Clamp On Power Logger PW3365
Safety Voltage Sensor PW9020

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Abstract—**The Clamp On Power Logger PW3365 is a power meter that can measure voltage, current, and power from outside a cable, without the need to establish contact with a metal surface. The Safety Voltage Sensor PW9020 is a voltage sensor designed specifically for use with the PW3365. This paper describes these products' features, architecture, and characteristics.**

I. Introduction

Awareness of the need to conserve energy continues to rise following the enactment of the ISO 50001 standard for energy management systems as well as laws mandating energy conservation in various countries. Against this backdrop, the need for electrical equipment maintenance, replacement of aging infrastructure with new equipment, demand monitoring capabilities, and other services is growing, creating new opportunities for workers who are unfamiliar with measuring instruments to perform power measurement. As a result, there is a rising level of need for the ability to measure power safely and easily, creating demand for power meters that are characterized by a high level of safety and ease of operation.

II. Overview

The Clamp On Power Meter PW3365 is the first power meter in the world to be able to measure voltage, current, and power from outside a cable. Technicians have been able to measure current using clamp-on current sensors instead of clipping directly onto live (metal) contacts for some time, but measuring voltage has required attaching metal clips directly to live parts such as the metal terminals of circuit breakers or busbars, posing the risk of short-circuit accidents in which a clip comes into contact with an adjacent terminal or electric shock due to unintended contact. To address these hazards, Hioki designed the new Safety Voltage Sensor PW9020 to measure voltage from outside the cable, eliminating the need to establish contact with metal. Used in combination with a clamp-on power meter, this sensor makes it possible to measure power safely.

The PW3365 represents an across-the-board continuation of the Clamp On Power Logger PW3360,

Appearance of the PW3365

Appearance of the PW9020

which was launched in 2012, including that Hioki's Quick Set functionality, which prevents setting and connection mistakes, and connection check functionality. In this way, the PW3365 is designed so that even workers who are unfamiliar with power meters can carry out measurement in a reliable, mistake-free manner.

III. Functions and Features

1) High level of safety thanks to the PW9020

Whereas voltage measurement has been restricted to live components until now, the PW9020 is able to make measurements safely from outside the cable. Measurements can also be made at live components, giving the device a high level of flexibility. Since there are no exposed metal parts on the sensor's enclosure, there is no risk of causing a short-circuit when it is attached to a live component. These advantages translate to improved safety and operability in the field, where power meters are used. The sensor's design satisfies the EN 61000 CAT III (600 V) standard.

2) Compact design

The power meter uses the same design as the PW3360 and can accommodate targets up to 3-phase/4-wire circuits despite its compact size. A small power meter is an extremely useful asset when performing measurement in a confined space such as a distribution panel.

3) Enhanced ease of use thanks to Quick Set function

To measure power reliably, it is essential to configure the instrument and connect it properly. Hioki's Quick Set function guides the user through the setup process, including configuration of settings, connection of the instrument, verification of the connection, and start of recording. This function helps prevent configuration and connection mistakes.

4) Wiring verification function (With wiring error display)

Help functionality lets end-users review pointers for fixing connection mistakes on the instrument's screen.

5) Demand and time-series ("TIME PLOT") graph displays

Demand graphs, which display the trend in demand values as a bar graph, are a useful tool in power management. Users can also review maximum demand values and the times at which they occurred during recording and measurement operation.

Time-series ("TIME PLOT") graphs display variations in the maximum, minimum, and average values for a user-selected measurement parameter as a graph. Values can be read using the cursor, allowing power utilization and other characteristics to be checked in the field when the operating status of the target equipment changes.

6) Battery-powered operation

The PW3365 can perform measurement continuously for about five hours in locations where a power supply is not available when using the Battery Set PW9002 (option). The PW9002 attaches to the rear of the PW3365.

7) Storage of long-term data on an SD memory card

The PW3365 supports SD memory cards of up to 32 GB in capacity, allowing up to one year of continuous measurement.

