Power Supply Measurement and Analysis

Primer
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Introduction

A power supply is a component, subsystem, or system that converts electrical power from one form to another; commonly from alternating current (AC) utility power to direct current (DC) power. The proper operation of electronic devices ranging from personal computers to military equipment and industrial machinery depends on the performance and reliability of power supplies.

There are many different kinds and sizes of power supplies from traditional linear types to high-efficiency switch-mode power supplies. All face a complex, dynamic operating environment. Device loads and demands can change dramatically from one instant to the next. Even a commodity switch-mode power supply must be able to survive sudden peaks that far exceed its average operating levels. Engineers designing power supply’s or the systems that use them need to understand their supplies behavior under conditions ranging from quiescent to worst-case.

Historically, characterizing the behavior of a power supply has meant taking static current and voltage measurements with a digital multimeter and performing painstaking calculations on a calculator or PC. Today most engineers turn to oscilloscopes for characterization and troubleshooting during design, and purpose-built power analyzers for system-level validation and compliance testing.

Modern oscilloscopes can be equipped with integrated power measurement and analysis software which simplifies setup and makes it easier to conduct measurements over time. Users can customize critical parameters, automate calculations, and see results, not just raw numbers, in seconds.

This primer will focus on switch-mode power supply design measurements with an oscilloscope and application-specific software. It will also introduce power analyzers, in the context of power quality testing.

Power Supply Design Questions Point Toward Measurement Needs

Ideally every power supply would behave like the mathematical models used to design it. But in the real world, components are imperfect; loads vary; line power may be distorted; environmental changes alter performance. Moreover, changing performance and cost demands complicate power supply design. Consider these questions:

- How many watts beyond rated output capacity can the power supply sustain, and for how long?
- How much heat does the supply dissipate, what happens when it overheats, and how much cooling airflow does it require?
- What happens when the load current increases substantially? Can the device maintain its rated output voltage (load regulation)? How does the supply react to a dead short on its output?
- What happens when the supply’s input voltage changes (line regulation)?

The designer is asked to create a power supply that takes up less space, is more efficient, reduces heat, cuts manufacturing costs, and meets tougher EMI/EMC standards. Only a rigorous regime of measurements can guide the engineer toward these goals.
Switch-Mode Power Supply Basics

The prevailing DC power supply architecture in most modern systems is the Switch-Mode Power Supply (SMPS), which is known for its ability to handle changing loads efficiently. The power signal path of a typical SMPS includes passive, active, and magnetic components. The SMPS minimizes the use of lossy components such as resistors and linear-mode transistors, and emphasizes components that are (ideally) lossless: switch-mode transistors, capacitors, and magnetics.

SMPS devices also include a control section containing elements such as pulse-width-modulated regulators, pulse-rate-modulated regulators, and feedback loops. Control sections may have their own power supplies. Figure 1 illustrates a simplified SMPS schematic showing the power conversion section with active, passive, and magnetic elements.

SMPS technology rests on power semiconductor switching devices such as Metal Oxide Semiconductor Field Effect Transistors (MOSFET) and Insulated Gate Bipolar Transistors (IGBT). These devices offer fast switching times and are able to withstand erratic voltage spikes. Equally important, they dissipate very little power in either the On or Off states, achieving high efficiency with low power dissipation.

Active Component Measurements: Switching Elements

Theory of Power Loss in Switch-Mode Devices

Transistor switch circuits often dissipate the most energy during transitions because circuit parasitics prevent the devices from switching instantaneously. As shown in Figure 2, “turn-off loss” describes the loss when the device transitions from ON to OFF. “Turn-on loss” describes the energy lost when the switching device transitions from OFF to ON.
Turn-Off Loss

Figure 3 shows a simplified approximation of turn-off loss. At $t_0$, $V_{DS}$ starts to increase as turn-off begins. After $t_1$, the switch current falls. The time ($t_0$-$t_1$) depends on how fast the driver can charge the gate-drain capacitance $C_{GD}$ of the MOSFET.

Energy loss during the transition can be calculated by the following equation:

$$E_{off} = \int_{t_0}^{t_2} V_{DS}(t) \cdot I_D(t) dt$$

Where:
- $E_{off}$ is the average energy loss in the switch during the turn-off transition.
- $V_{DS}(t)$ is the instantaneous voltage across the switch.
- $I_D(t)$ is the instantaneous current through the switch.
- $t_2$ is when the transition is complete.
- $t_0$ is when the transition begins.

In real-world devices, the parasitic capacitances $C_{GD}$ and $C_{DS}$ are highly non-linear, tending to vary with drain-source voltage. In case of an IGBT, the fall time of current would be higher due to the tail current phenomenon. These differences make it essential to capture the actual profile of the voltage variation. An oscilloscope with dedicated power measurement software can greatly simplify these measurements.

Turn-On Loss

Figure 4 shows the turn-on loss in a MOSFET.

Energy loss during the turn-on transition is calculated by the following equation:

$$E_{on} = \int_{t_0}^{t_2} V_{DS}(t) \cdot I_D(t) dt$$

Where:
- $E_{on}$ is the energy loss in the switch during the turn-on transition.
- $V_{DS}(t)$ is the instantaneous voltage across the switch.
- $I_D(t)$ is the instantaneous current through the switch.
- $t_2$ is when the transition is complete.
- $t_0$ is when the transition begins.
Power Loss

The total loss is the average power loss in the switch. This includes the switching losses and conduction losses. The total loss is given by the formula:

\[ P_{\text{loss}} = \frac{1}{T_s} \int_0^{T_s} V_{DS}(t) \cdot I_D(t) dt \]

Where:
- \( P_{\text{loss}} \) is the average power loss in the switch.
- \( V_{DS}(t) \) is the instantaneous voltage across the switch.
- \( I_D(t) \) is the instantaneous current through the switch.
- \( T_s \) is the switching period.

