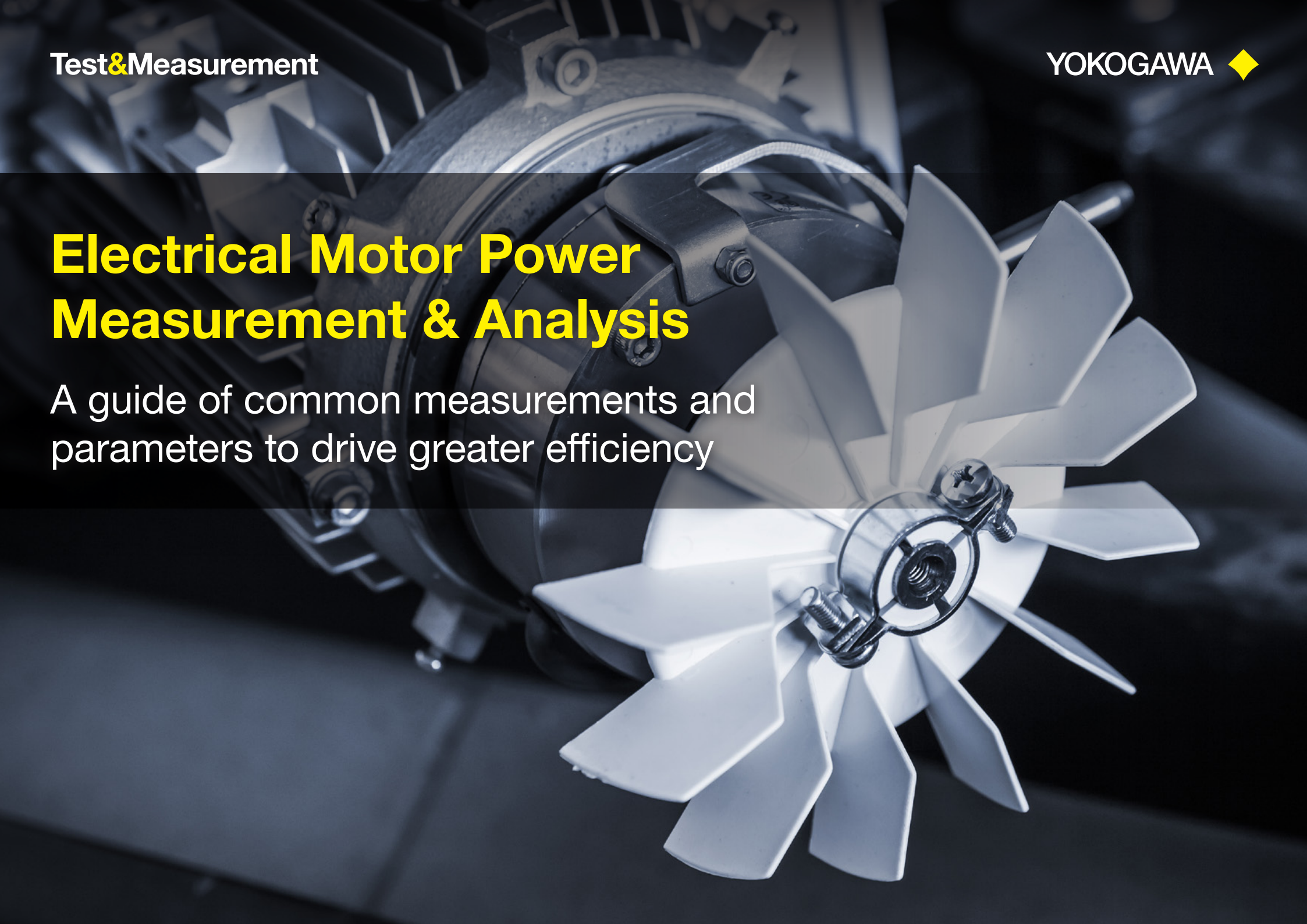# Electrical Motor Power Measurement & Analysis

A guide of common measurements and parameters to drive greater efficiency

What to expect

Foreword

Electric motors are the single biggest consumer of electricity. They account for about two thirds of industrial power consumption and about 42% of global power consumption, according to the International Energy Agency. Making sure motors are operating for efficiency is vital.

The increasing focus on efficiency can help to reduce energy consumption, as well as extend the life of the motor. Measurement is always the first step toward better performance and can also help extend the life of a motor.

Understanding motor power consumption and measuring efficiency is key to optimize motor development and usage. This eBook discusses the basics of power measurements of motor systems, including the drive system, while also looking at mechanical measurements.

