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Back-to-basics of Power Products

How to choose; How to use

Agilent Technologies
Innovating the HP Way

Back-to-Basics of Power Products
Agenda

- **Introduction**
- **Characteristics of DC power supply**
- **How to choose?**
- **How to use?**
- **Further information**

In this presentation, we will provide information on how to select an appropriate power product for your application from the wide variety of available choices.   Also included will be an overview of how to use power products in some of today's key applications, with an emphasis on potential pitfalls and some best practices that will allow you to get the best performance in your application.

While time limits the number of applications we can cover, those we will discuss were selected to be representative of features and issues that are common in many applications. At the end of the presentation, we will also provide references that will help you find additional help for power products and applications.

Back-to-Basics of Power Products
Introduction

- **What are power products?**
    - **DC power supplies**
    - **AC sources**
    - **DC electronic loads**
- **What will you learn?**
    - **Why DC power supplies are important**
    - **How to choose DC power supplies**
    - **How to use power products**
    - **What to do when you need additional help**

While we will touch on all 3 types of power products, in today's presentation we will concentrate primarily on DC Power Supplies. Why? Surveys continue to show that the DC Power Supply is on of the most frequently used electronic test instruments. Fully 85% of users of test and measurement equipment indicate that they use a power supply in their daily work.

Why are DC power supplies so important? Today, a tremendous number of manufactured products include some form of electronic content. Whether powered primarily off the AC line or by batteries, this electronic content needs to be tested both during development and again in production. The easiest way to do this, and to determine that the products meet their design goals is to test the equipment using a power supply, either manually on a bench, or via computer control in a test system.

A quick glance at the sales literature of any major manufacturer of DC Power Supplies will demonstrate the amazing breadth of available choices to meet almost any conceivable application need. Which ones will work in your application? Which will provide the optimum performance for a minimum cost? To choose properly requires familiarity with your application needs and the key specifications of power products. Ultimately, your choice will impact your capability to assess the quality of your products in both R&D and Manufacturing, as well as the production yield.

You will get better and faster results if you spend a little more time for selecting DC Power Supplies. Most engineers and technicians consider a power supplies to be a very simple instrument that simply sources power. As such, they tend to consider DC Power Supply last when they are configuring test systems. Today's power supplies offer much more including some very significant measurement capabilities that can improve your test capabilities and give you a competitive advantage in the market. If you spend a little more time up front in DC Power Supply selection, it will save you time, money and improve the chance of success in your application.

Back-to-Basics of Power Products
Agenda

- **Introduction**
- **Characteristics of DC power supplies**
  - **Basic characteristics**
  - **Frequently misunderstood characteristics**
- **How to choose?**
- **How to use?**
- **Further information**

Characteristics of DC Power Supply
Basic Characteristics

- **Output ratings: (V/I/P)**

- **Load regulation: change in output V or I / change in load**

- **Line regulation: change in output V or I / change in AC input**

- **Programming accuracy: the difference between programmed and actual V or I**

- **Programming resolution: the minimum V or I you can set**

- **Read-back accuracy: the difference between measured and actual   V or I**

There are many characteristics that describe a DC Power Supply. Some of these are fairly straightforward and we will assume that only a brief review of definition is necessary.

Choosing the maximum ratings is generally straightforward. These are the maximum values that the power supply can be programmed to produce continuously, or that can result from application of the programmed variable across a load based on V = IR. The product of maximum V and I results in the rated output power of the supply measured in watts.

Regulation specifications detail the ability of the power supply to maintain a constant output setting regardless of changes in load or input line voltage. These may be specified as a fixed voltage or current deviation or as a percentage of full scale, sometimes with a small fixed offset term.

Resolution and accuracy specifications detail the worst case deviations between the programmed and actual values, or the measured and actual values.

For the purposes of today's presentation we will now turn our attention to some more frequently misunderstood characteristics. Please refer to the Agilent web-site at "http://www.agilent.com/find/power" or to the Agilent Power Products Catalog for additional information. On these and other specifications. You can also find most of the same information on the Power Products CustomerCare CD-ROM, which we will hand out at the end of this session.

Characteristics of DC Power Supply
Frequently misunderstood characteristics

The following specifications generate the most questions; and actually seem to cause the most application difficulties:

- **Output noise**

- **Remote sense**

- **Transient response**

- **Throughput**

So, let's take a closer look at each of these.

While any characteristic can be critical to a specific application, there are some specifications which come up again and again. As a result, we will go over each of these in depth. We will cover a description of the characteristic and also why it is important in typical applications.

Then, as appropriate, we will discuss some of the issues with selecting or measuring this specification and how it shows up in an application.

Characteristics of DC Power Supply
Frequently misunderstood characteristics

- **Output noise**
- **Remote sense**
- **Transient response**
- **Throughput**

Let's start with the output noise characteristic of a DC power supply.

Output Noise

- **What is it?**
  - **Ac components in the output which cause deviations from the desired output voltage or current**
  - **Measured over a specific bandwidth**
  - **Either normal mode or common mode relative to the output**
- **Why is it important?**
  - **Affects measurement accuracy of the DUT current drain, or causes an error in other DUT parameters measured**
  - **Could cause improper circuit operation, for example in logic circuits**

AC ripple and noise is an unwanted, but always present, component of the output of a power supply. At one time, this was called PARD, an acronym for "Periodic and Random Deviations". This noise is composed of many different frequencies, which come from a variety of sources. It is measured over a specified bandwidth, with other variables that can affect the measurement maintained constant. A typical spec might be measured over a bandwidth of 20Hz to 20 MHz, with the outputs ungrou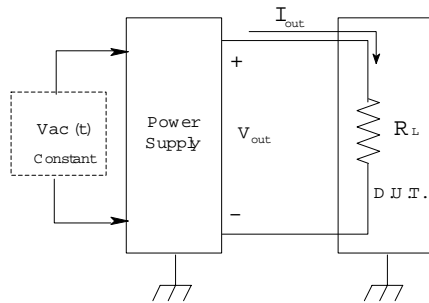nded or with either terminal grounded. Fluctuations below 20 Hz are treated as drift. Output noise can be either normal mode or common mode, and components of both are usually present together, but we'll discuss this further a little later in the presentation.

