Bandwidth and Phase Characteristic Requirements for High-Precision Power Measurement of High-Frequency and High-Current PWM Control Inverters

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In the development of electric vehicles (EVs) to contribute to a decarbonized society, higher-efficiency drive motors and control inverters are desirable, and highly precise and accurate power measurements are essential. As it is necessary to measure the pulse-width modulation (PWM) components and high currents of large-capacity inverters, there are key points to note especially on current measurement, and accurate power measurements require a flat measurement bandwidth including a current sensor and the phase correction. This paper describes the key points.

Introduction

The movement toward electrification of automobiles and transportation equipment is accelerating as decarbonization and building a sustainable society are becoming increasingly active in Japan and throughout the world. Since EV development is expanding rapidly worldwide, highly precise and accurate power measurement is indispensable.

For motor drive inverters, which convert DC power to three-phase power, higher-precision power measurements can be made by securing the necessary measurement bandwidth, applying phase correction, and selecting dedicated accessories that apply to the higher frequency components and noise effects caused by PWM and current sensor errors.

This paper studies the following three key points for accurate power measurement of PWM control inverter output:

・Characteristics of active power over a wide bandwidth due to distorted voltage and current waveforms

・Bandwidth required for power measurement of PWM control inverter

・Effect and correction of current sensor phase error

As a specific example of a power measurement instrument using a current sensor, the phase characteristics and correction effect of the Yokogawa CT Series of current sensors and the newly developed current sensor element (model number 760903) for the WT5000 Precision Power Analyzer (the flagship model of Yokogawa) is introduced here in Figure 1.

Figure 1: External view of the WT5000 (upper), and an example of connecting 760903 and CT1000A (lower)

Basics of AC power

When discussing the bandwidth required for power measurement of a PWM control inverter, it is important to understand the characteristics of active power over a wide bandwidth. When the voltage and current are DC or with no phase shift between voltage and current, the active power is the product of the rms voltage and the rms current. However, a phase difference occurs when the active power is the product of the rms voltage, the rms current, and the power factor. The power factor is cosφ and φ is the phase difference between voltage and current for one single frequency component. If the voltage and current waveforms are distorted, thus containing harmonic components, the power P is expressed by equation (1) as the time average of the instantaneous power, which is the product of the instantaneous voltage u (t), and the instantaneous current i (t).

$$P = \frac{1}{T}\int_0^T u(t) \times i(t)\, dt$$

$$= \frac{1}{T}\int_0^T \{+U_{R0} \textstyle\sum_{k=1}^{\infty} \sqrt{2}U_{Rk}\cos(k\omega t - \varphi_{uk})\}$$

$$\times \{I_{R0} + \textstyle\sum_{k=1}^{\infty} \sqrt{2}I_{Rk}\cos(k\omega t - \varphi_{ik})\}\, dt$$

$$= \frac{1}{T}\int_0^T \{U_{R0} \times I_{R0} + U_{R0} \times \sqrt{2}I_{R1}\cos(\omega t - \varphi_{i1}) + \cdots$$

$$2 \times U_{Rk}\cos(k\omega t - \varphi_{uk}) \times I_{Rk}\cos(k\omega t - \varphi_{ik}) + \cdots\}dt$$

$$= U_{R0}I_{R0} + \textstyle\sum_{k=1}^{\infty} U_{Rk}I_{Rk}\cos(\varphi_{ik} - \varphi_{uk})$$

...(1)

Here, T: period, U_{R0} : DC component of voltage, I_{R0} : DC component of current, k: order of harmonic component, U_{Rk} : rms voltage of the kth order component, I_{Rk} : rms current of the kth order component, φ_{uk} : voltage phase angle of the kth order component, φ_{ik} : current phase angle of the kth order component

This equation shows that the active power over a wide bandwidth due to distorted waveform voltage and current is the sum of the DC power and the active power given by [each frequency's rms voltage X rms current X power factor].

A characteristic, in this case, is that the term of the product of voltage and current with different frequencies becomes zero by periodic integration. This means that the bandwidth required for power measurement is equal to the required bandwidth of voltage or current that is the lowest, i.e., is the least distorted signal.

Frequency component of the power output from a PWM control inverter and applied to a motor

Three-phase PWM control inverters, used in many motor control systems, convert a DC input into a three-phase AC output power to control load motors. The output power has two main components, a fundamental frequency band related to the motor drive rotation frequency, and a carrier frequency band for PWM.