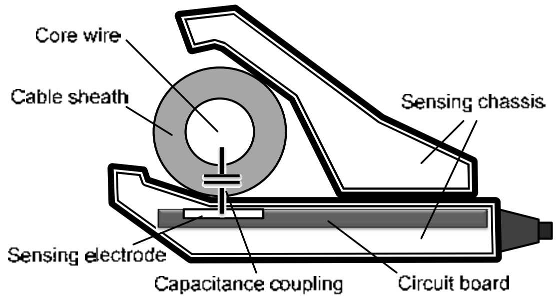


Fig. 1. PW9020 Electrode Design (Cross-sectional view)

8) Simultaneous measurement of power and leak current

For 1-phase/3-wire and 3-phase/3-wire (2-wattmeter) connections, the PW3365 can measure power and leak current simultaneously. The instrument can also be used as a leak current logger with up to three channels without measuring voltage. In addition to RMS values, the PW3365 allows users to check leak current values for only the fundamental wave component (50 Hz/60 Hz) after harmonic components have been eliminated.

9) Remote operation via a LAN connection

The PW3365's hypertext transfer protocol (HTTP) server function allows the unit to be operated remotely via a computer's Internet browser. In addition, dedicated freeware (PW3360/PW3365 Configuration and Download Software, which supports both instruments) can be used to download data from the instrument's SD memory card.

IV. Safety Voltage Sensor PW9020 Measurement Principles and Architecture

A. Measurement Principles

Fig. 1 provides a cross-sectional view of a PW9020 that has been clamped around a cable. Inside the sensor, the circuit board and its integrated sensing electrode are positioned so that they face the cable's conductor. As a result, electrical capacitive coupling occurs between the conductor and the sensing electrode across the cable's insulation, the sensor's plastic enclosure, and whatever space exists between the two. Equation (1) summarizes the relationship at this time, which causes a current that is proportional to changes in the voltage (differential values) to flow between the conductor and the sensing electrode.

$$i = C \frac{d}{dt} v \tag{1}$$

i: Current [A]
C: Coupling capacitance [F]
v: Potential difference [V]

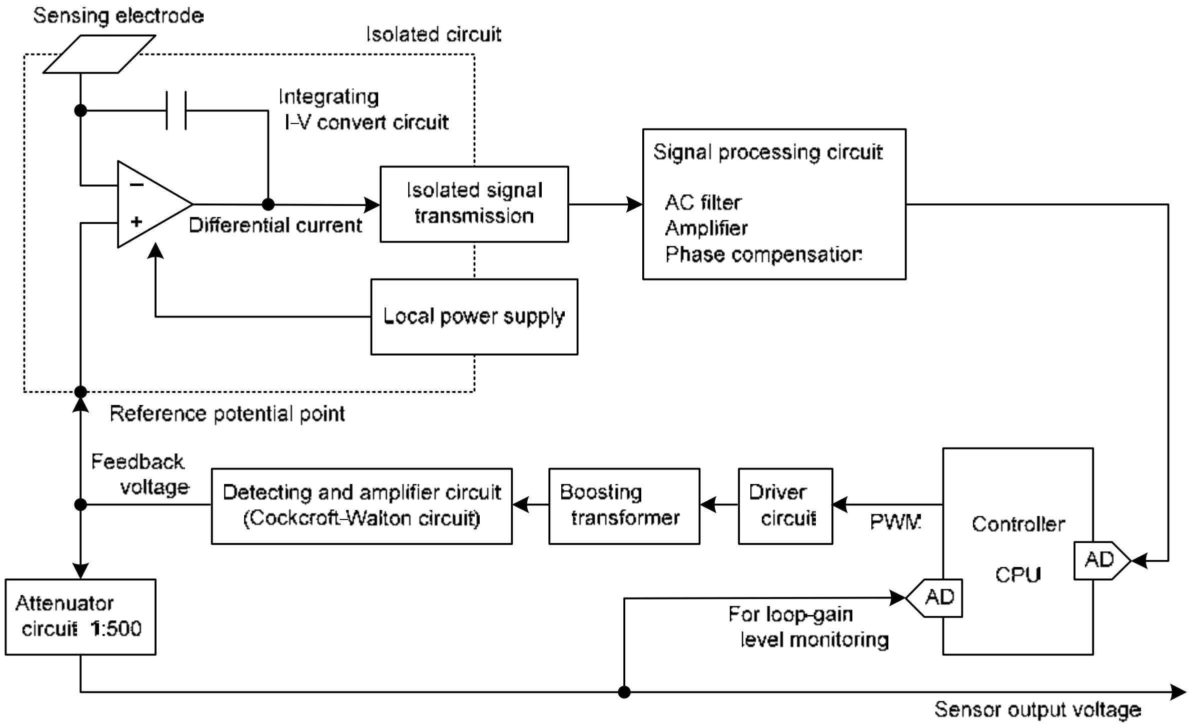


Fig. 2. Block Diagram (PW9020)

Consequently, in principle it is possible to calculate the voltage value by integrating the current if the coupling capacitance *C* is known. However, the material and thickness of the cable's insulation across which the capacitive coupling is occurring remain unknown parameters. Furthermore, variations in the dielectric constant caused by temperature and variations in characteristics caused by the existence of the space between the sensing electrode and the cable make it difficult to calculate the coupling capacitance *C* in advance.