For many applications, a power supply provides bias power for the DUT, and any noise present on the output of the supply can be injected into the DUT. Once in the DUT, this noise can become an inseparable part of the desired signal causing a variety of problems depending on the nature of the DUT. For analog or RF circuits, the noise can cause degradation of other DUT performance measurements, such as the signal to noise ratio of an amplifier. In digital circuits, high frequency spike content in the noise can cause "glitches" or inadvertent state changes.
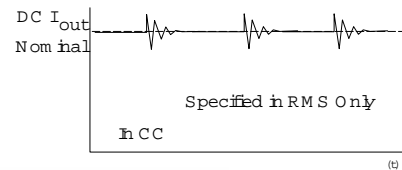
In general, it is almost always more difficult, and expensive to deal with the results of noise after it has been created. It is easiest, and cheapest in the long run, to deal with it at the source where it is generated. Thus much attention is given to the noise output of the power supply.

Output Noise
Periodic & Random Deviations (PARD)

peak-to-peak: the range between maximum and minimum amplitude of spikes content

DC V$_{out}$
Nominal

Specified in RMS and P/P
In CV

(t)

rms or effective amplitude: average level based on energy content

DC I$_{out}$
Nominal

Specified in RMS Only
In CC

(t)

I$_{out}$

+

Vac (t)
Constant

Power
Supply

V$_{out}$

R$_L$

D.U.T.

−

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There are several common representations of the noise output of a power supply. First, there are both peak-to-peak, and RMS (root mean square) measurements. The RMS or effective value of noise is an average measurement of the signal based on energy content. It is sometimes called the effective value because it is based on the amount of heat produced in a resistor. Thus waveforms with different amplitudes and frequencies that have the same energy, and thus have the same "effective" or RMS value, produce the same heat (temperature rise) in a resistor. Typically the signals measured are in a bandwidth of 20 Hz to 20MHz. If a different bandwidth is chosen, a given supply will have different RMS noise measurements.

Peak-to-peak noise is literally the range between maximum and minimum values of the output waveform. Sometimes the peaks are called "spikes". The energy content of these spikes is typically low, and thus they may not show up in an RMS measurement. However, their disruptive value to measurements usually makes the peak-to-peak measurement a better predictor of performance problems in an actual application. Again, the bandwidth needs to be specified or the results may vary significantly. Measuring with an instrument that has insufficient bandwidth can conceal spikes that could represent a problem for the application.

Noise measurements can be based on voltage or current. When operating in the constant voltage (CV) mode, noise voltage is the norm. When operating in the constant current (CC) mode,current measurements make more sense. Noise currents are typically measured in RMS only. This is because parasitic inductance in the load or wiring can dramatically affect the peak-to peak measurement (which is driven by spikes). Measuring peak-to peak noise in constant current mode tends to be highly dependent on the test setup and produces inconsistent results. However, the RMS measurement is not very much affected by the parasitic inductance since there is not much energy content in these spikes.

Output Noise
Normal Mode vs. Common Mode

Normal mode: Measured between the + and – terminals:
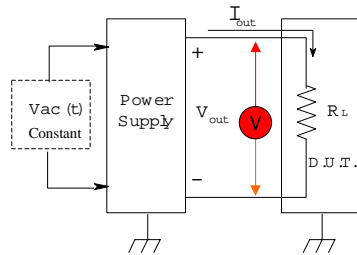
Common mode: Measured between both + and – terminals and ground:
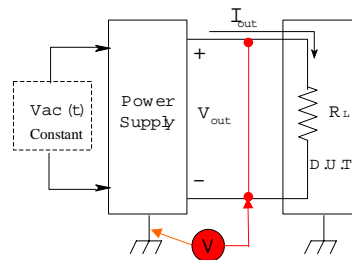
Normal mode noise is the most frequently specified parameter. If a given specification does not indicate which mode, it is usually safe to assume that it refers to normal mode. This is the value that you read when you place a voltmeter between the outputs terminals of the power supply.

Common mode current is measured between either output terminal and ground.

Output Noise
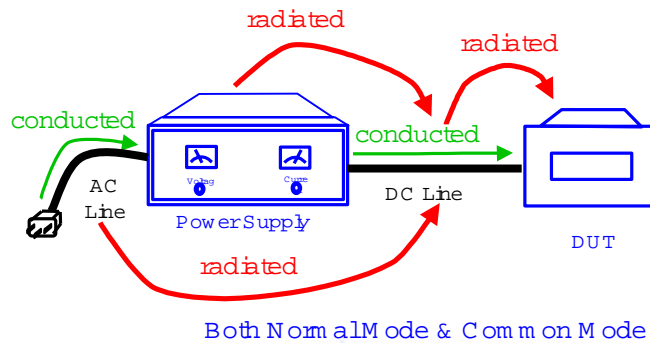## Common Mode Current Can Cause Problems!

- **Present in all supplies to some extent:**

    - Common mode current flows from each output terminal to ground

    - If the D.U.T. is floating, and the *impedance* from each terminal to ground is identical, the net effect on the load is 0. (This is rarely the case!)

- **Many switching power supplies generate a surprising amount of common mode current:**

    - Roughly speaking, this current can flow through the load impedance and look like additional normal mode output noise!

    - This is a good part of the reason why switching power supplies may produce unexpectedly higher noise output in typical applications.

All power supplies have some amount of common mode current, but it was not until the advent of switching mode power supplies that this specification gained much attention.   It has been responsible for giving switching power supplies a bad reputation in test and measurement applications, where the total noise across the DUT seems considerably larger than the normal mode spec would indicate.

To visualize how common mode currents are generated,consider an off-line switching supply. This basic power conversion topology uses power switching FETs to chop high voltage dc into a high frequency square wave, then passes it through a transformer to the secondary. The power FETs are mounted on large metal heatsinks which are placed in close proximity to the metal chassis and cover of the power supply. The combination of heatsink and cover form a capacitor one side of which is ground. As this capacitor charges to 400 volts and discharges it causes a significant current to flow between the power supply circuits and ground. Similarly,parasitic capacitance in the isolation transformer allows significant high frequency currents to flow from the isolated line side to the grounded secondary. Both of these phenomena contribute to the common mode current specification.