42%
of all electricity used
powers industry

2/3
of this is used
by electric motors

= 28%
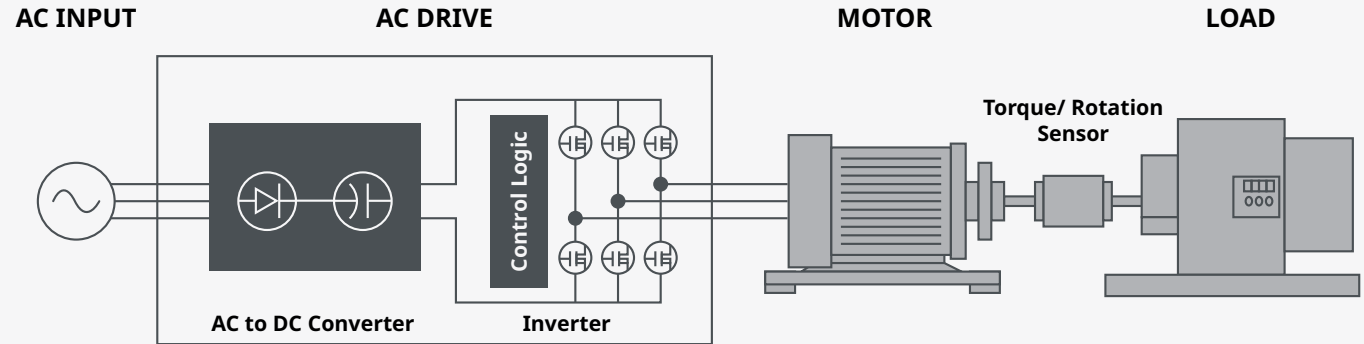Global electricity
consumption
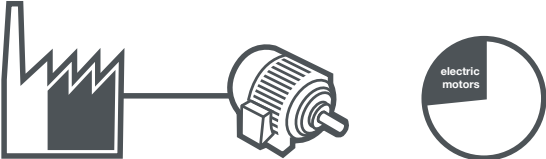
electric
motors

1. What is power?

What is power?

In this eBook you will learn common terms and methods for making power measurements on a motor and drive system, including DC, Multiphase AC, Harmonics and efficiency measurements.

AC INPUT   **AC DRIVE**   **MOTOR**   **LOAD**

Torque/ Rotation Sensor

Control Logic

AC to DC Converter   Inverter

Electric motors are electromechanical machines that convert electric energy into mechanical energy. Despite differences in size and type, all electric motors work in much the same way: an electric current flowing through a wire coil in a magnetic field creates a force that rotates the coil, thus creating torque.

What is power?

In the most basic form, power is work performed over a specific amount of time. In a motor, power is delivered to the load by converting electrical energy.

Since power is voltage times current (P = V × I), power is highest when the voltage and current are lined up together so that the peaks and zero points on the voltage and current waveforms occur at the same time. This would be typical of a simple resistive load. In this situation, the two waveforms are "in phase" with one another and the power factor would be 1. This is a rare case, as almost all loads aren't simply perfectly resistive.

What is a watt?

A watt (W) is a unit of power defined as one Joule per second. For a DC source the calculation is simply the voltage times the current: W = V x A. However, determining the power in watts for an AC source must include the power factor (PF), so W = V x A x PF for AC systems.

Power in DC circuits

DC circuits maintain a constant voltage and current with no cyclic changes and purely resistive loads. Thus when a battery lights up an electric bulb, the DC power (P) consumed by the bulb is calculated by the formula P = U x I where P is measured in Watts (W), U is the voltage measured in volts (V) and I is the current measured in amperes (A).
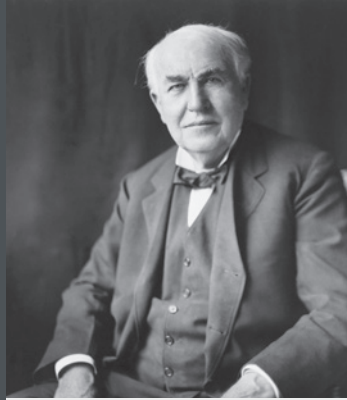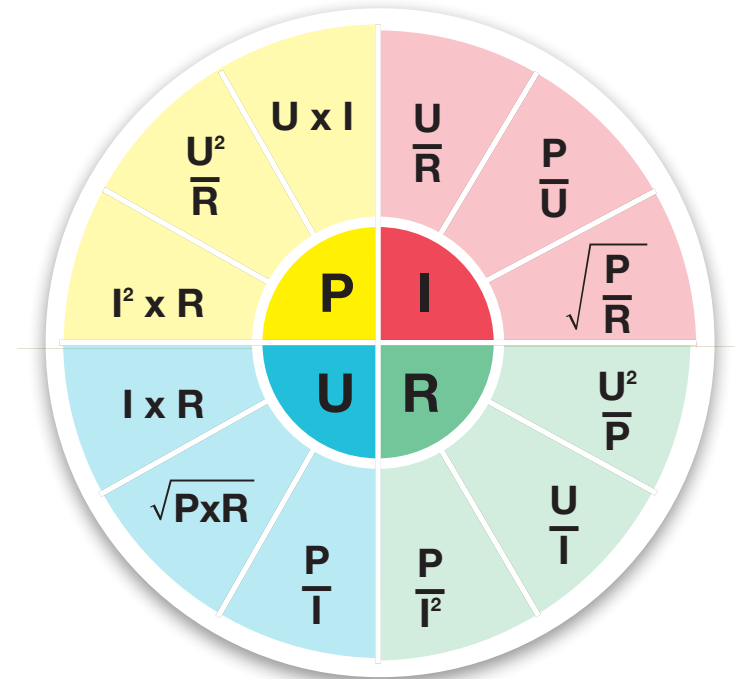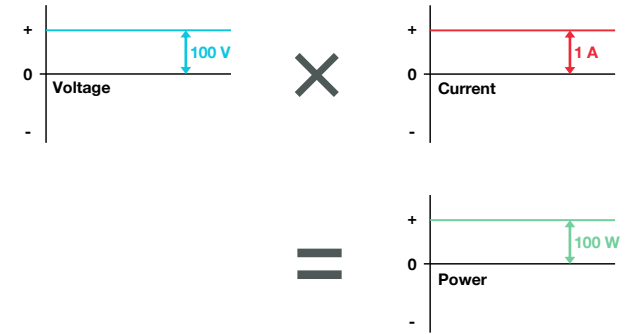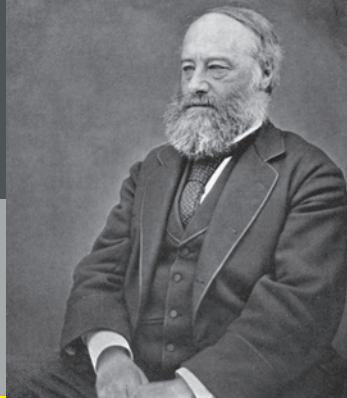
Thomas Edison (1847-1931) developed the first DC power supply system soon after devising the first commercially viable electric bulb.