Average power during any part of the switching cycle can be calculated using digitized voltage and current waveforms and waveform math to implement the equations above. Figure 5 shows how the current and voltage waveforms are multiplied point by point to generate the instantaneous power waveform. The average value of the instantaneous power is the mean power loss. The power waveform is also integrated to determine the energy loss.

Safe Operating Area

The Safe Operating Area (SOA) measurement on a switching device plots voltage vs. current to characterize the operating region of the device. It is often useful to create an SOA plot for the diverse operating conditions the power supply is expected to encounter.

The switching device manufacturer's data sheet summarizes certain constraints on the switching device. At minimum the constraints include maximum current, maximum voltage, and maximum power as shown in Figure 6.

In-circuit SOA testing may be performed to evaluate whether an actual switching device is performing within the safe operating area set forth in its datasheet, under various conditions. An oscilloscope equipped with a current probe and special power analysis software allows you to duplicate the datasheet limits. The instrument can plot voltage/current points on the display as power supply conditions are varied, and any excursions outside the limits are flagged.

Figure 5. Turn-off power loss measurement on an oscilloscope, determined by multiplying voltage and current point by point and taking the mean.

Figure 6. A safe operating area plot is found in a switching device datasheet. It is a log-log plot that sets limits for current, power, and voltage maximums.
Dynamic On Resistance

The resistance of a MOSFET switching device in the “on” state can be approximated by using the $R_{DS_{ON}}$ value found in the component’s data sheet. However, the actual resistance (and therefore the switch conduction loss) is not constant and may vary significantly with changes in switch voltage or current.

$\text{di/dt and dv/dt}$

A $\text{di/dt}$ measurement represents the rate at which the current changes during switching, while a $\text{dv/dt}$ measurement represents the rate at which the voltage changes during switching.

Making Active Component Measurements

To those accustomed to making high-bandwidth measurements with an oscilloscope, power measurements, with their relatively low frequencies, might appear simple. In reality, power measurements present a host of challenges that the high-speed circuit designer never has to confront.

The voltage across a switching device can be very large, and is often “floating,” that is, not referenced to ground. There are variations in the pulse width, period, frequency, and duty cycle of the signal. Waveforms must be faithfully captured and analyzed for imperfections.
Choosing the Right Measurement Solution

For switch-mode power supply measurements, it is important to choose the tools that can do the job. To turn the SMPS switching device on and off during test, a pulse stimulus from a signal source may be required. To accurately simulate the gate drive signal under normal operating conditions, the stimulus must have adjustable duty cycle, edge transition times, and frequency. To drive IGBT devices, the stimulus must also be able to generate the required voltage of typically 12 V to 15 V.

The oscilloscope must, of course, have the basic bandwidth and sample rate to handle the switching frequencies within an SMPS. And, it must have deep memory to provide the record length required for long, low-frequency acquisitions with high timing resolution. Power measurements also require at least two channels, one for voltage and one for current.

Equally important are the probes to connect the device to the oscilloscope. Multiple probe types – such as single-ended, differential, and current – are required simultaneously. Application software completes the toolset by making power measurements easier and more reliable.

Performance Considerations for the Oscilloscope

Key performance considerations when choosing an oscilloscope include rise time, sample rate, record length, and available power measurement analysis software.

Rise Time

Although the switching signal may be relatively low-speed, the rise time of the signal may be quite fast. For accurate measurements, the oscilloscope rise time should be at least five times as fast to capture the critical details of fast transitions.

\[
\text{Rise Time}_{\text{oscilloscope}} = \frac{\text{Rise Time}_{\text{Switching Signal}}}{5}
\]

For example, if the switching signal has a rise time of 5 ns, then the oscilloscope should have a rise time of at least 1 ns for accurate measurements. A rise time that fast is typically available on oscilloscopes with a bandwidth of at least 350 MHz.

Sample Rate

Sample rate – specified in samples per second (S/s) – refers to how frequently a digital oscilloscope takes a sample of the signal. A faster sample rate provides greater resolution and detail of the waveform, making it less likely that critical information or events will be lost. To characterize the ringing typical during switching in a SMPS, the oscilloscope’s sample rate must be fast enough to capture several samples on the edges of the switching signal.

Record Length

An oscilloscope’s ability to capture events over a period of time depends on the sample rate used and the depth (record length) of the memory that stores the acquired signal samples. The memory fills up in direct proportion to the sample rate. When the sample rate is set high enough to provide a detailed high-resolution view of the signal, the memory fills up quickly.

For many SMPS power measurements, it is necessary to capture a quarter-cycle or half-cycle (90 or 180 degrees) of the line frequency signal; some even require a full cycle. A half-cycle of a 60 Hz line frequency is over 8 ms of time. At a sample rate of 1 GS/s, a record length of 8 million points is needed to capture that much time.

