WT5000 Precision Power Analyzer

Katsuya Tachibana [*1]   **Toshiaki Shioda** [*1]   **Hiroyuki Suzuki** [*1]
Mitsuteru Shibata [*2]   **Masashi Kouno** [*1]

We have developed the WT5000 precision power analyzer featuring the world's highest measurement accuracy of ±0.03% and a measurement bandwidth of 0.1 Hz to 5 MHz including DC signals. This model features 50 times the sampling rate and 4 times the resolution of the conventional model WT3000E. With the adoption of modular-type systems, the WT5000 offers improved convenience and expandability, and can be equipped with up to seven input elements. Also, the WT5000 can measure the efficiency of input-output power such as electric vehicles (EV) and plug-in hybrid vehicles (PHV), the rotational speed of up to four motors, and the change of mechanical power with torque, all at the same time. In addition, the large screen and touch-screen display have greatly improved both visibility and usability. This paper describes the technologies that lie behind the world's highest performance, and examples of applications.

INTRODUCTION

To achieve a sustainable society, there is an urgent need to develop devices related to renewable energy such as solar- and wind-generated power and energy-efficient home electric appliances, in addition to electric vehicles (EVs) and plug-in hybrid vehicles (PHVs and PHEVs). To achieve further energy saving and higher efficiency in such vehicles, devices, and systems, demand is increasing globally for precision power analyzers that can accurately measure and evaluate small improvements in power consumption and power utilization efficiency.

To meet the demand for more precise power measurement, and also customer requests for simultaneous measurement of multiple points by a single analyzer, Yokogawa has developed the WT5000 precision power analyzer with the world's highest measurement accuracy and broadest measurement bandwidth, by improving its accumulated analog measurement and sophisticated power calibration technologies. Figure 1 shows an external view of the WT5000.

Figure 1 External view of the WT5000

*1 1st Engineering Department, Technology Development Division, Yokogawa Test & Measurement Corporation

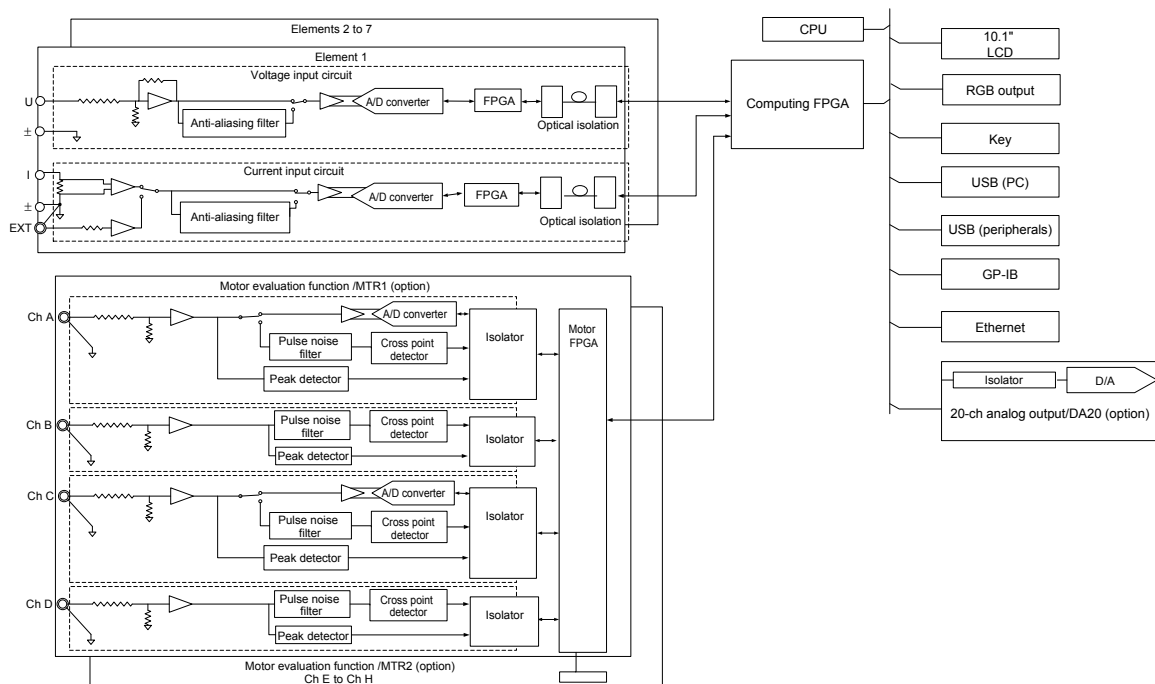*2 Common Technology Dept., Technology Development Division, Yokogawa Test & Measurement Corporation