Ohm's law states that the current I flowing in a circuit is directly proportional to the applied voltage U and inversely proportional to the resistance R provided the temperature remains constant. Thus, *I = U/R*

Joule's law states that the power of heating generated by an electrical conductor is proportional to the product of its resistance and the square of the current: Thus $P = I^2 \times R$

100 V
Voltage
+
0
-

×

1 A
Current
+
0
-

=

100 W
Power
+
0
-

$U \times I$

$\dfrac{U^2}{R}$

$I^2 \times R$

$\dfrac{U}{R}$

$\dfrac{P}{U}$

$\sqrt{\dfrac{P}{R}}$

P

I

U

R

$I \times R$

$\sqrt{PxR}$

$\dfrac{P}{I}$

$\dfrac{P}{I^2}$

$\dfrac{U^2}{P}$

$\dfrac{U}{I}$

- P = Power (W)
- U = Voltage (V)
- I = Current (A)
- R = Resistance (I)

Power in AC circuits

Power in an AC circuit

Obtaining power values in AC circuits isn't as simple as the multiplication of voltage and currents in DC circuits. This is because inductive or capacitive elements in an AC circuit cause a reactance in the circuit and phase difference between voltage and current, which in turn gives rise to three types of AC power: true power, apparent power and reactive power.

As with DC, the instantaneous power at a certain point in time is given by:
Instantaneous Power (p) = Instantaneous Voltage (u) x Instantaneous Current (i).
Since active power P is power per second, it can be obtained by dividing the average instantaneous power, i.e. area enclosed by power waveform by time.

$$P = \frac{1}{T}\int_0^T u(t) \times i(t)dt$$
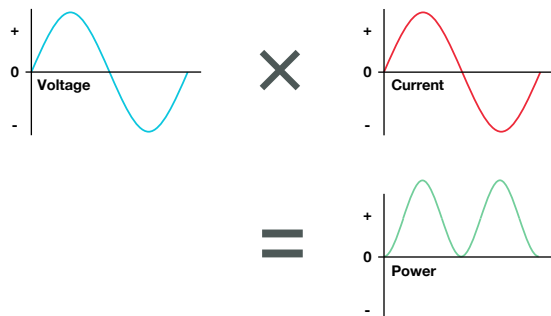
However, this formula for power only holds true when there is no phase difference between current and voltage due to inductive or capacitive reactance. This maximum power available when current and voltage are in phase is known as apparent power and is calculated by simply multiplying the voltage and current rms readings.
In real world conditions, however, there is always a phase difference that needs to be taken into account. So the real power consumed is given by the formula:

$$P = U \times I \times cos\varphi$$

where φ is the phase difference between voltage and current and cosφ is known as power factor or the ratio between real and apparent power. Meters installed by utility companies measure and charge for only the kilowatts of real power consumed by households and offices.

Another component of AC power is reactive power. Unlike real power, reactive power cannot perform work so households are not charged for it. However some industries/plants with low power factors are penalized when they draw a large amount of reactive power.