Output Noise
RFI Noise Sources

- **More unexpected contributions to the noise problem!**

  - **Switching (and linear) supplies and their connecting leads can create both conducted and radiated noise sources**

  - **Careful attention to wiring can minimize these problems!**

radiated

radiated

conducted

conducted

AC
Line

Voltage   Current

DC Line

Power Supply

DUT

radiated

Both Normal Mode & Common Mode

Some, but not all, of the components of noise on the output of a power supply are generated internal to the power supply. The diagram above shows two types of RFI noise coming from switching mode power supply (radiated and conducted). These noise sources are a result of the high dv/dts and di/dts that are inherent in switching power supply topologies. Both radiated and conducted noise can affect the load or device under test, thus interfering with testing.

Other noise components on the output originate outside the supply, but are either conducted into the supply via the AC input line, or are picked up from the environment in which the supply operates.
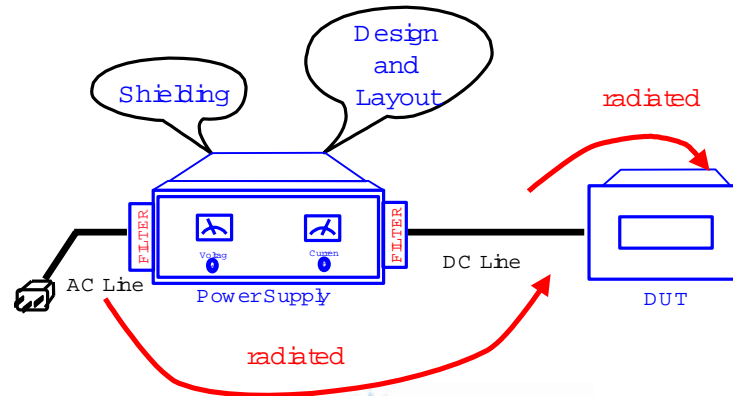
Some conducted noise sources on the power line are created by other power users whose equipment causes spikes on the line when it turns on or off. Conducted noise sources can also result from natural phenomena such as lightning strikes. Unless specific care is taken in power supply design, high voltage high energy spikes can be transmitted through the power supply and be presented at the DUT.

Some noise sources are caused by radiated signals from other equipment or machinery that may be physically close to the power supply. This energy can be picked up both by the power supply, and by the wiring to the DUT.

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- **Part of the Solution:**

  - Agilent supplies have internal circuit modifications that reduce high speed switching transients and control common mode current.

Design and Layout

Shielding

radiated

FILTER

Voltage   Current

FILTER

AC Line

Power Supply

DC Line

DUT

radiated

Agilent has worked hard to eliminate the effects of the noise generated by the switching process. Effort is made to eliminate excessive dv/dt and di/dt through choice of switching frequencies and device characteristics, by filtering the conducted noise, and by shielding the circuit to confine the radiated noise. These same design considerations help to minimize the transmission of noise sources that are external to the power supply (radiated or conducted).

These newer switching mode power supply designs have noise specifications and performance that are very similar to linear supplies. So you no longer need have any hesitation in selecting a SMPS where it seems appropriate for your application requirements.

In other cases, some engineers are drawn to choosing a switching power supply because it is smaller and lighter than a high power linear. At first glance it may also appear less expensive. However, not every switching power supply provides satisfactory performance. Some inexpensive, compact switchers still produce a fair amount of noise. While the purchase price may seem lower, this may be a false economy. It is often vastly easier, and less expensive, to eliminate noise at the source, than to try and deal with the effects of it elsewhere in the system.

Output Noise
Common Mode Current Resolution / Workaround

- **Note: placing a filter capacitor *across* the DUT input is not effective in reducing common mode current!**

- **Balancing the impedance to ground from each lead and careful connections from supply to DUT can minimize the problem.**

- **The best solution is to choose a power supply which has very low common mode current!**

  - **Check the data sheet carefully for a maximum common mode current specification**

  - **Most Agilent switching supplies generate less than 20 mA of common mode current!**

Since common mode current flows from both terminals to ground,placing a capacitor across the terminals will not eliminate the noise from the DUT.

Attention to proper layout and single point grounding is important. While matching impedance from each output terminal to ground can help somewhat, it is not always practical to do this from an application perspective. The only completely satisfactory solution is to start with a product that has very low common mode current to start with.

If the data sheet for the power supply does not include a common mode current spec, call the manufacturer in request the information. Quite frequently, more technical data is available than that which appears on the data sheet. If this is unsuccessful, you can characterize the common mode noise source by developing a traditional Thevenin equivalent model. With the power supply loaded with a floating load, use a scope to measure the open circuit voltage potential between either terminal and the chassis ground of the power supply. Then, alternately short each terminal to ground and use use a good quality current probe to measure the current flowing in the short. Make sure the current probe has adequate bandwidth to include the switching frequency and several orders of harmonics. From this information you can assemble a fairly complete characterization of this noise source. You can also develop an appreciation for a better designed power supply.

Output Noise
Eliminating Sources of Noise

- **Start with a low noise power supply**
    - it's easier to eliminate noise at the source than to filter it out later
- **Use good connection practice to avoid pickup:**
    - eliminate loops; twist and shield connections from power supply to DUT
    - carefully route power lines from ac mains to supply
    - think through grounding connections; prefer a single point ground
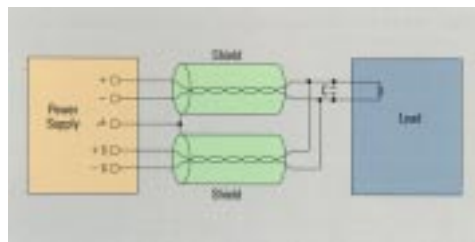
In summary, the figure above provides the key recommendations for achieving best performance from a given power supply for your application.

Remember that noise can be picked up by the remote sense leads as well as the load leads. Using twisted shielded connectors is excellent practice, although this can be challenging at really high currents.

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Characteristics of DC Power Supply
Frequently misunderstood characteristics

- Output noise
- **Remote sense**
- Transient response
- Throughput

The next topic is remote sense.