Power Measurement and Analysis Software

Application software can make power measurements and analysis on an oscilloscope much easier and repeatable by automating common measurements, providing detailed test reports and simplifying certain complex measurement situations like measuring both high and low voltage signals for switching and power loss measurements.
Measuring 100 Volts and 100 Millivolts in One Acquisition

To measure switching loss and average power loss across the switching device, the oscilloscope must first determine the voltage across the switching device during the OFF and ON times, respectively. In an AC/DC converter, the voltage across the switching device has a very high dynamic range. The voltage across the switching device during the ON state depends upon the type of switching device. In the MOSFET illustrated in Figure 8, the ON voltage is the product of channel resistance and current. In Bipolar Junction Transistors (BJT) and IGBT devices, the voltage is primarily based on the saturation voltage drop (VCEsat). The OFF state voltage depends on the operating input voltage and the topology of the switch-mode converters. A typical DC power supply designed for computing equipment operates on universal utility voltage ranging from 80 Vrms to 264 Vrms. At maximum input voltage, the OFF state voltage across the switching device (between TP1 and TP2) can be as high as 750 V. During the ON state, the voltage across the same terminals can range from a few millivolts to about one volt. Figure 9 shows the typical signal characteristics on a switching device.

These OFF and ON voltages must be measured first in order to make accurate power measurements on a switching device. However, a typical 8-bit digital oscilloscope lacks the dynamic range to accurately acquire (within the same acquisition cycle) the millivolt-range signals during the ON time as well as the high voltages that occur during the OFF time.

To capture this signal, the oscilloscopes vertical range would be set at 100 volts per division. At this setting, the oscilloscope will accept voltages up to 1000 V; thus the 700 V signal can be acquired without overdriving the oscilloscope. The problem with using this setting is that the minimum signal amplitude a typical 8-bit digital oscilloscope can resolve is 1000/256, or about 4 V.

The oscilloscope’s vertical sensitivity can be improved by increasing the vertical resolution either by using a higher-resolution digitizer or with digital signal processing. One technique, called HiRes, trades off horizontal resolution for increased vertical resolution using a boxcar averaging technique.

With the power application software offered with modern oscilloscopes, the user can enter RDSon or VCEsat values from the device data sheet into the measurement menu, as shown in Figure 10. Alternatively, if the measured voltage is within the oscilloscope’s sensitivity, then the application software can use acquired data for its calculations rather than the manually-entered values.
Eliminating Skew Between Voltage and Current Probes

To make power measurements with a digital oscilloscope, it is necessary to measure the current through and the voltage across the drain-to-source of a MOSFET switching device or the current through and the voltage across the collector-to-emitter of an IGBT. This task requires two separate probes: a high-voltage differential probe and an AC/DC current probe. The latter probe is usually a non-intrusive Hall Effect type. Each of these probes has its own characteristic propagation delay. The difference in these two delays, known as skew, causes inaccurate timing measurements and distorted instantaneous power waveforms.

Figure 11. The effect of propagation delay on a power measurement.

It is important to understand the impact of the probes’ propagation delays on maximum peak power and area measurements. After all, power is the product of voltage and current. If the two multiplied variables are not perfectly time-aligned, then the result will be incorrect. The accuracy of measurements such as switching loss suffer when the probes are not properly de-skewed.

The test setup shown in Figure 11 compares the signals at the probe tip (lower trace display) and at the oscilloscope front panel after the propagation delay (upper display).
Figures 12 through 15 are actual oscilloscope screen views that demonstrate the effects of skew in probes. Figure 9 reveals the skew between the voltage and current probes, while Figure 13 displays the results (mean value of 939 mW) of a measurement taken without first de-skewing the two probes.

Figure 14 shows the effect of de-skewing the probes. The two reference traces are overlapping, indicating that the delays have been equalized. The measurement results in Figure 15 illustrate the importance of proper de-skewing.

As the example proves, skew introduced a measurement error of over 6%. Accurate de-skew reduces error in peak-to-peak power loss measurements.
Some power measurement software will automatically de-skew the chosen probe combination. The software takes control of the oscilloscope and adjusts the delay between the voltage and current channels using live current and voltage signals to remove the difference in propagation delay between the voltage and current probes.

Also available is a static de-skew function that relies on the fact that certain voltage and current probes have constant and repeatable propagation delays. The static de-skew function automatically adjusts the delay between selected voltage and current channels based on an embedded table of propagation times for selected probes. This technique offers a quick and easy method to minimize de-skew.

**Eliminating Probe Offset and Noise**

Differential and current probes may have a slight offset. This offset should be removed before taking measurements because it can affect accuracy. Some probes have a built-in, automated method for removing the offset while other probes require manual offset removal procedures.

**Automated Offset Removal**

A probe that is equipped with the Tektronix TekVPI™ Probe Interface works in conjunction with the oscilloscope to remove any DC offset errors in the signal path. Pushing the Menu button on a TekVPI probe brings up a Probe Controls box on the oscilloscope that displays the AutoZero feature. Selecting the AutoZero option will automatically null out any DC offset error present in the measurement system. A TekVPI current probe also has a Degauss/AutoZero button on the probe body. Depressing the AutoZero button will remove any DC offset error present in the measurement system.

**Manual Offset Removal**

Other differential voltage probes have built-in DC offset trim controls, which makes manual offset removal a relatively simple procedure. Similarly, it is necessary to adjust the current probe before making measurements.

Note that differential and current probes are active devices, and there will always be some low-level noise present, even in the quiescent state. This noise can affect measurements that rely on both voltage and current waveform data. Some power measurement software includes a signal-conditioning feature (Figure 16) that minimizes the effect of inherent probe noise.