To distinguish from real power, apparent power is measured in VA instead of Watts (W) while reactive power is measured in VAr.
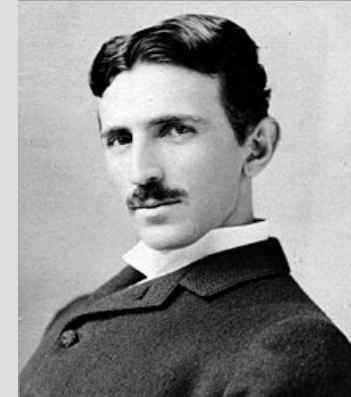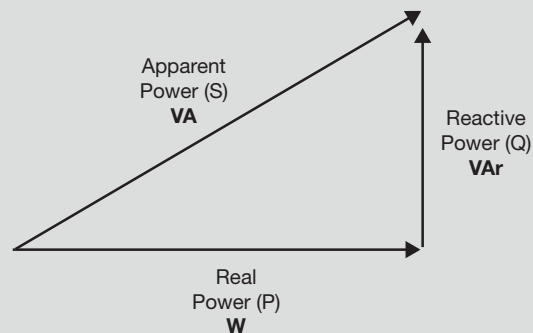
Nikola Tesla (1856-1943) is credited with the design of the modern AC electricity supply system.
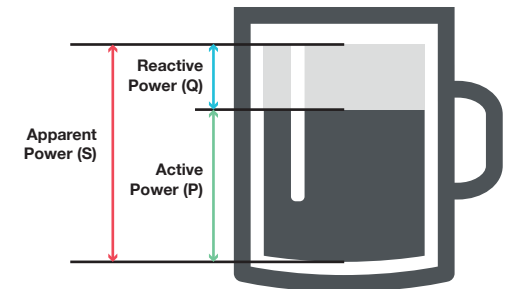
Beer Analogy of AC power depicts how Apparent Power is the vector sum of useless (reactive) and useful (true) power.
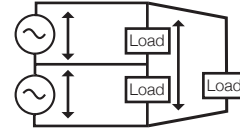
2. AC power systems

Single-phase and three phase AC power systems

Unlike single-phase systems, the conducting wires in a three phase power supply each carry an alternating current of the same frequency and voltage amplitude relative to a common reference but with a phase difference of one third the period. Three phase systems have advantages over single-phase that make it suitable for transporting power and in applications such as induction motors.

- Three phase supplies can transmit three times as much power using just 1.5 times as many wires as a single-phase supply (i.e., three instead of two). Thus, the ratio of capacity to conductor material is doubled.

- Three phase systems can produce a rotating magnetic field with a specified direction and constant magnitude, which simplifies the design of electric motors.
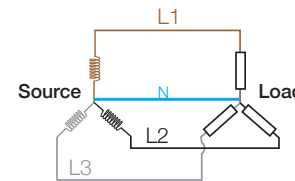
Single-phase 2-wire
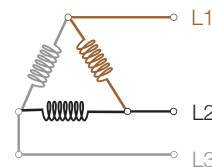AC power supply and load are connected by two conducting wires

Split-phase 3-wire
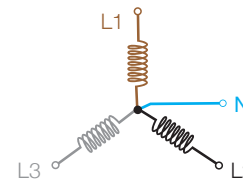Single-phase AC power is supplied through three conducting wires
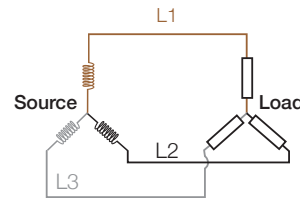
Three-phase 3-wire system
Three-phase AC power supply is connected to load via three conducting wires

Three-phase 4-wire system
Three-phase four wire system uses a neutral wire (N) connecting to ground reference

Delta connection

Star connection

Three-phase AC systems may use three or four wires – the fourth being a neutral reference. They may be in delta or star wiring configuration.

- The current through and voltage across each phase has a phase difference of 120° in a balanced system.

- Line voltage is the voltage measured between any two lines in a three-phase circuit.

- Phase voltage is the voltage measured across a load in a particular phase

- Line current is the current through any one line between a three-phase source and load.

- Phase current is the current through any one component comprising a three-phase source or load.

- In a delta connection, the line voltage is same as the phase voltage. The line current is $\sqrt{3}$ times the phase current.

- In a star connection, the line voltage is $\sqrt{3}$ times the phase voltage while the currents are the same.

Harmonic analysis

Harmonics refer to all sine waves whose frequency is an integer multiple of the fundamental wave (normally a 50 Hz or 60 Hz sinusoidal power line signal) except for the fundamental wave itself.
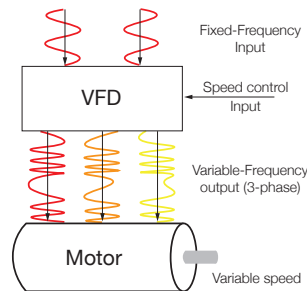
Harmonics are a distortion of the normal electrical current waveforms generally transmitted by nonlinear loads. Unlike linear loads where the current drawn is proportional to and follows the waveform of the input voltage, non-linear loads such as variable speed motors draw current in short abrupt pulses. When the fundamental wave and the integer multiple of the fundamental waves are combined, waveforms become distorted, and interference occurs.
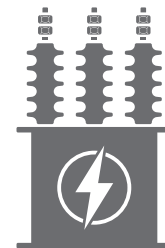
Switch mode power supplies in PCs, TVs, mobile chargers, LEDs