The fundamental frequency is determined by the drive motor's pole count and rotational speed. For example, if the pole count is eight and the rotational speed is 1500 rpm, the fundamental frequency will be 100 Hz. The carrier frequency is set to a higher frequency than the fundamental frequency and controls the load motor based on the PWM principle.

The components in the carrier frequency domain of the current and power output from the inverter vary greatly and depend on the parameters that make up the load motor. When the inductance, Lm, between the motor terminal and the neutral point is small, a current in the higher band flows easily and power at frequencies other than the fundamental frequency becomes relatively large. On the other hand, when the Lm is large, the current components at high frequencies are smaller than those at the fundamental frequency. Consequently, the power at the fundamental frequency is considered to be dominant.

A simulation was performed with an assumed circuit. Figure 2 shows an example circuit of a three-phase PWM control inverter and a RL load simulating a motor load. The configuration parameters were 100 Hz fundamental waveform, 10 kHz carrier, 100 Vdc inverter input, 1 Ω resistance, and 1 mH inductance on the assumption of a load motor. In this simulation, the frequency components of the power were analyzed in phase R only, assuming that the circuit conditions of each phase were the same.

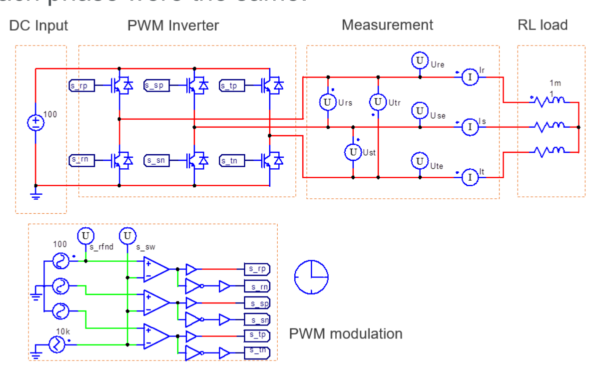

Figure 2. Circuit of three-phase PWM control inverter and RL load

The active power at each frequency was calculated based on the FFT analysis data of the voltage and current waveforms. With the active power at the fundamental frequency being 100%, the change in active power when the measurement bandwidth was expanded was observed. The results are shown in Figure 3.

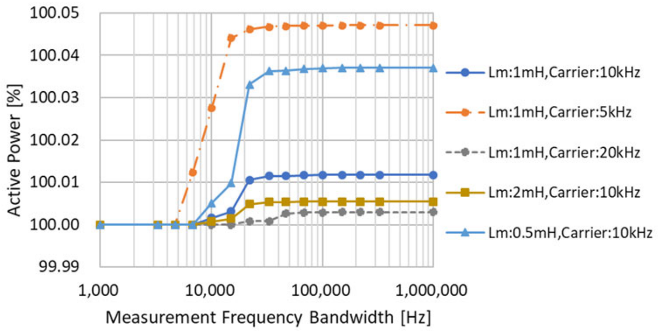

Figure 3: Relationship between measurement bandwidth and active power with the fundamental frequency as 100%. (Inductance 0.5 to 2mH, carrier frequency 5 to 20kHz)

In cases where the inductance of the motor is changed and the carrier frequency of the inverter is changed, the increase in active power saturates as the measurement bandwidth expands, indicating that the active power is made up of the fundamental waveform component and power components up to several times the carrier frequency. When the inductance component of the load motor is large or when the carrier frequency is high, the increase to saturation is small. The simulation results confirm that the current flow is suppressed by the inductance component.

The next part discusses the effect of the phase characteristics of a current sensor, which is essential for high current measurements on the active power. The propagation delay characteristics of a current sensor appear as phase characteristics for each frequency component and are added as an error factor to the voltage/current phase difference in power measurement.

The relationship between the current sensor's propagation delay, dly [s], and the active power, $P(f)$ [W], at frequency f [Hz] is shown in equation (2). Figure 4 shows the results when a propagation delay of 1000 ns was given to the power calculations in Figure 3 according to the equation (2).

$$P(f) = S(f) \times \cos\{\varphi(f) + \Delta\varphi\}$$
$$= S(f) \times \cos\{\varphi(f) + (dly) \times f \times 360\}$$
... (2)

Here, $S(f)$ is the apparent power at frequency f, [VA]; $\varphi(f)$ is the voltage-current phase difference of the measurement target at frequency f, [°]; $\Delta\varphi$ is the phase error of the current sensor, [°].

