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Study on Generation of Harmonic Voltage using Synchronous Machine with d- and q-axis Harmonic Field Windings - Part 2

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Abstract – We investigated the harmonic voltages generated by a synchronous machine adding d-axis and q-axis harmonic field windings to reduce the harmonics in a power line. First, electronic circuits such as a frequency multiplier, band-pass filter, and phase shifter were newly designed and made to carry out the experiment. Next, an experimental circuit, for which an AC voltage of frequency $6f$ synchronized to the power line voltage of frequency f could be obtained, was constructed to examine the generation of harmonic voltage in more detail. Finally, an experiment involving the generation of harmonic voltage was performed using an experimental synchronous generator with harmonic windings in the d-axis and q-axis. In this paper, the power spectrum and the waveforms of the harmonic voltages in the armature winding are presented. Moreover, the values calculated from theoretical expressions of harmonic voltages in armature winding are compared with the values obtained by the experiment.

Keywords: Harmonic voltage, Synchronous machine, Harmonic field winding, Waveform

1. Introduction

With the popularization of equipment using power semiconductors, harmonics have become a significant problem in power systems. Harmonics in power systems cause undesirable effects in the electrical machinery and apparatus on the load side. In particular, it is very important to remove low order harmonics such as the 5th and 7th harmonics, because they have a large influence on the electrical machinery and apparatus.

An LC filter is generally used to reduce the harmonics, but the LC filter is subject to the influence of the impedance value, which changes with the load condition in the power system. The LC filter may also succumb to burnout by overload. Therefore, an active filter has been studied to avoid these disadvantages in the LC filter [1]. However, the active filter will generate other harmonics in a different order because of the switching of the semiconductor. Moreover, there is the problem of the costs involved in the enlargement.

An absorption method of the power line harmonics using a synchronous machine has recently been investigated [2]-[4]. When the synchronous machine is used for reducing the harmonics, the equipment using the synchronous machine is expected to be more advantageous than the LC filter and the active filter in terms of cost.

We constructed a synchronous machine to finally demonstrate the reduction of the harmonics in a power line [5], [6]. The structure of this experimental synchronous machine is different from that of a usual synchronous machine and the experimental machine has both d-axis and q-axis field windings. In the previous paper [7], the power spectrum of the armature voltage was measured in the case of supplying AC currents with frequency $6f$ (f : frequency of the power line) to the harmonic field windings of the experimental synchronous machine. An AC voltage with frequency $6f$ generated by an oscillator was used.

In this paper, however, AC voltage with frequency $6f$ synchronized to the voltage of the power line is used to examine the generation of harmonic voltages in more detail. The AC voltage with frequency $6f$ is made by using a 6 times frequency multiplier. The power spectrum and the waveforms of the harmonics in the armature voltage were measured in the case of supplying the AC currents with frequency $6f$ to the harmonic field windings of the experimental synchronous machine. Moreover, the values calculated from the theoretical expressions [7] of harmonic voltages in armature winding are compared with the values obtained by the experiment. Consequently, it was confirmed that the values of harmonic voltages obtained by the theoretical expressions agree comparatively well with the experimental values.

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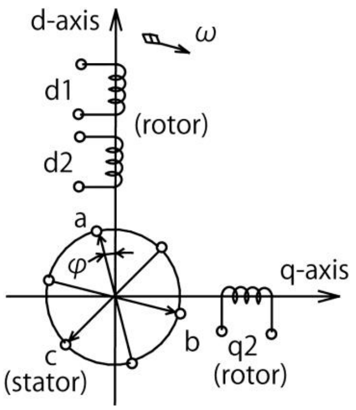


Fig. 1. Winding diagram of synchronous machine

Table 1. Design Parameter of experimental synchronous machine

Frequency	60 Hz
Voltage	200 V
Current	1.9 A
Power	500 W
Number of Poles	4

2. Model of Synchronous Machine

Fig. 1. shows the winding diagram of a synchronous machine with dual harmonic field windings d2 and q2. In this figure, a, b and c are 3-phase armature windings to absorb the harmonics contained in the power line. Winding d1 on the d–axis is the field winding. DC voltage is applied to the field winding d1. Moreover, AC voltage of frequency $6f$ is applied to the harmonic field windings d2 and q2. The design parameters of an experimental synchronous machine are given in Table 1.