![Figure 16. Signal conditioning option on the DPOPWR software menu. This selection sets the current to zero during the “Off” time of the switching device.](image-url)
Passive Component Measurements: Magnetics

Passive components are those which do not amplify or switch signals. Power supplies employ the full range of passive components such as resistors and capacitors, but from a measurement standpoint, the main focus is on the magnetic components (magnetics) particularly inductors and transformers. Both inductors and transformers consist of ferrous cores wound with turns of copper wire.

Inductors exhibit increasing impedance with frequency, impeding higher frequencies more than lower frequencies. This makes them useful for filtering current at the power supply input and the output.

Transformers couple voltage and current from a primary winding to a secondary winding, increasing or decreasing signal levels (either voltage or current but not both). Thus a transformer might accept 120 volts at its primary and step this down to 12 volts on the secondary with a proportional increase in current on the secondary. Note that this is not considered amplification because the signal’s net power does not increase. Because the transformer’s primary and secondary are not electrically connected, they are also used to provide isolation between circuit elements.

Some measurements that help to determine power supply performance include:

- Inductance
- Power Loss (Magnetic)
- Magnetic Properties

Inductance Basics

Power supplies use inductors as energy storage devices, filters, or transformers. There are several different solutions available for measuring inductance. The LCR meter, for example, excites the inductor under test using a built-in signal generator and then uses a bridge-balancing technique to measure the device impedance. The LCR meter uses a sinusoidal wave as the signal source.

In a real-world power supply, however, the signal is a high-voltage, high-current square wave. Therefore, most power supply designers prefer to get a more accurate picture by observing the inductors behavior in the dynamically changing environment of a power supply. The magnetic properties of inductors vary with the current and voltage source, excitation signal, wave shape, and the frequency of operation. When voltage and current are measured, inductance may be determined by:

\[ L = \frac{\int V(t)dt}{I(t)} \]

Where:

- \( L \) is the inductance (Henry).
- \( V \) is the voltage across the inductor.
- \( I \) is the current through the inductor.

Making Inductance Measurements with an Oscilloscope

The most expedient tool for inductor measurements in a live power supply is an oscilloscope. The inductance measurement itself is as simple as probing the voltage across and the current through the magnetic component, much like the switching device measurements described earlier.

Figure 17 shows the result of such an inductance measurement. Here, the software has computed the inductance to be 65.043 microhenries.
Magnetic Power Loss Basics

Magnetic power loss affects the efficiency, reliability, and thermal performance of the power supply. Two types of power losses are associated with magnetic elements: core loss and copper loss.

Core Loss

The core loss is composed of hysteresis loss and eddy current loss. The hysteresis loss is a function of the frequency of operation and the AC flux swing. It is largely independent of DC flux. The hysteresis loss per unit volume is expressed by the following equation:

$$P_{\text{Hyst}} = \int H \cdot dB$$

Where:

- $P_{\text{Hyst}}$ is the hysteresis loss per unit volume.
- $H$ is field strength.
- $B$ is the flux density.

It is possible to calculate the core loss using the core manufacturer’s data sheet such as that shown in the Figure 18. Here the manufacturer has specified the loss for sinusoidal excitation in the I and the III quadrant operation. The manufacturer also specifies an empirical relationship to calculate the core loss at different AC flux densities and frequency.

Copper Loss

The copper loss is due to the resistance of the copper winding wire. The copper loss is given by:

$$P_{\text{Cu}} = I_{\text{rms}}^2 \cdot R_{\text{wdg}}$$

Where:

- $P_{\text{Cu}}$ is the copper loss.
- $I_{\text{rms}}$ is the rms current through the magnetic component.
- $R_{\text{wdg}}$ is the winding resistance. This resistance depends on the DC resistance, skin effect, and proximity effect.
Making Magnetic Power Loss Measurements with an Oscilloscope

The total power loss and the core loss can be quickly derived using information from the core vendor’s data sheet and results from an oscilloscope running power measurement software. Use both values to calculate the copper loss. Knowing the different power loss components makes it possible to identify the cause for power loss at the magnetic component.

The method for calculating the magnetic component power loss depends in part on the type of component being measured. The device under test may be a single-winding inductor, a multiple-winding inductor, or a transformer. Figure 19 shows the measurement result for a single winding inductor.

Channel 1 (yellow trace) is the voltage across the inductor and Channel 2 (blue trace) is the current, measured with a non-intrusive current probe, through the inductor. The power measurement software automatically computes and displays the power loss figure, here shown as 48.472 milliwatts.

Multiple-winding inductors call for a slightly different approach. The total power loss is the sum of the losses from the individual windings:

$$\text{TotalPowerLoss} = PowerLoss_{\text{w1}} + PowerLoss_{\text{w2}} + PowerLoss_{\text{w3}} + \ldots$$

Computing power loss at a transformer further varies the formula:

$$\text{TotalPowerLoss} = PowerLoss_{\text{p}} - (PowerLoss_{\text{s1}} + PowerLoss_{\text{s2}} + \ldots)$$

The measured power loss at the primary winding will include the reflected power of the secondary winding. Therefore, it is necessary to measure power at the primary and secondary windings and compute the power loss using the transformer equation.

Magnetic Properties Basics

Switch-mode power supplies must be reliable over a wide range of operating conditions. For optimum performance, designers generally specify magnetic components, transformers and inductors, using B-H (hysteresis) curves supplied by the manufacturers. These curves define the performance envelope of the magnetic’s core material. Factors including operating voltage, current, topology, and type of converter must be maintained within the linear region of the hysteresis curve. Obviously, with so many variables, this is not easy.