Remote Sense

- **What is it?**
    - **Method of connecting the load to the power supply output can impact the regulation and programming accuracy**
    - **Remote sensing monitors output voltage directly at the DUT (rather than at the output terminals of the power supply)**

- **Why is it important?**
    - **Long load leads or contacts of relays in the load circuit can add significant resistance; degrades output voltage regulation**
    - **In severe cases, lead resistance could cause device under test to malfunction, due to insufficient supply voltage**
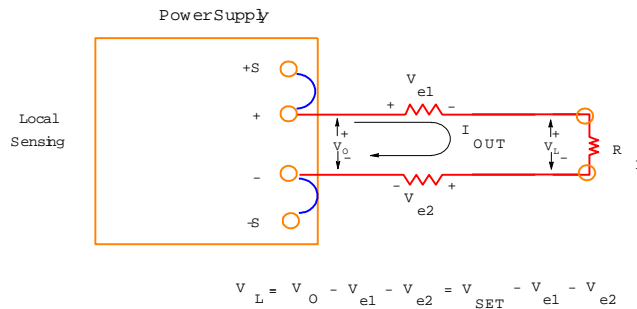
Most customers take for granted that a power supply will put out the programmed voltage at the specified accuracy. As they would with a signal generator, there is a tendency to simply connect the output terminals to the DUT and set the voltage to the desired level. However, power supplies differ dramatically in the level of current supplied to the DUT. A signal generator may produce an output of 5 volts into 50 ohms, resulting in currents on the order of 100 mA . Even a relatively low power supply, feeding power to a small battery powered cell phone, may be called on to provide 2 Amps at 5 volts. This is 10 watts, and it is not uncommon to find power supplies of 500 to 1000 watts at work in the lab or in an automated test set.

There is always some series impedance in the connections from the source to the DUT. Creating a voltage at the DUT causes current to flow through this resistance. This current flow across the series resistance causes a voltage drop which causes the output at the DUT to deviate from the desired/programmed level. With signal generators, this voltage drop is usually entirely negligible for most purposes.

With the higher currents that power supplies routinely supply, the voltage drop in the connections to the DUT under test can be significant. Furthermore, this voltage drop in the leads is load dependent, and subtracts from the programmed output voltage. This essentially degrades the power supply's load regulation specification. In fact, inaccuracies of 5-10% or more are possible in real application situations. This in turn can create inaccurate measurements on the DUT.

To counteract these problems, most manufacturers bring error sensing leads to the output terminals of the power supply. If the load is at some distance from the power supply, it would clearly be desirable to provide remote sensing capabilities in addition to local sensing.

Remote Sense
Starting with Local Sensing

PowerSupply

Local Sensing

+S

+

V_{e1}

I_{OUT}

V_O

V_L

R_L

-

V_{e2}

-S

$$V_L = V_O - V_{e1} - V_{e2} = V_{SET} - V_{e1} - V_{e2}$$

This is how the power supply is normally used in bench applications where load leads are short.
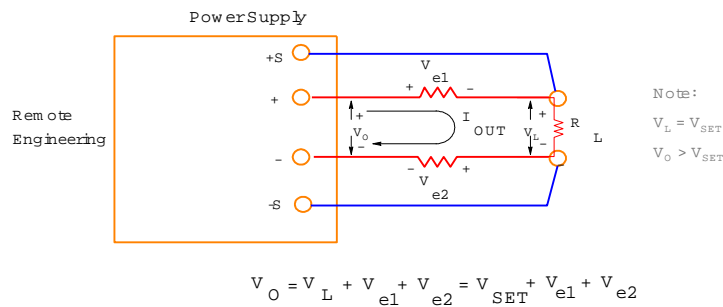
Virtually all power supplies use some form of internal amplifier to control the actual output level. Sensing the output and feeding back the result to this internal "error" amplifier is essential to maintaining programmed output voltage over a wide range of load currents. Many power supplies have the sense leads connected to the output leads at a rear panel connection strip, or front panel binding posts to allow the user flexibility in choosing where to have the power supply sense the output.

When the power supply is shipped from the factory, it is virtually always set up for local sensing. This means that the connections from the output to the internal error amplifier are made either internally, or at the output terminals. This is convenient for most bench applications, with short leads and reasonably low currents. Under these conditions, the voltage drop, caused by combination of resistance in the load leads and current through the leads as shown in the figure above, results in an acceptably small error at the load. This also helps prevents the inexperienced user from getting into trouble. Since, most power supply's characteristics are specified at the front panel binding posts or the rear terminals, this also provides a standard configuration for measuring performance.

In situations where the sense leads are provided to the user, there is usually a back-up higher resistance connection between the sense inputs and the output leads. If the sense leads were ever to be disconnected while the power supply was operating, the error amplifier could drive the power supply output to the maximum possible level. So, this high resistance connection assures that there will always be some feedback to the sense inputs. This protects the DUT from being subjected to potentially damaging voltages. Once the correct connections are made, these internal connections are "swamped out" by the far lower impedance of the direct connection between sense leads and output leads, and thus causes no significant error.

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Remote Sense

A constant voltage power supply monitors and regulates its output voltage directly at the DUT input terminals (instead of at the power supply output terminals).

Power Supply

Remote Engineering

+S

+

−

−S

V_{e1}

V_{e2}

V_O

I_{OUT}

V_L

R_L

Note:
$V_L = V_{SET}$
$V_O > V_{SET}$

$$V_O = V_L + V_{e1} + V_{e2} = V_{SET} + V_{e1} + V_{e2}$$

Of course, the assumptions made for local sensing are not always valid for every application, especially with higher power loads. In situations when the load is located at some distance from the power supply, for example inside an environmental chamber, the resistance in the load leads may be substantial.

In an automated test set, longer test leads are typically required since the DUT may be located at some distance from the power supply. Furthermore, relays may be used to make or break connections between power source and the DUT. These relays may not always be selected to have the absolute minimum contact resistance, and contact resistance increases with wear and age. In an automated test environment with long leads and relays, a combined series resistance of 1-2 ohms is not at all impossible. With currents in excess of 1 amp, voltage drops over a volt are easily encountered.

To resolve these problems, power supplies with remote sense terminals should be used. The sense leads can be extended to measure or "sense" the voltage level at the load. The power supply always tries to maintain the set voltage at the +S and -S terminals which have a high input impedance. No matter how much current flows through the load leads, the current in the sense leads is always small. Therefore there will be less IR drop than in the load leads. This allows the power supply to maintain it's excellent regulation specifications even at a considerable distance.