Lighting - most LEDs produce harmonics higher than IEC61000-3-2 standards

VFD / Motor diagram

Fixed-Frequency Input

Speed control Input

VFD

Variable-Frequency output (3-phase)

Motor

Variable speed

Heating or undesired vibrations in variable speed motors

Transformer losses under no load conditions

A signal of any waveform can be broken down into sinusoidal waves of different amplitudes across the frequency spectrum. Harmonics are then essentially the higher frequency components of a fundamental sinusoidal waveform.

Amplitude

Time domain

Frequency domain
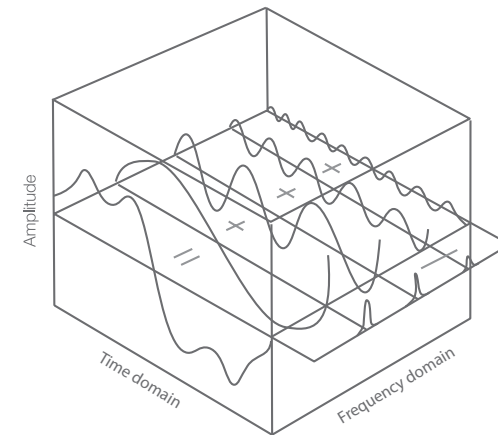
Harmonics must be controlled as they can cause abnormal noise, vibration, heat, or improper operation in devices and shorten their life. Domestic and international standards such as IEC61000-3 exist for the purpose of harmonic control. Therefore, engineers need to detect harmonics and assess their effects on components, systems, and subsystems within an application. The size and phase difference should be measured for not only the fundamental frequency but also for each higher frequency component. Highly accurate power analyzers/instruments can measure harmonics upwards of the 500th order.

# 3. Motors

Three-phase motor wiring diagrams

Measuring power on a three-phase AC motor can be confusing depending on the wiring configuration from the source to the load. Understanding the wiring for voltage and current measurements can simplify the power measurement setup.

Blondel's theorem

When discussing power measurements with wattmeters, Blondel's Theorem is often referenced when determining the correct method of connecting the wattmeters and how many are required for the most accurate measurement. The Theorem states that the power provided to a system of N conductors is equal to the algebraic sum of the power measured by N wattmeters. Additionally, if a common point is located on one of the conductors, that conductor's meter can be removed and only N-1 meters are required.
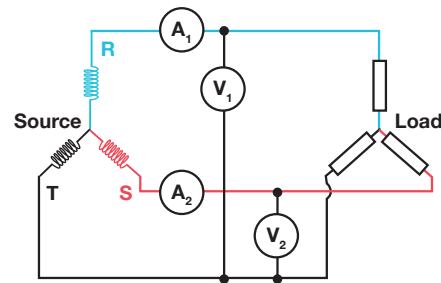
Three-phase Delta 2 Wattmeter (3P3W)
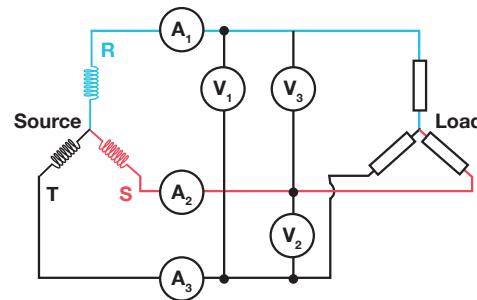
Three-phase Delta Connection (3V3A)
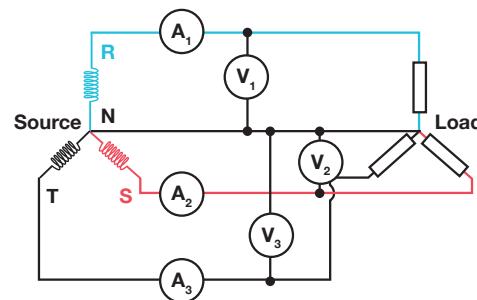
Three-phase Star Connection (3P4W)

Three-phase Delta 2 Wattmeter (3P3W)

Measurement with the three-phase 3-wire system is a bit more complicated because the neutral conductor that was used as the base for the three-phase 4-wire system is absent and phase voltage cannot be measured. Measurement under the three-phase 3-wire system involves obtaining the three-phase AC power value using a method called the 2-wattmeter method.

Three-phase Delta Connection (3V3A)

There is one more measurement method under the three-phase 3-wire system: three-voltage three-current measurement (3V3A). Like the two-wattmeter method, this method measures phase current and line voltage between R and S. The following is a connection diagram.

As the three-voltage three-current method (3V3A) measures phase current, it allows for seeing the current balance among the phases that was not possible using the two-wattmeter method.