A potential is generated on the sensing electrode side such that the current *i* approaches zero in accordance with (1) (in other words, such that the potential difference *v* decreases). When the current *i* reaches zero, the voltage in the cable and the voltage being generated at the sensing electrode have the same AC amplitude and phase. At this time, measuring the generated voltage is equivalent to measuring the voltage in the cable, even if the coupling capacitance *C* remains unknown.

This method can be used to make measurements at live contacts as well as with cables since the space between the conductor and the sensor's plastic enclosure results in capacitive coupling.

B. *Electrical Circuit Architecture*

The PW9020 comprises a negative feedback system in order to implement the functionality described in 4.1 above.

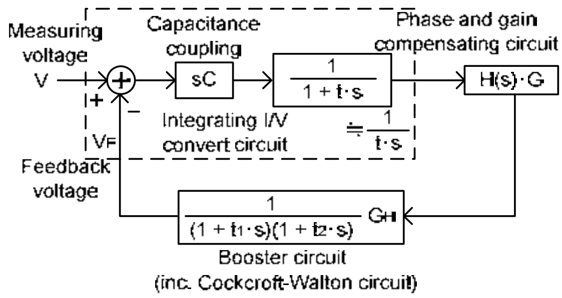


Fig. 3. Simplified Model of Negative Feedback System

Fig. 2 provides a block diagram of the PW9020's electrical circuit, while Fig. 3 provides a general model corresponding to Fig. 2. Following is a description of the negative feedback system.

First, a miniscule current is detected with the I-V converter, which provides integration functionality. Since I-V converter output is subject to integration as described in (1), it results in a waveform that resembles the voltage of the measurement target V. This waveform is given the necessary gain to create the negative feedback voltage Vf, which is applied at the I-V converter's reference potential point. If the negative feedback system's loop gain is sufficiently large, the current will approach a value of zero, and the amplitude and phase of the feedback voltage will be approximately equal to those of the measurement target's voltage.

The actual sensor architecture consists of a microcontroller (CPU) positioned on a loop. The microcontroller's principal tasks are to generate the pulse width modulation (PWM) signal used to drive the step-up transformer and to monitor the circuit to ensure that the loop gain is appropriate. The focus on miniaturization in the PW9020's design process made it necessary to shrink the size of its circuitry, making it difficult to implement an advanced phase compensation circuit. Consequently, excessively large loop gain values raise the risk of oscillation. In Hioki's design, it sought to achieve stabilization by using the microcontroller to correct the loop gain.

The sensor's electrical circuit operates using power supplied from the PW3365 power meter.

C. Mechanisms

1) Architecture and features

Fig. 4 depicts the external appearance of the PW9020, which consists of a sensor assembly and relay box assembly. The sensor assembly in turn incorporates a sensor board that includes a sensing electrode, while the relay box assembly houses the control board for the negative feedback system, including the microcontroller and step-up transformer.

The top and bottom parts of the sensor assembly's enclosure, which are clipped to the measurement target, differ in their shape (see Fig. 5). The reason for this difference is explained below.

The PW9020 can measure conductors with an outer diameter ranging from 6 mm to 30 mm. Use of a clip design with symmetrical upper and lower elements shaped to accommodate cables with a large diameter (30 mm) would result in a larger clip with a larger curved profile. In addition to making it difficult to clip the sensor to cables with a small diameter (6 mm), such a design would compromise sensing accuracy by preventing the cable from being held near the sensor's internal electrode (whose location is indicated by the triangular mark on the enclosure).

To resolve this issue, Hioki lengthened the curve on the lower clip to accommodate large-diameter cables and shortened the profile of the upper clip for use with small-diameter cables. As a result, at least one of these curves will serve to hold the cable in the proper position, enabling the sensor to measure cables with outer diameters ranging from 6 mm to 30 mm in a stable and consistent manner (see Figs. 6 and 7).