Remote Sense
Application Issues

- **Make sure remote sensing connections are properly made**

    - **Make the sense wire connections (+S to +; -S to the -)**
    - **Check if there is a Remote/Local switch on the back of the unit ; set to "Remote"**
    - **Note: most front panel binding posts <u>do not</u> have remote sense capability**
    - **If outputs are connected to the DUT through relays, separate contacts are needed for both load and P.S. sense leads**

- **Use a large enough wire gauge to minimize voltage drops**

AWG (B&S) Wire Size	Annealed Copper Resistance at 20 deg C in milli-ohms/foot	Nominal current rating (amps) single conductor at 30 deg C
22	16.1	5
20	10.2	7
18	6.39	10
16	4.02	13
14	2.53	20
12	1.59	25
10	0.999	40
8	0.628	55
6	0.395	80
4	0.249	105
2	0.156	140
0	0.0993	195
00	0.0779	260

Choosing the correct gauge and type of wire can helps to minimize the voltage drop that will occur. The chart above shows the resistance of different gauge wire. Thus, given the output current, the voltage drop can easily be calculated. If the resultant voltage drop will not be acceptable for the application, one solution is to employ remote sensing. Of course, if the drop is substantial, it is also advisable to verify the temperature rise in the wire, and ascertain that the insulation will withstand the maximum temperature.

Setting the power supply up for remote sensing operation is generally straightforward. Depending on the specific power supply, there may be a rear panel switch to choose between local and remote sensing operation. It will be necessary to disconnect the sense leads from the output leads at the rear panel, and run extra wires to the load. Some bench power supplies have extra front panel sense connections which can be utilized for remote sensing. However, this is generally limited to currents below 5-10 Amps. The standard 3 way binding posts on most bench supplies, have a maximum current limit and should not be used above 10 Amps.

In the case of an automated test set where relays are used to connect to the DUT, the sense leads require their own set of contacts. This allows any contact resistance in the relays to be brought "inside the feedback loop" of the power supply, and corrected for. However additional problems can be created when the relay is opened. Since the sense leads are then disconnected the power supply output voltage may rise to the maximum output. When reconnected, it will generally take some time to return to the programmed level. This may cause damage to the DUT. To prevent this, it is important to be sure that the manufacturer has implemented a fail-safe back-up connection internal to the power supply. It would be advisable to test the connections with out the DUT to make sure that the behavior is as expected. If necessary, external connected resistors of approximately 10kohms between sense leads and output leads on the power supply side of the relay will generally suffice to maintain the power supply output close to the desired level.
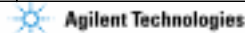
Remote Sense
Impact of Voltage Drop

- **Maximum allowable voltage drop in load leads:**
    - **Check the power supply data sheet for each product, to determine the maximum load lead drop that the remote sense can correct for.**
    - **Exceeding the maximum drop will cause degradation in regulation.**
- **Specifications for some common Agilent power supplies:**

Model	V_{drop} max	Voltage Regulation Impact
E364xA	Up to 1V in each lead	Add 5mV to regulation spec for each 1V drop.
66319-21B, -D	Up to 3V in both leads (main output); up to 4V in each lead (aux output)	Add 2mV to regulation spec for each 1V drop in the positive lead
6621-24A, 6627A	Up to 1.5V in either lead	None
6625-26A, 6628-29A	Up to 10V in both leads	None
663xA	Up to 2V in each lead	Add 5mV to regulation spec for each 1V drop in the *negative* lead
654xA, 655xA, 664xA, 665xA	Up to ½ the rated voltage	Add 3mV to regulation spec for each 1V drop in the *positive* lead
657xA, 667xA	Up to ½ the rated voltage	Add to the regulation spec as follows: # of mV = $2(V_{drop})*(V_{rating}/(V_{rating}+10V))$

Even with remote sensing, it is important to choose the correct gauge of wire to minimize the voltage drop in the power leads for two reasons.

First, any voltage drop in the load leads subtracts from the maximum voltage available to be delivered to the DUT. For example with an 8 volt power supply, a 1 volt drop in each load lead means the maximum voltage that can be delivered to the load is 6 volts.

Second, the voltage drop in the load leads still causes some degradation of regulation. There is no easy "rule of thumb" that applies to all power supplies, since the internal design may vary considerably from one product to another. The chart above shows the impact for a wide range of Agilent Technologies power supplies.

Remote Sense
Input impedance

- **Remote sense inputs are not easily characterized as an impedance.**

- **Inputs are typically connected to an op-amp input.**
    - **Look more like a current source, i.e. sense current is independent of sense voltage input.**
    - **Typically input current is well under 1 mA.**

Since the sense leads carry negligible current, they don't need to be heavy gauge wire. In fact, the questions often arises, as to what the "input" impedance is for the sense lead / error amplifier. The sense leads are connected to the inputs of the error amplifier which is typically an operational amplifier circuit. Thus, it is easier to think of the inputs as a current source with current in the range range of 10μA to 100μA.

Remote Sensing
Best Practice: Minimize Wiring Path Impedance

- **Four steps to minimize path impedance:**
  - **Use larger gauge, twisted pair wire.**
  - **Reduce distance between power supply and DUT.**
  - **Minimize the use of relays / connectors.**
  - **Select relays / connectors to minimize contact resistance; consider initial and end of life specs.**
- **Beware of transient response issues for dynamic loads**
  - **Use an adequate bypass capacitor at the DUT**
  - **Consider a supply tailored for remote sensing with pulsed loads**

To optimize performance, the overall wiring path impedance needs to be considered. It is always a best practice to minimize the wiring path inductance and resistance. We can accomplish this with the following steps:

1. Use larger gauge wire and reduce the distance between the power source and fixture as much as possible.

2. Always use twisted pair wires to minimize inductance. Use one pair for the load leads and a second pair for the sense leads. This also helps minimize noise pickup.

3. Eliminate or minimize use of relays & connectors or use low contact resistance power relays & connectors. Always consider the end of life resistance specifications as well.

All of the previous discussion was appropriate for the dc and low frequency considerations of powering a DUT. However, in real applications the dynamic behavior of the DUT is usually an additional factor to be considered. When the DUT causes current draw in pulses, the concept of transient response needs to be introduced. While there are some additional steps that can be taken, it may be important to consider a power supply specifically designed to handle this type of situation. More about this in a later section!

Characteristics of DC Power Supply
Frequent misunderstood characteristics

- Output noise

- Remote sense

- **Transient response**

- Throughput

Are you with the transient response of a DC power supply?

Let's talk about that.