Figure 2 Block diagram of the WT5000

HIGH PRECISION POWER MEASUREMENT AND CALIBRATION TECHNOLOGIES

Configuration

Figure 2 shows a block diagram of the WT5000, which consists of the main unit and modular-type elements for voltage and current inputs. The main unit contains the power arithmetic processing unit, display and operation panel, and communication interfaces. For the input elements, 30A (760901) and 5A (760902) high-accuracy input elements have been developed.

The WT5000 features 8 input channels for motor evaluation that enable simultaneous evaluation of 4 motors (with /MTR1 and /MTR2 options). The WT5000 also features 20 output channels, the same as the previous model (/DA20 option, although this option cannot be installed together with /MTR2).

The voltage input circuits of the input elements employ the resistive voltage division method, and the current input circuits employ the current shunt resistor method. The inputs for motor evaluation also employ the resistive voltage division method. Each signal is A/D-converted after being normalized to the required voltage level. The converted digital data is transferred to the computing unit via isolators. The voltage, current, and motor inputs are insulated individually.

Wide Measurement Range

The WT5000 features wide power measurement ranges. In addition to the 15 V to 1,000 V ranges of the previous model, 1.5 V, 3 V, 6 V, and 10 V ranges are available with the WT5000. Measurements in the 1,500 V_{dc} input is also possible. The 5A high-accuracy element (760902) has a 5 A range in addition to the 5 mA to 2 A ranges of the previous model, to meet diverse measurement needs.

High-precision, Broad-bandwidth Power Measurement

The input resistor of the voltage input circuit is 10 MΩ, to reduce the instrument loss which leads to measurement error and to suppress the variation caused by self-heating when operating on high voltage inputs. The inter-terminal capacitance for the input resistor is formed with mechanical parts, and the signal is voltage-divided by a DC-AC separated addition zero-drift composite amplifier to achieve high precision and wide bandwidth.

In the current input circuit, the 30A high-accuracy element (760901) inherits the technology used in the previous model, and the shunt resistor adopts a 5 mΩ coaxial 4-terminal structure. The low-voltage output converted by the shunt resistor is amplified by an inversion zero-drift composite amplifier, to minimize the accumulated current measurement error. In addition, the current input circuit uses different amplifier gains for each measurement range, and employs an amplifier that minimizes the variation in precision and bandwidth associated with the gain changes. Also, the voltage input circuit achieves high precision and wide bandwidth by using a DC-AC separated addition amplifier.

In addition to the performance improvement in analog circuits, the A/D converter has been improved in terms of resolution and conversion rate, 18 bit and 10 MSps, respectively, compared to those of the previous model, 16 bit and 200 kSps.