Characterizing the operating region of the magnetic component while it is operating within the SMPS is essential to determining the power supply’s stability. The measurement procedure includes plotting the hysteresis loop and looking at the magnetic properties of the inductor and transformer.
The B-H plot characterizes the magnetic properties. Figure 20 shows a typical B-H plot for a sinusoidal excitation.

To make B-H plot measurements, the following information is needed at the outset:

- Voltage across the magnetic component, \( V \)
- Magnetizing current, \( I \)
- Number of turns, \( N \)
- Magnetic Length, \( l \)
- Cross Sectional Area, \( A \)
- Surface Area, \( S \)

These variables are used in the following definitions that pertain to Figure 20:

**Magnetic Field Strength (H)** is the magnetic field used to induce magnetic flux in the material under test. Units are expressed in amperes per meter.

\[
H_k(t) = I_k(t) \cdot \frac{N}{l}
\]

**Saturation Flux Density (B_s)** is the maximum magnetic flux density that can be induced in the material regardless of the magnitude of the externally applied field \( H \).

\[
\Phi_k = \int V_k(t) \, dt
\]

And:

\[
B_k(t) = \frac{\Phi_k}{(N \cdot S)}
\]

**Remanence (B_r)** is the induced magnetic flux density that remains in the material after the externally applied magnetic field \( H \) returns to zero while generating the hysteresis loop.

**Coercive Force (H_c)** is the value of \( H \) found at the intercept of the \( H \)-axis and the hysteresis loop. This represents the external field required to cause the induced flux density \( B \) to reach zero during the measurement cycle of a hysteresis loop. \( H_c \) is symmetrical with the positive and negative axes.

**Initial Permeability (\( \mu_I \))** is the ratio of induced magnetic flux densities \( B \) to apply field \( H \) as \( H \) approaches zero. It is the ratio of \( B \) to \( H \) at any point on the hysteresis loop. In addition, **Maximum Amplitude Permeability** is the maximum ratio of \( B \) to \( H \) on the first quadrant of the positive cycle of the hysteresis loop. It is the slope drawn from the origin.
Magnetic Property Measurements

Inductors are used as filters at the input and the output of the power supply, and may have single or multiple windings.

To make magnetic property measurements, the following information is necessary:

- Voltage across the magnetic component, \( V \)
- Magnetizing current, \( I \)
- Number of turns, \( N \)
- Magnetic Length, \( l \)
- Cross Sectional Area, \( A \)

The inductor voltage and current follow the following equation:

\[
V_{L}(t) = R \cdot i_{1}(t) + L \cdot \frac{di_{1}(t)}{dt}
\]

In a typical DC-to-DC converter, the flux in the winding is expressed by:

\[
L \cdot \frac{di_{1}(t)}{dt} = N \cdot \frac{d\Phi_{L}(t)}{dt}
\]

and:

\[
\Phi_{L}[(n+1)T_{S}] = \Phi_{L}[nT_{S}]
\]

Figure 21 shows a typical multi-winding magnetic element that might be used as a coupled inductor or transformer.

The electrical equations governing the operation of this circuit are as follows:

\[
\frac{v_{1}(t)}{n_{1}} = \frac{v_{2}(t)}{n_{2}} = \frac{v_{3}(t)}{n_{3}}
\]

and

\[
i_{1}(t) \cdot n_{1} = -i_{2}(t) \cdot n_{2} - i_{3}(t) \cdot n_{3}
\]

To calculate the net magnetizing current, it is necessary to measure \( i_{1}(t), i_{2}(t) \) and \( i_{3}(t) \). Given the net magnetizing current, the B-H analysis procedure is similar to that used for a single-winding inductor. The flux depends upon the net magnetizing current. The vector sum of the measured currents in all the windings produces the magnetizing current.
Measuring Magnetic Properties with an Oscilloscope

Dedicated power measurement software can greatly simplify magnetic properties measurements with an oscilloscope. In many instances, it is necessary only to measure the voltage and magnetizing current. The software performs the magnetic property measurement calculations for you. Figure 22 depicts the results of a magnetic property measurement on a single-winding inductor. The measurement can also be performed on a transformer with a primary and secondary current source.

In Figure 23, Channel 1 (yellow trace) is the voltage across the inductor and Channel 2 (blue trace) is the current through the inductor. After running the inductance and magnetic loss measurements 100 times, the minimum, maximum, and mean measurement values are displayed.

Some power measurement software can also create an exact B-H plot for the magnetic component and characterize its performance. The number of turns, the magnetic length and the cross-sectional area of the core must first be entered before the software can compute a B-H plot.
Power Supply Measurement and Analysis

Power Line Measurements
Power line measurements characterize the interaction of the supply and its service environment. It is good to remember that power supplies can be of any size, from the small fan-feed boxes inside a personal computer, to the sizeable devices supplying factory motors, to the massive supplies supporting phone banks and server farms. Each of these has some effect on the incoming power source (typically utility power) that feeds it.

To determine the effect of the insertion of the power supply, power voltage and current parameters must be measured directly on the input power line.

Power Quality Measurement Basics
Power quality does not depend on the electricity producer alone. It also depends on the design and manufacture of the power supply and on the end-user’s load. The power quality characteristics at the power supply define the “health” of the power supply.

Real-world electrical power lines never supply ideal sine waves. There is always some distortion and impurity on the line. A switching power supply presents a non-linear load to the source. Because of this, the voltage and current waveforms are not identical. Current is drawn for some portion of the input cycle, causing the generation of harmonics on the input current waveform. Determining the effects of these distortions is an important part of power engineering.