Transient Response

- **What is it?**
  - **Characteristic which describes the power supply's response to an instantaneous change in the current demanded by the DUT**
  - **Specified only in the constant voltage mode with a resistive load**
  - **Typically specified for a 50% change in current demand**
- **Impact of characteristic**
  - **Can affect measurement accuracy of the DUT current drain, or cause an error in other DUT parameters measured**
  - **Negatively impacts time related tests**
  - **Artificially reduces DUT inrush current demands**

Transient Response is a frequently misunderstood specification.   It's NOT how fast the power supply can be programmed or slewed up or down. It is a measure of how quickly the power supply can return the output voltage to a programmed state after a disruptive change in load current.

When this change occurs, the power supply's internal error amplifier simply does not have the ability to respond instantaneously to this change. Instead, as more (or less) current is drawn, the voltage drop across many of the internal "resistances" in the power supply circuitry changes. This causes a corresponding change to take place in the output level of the power supply. For a significant current change, the output will temporarily leave the regulation band of the power supply.   Some time later the power supply error amplifier "recognizes" the change in output voltage and begins to adjust the output to restore the originally programmed level.

Transient response is always specified in the Constant Voltage mode and is performed and specified with a purely resistive load. It is specified as the length of time required for the output voltage to return to within a specified band (or percentage of output rating) of it's previous value after a change of a certain amount of current(usually 50% of rating). It's typically specified for a 50% change in the rated output current at an output voltage equal to or greater than 10% of the rated output voltage. Except in unique cases, this performance is specified at the rear output terminals of the power supply.

Transient response is not specified with loads other than pure resistances. Specifying for an inductive or capacitive load could typically require the power supply to exceed its max voltage or current specifications while it was restoring operation within the regulation band. Additionally, the error correction bandwidth of the power supply's error amplifier is significantly altered with the addition of a reactive load.

Finally, transient response varies with the type of power supply topology. As a rule, linears are much faster responding than switching power supplies.

Transient Response
Ideal (battery) Response

• **First, let's consider the response to a load change for a battery**
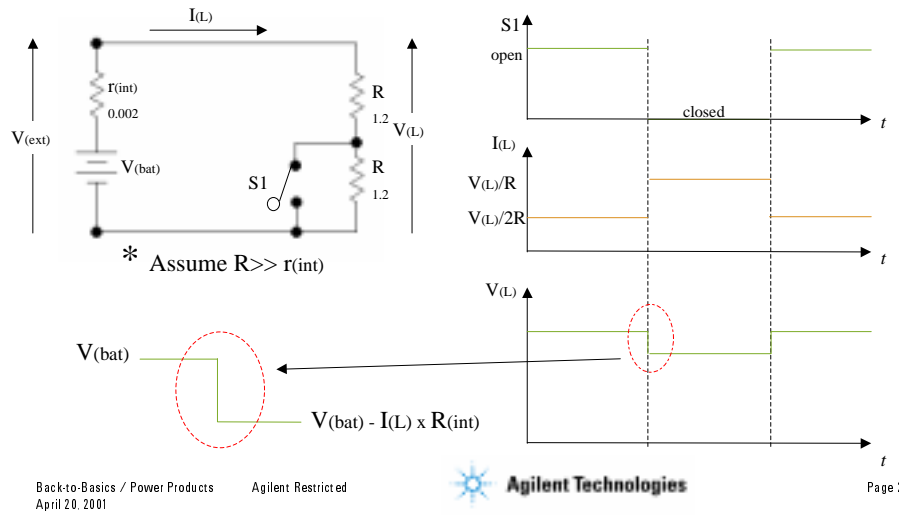
Here's a circuit which depicts the way a battery would respond to an instantaneous change in current demanded by a resistive load. For this example, let's assume that the load leads have no inductance and very little resistance. Also, let's assume that the internal resistance of battery is 0.002 ohms; small compared to 1.2 ohms resistance in the circuit.

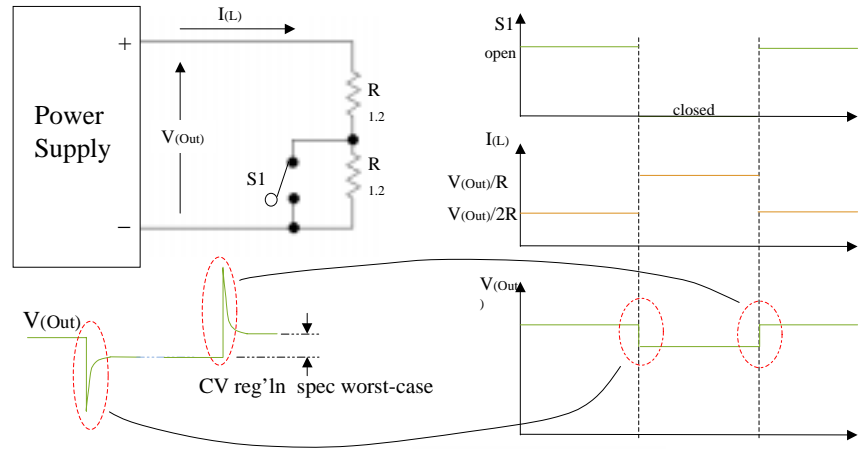If V(ext) is initially 12 volts, and S1 is "open", then the load current would be approximately 12v/2.4 ohms = 5 amps.

When S1 is closed, the load current instantly jumps by 5amps to a value of approximately 12v/1.2ohms = 10 amps. Additionally, the voltage across the external battery terminals now instantly drops by 0.002 x 5 amps or 0.010 volts. The external battery voltage is now about 11.990 volts.

Note that the battery, unlike a power supply, has no internal error amplifier to correct for this internal drop. When S1 is "opened", the load current instantly decreases by 5 amps, and the external battery voltage, V(ext) returns to 12.0 volts.