The optical isolation method is used to handle the high-speed data transfer associated with the adoption of high-precision, high-speed A/D converters. The data transfer rate is 600 Mbps. The A/D converter circuit consists of only three channels for signal information from the input element, control signal, and bidirectional communication. The insulating part
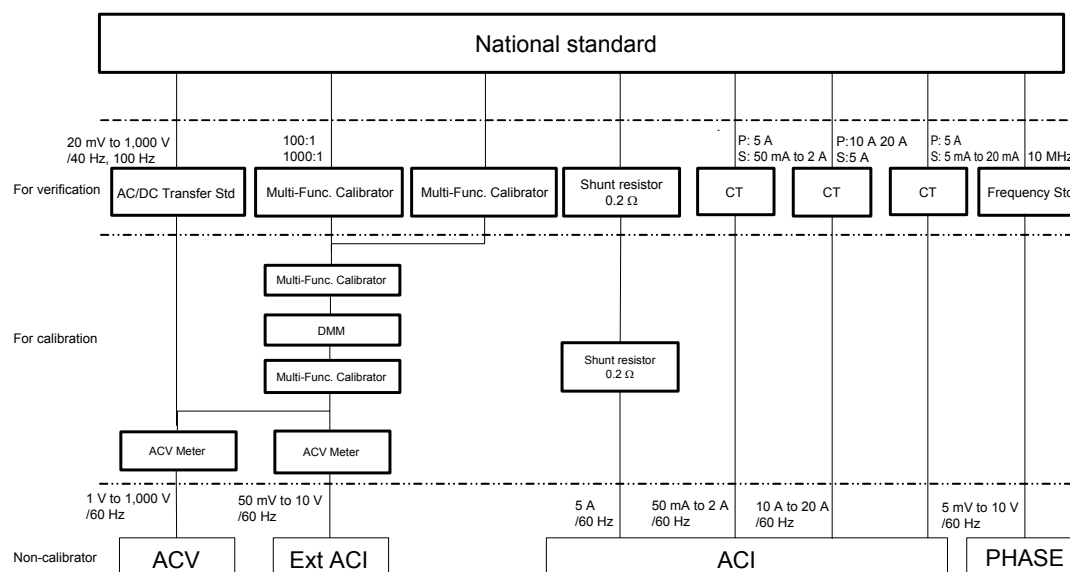
Figure 3 Power traceability system diagram

has been successfully downsized.

Improved Measurement Accuracy

The basic accuracy (measurement accuracy at the commercial frequency, 50/60 Hz) of the 30A (760901) and the 5A (760902) high-accuracy elements is ±(0.01% of reading + 0.02% of range) at power factor = 1, and ±0.02% at power factor = 0, which is the world's highest power measurement accuracy. To achieve this high accuracy, Yokogawa has developed new power standards and a traceability system, through collaboration by the Audit, QHSE Control Division Measurement Standards Department. Figure 3 shows the traceability system diagram. The uncertainty in the new power standard for 100 V, 5 A, 60 Hz is 45 ppm at power factor = 1 and 24 ppm at power factor = 0, whereas the uncertainties in the conventional power standard under the same conditions are 54 ppm and 84 ppm, respectively.

In the new power standard system, the power calibration value is generated from the voltage standard, current standard, and the phase, to replace the conventional power standard. A shunt resistor and a new phase calibration method have been developed for the current standard.
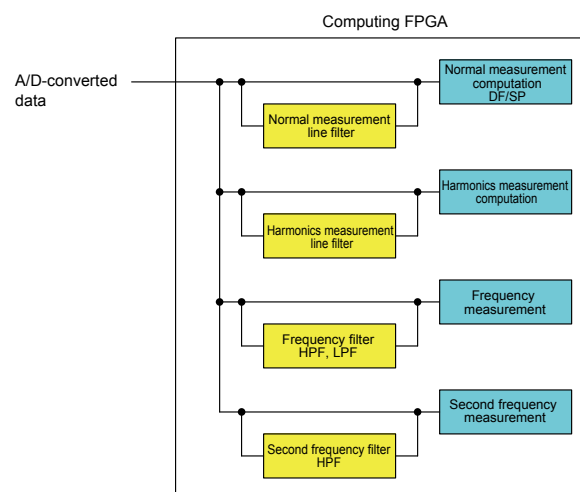
Diverse Signal Processing

Figure 4 shows a block diagram of the signal processing in the WT5000.

Flow of signal processing

The computing FPGA treats the A/D-converted data from the input element as instantaneous values and measures their normal parameters (voltage, current, and power) and harmonics and frequencies.