To determine the power consumption and distortion on the power line, power quality measurements are made at the input stage, as shown by the voltage and current test points in Figure 24.

Power quality measurements include:
- True Power
- Apparent Power or Reactive Power
- Power Factor
- Crest Factor
- Current Harmonics Measurements to EN61000-3-2 Standards
- Total Harmonic Distortion (THD)

Figure 24. Simplified view of an SMPS power supply (primary side only) and its power quality measurement test points. Simultaneous input \( V_{ac} \) and \( I_{ac} \) readings are necessary for power quality measurements.
Making Power Quality Measurements with an Oscilloscope

Digital oscilloscopes running power measurement application software are a powerful alternative to the power meters and harmonic analyzers traditionally used for power quality measurements.

The benefits of using an oscilloscope rather than the older toolset are compelling. The instrument must be able to capture harmonic components up to at least the 50th harmonic of the fundamental. Power line frequency is usually 50 Hz or 60 Hz, according to applicable local standards. In some military and avionics applications, the line frequency may be 400 Hz. And of course, signal aberrations may contain frequencies that are higher yet. With the high sampling rate of modern oscilloscopes, fast-changing events are captured with great detail (resolution). In contrast, conventional power meters can overlook signal details due to their relatively slow response time. And, the oscilloscope’s record length is sufficient to acquire an integral number of cycles, even at very high sampling resolution.

Software tools speed measurement procedures and minimize setup time. Most power quality measurements can be automated by full-featured power measurement software running on the oscilloscope itself, performing lengthy procedures in seconds. By reducing the number of manual calculations, the oscilloscope acts as a very versatile and efficient power meter. Figure 25 shows an example of robust power measurement software.

The oscilloscope probes, too, assist in safe, reliable power measurements. High-voltage differential probes designed for power applications are the preferred tools for observing floating voltage signals.

Current probing is a special consideration. There are several implementations of current probing architecture:

- The AC current probe may be based on current transformer (CT) technology or Rogowski coil technology. These AC current probes are minimally-intrusive but cannot sense the DC component in the signal, which can result in inaccurate measurements.
- The current shunt. This design requires interrupting the circuit and can cause a voltage drop within the circuit itself, potentially compromising power measurement accuracy.
- The AC/DC current probe is typically based on Hall-Effect sensor technology. This device senses AC and DC currents with minimal intrusiveness and is able to read both the AC and the DC signal components with one connection.

The AC/DC current probe has become the tool of choice for challenging power quality measurements in switch-mode power supplies.
Power Supply Measurement and Analysis

Power Line Measurements with a Power Analyzer

A precision power analyzer is the ideal tool to use when measuring the power drawn from the AC line by a power supply. Accurate power and related measurements are used to confirm the power supply’s overall electrical ratings and its compliance to international requirements for power, efficiency and current wave shape.

Measurements include:
- Power (watts)
- Low power standby (mW)
- Apparent power (VA)
- True RMS V and A
- Power Factor
- Inrush Current
- Crest Factors and Peak Values
- Harmonics (V, A and W)
- THD (V, A)

Accuracy

A power analyzer connects directly to the AC line and uses precision input circuits (a voltage divider and a current shunt) to provide power measurements with a basic accuracy of 0.05% or better. This class of accuracy is required to confirm high levels of accuracy as well as for conformance to power and harmonics standards.

For example, a typical oscilloscope and probe combination may provide 3% of amplitude accuracy for voltage and current. The total power uncertainty will be even greater, resulting in 3% uncertainty for overall power and efficiency measurements. This can be very important when designing to achieve a high efficiency. For example, a nominal 90% efficiency may be as high as 93% or as low as 87% when measured with an oscilloscope. This uncertainty could then result in either a non-conforming design (measuring above 90% but actual efficiency less than 90%) or unnecessary extra design optimization (measuring below 90% but actual efficiency already greater than 90%).

An oscilloscope is the right tool for confirming and optimizing high-speed switching and other component losses inside the power supply but a precision power analyzer is the best tool for measuring overall power, efficiency and harmonic distortion.
Connections

The standard current inputs of a power analyzer will measure a large range of current, from milli-amps to 20 or 30 amps RMS. This is suitable for most power supplies up to 3kW.

A single power analyzer wattmeter input channel consists of a voltage input pair \( V_{HI} \) and \( V_{LO} \) and a current input pair \( A_{HI} \) and \( A_{LO} \).

These connections are simplified by use of a break-out box that makes the analyzer connections with 4mm safety connectors and provides a standard AC outlet for connection to the power supply.

Connections for low power standby.

The standard current inputs of a power analyzer will measure a large range of current, from milli-amps to 20 or 30 amps RMS.

To measure low power standby (milli-watts) use the low current input on the power analyzer. This is labelled \( A_{1A} \) to signify a maximum 1A RMS input that whose range runs from micro-amps up to 1 Amp RMS.

To avoid errors, special care should also be taken with the voltage connection such that it is made on the source side of the current shunt. An extra terminal \( V_{LO} \) (Source) on the break-out box makes this convenient.

Details of these connections and the measurement methods can be found in another Tektronix primer, “Standby Power Primer” available from www.tek.com/power.

Figure 26. Connecting directly to a power analyzer.

Figure 27. Using a break-out box for safe and simple product testing.
Connections for high power

To extend the measurement range of a power analyzer above its rated direct input (typically 20 or 30A RMS), current transducers are used.