The transitions in output voltage (since we neglected the lead inductance) are virtually instantaneous. There is no measurable "transient response time", nor is there any over- or under-shoot in the waveforms.
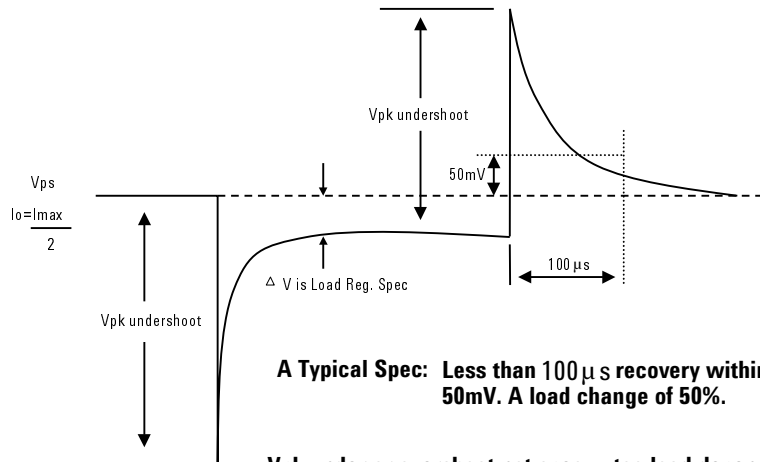
Here's the same circuit we just saw, but now with a power supply in place of the battery. Again, we'll assume that the load leads have no inductance and very little resistance. But now, of course, the power supply has an internal error amplifier to correct for the changes in output current, so it's internal impedance is negligibly low.

 If V(out) is set for 12 volts, and S1 is "open", the load current would be approximately 12v/2.4 ohms = 5 amps, just as before. Now when S1 is closed, the load current attempts to instantly jump by 5 amps to a value of approximately 12v/1.2ohms = 10 amps. However, the power supply's error correction circuitry does not have infinite bandwidth and a finite amount of time is required for the supply to source the additional 5 amps. Depending on a number of power supply internal characteristics, the output voltage could actually fall 1-3 volts on a temporary basis. Shortly thereafter, the power supply begins exponentially increasing its out voltage to provide the increased demand in current. However, the voltage returned to is a value slightly lower value than the initial value and is determined by the CV regulation spec.

Opening S1 would intend to instantly decrease the output current by 5 amps. Again, the bandwidth of the power supply prevents this from happening instantly. Instead, the output voltage actually spikes up, overshooting the desired value by the same 1-3 volts (due to internal supply characteristics. In short order, the power supply exponentially decreases the output voltage to the value initially programmed.

In this idealized case, the output voltage smoothly returns to the regulation band. In real applications, the non-resistive nature of both the load and the leads can actually cause some damped oscillatory ringing as the voltage returns to the regulation band.

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Transient Response Specification

Vpk undershoot

50mV

Vps

Io=Imax/2

△ V is Load Reg. Spec

Vpk undershoot

100 µs

Vpk undershoot

**A Typical Spec:** **Less than $100\mu s$ recovery within 50mV. A load change of 50%.**

Vpk under or overshoot not spec. – too load dependent. Could be 1-4 volts depending on supply, leads, load, etc.

This is a close-up of the loading and unloading transient on a power supply output shown on the previous slide.

**Transient Response
When using Remote Sensing**

- **Additional lead resistance and inductance worsen performance**

- **If the output current is drawn in pulses the power supply may not be able to maintain the programmed voltage at the DUT**

- **This poor voltage transient response may cause measurement problems, and could even cause some DUTs to shut down**

  - **for example a digital cell phone in talk mode**
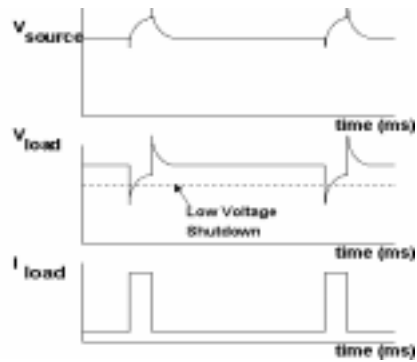
Bandwidth is kept low for a *general purpose* PS to assure stability in most applications. High bandwidth makes a supply more susceptible to oscillations with reactive loads. When remote sensing, load leads add considerable series resistance and inductance. This causes a degradation in transient response in proportion to how much resistance and inductance are added.

With a good quality linear supply transient response can typically be less than 50usec. However, in a high volume automatic test set, it is not uncommon to find 20-30 feet of leads to the fixture where the DUT is connected. In this situation, the transient response time can easily degrade by a factor of 10 or higher.

The initial load current is supplied by the power supply output capacitor. But with high resistance load leads, a large voltage drop across load leads can reduce the voltage at the DUT by a volt or more. For some test situations, before the internal power conversion circuits begin to supply the load current, the pulse is gone requiring a return to the original current level. This is usually not an acceptable situation for the test engineer, and some form of modification is required.

**Transient Response
Common Work Around: Add a Large Filter Cap**

+Vout   Zpath   +Vin

POWER
SUPPLY   +Sense   C
-Sense   Rc

DUT

-Vout   Zpath   -Vin
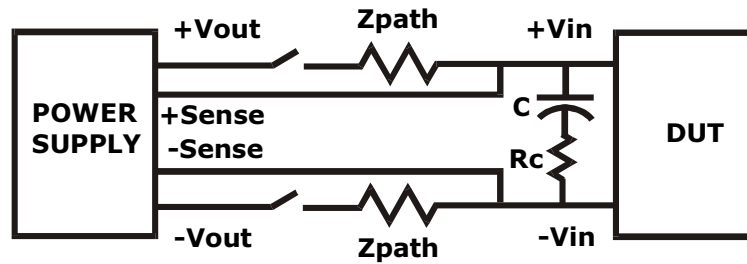
• Note: while this can help, it isn't the best solution in all cases.

A common work around is to place a large electrolytic capacitor across the terminals of the DUT at the test fixture. For the test conditions and configuration typical in automated testing of a cell phone, adding a 3,000 microfarad capacitor, can limit the transient amplitude to 100 millivolts.

There are, however, some drawbacks to this solution:

1. Electrolytic capacitors of this magnitude are large and may be difficult to mount at a test fixture, close to the DUT, and this can impose limitations on flexibility.

2. In many test applications, especially with battery powered DUTs such as cell phones, we want to measure the DUT's standby and off state current. In some cases, the leakage current of a large electrolytic capacitor may be too great in comparison to the DUT's off or standby current. Further, the leakage current of an electrolytic is a function of time, voltage, and temperature. This can seriously impact the accuracy of the measurement.

3. If we want to measure the magnitude of the pulse current drawn by the DUT, we find that a large capacitor at the DUT terminals can corrupt this measurement because the capacitor, and not the power supply, is providing the pulse current.

4. A large capacitor also impacts test time two ways. First it can slow down low level measurements by creating a long settling time. Second it can add time for the source voltage to reach its final value during powering up or powering down.