In addition, use of a long curve profile for the lower clip enables the sensor to cover much of the measurement target. The lower clip incorporates a guard electrode sheet designed to block external electrical fields, and this design reduces the effects of these fields by covering a large amount of the measurement target.

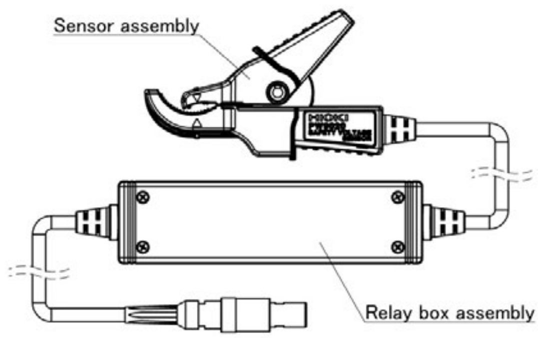


Fig. 4. Appearance of the PW9020

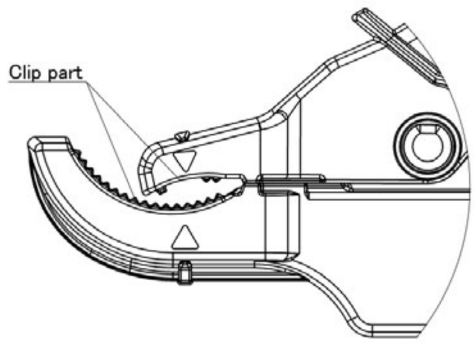


Fig. 5. Enlarged View of Clip

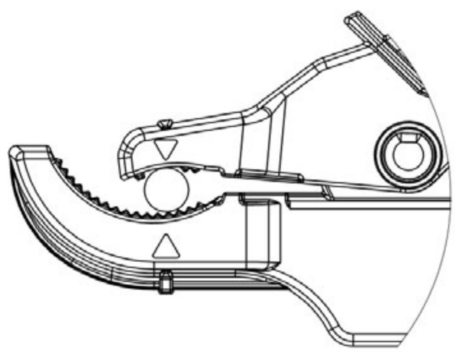


Fig. 6. When Clipping to a Cable With a Diameter of 6 mm

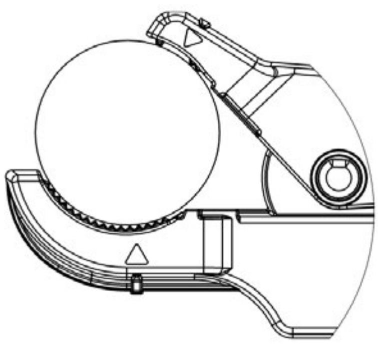


Fig. 7. When Clipping to a Cable With a Diameter of 30 mm

Furthermore, use of a shortened upper clip limits the clip position for small-diameter cables, making it possible to structurally position them near the electrode (see Fig. 6).

In this way, the PW9020's asymmetrical clip design provides both mechanical and electrical advantages.

2) Enclosure material and insulated design

The sensor assembly's enclosure is made of resin that delivers an exceptional level of rigidity, resistance to chemical substances, and resistance to heat. The resulting resistance to damage serves to improve safety during measurement. In addition, enclosure components are bonded together by means of ultrasonic welding and designed to stay isolated from the sensor assembly's internal components.

3) Exploded view of sensor assembly

Fig. 8 illustrates the internal structure of the sensor assembly. The lower enclosure piece incorporates the sensor board, and both the upper and lower enclosure pieces have guard electrode sheets. This simple design contains only a small number of parts, reflecting Hioki's efforts to lower assembly man-hours and reduce the unit's weight.

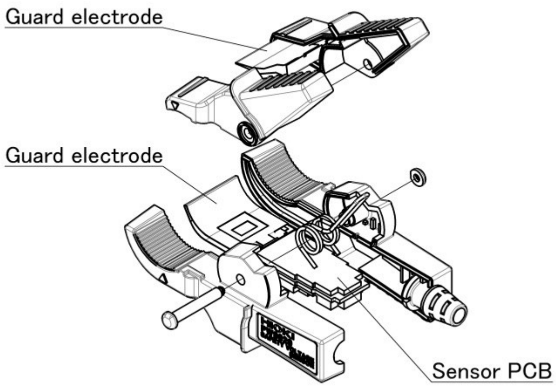


Fig. 8. Exploded View of the Sensor Assembly

V. PW3365 Power Meter Architecture

A. Measurement Circuit

Fig. 9 provides a block diagram for the PW3365 power meter's measurement circuit. The instrument's measurement circuit consists of three voltage channels and three current channels. Voltage inputs are isolated from the measurement target (device under test) by the PW9020, while current inputs are isolated by a voltage output-type clamp-on current sensor.