The transducer may be a simple current transformer, a high performance active current transducer or a device (a resistive shunt or Rogowski coil) that produces a voltage output that is proportional to the current being measured.

<table>
<thead>
<tr>
<th>Power</th>
<th>Transducer</th>
<th>Power Analyzer Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 100W</td>
<td>None</td>
<td>Low current (1A) input</td>
</tr>
<tr>
<td>0.5W – 3kW</td>
<td>None</td>
<td>Normal (20A) input</td>
</tr>
<tr>
<td>1kW +</td>
<td>Simple current Transformer</td>
<td>1A or 20A input to match the transformer output</td>
</tr>
<tr>
<td></td>
<td>Precision current transducer</td>
<td>1A or 20A input to match the transformer output</td>
</tr>
<tr>
<td></td>
<td>Transducer with a voltage Output (Shunt or Rogowski coil)</td>
<td>EXT A1 Voltage input</td>
</tr>
</tbody>
</table>

Table 1. Current measurement technique for different power supply input power.

In each case the power analyzer provides a suitable, matched current input and that input may be selected and scaled such that the correct actual current is displayed and recorded by the power analyzer.
Power Measurements with a Power Analyzer

For basic power supply measurements, no set up of the analyzer is required.
Making Standards Compliance Measurements

Power, standby power and efficiency

Many international agencies lay down limits for different aspects of power supply and end-product power and energy performance.

For power supplies, efficiency and no-load (or standby) power is regulated by:

- US Energy Independence and Security Act
- EC Ecodesign Directive
- EC IPP Mobile Device Charger Rating

For the domestic and office devices and appliances that are powered by power supplies then further programs limit the energy efficiency and standby power of the complete end product:

- ENERGY STAR™
- California Energy Commission
- EU Eco-Label
- Nordic EcoLabel
- Blue Angel (Germany)
- Top Runner (Japan)
- Energy Saving (Korea)

Power is measured using a power analyzer as described above and compliance is checked by comparison with the limits described by the relevant program above.

Efficiency is calculated from a measurement of input power ($P_{IN}$) and output power ($P_{OUT}$).

$$Efficiency = \frac{P_{OUT}}{P_{IN}} \times 100\%$$

Power analyzers measure a wide range of both AC and DC signals and so convenient and accurate efficiency measurements can be provided by using multiple power analyzers simultaneously.

Measurements of standby power to the above programs require special techniques that are described by the European standard IEC62301 Ed.2. To measure standby power in this way, PC software is used to calculate and verify the measurement stability and uncertainty that is required.

Harmonics Limits

Using PC software coupled to the power analyzer, harmonics measurements may be quickly and conveniently recorded and compared to the limits of IEC61000-3-2 and others.

Software features such as PDF report export provide complete reporting functions for power supply conformance measurements.
Conclusion

The power supply is integral to virtually every type of line-powered electronic product, and the switch-mode power supply (SMPS) has become the dominant architecture in digital computing, networking, and communications systems. A single switch-mode power supply’s performance or its failure can affect the fate of a large, costly system.

Measurements are the only way to ensure the reliability, stability, compliance, and safety of an emerging SMPS design. SMPS measurements fall into three principal categories: active device measurements; passive device measurements (mostly magnetics); and power quality tests. Some measurements may deal with floating voltages and high currents; others require math-intensive analysis to deliver meaningful results. Power supply measurements can be complex.

The modern digital oscilloscope has become the tool of choice for characterization and troubleshooting measurements. When equipped with appropriate probing tools and automated measurement software, the oscilloscope simplifies challenging SMPS measurements while providing fast, accurate answers. For system-level validation and compliance testing, power analyzers deliver measurements with specified accuracy and traceability.
### Power Measurements

Which Tektronix oscilloscope is right for your power applications?

- **Automatic**
- **Manual**

<table>
<thead>
<tr>
<th>Specifications</th>
<th>TPS2000B Series with TPS2PWR1 Module</th>
<th>MD04000 and MD03000 Series with DPO4PWR or MD03PWR App. Module</th>
<th>MSO/DPO5000B Series with DPOPWR Option</th>
<th>DP07000C Series with DPOPWR Option</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bandwidth</strong></td>
<td>100 MHz to 200 MHz</td>
<td>100 MHz to 1 GHz</td>
<td>350 MHz to 2 GHz</td>
<td>500 MHz to 3.5 GHz</td>
</tr>
<tr>
<td><strong>Record Length</strong></td>
<td>2.5 k</td>
<td>Up to 20 M</td>
<td>Up to 250 M</td>
<td>Up to 500 M</td>
</tr>
<tr>
<td><strong>Sample Rate</strong></td>
<td>Up to 2 GS/s</td>
<td>Up to 5 GS/s</td>
<td>Up to 10 GS/s</td>
<td>Up to 40 GS/s</td>
</tr>
<tr>
<td><strong>Maximum Input Voltage</strong></td>
<td>300 V&lt;sub&gt;max&lt;/sub&gt; CAT II</td>
<td>300 V&lt;sub&gt;max&lt;/sub&gt; CAT II</td>
<td>300 V&lt;sub&gt;max&lt;/sub&gt; CAT II</td>
<td>150 V&lt;sub&gt;max&lt;/sub&gt;</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Special features</th>
<th>TPS2000B Series with TPS2PWR1 Module</th>
<th>MD04000 and MD03000 Series with DPO4PWR or MD03PWR App. Module</th>
<th>MSO/DPO5000B Series with DPOPWR Option</th>
<th>DP07000C Series with DPOPWR Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automated De-skew</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Isolated and Floating Channels</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Windows Operating System and Desktop</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Battery Powered Operation</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>FFT Plots</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Line Power Quality Measurements</th>
<th>TPS2000B Series with TPS2PWR1 Module</th>
<th>MD04000 and MD03000 Series with DPO4PWR or MD03PWR App. Module</th>
<th>MSO/DPO5000B Series with DPOPWR Option</th>
<th>DP07000C Series with DPOPWR Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>VRMS</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>IRMS</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>True (Real) Power</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Reactive Power</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Apparent Power</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Power Factor</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Crest Factor</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Phase Angle</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Harmonics</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Total Harmonic Distortion</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Passive Component Measurements</th>
<th>TPS2000B Series with TPS2PWR1 Module</th>
<th>MD04000 and MD03000 Series with DPO4PWR or MD03PWR App. Module</th>
<th>MSO/DPO5000B Series with DPOPWR Option</th>
<th>DP07000C Series with DPOPWR Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Magnetic Power Loss</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Flux Density</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>B-H Plots</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