Line filters may be inserted in front of normal and harmonics measurement computation circuits. The previous model has only one line filter which is used for both normal

and harmonics measurements. The WT5000 features two line filters whose cut-off frequencies can be set separately for normal and harmonics measurements. Thanks to the two line filters, voltages, currents, and powers can be measured in normal measurement including their high-frequency components, and at the same time the harmonics can be analyzed with reduced aliasing noises of harmonic components by setting a low cut-off frequency for the harmonics measurement line filter.

Figure 4 Signal processing in the WT5000

The WT5000 also features two frequency filters, whereas there is only one in the previous model. For example, in measuring pulse width modulation (PWM) waveforms, the fundamental frequency can be measured by setting the frequency filter to low-pass filter (LPF), while the carrier frequency can be measured by setting the second frequency filter to high-pass filter (HPF).

These line filters and frequency filters (fourth-order

filters) are formed by digital filters. The fourth-order filters are compact circuits despite the high sampling rate of 10 MHz thanks to a sophisticated processing method, and can perform computation with enough precision even at a low cut-off frequency of 0.1 Hz.

Anti-aliasing filters (AAFs) composed of analog circuits are arranged at the previous stage of A/D converters. When aliasing noises caused by sampling affect measurements, users can turn the AAF on to suppress the influence of the noises.

Two computing modes for normal measurements

For normal measurement computing, two computing methods are available: digital filter average (DF) mode and synchronization source period average (SP) mode.

In the DF mode, the average value is obtained by cutting the AC components of higher frequencies than the lower limit frequency of the measurement bandwidth and leaving only the DC component. The lower limit frequency can be selected from among FAST = 100 Hz, MID = 10 Hz, SLOW = 1 Hz, and VSLOW = 0.1 Hz. The digital filter has been newly designed for the WT5000 to secure enough attenuation at the lower limit frequency. The DF mode has the advantage of obtaining measurement values stably even when the cycle of the synchronization source is not detected correctly. The DF mode requires instantaneous values for a certain length of time to perform filtering computation. For example, instantaneous values for four cycles of waveform are required at the lower limit frequency even for the fastest case.

In the SP mode, the measurement period is set within the data update interval between the first point where the synchronization source crosses the specified level (cross point) on a rising (or falling) slope and the last cross point, and the average value of instantaneous values within this measurement period is calculated. When the cycle of the synchronization source is detected correctly, the SP mode has the advantage of obtaining measurement values stably even for a short data update interval in which the interval contains only one cycle of waveform.

Switching between the two measurement modes depending on the measurement object enables high-speed acquisition of stable measurement data.

MODULAR-TYPE INPUT ELEMENTS

The WT5000 adopts modular-type input elements to improve user-friendliness and expandability while maintaining nearly the same external dimensions as the previous model. The modular-type design enables the accommodation of up to 7 input elements under severe physical restrictions.

Noise Immunity

High noise immunity is required for a power analyzer, especially against the noises present when measuring inverters. In the WT5000, the body grounding has been strengthened and shield plates at the case potential are installed between the body and the elements so that the element and the shield plates contact each other adequately. As a result of these measures,

the elements are kept at the same potential as the body and high noise immunity is achieved.

Uniform Temperature among Elements

In a power analyzer with multiple elements, the temperature of the shunt resistors at the current input circuits must be uniform over elements irrespective of the number and combination of elements to ensure no difference in measurement values among elements. The positions of air holes and wind flow have been optimized for the WT5000 based on the results of thermal simulations. As a result, uniform temperature has been achieved for each element in spite of the modular-type design (Figure 5).

Figure 5 Modular-type design

Reduced Interference among Elements

The 30A (760901) and the 5A (760902) high-accuracy elements adopt the direct current input method with shunt resistors. Therefore, measurements may be affected by the input current to the adjacent element when the two elements are physically close, making accurate measurement difficult. The shield plates at the case potential installed between the elements and the body of the WT5000 help reduce the effect of adjacent elements and ensure high-accuracy measurement, in spite of the increased number of elements and resulting short distance between adjacent elements.