3. Experiment on Generation of Harmonic Voltage using Experimental Synchronous Machine

3.1 Circuit for Experiment

Fig. 2. shows the circuit diagram for carrying out an experiment on the generation of harmonic voltages using the experimental synchronous machine. Here, the windings d2 and q2 are separately connected to voltages with frequency $6f$ synchronized to the voltage of the power line (frequency: f) and the phases of both currents i_{d2} (maximum value: I_{d2}) and i_{q2} (maximum value: I_{q2}) can be changed separately by using phase shifters. Moreover, the magnitudes of both currents are regulated by the gains of the pre-amplifiers. The voltage with frequency $6f$ is made by the 6 times frequency multiplier circuit FM6 in Fig. 2 in order to synchronize to the voltage of the frequency f of the power line.

The waveform of fundamental wave of the armature voltage was measured through the band-pass filter BPF in Fig. 2. On the other side, by connecting x_1-y_1 of Fig. 2 with band-pass filters of Fig. 3 (a), the harmonic waveforms of $5f$ and $7f$ were measured. In addition, by using $6f$ band-pass filter circuits through x_2-y_2 and x_3-y_3 of Fig. 3 (b), the waveforms of i_{d2} and i_{q2} were observed.

Figure 4 shows the electronic circuit of the band-pass filters BP5 with center frequency $5f$ (in the case of C=70.15nF) and BP7 with center frequency $7f$ (in the case of C=50.11nF).

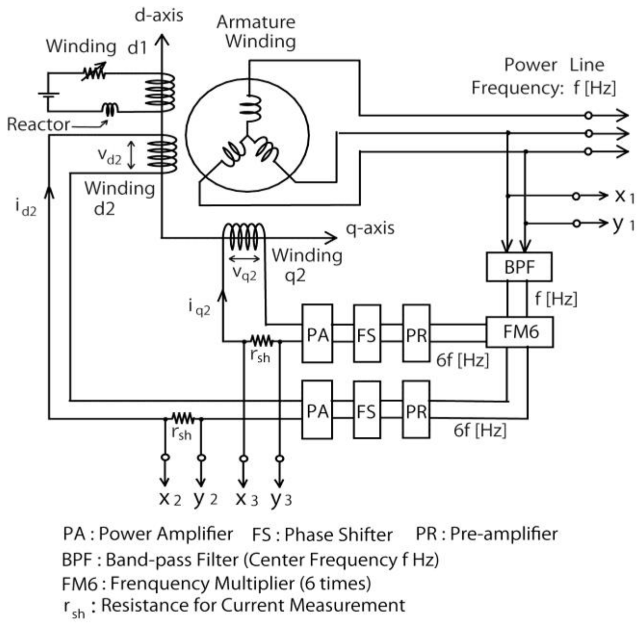
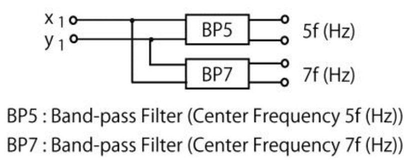
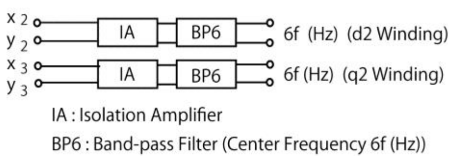


Fig. 2. Circuit diagram for experiment



(a) Circuit for measurement of harmonic voltages



(b) Circuit for measurement of current waveforms

Fig. 3. Circuit for measurement adding to the experimental circuit of Fig.2

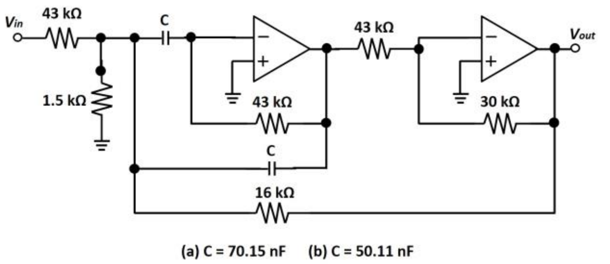


Fig. 4. Band-pass filters of (a) BP5 with center frequency 5*f* and (b) BP7 with center frequency 7*f*