Three-phase Star Connection (3P4W)

Obtain power for each phase by measuring voltage (phase voltage) and current (phase current) for each phase with different wattmeters. Totaling this will give the three-phase AC power value. Measuring three-phase 4-wire power requires three wattmeters.

Designing for efficiency

Accelerate the Design, Validation, and Test of Motors and Drives

The key to making efficient motors while minimizing overall lifecycle costs is to ensure every stage of design and manufacturing is executed to the highest level of quality.

AC INPUT   **AC DRIVE**   **MOTOR**   **LOAD**

AC to DC Converter   Inverter

Control Logic

AC/DC Efficiency   Motor Control Analysis   Motor State Analysis

Drive Efficiency   Motor Efficiency

Powertrain Efficiency
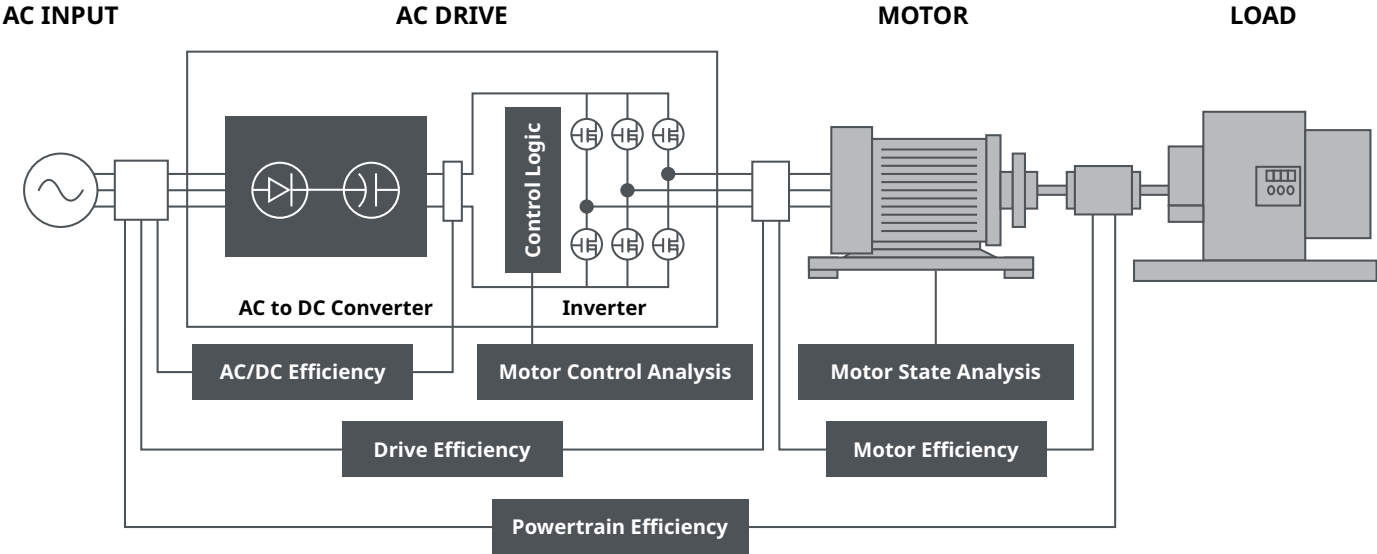
The measurement challenge

Various measurements at test points on the motor and drive system require specialized test equipment optimized to ensure the highest quality with few trade-offs.

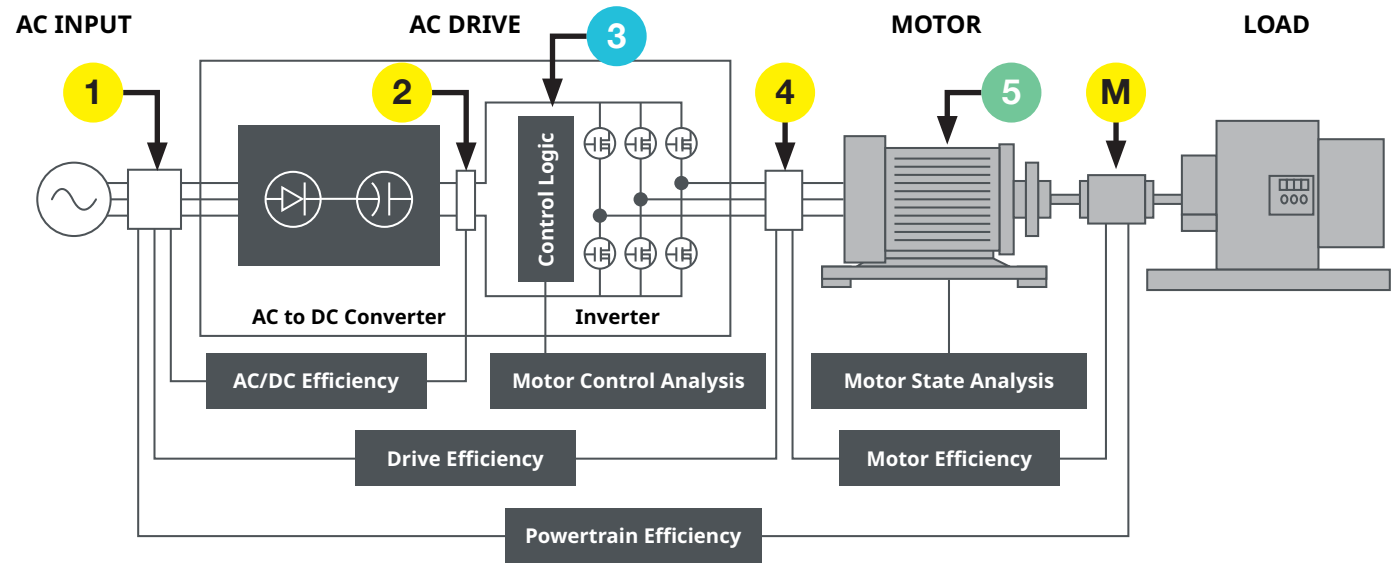The correct instrument may depend on the level of accuracy, number of channels, or type of signal being acquired.

