current decreases in the industrial and commercial area, but the cancellation effect decreases in the residential area. In the rural area, there was a different trend in the fifth and seventh harmonics.

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