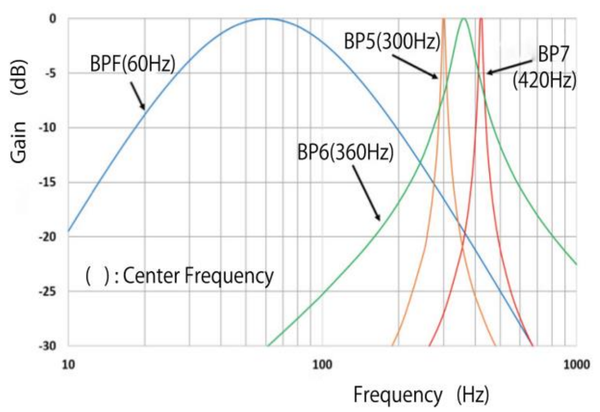


Fig. 5. Frequency characteristics of band-pass filters (BPF, BP5, BP6 and BP7)

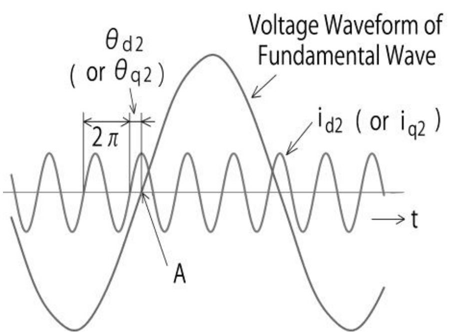


Fig. 6. Phase θ_{d2} of i_{d2} (or phase θ_{q2} of i_{q2})

The electronic circuits of the 6-times frequency multiplier and the band-pass filters containing the BP5, BP7 reported in the paper [8]. The simulation results of frequency characteristics of the produced band-pass filters are given in Fig.5. The band-pass filters produced actually have the characteristics which are almost same to the simulation results in Fig.5.

As shown in Fig. 6, the phase θ_{d2} of i_{d2} (or θ_{q2} of i_{q2}) is made to be a phase difference from the point A, in which the voltage of the fundamental wave changes from negative value to plus value.

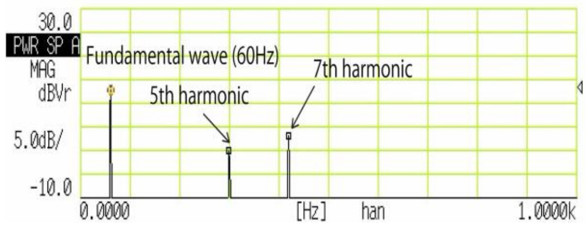
3.2 Results of Experiment

Since to examine the power spectrum and the waveforms of harmonics in the armature voltage is main purpose of this paper, an experiment carried out at no-load condition. Moreover, the voltage of the fundamental wave in an effective value was set to 100V by adjusting the DC current in the winding d1.

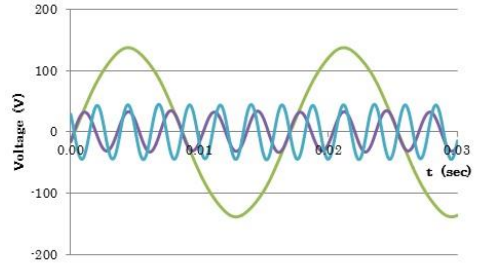
Figure 7 (a) shows the power spectrum (indicated in dB) of the armature voltage obtained by an FFT analyzer in the case of supplying the current ($I_{q2}/\sqrt{2}=0.1\,\mathrm{A}$, $\theta_{q2}=0\,\mathrm{rad}$) with frequency $6f$ to only the winding q2. In addition, Fig. 7 (b) shows the waveforms of the fundamental wave, 5th and 7th harmonic waves. In this figure, the green line, purple line and blue line show the fundamental wave, 5th harmonic wave and 7th harmonic wave, respectively. From the same figure, it is possible to know the relationship between the fundamental wave and the harmonic waves.

Figure 8 shows the power spectrum and the waveforms in the case of changing only $\theta_{q2}=-\pi/2$ rad. It is recognized that the amplitudes of the 5th and 7th harmonic waves are almost the same respectively compared with Fig. 7, but the relationship of phase changes.

When an AC current with frequency $6f$ is supplied to the winding d2, induced current flows in the winding d1 on the same d-axis and the magnetic flux due to the current in the winding d2 greatly decreases. Therefore, in order to prevent induced current, the reactor shown in Fig. 2 is connected to a circuit for the winding d1. However, the reduction of the magnetic flux due to the induced current occurs, since the inductance value of the reactor is finite.