IMPROVED SAFETY

In line with the suppressed internal connection loss and the reduced circuit area, safety terminals designed to prevent coming off are adopted for high current terminals instead of the conventional screw-fastened type current terminals. The latter type of terminals can also be used safely with the terminal adapter shown in Figure 6, which ensures compatibility between the safety terminal and the conventional terminal.

Figure 6 High-current safety terminal adapter

EXCELLENT OPERABILITY

Power analyzers feature many functions to achieve highly precise measurement. Accordingly, the setting options and menus have a multilevel structure that may make operation

inconvenient. The method of setting and display has been revamped for the WT5000 to improve operability compared with the previous model by collaborating with the Experience Design Department, Marketing HQ of Yokogawa for this project. The improvements and advantages of the operation of the WT5000 are described below.

Intuitive Operation on Touchscreen

The WT5000 features a touchscreen for the first time among Yokogawa's power analyzers. Touch and swipe actions are used for selecting functions, switching the display, and other operations to make operation intuitive, which is difficult to achieve by hardware keys alone. For example, users of the previous model had to press a hardware key repeatedly to move to the desired page. In contrast, users of the WT5000 can easily jump to the desired page by a single touch action, as shown in Figure 7 (patent pending).
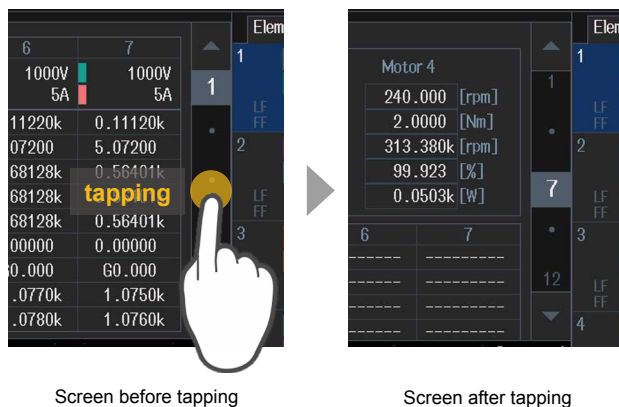

Screen before tapping   Screen after tapping

Figure 7 Moving to another page

Improved Operability with Hardware Keys and Cursor Keys

Hardware keys have the advantage of prioritized operation with a one-touch action. The WT5000 features hardware keys on the front panel with specific functions assigned to shortcut keys (display format keys, patent pending) (Figure 8).
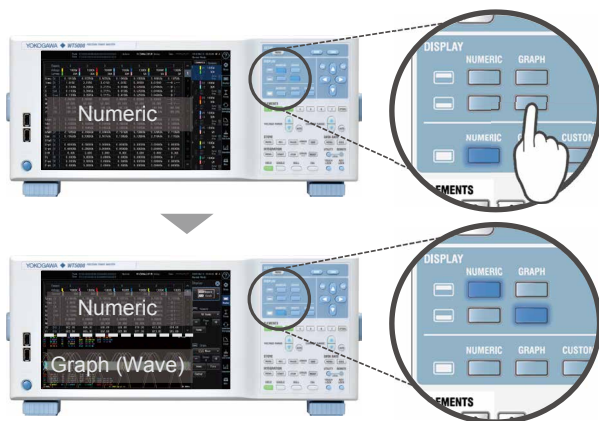

Figure 8 Display format keys

The menu operations can also be executed by using cursor keys. All functions of the WT5000 can be executed by using cursor keys, which is especially useful when the environment does not allow easy access to the touchscreen.

Systematic Menu Structure

The functions of the WT5000 are classified into three categories, Input (processing of input signal), Computation/Output (computation on measured signals, display, and saving in files), and Utility (device information and communication settings), and the menu structure is designed for each category.

This categorized menu structure improves operability of the WT5000 substantially compared with the previous model, which required much time to locate a particular function among many unclassified function menus.