AC INPUT | AC DRIVE | 3 | MOTOR | LOAD

1 | 2 | 4 | 5 | M

AC to DC Converter | Control Logic | Inverter

AC/DC Efficiency | Motor Control Analysis | Motor State Analysis

Drive Efficiency | Motor Efficiency

Powertrain Efficiency

Power Analyzer

| 1 / 4 | AC Voltage | AC Current | Power | η Efficiency | λ Power Factor | THD |

| 2 | DC Power | DC Voltage | DC Current | η Efficiency |

| M | Angle | Encoder | rpm RPM | τ Torque | η Efficiency |
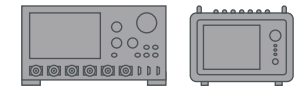
Oscilloscope / ScopeCorder

| 3 | CAN bus | SPI bus | IGBT | Voltage (Isolated) | GPS | I2C Bus | Flow |
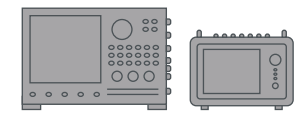
ScopeCorder

| 5 | Temperature | Flow | Vibration | Resolver | CAN bus |

Efficiency measurements

Efficiency and losses

Because of the large global energy consumption of motors, increased focus is being placed on measuring and improving efficiency. Efficiency is measured by dividing the output power by the i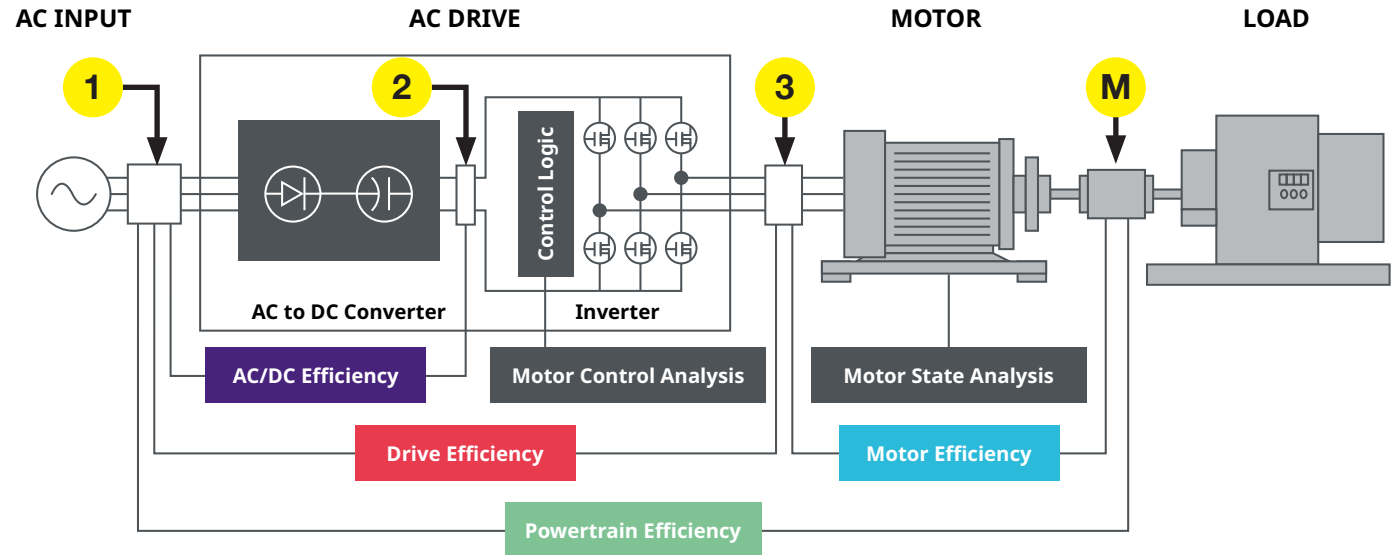nput power, resulting in a plot over time with various load scenarios. This measurement can be taken with a traditional power analyzer.