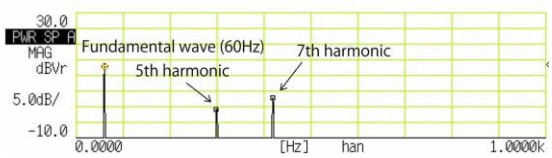


(a) Power spectrum

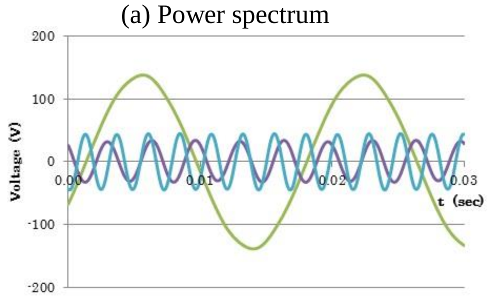


(b) Waveforms of fundamental and harmonic waves

Fig. 7. Power spectrum and waveforms of armature voltage ($I_{d2}=0\,\mathrm{A}$, $I_{q2}/\sqrt{2}=0.1\,\mathrm{A}$ and $\theta_{q2}=0\,\mathrm{rad}$)

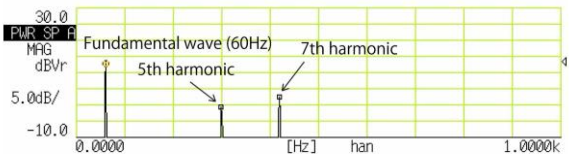


(a) Power spectrum

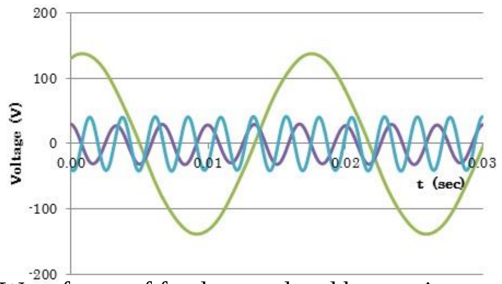


(b) Waveforms of fundamental and harmonic waves

Fig. 8. Power spectrum and waveforms of armature voltage ($I_{d2}=0$ A, $I_{q2}/\sqrt{2}=0.1$ A and $\theta_{q2}=-\pi/2$ rad)



(a) Power spectrum



(b) Waveforms of fundamental and harmonic waves

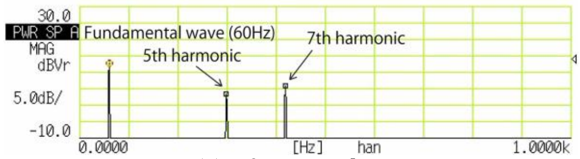
Fig. 9. Power spectrum and waveforms of armature voltage ($I_{d2e}/\sqrt{2}=0.1$ A, $I_{q2}=0$ A and $\theta_{d2}=0$ rad)

The maximum value I_{d2} of AC current i_{d2} in the winding d2 can be separated as the following equation.

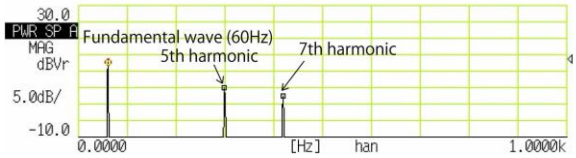
$$I_{d2}=I_{d2e}+I_{d2i} \tag{1}$$

Where, I_{d2e} is an effective component, which generates the magnetic flux and I_{d2i} is a non-effective component of which the magnetic flux is canceled by the magnetic flux due to the induced current of the winding d1.

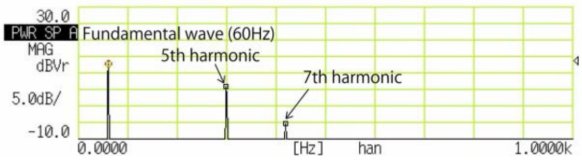
Fig. 9. shows the power spectrum and the waveforms in the case of supplying the current ($I_{d2e}/\sqrt{2}=0.1$ A, $\theta_{d2}=0$ rad) to only the winding d2. The amplitudes of the 5th and 7th harmonic waves are almost the same respectively compared with Fig. 7 and Fig. 8, but the relationship of phase changes.