Large and Small Setting Menus Tailored to Purposes

The WT5000 features full-screen setting menus to display the list of diverse setting items. In the full-screen displays, setting items are arranged so that their meanings and mutual relations are easily understandable.

The WT5000 also features small setting menus for functions that are set while checking the actual measurement data and waveforms.

Figure 9 shows examples of large and small setting menus. The areas surrounded by dotted lines show the sizes of the menus.
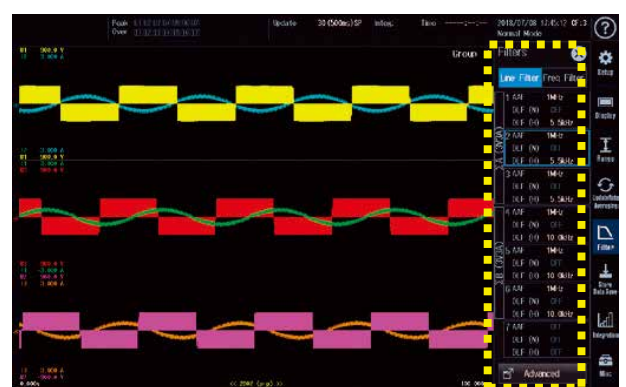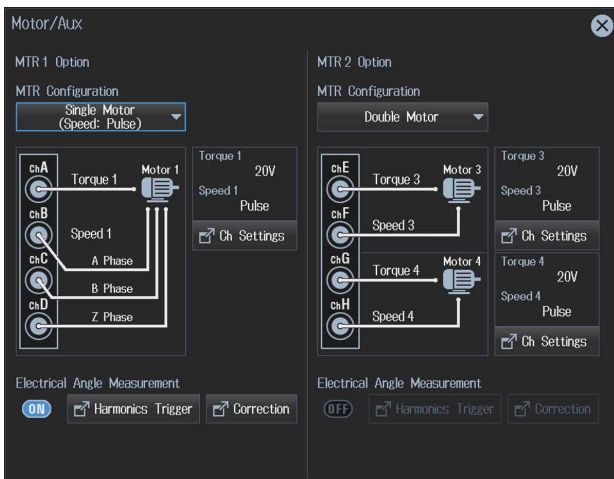

Figure 9 Setting menus, large (upper) and small (lower)

Easy-to-understand Menus with Graphic Display

Graphic display is used for the setting menus of the WT5000 to make the functions easy to grasp (Figure 10).

Figure 10 Setting menus of filters (upper) and motors (lower)

APPLICATION EXAMPLES IN VARIOUS FIELDS

Evaluation of Motors and Inverters for Next-generation Vehicles

With its ability to mount up to 7 power input elements, the WT5000 is ideal for evaluating the efficiency of input-output power of EVs and PHVs. Besides voltage, current, and power, the WT5000 can also measure the rotational speed, torque, and mechanical power of up to 4 motors simultaneously using the motor evaluation function (/MTR1 and /MTR2 options).

Figure 11 shows an example of measuring an inverter (1 to 3 and 4 to 6) and a DC power (7), as well as electric angles of two motors (M1 and M2) using the motor evaluation function, employing 7 power input elements.

The WT5000 has the following advantages for measurements such as this example.

- DC measurement and two three-phase (three inputs)

measurements can be performed simultaneously using 7 input elements.

- The mechanical power (Pm) of each motor in a two-motor system can be measured simultaneously.
- The digital filter method allows stable data acquisition independently of period detection.
- The harmonics measurement function, a standard feature, allows simultaneous measurement of the fundamental component and harmonic components.
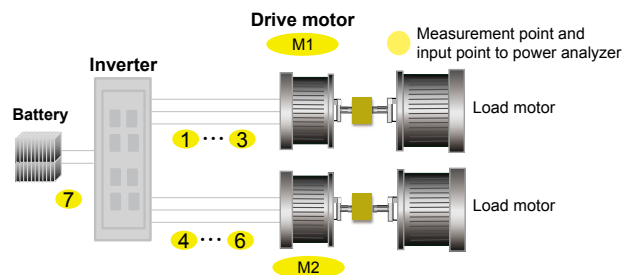
Figure 11 Power measurement of motors and an inverter