The voltage sensor inputs consist of four terminals (N, U1, U2, and U3). Since the voltages between U1 and N, between U2 and N, and between U3 and N are measured using the potential detected by the PW9020 that is connected to the N terminal, as a reference, this design has three channels. The PW9020's output signal is input to the initial-stage buffer circuit, and then the voltage between the reference potential N and each channel is detected by the differential amp at the next stage.

The current sensor inputs are ranged from 1× to 50×, and users can select ranges from 0.5 A to 5,000 A depending on the combination of clamp-on current sensor and instrument range.

The A/D conversion unit switches among the three voltage channels and the three current channels by means of a multiplexer (MUX) at the speed of 61.44 kHz, with each signal being sampled by the voltage or current A/D converter. The sampling speed for each channel is 10.24 kHz. Simultaneous sampling of U1 and I1, U2 and I2, and U3 and I3 eliminates any phase difference so that there is no power error.

B. Digital Control Circuit and Software

The PW3365's digital control circuit and software use much the same design as the PW3360. Since citations in the "Reference" section[1] point the way to more detailed information, a description has been omitted here.

VI. Characteristics

Figs. 10 through 15 and TABLE I describe the characteristics of a testing setup consisting of the PW3365, PW9020, and a clamp-on current sensor (specifically, Clamp On Sensor 9660, 9661, and 9694).

A. Linearity Characteristics

Fig. 10 illustrates linearity characteristics for voltage. The vertical axis in Fig. 10(a) represents voltage display values relative to the input voltage, while the horizontal axis in Fig. 10(b) represents the logarithm to provide a graph calculated by converting the data from (a) to an error component. The graphs demonstrate that voltage error falls well within the accuracy described in the specifications thanks to the instrument's excellent linearity characteristics.

Figs. 11 and 12 illustrate linearity characteristics for current and power, respectively. The instrument delivers excellent linearity characteristics for both, and different ranges result in almost no difference in characteristics.

B. Effects of Power Factor

Fig. 13 illustrates the effects of power factor. The phase accuracy when the PW3365 and PW9020 are combined is (±1.3 deg. ±[clamp-on current sensor accuracy]). In fact, because the PW3365 has been designed to exhibit leading phase characteristics to compensate for the PW9020's lagging phase characteristics, the voltage error approaches 0 deg. when the two pieces of equipment are combined. Consequently, actual performance exhibits phase characteristics that approach those of a conventional power meter whose sensors must be attached to metal contacts.