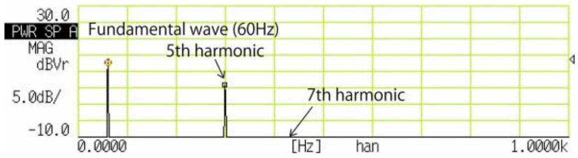
(a) $\theta_{d2}=0$ rad



(b) $\theta_{d2}=-\pi/6$ rad



(c) $\theta_{d2}=-\pi/3$ rad

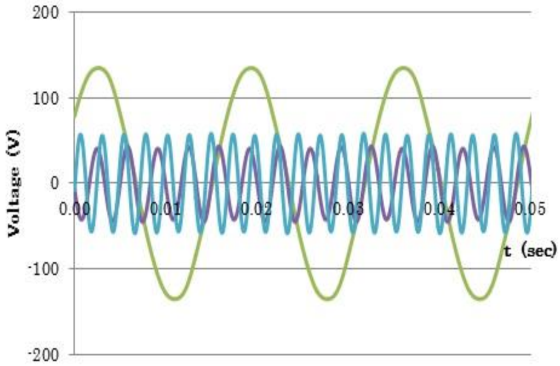


(d) $\theta_{d2}=-\pi/2$ rad

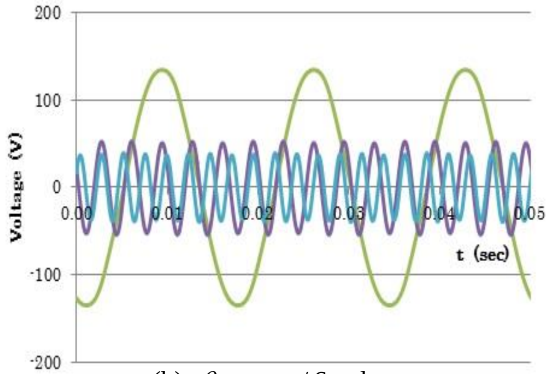
Fig. 10. Power spectrum of armature voltage in delaying only θ_{d2} ($I_{d2e}/\sqrt{2}=I_{q2}/\sqrt{2}=0.1$ A, $\theta_{q2}=0$ rad: constant)

Fig. 10. (a) - (d) show the power spectrums of the armature voltage in the case of supplying simultaneously the currents of $I_{d2e}/\sqrt{2}=0.1$ A and $I_{q2}/\sqrt{2}=0.1$ A to the windings d2 and q2 respectively, and in delaying only the phase θ_{d2} at each $\pi/6$ rad. Moreover, the waveforms of the fundamental, 5th and 7th harmonic waves are given in Fig. 11. It is confirmed that the 5th harmonic wave increases and the 7th harmonic wave decreases, when θ_{d2} decreases. In the case of $\theta_{d2}=-\pi/2$ rad, it is recognized that the 7th harmonic wave becomes almost 0.

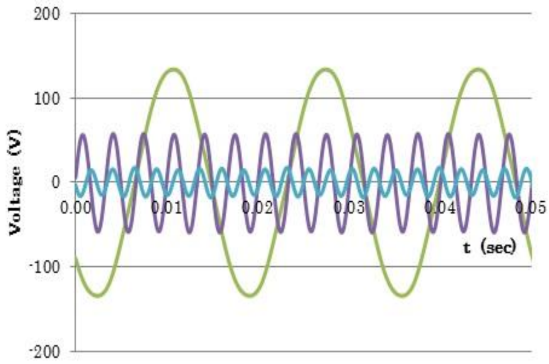
Figure 12 (a) - (c) shows the power spectrums of the armature winding voltage in delaying only the phase θ_{q2} at each $\pi/6$ rad. Moreover, the waveforms of the fundamental, 5th and 7th harmonic waves are given in Fig. 13. It is confirmed that the 7th harmonic wave increases and the 5th harmonic wave decreases, when θ_{q2} decreases. In the case of $\theta_{q2}=-\pi/2$ rad, it is recognized that the 5th harmonic wave becomes almost 0.