High-precision Power Measurement of DC-DC Converters

The conversion efficiency of a DC-DC converter is measured based on the measured DC power, frequency, and power factor of the input and the measured DC power of the output. High-precision measurement of each item is essential, because the switching waveforms and harmonics data must also be taken into account.
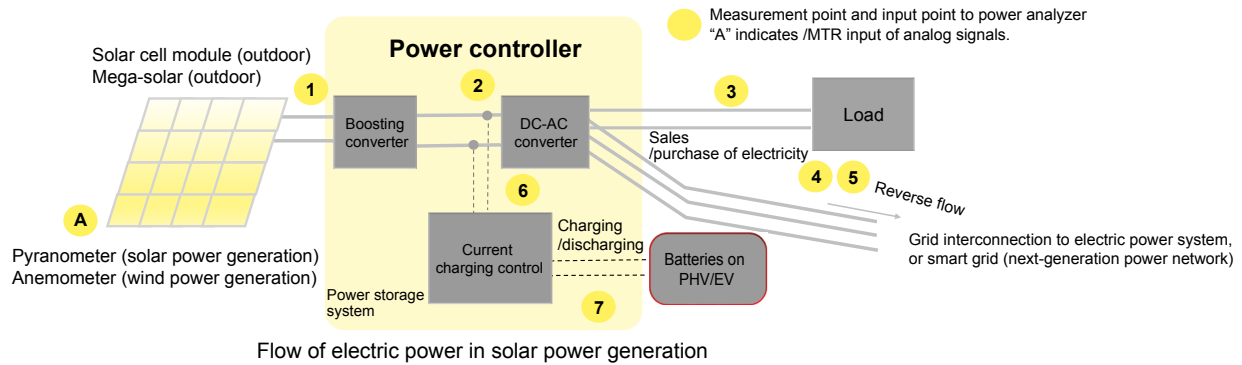
The WT5000 has the following advantages for such measurements.

- With its wide bandwidth, 10 MHz voltage and 5 MHz current, the WT5000 can capture the internal switching waveforms of DC-DC converters accurately and enable precise measurements.
- The high sampling rate of 10 MS/s enables capturing of narrow pulses.
- The WT5000 is capable of high-precision measurement of direct current input of up to 30 A with the wide bandwidth of 5 MHz.
- The direct current input method of up to 30 A allows high-precision measurements excluding current sensor errors even at high current.

Power Measurement of Renewable Energies such as Solar Power Generation

The energy generated by a solar or wind power generator is converted from DC or AC to AC of the commercial frequency inside a power conditioning system, or to the charging current by charging controllers for storage batteries. It is essential to minimize the loss during these conversion processes to achieve high efficiency of the entire system.

Figure 12 shows an example of measuring the voltage, current, power, frequency, efficiency of power conditioning system, and charging efficiency at the input/output point of each converter (1 to 7), using 7 power input elements.

Flow of electric power in solar power generation

Figure 12 Direct measurement of 7 lines of up to 1,500 V_{dc}/30 A

The WT5000 has the following advantages for such measurements.

- The WT5000 allows high-precision measurement of up to 7 input elements. The WT5000 also allows direct input measurement of up to 1,500 V_{dc}/30 A.
- With its capability of high-precision DC measurement and wide-bandwidth AC measurement, the WT5000 can measure power converters with high precision.
- The harmonics measurement function, a standard feature, allows simultaneous checking of total harmonic distortion (THD) and harmonics components.

CONCLUSION

This paper described the high-precision power measurement technologies, features, and application examples of the WT5000 precision power analyzer. The WT5000 is expected to be used in a wide range of power measurements to solve customers' problems by taking full advantage of its features, high precision, wide bandwidth, expandability, and user-friendliness.

* All company names, group names, product names, and logos that appear in this paper are either trademarks or registered trademarks of their respective holders.