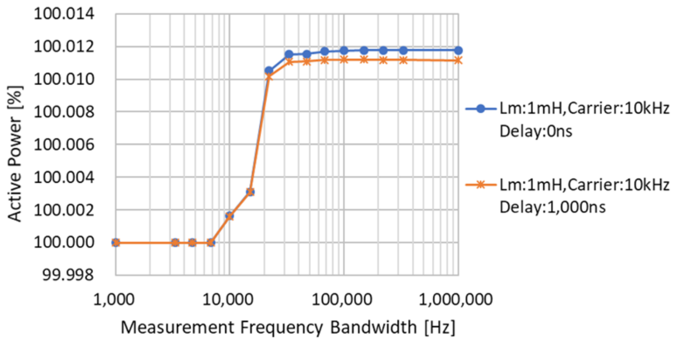

Figure 4 Relationship between measurement bandwidth and active power, with the fundamental frequency as 100%. (Effect of phase error due to propagation delay)

With the power calculation results with no propagation delay taken as the true values, differences due to the phase error can be seen especially in the higher frequency range than a frequency that is about twice the carrier frequency. In addition, the differences remain almost constant over the high-frequency range. This can be attributed to the fact that in the high-frequency band, the inductance is dominant with the power with zero power factor and, at the same time, the apparent power is small, and the effect of phase error on the active power is small. From the above, it can be seen that in terms of the voltage-current phase difference characteristics including the current sensor, the bandwidth required for power measurement is limited by the inductive load in a motor drive inverter or the like.

Correction function required for the power analyzer and current sensor

Measurement with a current sensor is essential for power measurement of a large-capacity inverter, and the measurement accuracy depends heavily on the current sensor. Accordingly, a function to correct the characteristics of current sensors is desired for power analyzers. While conventional power analyzers have provided the correction of the gain and offset of current signals, the phase correction is now also required as the carrier frequency becomes higher.

Accurate current and power measurements can be obtained by correcting the gain and offset. By correcting the gain characteristics based on the calibration value of the current sensor, the measurements corrected with the calibration value can be obtained. The offset function cancels (makes it zero) the measured value at the point of no input (offset) while the current sensor is connected to the power analyzer's main body. This enables measurement with unnecessary residual offset removed.

Correcting the phase characteristics is another measure that should be considered to improve the measurement accuracy. The Yokogawa WT5000 Precision Power Analyzer is equipped with a function to correct the phase difference error between voltage and current caused by the phase error of a current sensor.

Table 1 shows the propagation delay of current sensors when using the WT5000, 760903 current sensor element, and current sensor (CT series).

Table 1: Propagation delay of current sensor (CT series)

Current sensor	CT60	CT200	CT1000	CT1000A	CT2000A
Propagation delay (Typical) [ns]	70	70	110	10	40

For propagation delay, the + (plus) sign indicates the delay.
CT preset of the current sensor element 760903 was set.
761954/761955/761956 dedicated cables were used.

The WT5000 employs a method of setting the phase error value at a specific frequency as a function to correct the propagation delay time of a current sensor. Table 2 shows typical phase error values for each CT sensor in the range from low frequencies to the frequency at which the phase characteristics are flat, assuming a significant power measurement of an inverter whose bandwidth is limited by driving an inductive load.

Table 2: Frequency and phase error corresponding to propagation delay

Current sensor	CT60	CT200	CT1000	CT1000A	CT2000A
Frequency [kHz]	10	10	5	5	10
Phase error [°]	−0.252	−0.252	−0.198	−0.018	−0.144

For phase error, the − (minus) sign indicates the phase delay.

Figures 5, 6, 7, and 8 show the phase characteristics when the corrections were made using the values in Table 2.

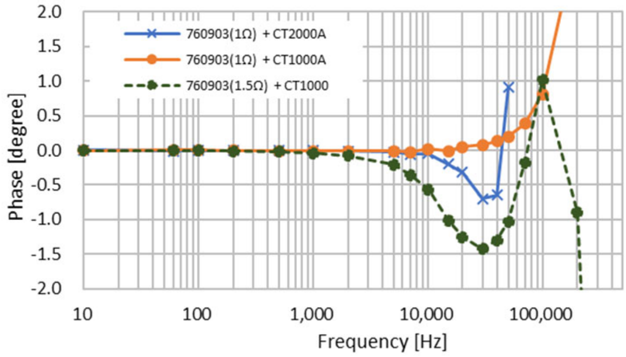

Figure 5: Current phase frequency characteristics when a current sensor is combined with WT5000 before correction 1