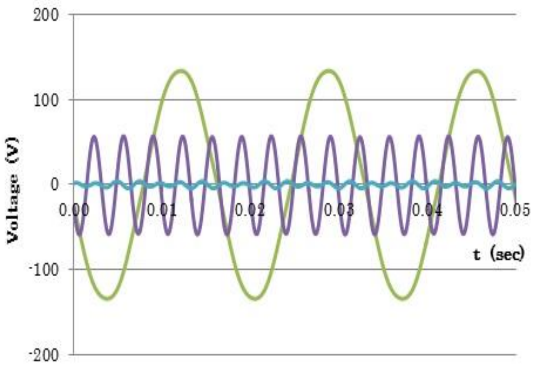
(a) $\theta_{d2} = 0$ rad



(b) $\theta_{d2} = -\pi/6$ rad

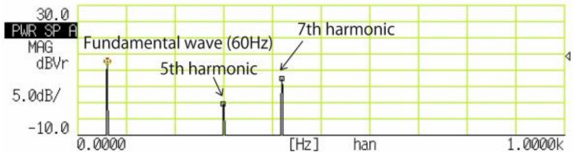


(c) $\theta_{d2} = -\pi/3$ rad

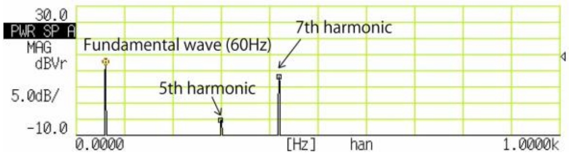


(d) $\theta_{d2} = -\pi/2$ rad

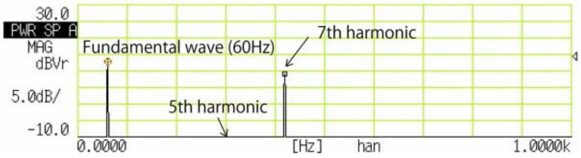
Fig. 11. Waveforms of fundamental and harmonic waves of armature voltage in delaying only θ_{d2}
($I_{d2e}/\sqrt{2} = I_{q2}/\sqrt{2} = 0.1$ A, $\theta_{q2} = 0$ rad: constant)



(a) $\theta_{q2} = -\pi/6$ rad

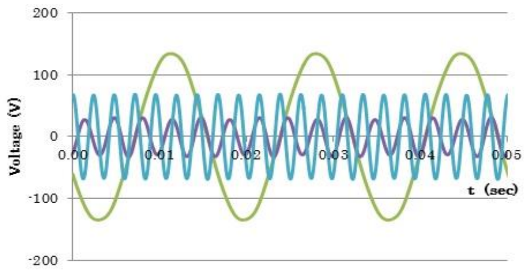


(b) $\theta_{q2} = -\pi/3$ rad

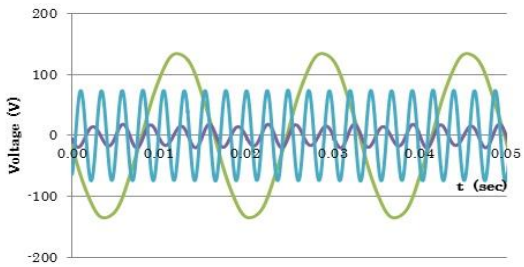


(c) $\theta_{q2} = -\pi/2$ rad

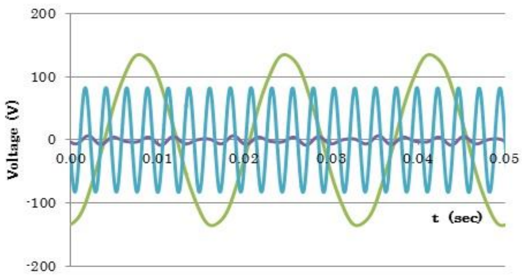
Fig. 12. Power spectrum of armature voltage in delaying only θ_{q2}
($I_{d2e}/\sqrt{2} = I_{q2}/\sqrt{2} = 0.1$ A, $\theta_{d2} = 0$ rad: constant)



(a) $\theta_{q2} = -\pi/6$ rad



(b) $\theta_{q2} = -\pi/3$ rad



(c) $\theta_{q2} = -\pi/2$ rad

Fig. 13. Waveforms of fundamental and harmonic waves of armature voltage in delaying only θ_{q2}
($I_{d2e}/\sqrt{2} = I_{q2}/\sqrt{2} = 0.1$ A, $\theta_{d2} = 0$ rad: constant)

4. Comparison between Experimental Value and Theoretical Value

In this section, the values calculated from the theoretical expressions [7] of harmonic voltages in armature winding are compared with the values obtained by the experiment in the previous section.