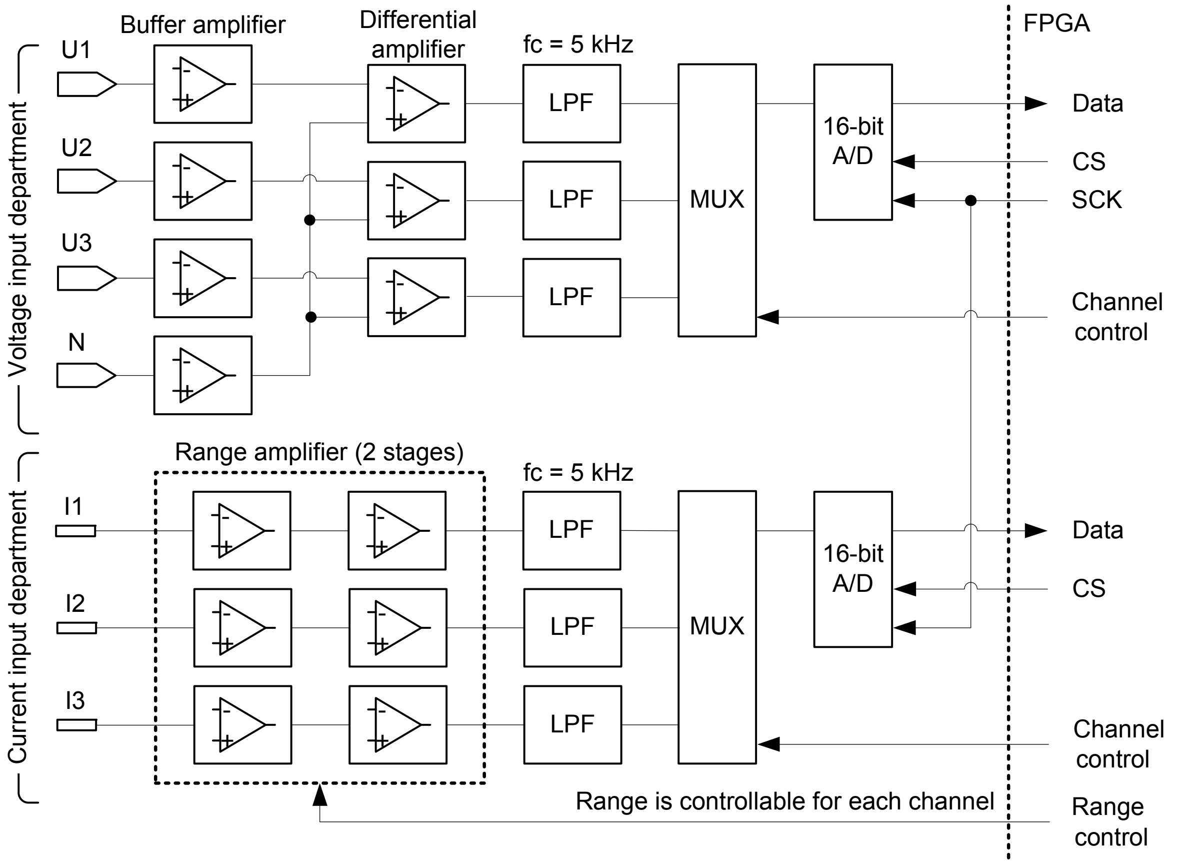
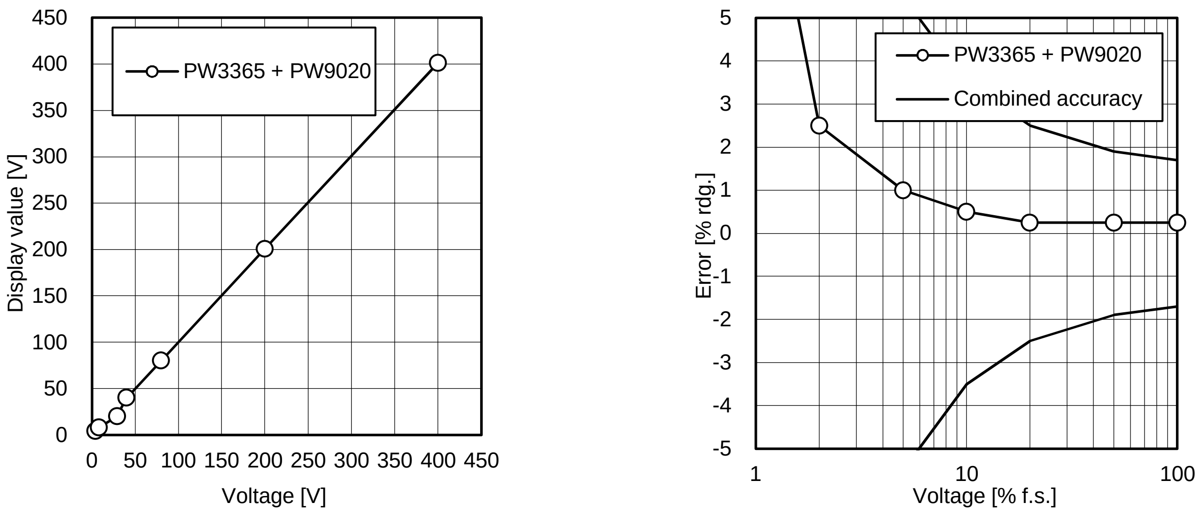


Fig. 9. Block Diagram (PW3365)



(a) Vertical axis: Voltage display value

(b) Vertical axis: Measurement error

Fig. 10. Voltage Linearity Characteristics (50 Hz)