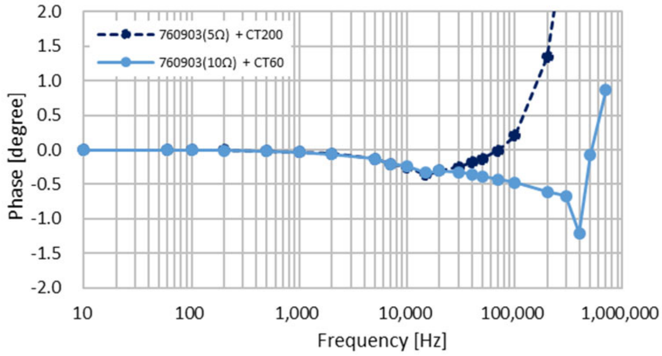

Figure 6: Current phase frequency characteristics when a current sensor is combined with WT5000 before correction 2

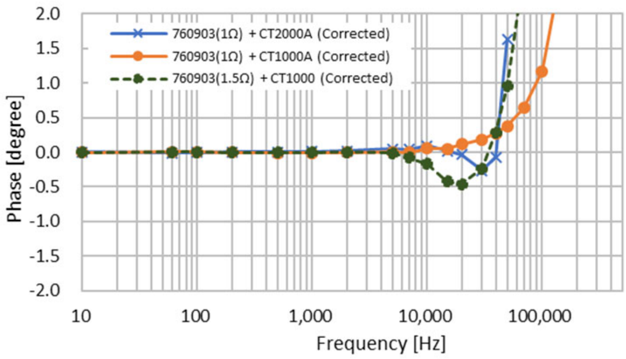

Figure 7: Current phase frequency characteristics when a current sensor is combined with WT5000 after correction 1

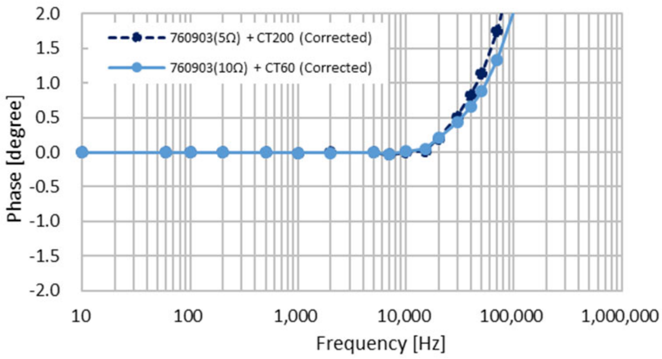

Figure 8: Current phase frequency characteristics when a current sensor is combined with WT5000 after correction 2

Output power of PWM control inverter and effect of phase correction of current sensor

Figure 9 shows the results when a current sensor (CT1000A and CT200) is used for the inverter output in the actual measurement of the power conversion efficiency of a three-phase PWM control inverter. The measurements with the CT1000A before and after phase correction are close to each other. This seems to be because the propagation delay of the CT1000A is small. The measurement with the CT200 after phase correction is closer to the measurements with the CT1000A, suggesting that the effect of phase correction is greater for current sensors with larger propagation delays.

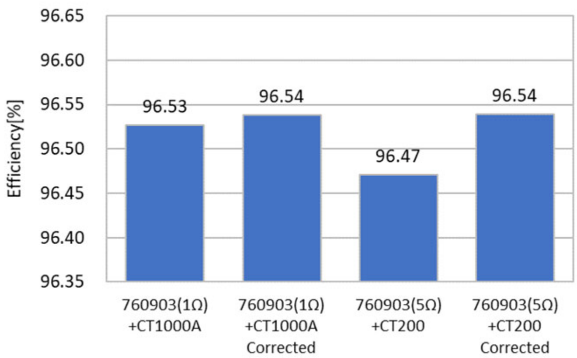

Figure 9: Measurement results of power conversion efficiency

Conclusion

This study indicates that accurate and highly precise active power measurement required in the development of motors and inverters for EVs, which drive inductive loads, requires a measurement bandwidth of several times the carrier frequency and a current sensor with a small propagation delay. The Yokogawa WT5000 Precision Power Analyzer has a phase correction function and provides higher-precision power measurement in combination with the 760903 current sensor element and current sensor (CT series).

The PWM control inverter is considered to be an indispensable power conversion technology for decarbonization and the creation of a sustainable society. Yokogawa remains committed to contributing to a more enriched human society through high-precision power measurement and analysis of PWM control inverters under the theme of measurement, control, and information.

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