In the calculation due to the theoretical expression, since the values of the mutual inductance M_{ad2} (between the winding d2 and the armature winding) and the mutual inductance M_{aq2} (between the winding q2 and the armature winding) are required, these values were measured. Table 2 shows the measured values of these mutual inductances. Measurement frequency was changed from 60Hz to 420Hz. Because the variation of these values is small within the frequency, then, the value of $M_{ad2} \approx M_{aq2} = 0.13$ H will be used in the following.

Table 2. Mutual inductance of experimental synchronous machine (Measured Value)

Mutual inductance	Measured Value (H)
M_{ad2}	0.13
M_{aq2}	0.13

4.1 Case of Supplying Current to only Winding q2

In the case of supplying the current ($I_{q2}/\sqrt{2} = 0.1$ A, $\theta_{q2} = 0$ rad) with frequency $6f$ to only the winding q2, the measured values of the 5th and 7th harmonic voltages of the armature winding in an effective value were 12.1V and 16.9V, respectively.

The theoretical expressions of the 5th harmonic voltage v_{aq5} and the 7the harmonic voltage v_{aq7} in this case are given by the following equations.

$$v_{aq5} = 5\omega \cdot M_{aq2} \cdot (I_{q2}/2) \cdot \cos(5\omega t - \pi/2) \qquad (2)$$

$$v_{aq7} = 7\omega \cdot M_{aq2} \cdot (I_{q2}/2) \cdot \cos(7\omega t + \pi/2) \qquad (3)$$

The 5th harmonic and 7th harmonic voltages in an effective value are calculated from these equations. Consequently, the 5th harmonic voltage and the 7th harmonic voltage in an effective value are 12.3V and 17.2V, respectively.

It is confirmed that the values of harmonic voltages obtained by the theoretical expressions agree comparatively well with the experimental values.

4.2 Case of Supplying Currents to both Windings

In the case of supplying the currents ($I_{d2e}/\sqrt{2} = I_{q2}/\sqrt{2} = 0.1$ A, $\theta_{d2} = \theta_{q2} = 0$ rad) with frequency $6f$ to the winding d2 and the winding q2, the measured values of the 5th and 7th harmonic voltages of the armature winding in an effective value were 17.7V and 23.2V, respectively.

The theoretical expressions of 5th harmonic voltage v_{a5} and 7th harmonic voltage v_{a7} are given by the following equations.

$$\begin{aligned} v_{a5} &= v_{ad5} + v_{aq5} \\ &= 5\omega \cdot \{M_{ad2} \cdot (I_{d2}/2) \cdot \cos(5\omega t) \\ &\quad + M_{aq2} \cdot (I_{q2}/2) \cdot \cos(5\omega t - \pi/2)\} \end{aligned} \qquad (4)$$

$$\begin{aligned} v_{a7} &= v_{ad7} + v_{aq7} \\ &= 7\omega \cdot \{M_{ad2} \cdot (I_{d2}/2) \cdot \cos(7\omega t) \\ &\quad + M_{aq2} \cdot (I_{q2}/2) \cdot \cos(7\omega t + \pi/2)\} \end{aligned} \qquad (5)$$

Using these equations, the results that the 5th and 7th harmonic voltages in an effective value are respectively 17.3V and 24.2V are obtained.

In this case, it is also confirmed that the value of harmonic voltage obtained by the theoretical expression agree comparatively well with the experimental value.

5. Conclusions

In this study, the following results were obtained.

(1) By using the 6 times frequency multiplier, it was possible to make the voltage with frequency $6f$ synchronized to the frequency f of the power line.

(2) The waveforms of the harmonic components of armature voltage in supplying the current of frequency $6f$ to only the harmonic winding d2 or q2 were clarified together with the fundamental waveform.

(3) The waveforms of the harmonics of the armature voltage in the case of supplying simultaneously the currents to the windings d2 and q2 became clear.

(4) It was shown by the power spectrum and the waveforms that 5th or 7th harmonic of the armature voltage become almost zero when I_{d2e} is equal to I_{q2} and the phase difference between the currents is $\pi/2$ rad.

(5) It was confirmed that the values of harmonic voltages obtained by the theoretical expressions agree comparatively well with the experimental values.

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