AC INPUT	AC DRIVE	MOTOR	LOAD

AC to DC Converter · Inverter · Control Logic

AC/DC Efficiency · Motor Control Analysis · Motor State Analysis

Drive Efficiency · Motor Efficiency

Powertrain Efficiency

$$\eta = \frac{P_2}{\Sigma P_1}$$

$$\eta = \frac{\Sigma P_3}{\Sigma P_1}$$

$$\eta = \frac{P_m}{\Sigma P_3}$$

$$\eta = \frac{P_m}{\Sigma P_1}$$

AC/DC Efficiency

AC/DC converters inevitably introduce highly distorted input current, resulting in serious current harmonics and low power factor.

Drive Efficiency

The job of the AC drive is to adjust the speed of the AC output signal to the motor to achieve optimal performance. AC drive efficiency is important when designing the controller algorithms.

Motor Efficiency

The efficiency of a motor is a measure of how well it converts electrical energy into useful work. Determining motor efficiency will help to measure how much energy is lost to heat.

Powertrain Efficiency

Drive efficiency is dependent on motor load. Determining the efficiency versus load to characterize the best system performance conditions depends on maximizing torque per amps for as many load points as possible.

What to measure

Depending on the application, industry and development phases, power measurements may have varying requirements. Some of the key considerations are listed here.

What do I need to measure?

- What levels of AC/DC voltage and current at what frequencies?
- What wiring is used? Single phase, three phase or combination?
- What is the shape of the signal and how stable or distorted is it?

What accuracy will I need?

- What needs to be shown to customers?
- What industry/quality standards need to be adhered to?
- What level of harmonics are allowed?

Can I trust my measurements?

- Is the measuring instrument stable? Are these repeatable measurements?
- How can I have confidence in the specified accuracy?
- Is traceability of measurement necessary?

Measuring power

With the increasing emphasis on energy efficiency across power generation, transmission, distribution and consumption, governments and regulators are taking greater steps to encourage better generation and use of power.

Whether it is for cost efficient transmission to homes and businesses, energy efficient manufacturing in industries, or efficient production and usage of products, accurate power measurement plays an important role in ensuring safety, quality and performance while ensuring energy efficiency and compliance to industrial and governmental standards.

When choosing a solution for measuring power and related electromechanical parameters however, it becomes essential to consider the application use case including the stage in the product's lifecycle, the measurement environment and levels of accuracy required before deciding on the ideal instrument.

Power analyzers automatically measure the complicated electrical energy we've discussed at high accuracy and enable users to graphically (waveforms, bar graphs, trends and vectors) or numerically analyze electrical signals which they would otherwise not be able to see. Understanding the increases and decreases in electrical power is essential in gauging the performance and energy efficiency of electrical devices.

Accurate power measurements cannot be achieved without each factor in the measurement optimized for accuracy. This means that not only do current and voltage need to be accurate but also other factors such as power factor, phase angle, crest factor, harmonics, temperature etc.

Current transformers
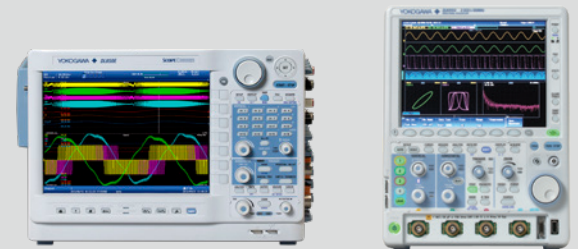
ScopeCorders

Oscilloscopes

Power analyzers

Thank You For Reading This eBook!

For more information on Yokogawa's Power Measurement Solutions please visit
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Electrical Motor Power Measurement & Analysis

A guide of common measurements and parameters to drive greater efficiency.

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To download the Motors and Drives white paper, visit:
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ABOUT YOKOGAWA

Yokogawa's global network of 113 companies spans 60 countries. Founded in 1915, the US$3.5 billion company engages in cutting-edge research and innovation. Yokogawa is active in the industrial automation and control (IA), test and measurement, and aviation and other businesses segments.

Yokogawa has been developing measurement solutions for 100 years, consistently finding new ways to give R&D teams the tools they need to gain the best insights from their measurement strategies. The company has pioneered accurate power measurement throughout its history, and is the market leader in digital power analysers.

Yokogawa instruments are renowned for maintaining high levels of precision and for continuing to deliver value for far longer than the typical shelf-life of such equipment. Yokogawa believes that precise and effective measurement lies at the heart of successful innovation - and has focused its own R&D on providing the tools that researchers and engineers need to address challenges great and small.

Yokogawa takes pride in its reputation for quality, both in the products it delivers - often adding new features in response to specific client requests - and the level of service and advice provided to clients, helping to devise measurement strategies for even the most challenging environments.

Meet the Precision Makers at
tmi.yokogawa.com