*1 On One Channel
Primer

TPS2000B Series

with TPS2PWR1 Module

MDO4000 and MDO3000 Series

with DP04PWR or

MDO3PWR Application Module

MSO/DPO5000B and

DPO7000C Series

with DP08PWR Option

Power Applications

- Industrial Power
- Automotive
- Power Supply Troubleshooting
- SMPS Design & Development
- Pre-Compliance
  (Military and Industrial)

Probes

TPS2000 Series oscilloscopes achieve the
best power measurement performance when
combined with the following probes.

High Voltage Differential Probes

- Safely make measurements of floating
  or elevated circuits with the oscilloscope
grounded.
- Wide dynamic voltage range from
  milli-Volts to kilo-Volts.

Model Numbers

- P5150
- P5122

TekVPI High Voltage Differential Probes

- Offers GHz performance to
  analyze Switch Mode Power
  Supply (SMPS) designs.
- Versatile device under test (DUT)
  connectivity and ease-of-use.

Model Numbers

- TDP1000*1
- TDP0500*1
- THDP0200*1
  (measures up to ± 1500 V)
- THDP0100*1
  (measures up to ± 6000 V)

Current Probes

- Transformer and Hall effect technology
  enhance AC/DC measurement capabilities.
- Wide dynamic current range from milli-
  Amps to kilo-Amps.

Model Numbers

- TCP2020
- TCP3000 with
  TCP300A, TCP305A,
  and/or TCP312A

TekVPI Current Probes

- Exceptional bandwidth (DC to 120 MHz)
  and broad dynamic range (milli-Amps tp
  hundreds of Amps.)
- Split core construction makes it easier and
  quicker to connect to the device under
  test (DUT).

Model Numbers

- TCP0020*2
- TCP0030A*2
- TCP0150*2

*1 TPS2000 Series requires 1103 power supply.
*2 MSO/DPO5000B Series requires TekVPI external power supply 119-7465-XX when total oscilloscope-probe power usage exceeds 15W.
*3 MDO3000 Series supplies up to a total of 25W of oscilloscope-probe power.

28 www.tektronix.com/power
Power Supply Measurement and Analysis Application Software

DPOPWR for the MSO/DPO5000, DPO7000, and MSO/DSA/DPO70000 Series Oscilloscopes
- Multi-vendor probe support with auto-deskew capability
- Quickly measure and analyze power dissipation in power supply switching devices and magnetic components
- Generate detailed test reports in customizable formats

DPO4PWR for the MDO4000 Series and MDO3PWR for the MDO3000 Series Oscilloscopes
- TekVPI probe support with auto-deskew capability
- Quickly measure and analyze power quality, switching loss, harmonics, SOA, modulation, ripple and slew rate in power supply switching devices

TPS2PWR1 for the TPS2000 Series Oscilloscope
- Quickly measure and analyze instantaneous power, harmonics, switching loss, phase angles, dv/dt and di/dt
Choosing Your Next Power Analyzer

Measuring Power and Energy.

The PA1000 power analyzers combine accuracy with ease of use to provide design and test engineers with high-value measurement solutions. They feature patent-pending SpiralShunt™ technology to guarantee robust performance over a 1-year calibration interval and during changes of current and temperature.

PA1000 Single-Phase Power Analyzer

Best in class accuracy and connectivity. Easy to use yet packed with features to speed the design and test of power supplies and any product connected to the AC line.

Product Highlights
- 0.05% reading + 0.05% range basic accuracy
- Dual shunts maximize accuracy for low and high current measurements
- USB, Ethernet and GPIB interfaces
- PWRVIEW PC software for measurement and control. Includes IEC62301 Ed.2 standby power
- Harmonics, Inrush and Energy (W-h) measurements

Color display of 4 or 14 measurements and waveform, harmonics and energy trend graphics.

AFG3000 Series Arbitrary/Function Generator

Save cost and set-up time by creating high amplitude signals to stimulate your device without using an external power amplifier. The AFG3011 offers up to 20 Vp-p amplitude (into a 50 Ω load) at frequencies up to 10 MHz. Other models of the AFG3000 Series offer frequencies up to 240 MHz with one or two channels to create up to two synchronized or completely independent signals.
For Further Information

Tektronix maintains a comprehensive, constantly expanding collection of application notes, technical briefs and other resources to help engineers working on the cutting edge of technology. Please visit www.tektronix.com

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