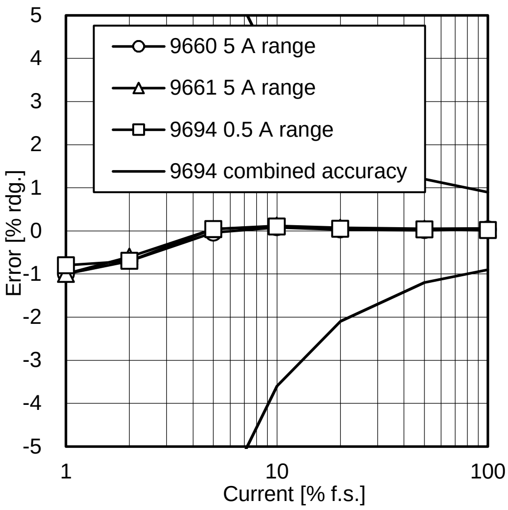


Fig. 11. Current Linearity Characteristics (50 Hz)

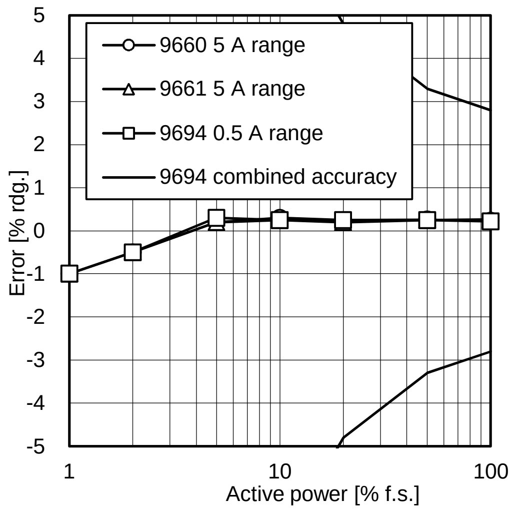


Fig. 12. Power Linearity Characteristics (50 Hz)

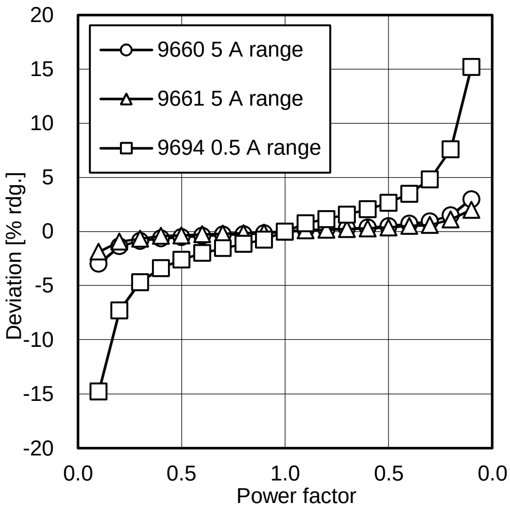


Fig. 13. Effects of Power Factor (50 Hz)

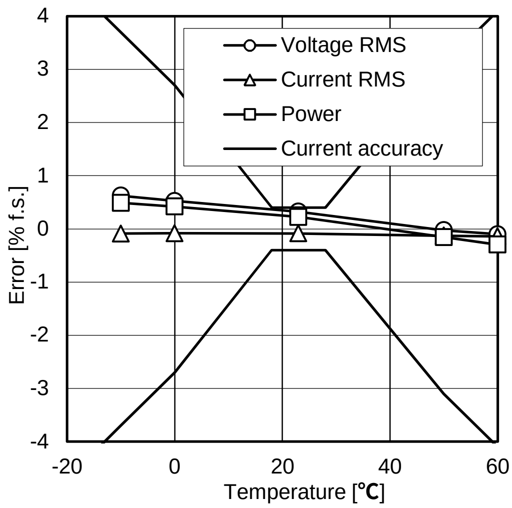


Fig. 14. Effects of Temperature (50 Hz)

C. Effects of Temperature

Fig. 14 illustrates the effects of temperature (current: 9661, 5 A range). Although measured values evidence a tendency to become somewhat higher as the temperature falls, the temperature coefficient (graph slope) exhibits sufficient margin relative to the specifications accuracy, and there is a high degree of stability. Additionally, the figure illustrates the basic accuracy (23°C ±5°C [73.4°F ±9.0°F]) under the most demanding current conditions (±0.3% rdg. ±0.1% f.s.). Since the basic accuracy figures are ±1.5% rdg. ±0.2% f.s. for voltage and ±2.0% f.s. ±0.3% f.s. for power, there is ample margin.

D. Effects of Nearby Wires (Voltage)

The extent of the effect of electric fields caused by nearby wires is inversely proportional to the distance between the nearby wire's conductor and the PW9020's sensor assembly. Consequently, if the effects of a bare wire would exert a larger effect to due to its thinner insulation.

Fig. 15 illustrates the effect of placing a bare wire carrying 400 V relative to ground in contact with the sensor assembly while measuring 0 V relative to ground. The guard electrode sheets incorporated into the sensor assembly limit the effect even when the bare wire is placed in contact with the sensor assembly at positions 1 through 5.

E. Effects of Wire Type and Outside Diameter (Voltage)

TABLE I summarizes the measurement voltage error due to the effects of wire type (CV cable, IV cable, bare wire) and outside diameter.

The PW9020's negative feedback control serves to reduce the effect of differences in coupling capacitance with the measurement target. Consequently, the maximum error

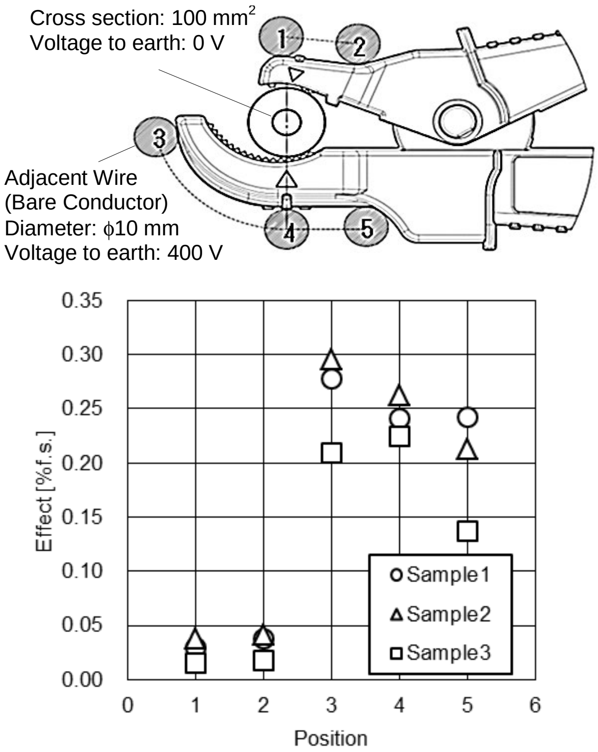


Fig. 15. Effects of Nearby Wires (50 Hz)

caused by wire type and outside diameter is about one-third the specifications accuracy.

VII. Conclusion

This paper has described Hioki's development of a power meter that can measure power safely from outside a cable by means of a voltage sensor that does not need to make contact with a metal surface. It is hoped that the instrument will be utilized in numerous applications and prove useful in power management and energy-saving activities.

TABLE I. VOLTAGE ERROR CAUSED BY WIRE TYPE AND OUTSIDE DIAMETER

Measurement wire	Input Voltage 100 V (50 Hz)		Input Voltage 400 V (50 Hz)	
	Display value **[V]**	***Error*** **[% rdg.]**	***Display value*** **[V]**	***Error*** **[% rdg.]**
CV cable†1 2 mm^2 (Diameter: 6 mm)	99.6	−0.40	398.7	−0.33
CV cable 38 mm^2 (Diameter: 13 mm)	100.2	0.20	401.0	0.25
CV cable 100 mm^2 (Diameter: 19 mm)	100.2	0.20	401.1	0.28
CV cable 200 mm^2 (Diameter: 26 mm)	100.3	0.30	400.9	0.23
IV cable†2 14 mm^2 (Diameter: 8 mm)	100.3	0.30	401.3	0.33
IV cable 60 mm^2 (Diameter: 14 mm)	100.6	0.60	402.3	0.58
Bare conductor (Diameter: 10 mm)	100.6	0.60	402.3	0.58
Busbar (Cross-section: 10 mm × 2 mm)	100.6	0.60	402.2	0.55

Environmental conditions: 25ºC (77.0ºF), 43% RH

†1 CV cable: Cross-linked polyethylene insulated vinyl sheath cable
†2 IV cable: Indoor polyvinyl chloride cable

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References

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[2] Yanagisawa, K. Non-contact voltage sensing by negative-feedback current integration. Keisoku Seigyo Gakkai, Chubu Shibu Sinpojiumu 2014, Koenronbunshu. pp. 1-4. The Cubu Chapter, The Society of Instrument and Control Engineers. (Japanese).

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