When any of these factors is important in the application, adding a capacitor at the DUT is not a practical solution. Instead the major focus should be on reducing wiring impedance as mentioned in a previous section.

Characteristics of DC Power Supply
Frequently misunderstood characteristics

- Output noise

- Remote sense

- Transient response

- **Throughput**

Many of you may have applications in production involving high volume. If so, you realize that throughput of the test system can be a critical determinant of yield. There are times when the power supply can contribute to the test speed (or lack of speed!) of your system. Let's take a look at some of the key influences.

Throughput

- **What is it?**
    - **DUTs tested / per hour: gauge of manufacturing efficiency**
    - **Can include many factors unrelated to power supply**
    - **May include: test, calibration, and product repair**

- **Impact of characteristic**
    - **Test yield often more important than cost of test system**
    - **Speed to test vs. quality/accuracy always at odds**
    - **Appreciably impacts price of end product**
    - **Significantly affects support costs**

A major concern for any high volume manufacturer today is to ramp up production quickly, and assure a good yield while maintaining quality. If the test time is too high and yield suffers, the manufacturing cost of the product will not meet target. On the other hand, it is small comfort to be able to produce a high number per hour if the reject rate is also high. Even worse, the wrong balance between yield and quality can destroy a company's reputation, or lead to expensive product performance/safety recalls. In some cases, there can be the potential for law suits. Clearly, the stakes are high.

The concern for "just enough test" to verify the quality of the product seeks to strike the balance between . The possibility of rejecting good products unnecessarily and distributing a large quantity of defective or out-of-spec product to customers.

The power supply can be one of the factors that limit throughput. It takes a finite time to change the output of the power supply, and to make measurements of DUT drain current. The more measurements that need to be made, especially at different voltages, the more the potential for the power supply to impact throughput. Furthermore, time spent calibrating the power supply, or removing it from the test set for repair, can cause expensive down time which is even more undesirable.

As a result, experienced manufacturers are generally willing to spend whatever is necessary to let them sleep at night. Since the power supply is not usually a major component of test system cost, this is NOT the place to cut corners.

Throughput
DUT Requirements to consider

- **Number of tests required to be made**
- **Number of discrete power supplies/loads required**
  - **isolation between supplies &/or earth required?**
  - **how much leakage is tolerable?**
- **Voltage and current levels required for various tests**
  - **test order affects number of voltage settings required?**
- **Necessity for precise voltages**
  - **increases settling time**
  - **over voltage protection required?**
- **Will voltage and current measurements be required?**

First, we need to consider the number and type of tests that need to be made on the DUT. While some devices simple operate at one voltage, other have specific voltage levels required for different tests. In this case, it may not be appropriate to leave the power supply set to the working voltage and just slap one device after another on the test set. And of course, once the test is completed, it is usually desirable to return the input voltage to the DUT back to 0.0 volts, so it is not left in a charged state.

If the voltage on the device must be maintained with great precision, it will take extra set-up time. And if protection features such as current limit and over-voltage protection are to be adjusted for each test, additional set-up time is required. Are measurements of DUT current required? Will other measurements have to be made after the device has stabilized to the new input voltage?

Sometimes tests can be sequenced in an order that minimizes the number of power supply output changes required. But there are clearly a lot of factors that need to be considered to optimize the test routine for best throughput.

Throughput
Power Supply Selection Considerations

- **Power Supply response:**

  - **Command processing time: t_0 - t_1**

  - **Slew time: t_1 - t_2**

  - **Settling time: t_2 - t_3**

- **Downprogrammers can decrease time to return to v_0**

- **Don't "overbuy" power capability: lower power supplies are *usually* dynamically faster**
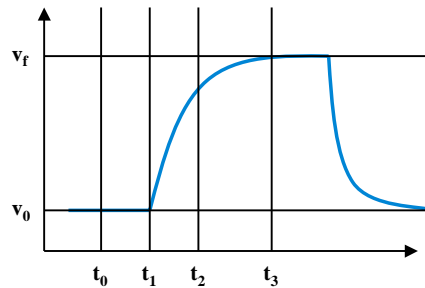
Once the profile of tests has been determined, attention can be focused on power supply selection. First, lets look at the anatomy of a programmed change in voltage. Initially the computer transmits the command to the power supply move from v_0 = 0 volts, to set a specific output voltage of vf, the desired test voltage. The power supply command processing time, represented by t_0 - t_1 in the diagram above, is typically 5 to 20 msec. The next segment, slew time, represented by t_1 - t_2 can be anywhere from 2msec to 100s of msec depending on the type and power level of power supply. Finally the settling time, here represented by t_2 - t_3 can be 50 to 100msec. The sum of these 3 intervals represents the total time it takes to set a voltage before an accurate measurement can be made.

Note that to return to 0 volts after the test is completed also takes a significant time. If the power supply is not equipped with a downprogrammer to sink current, and then DUT has any capacitive storage on the input, this time can be substantial. With a downprogrammer,not only is the transition achieved more quickly, but the DUT is left in an uncharged, and therefore safer, state.

Another point to be considered is the overall power supply rating. Sometimes a variety of different DUTs to be tested, at different power levels, makes it desirable to buy a larger power supply than needed for most DUTs. However, note that lower power supplies are typically faster responding. So, the throughput limiting specifications will be set by the largest DUT to be tested.

There are some further points to be considered in the choice of the optimum power supply. As mentioned previously, larger power supplies can be slower, especially if they are switchers, rather than linears. Where linears can execute a complete cycle in 10 to 50 msec, a larger switcher may take as much as 500msec or more.

Of course, all quoted specifications are for purely resistive loads. If the actual DUT has a reactive component to the load, the time for slew rate can dramatically increase. For example, is there is a large capacitor on the input, which will need to be charged, the current limit setting on the power supply may determine how fast it can be charged according to the formula:

$$t = (V \, C) / I_{limit}$$

Similarly, inductors require large voltages to ramp up current flow. These deviations from a resistive load need to be evaluated in determining the actual throughput impact.

Lastly, each specific command that the power supply processes has a characteristic processing time. For example, measurement cycles take significantly longer than voltage setting cycles. One way to reduce the time for measurement is to disable the front panel display so that the processor does not take time to write individual measurements to the display.

Back-to-Basics of Power Products
Agenda

- Introduction

- Characteristics of DC power supply

- **How to choose?**

- How to use?

- Further information

Now that we are familiar with most of the key specifications, let's take a look at the process of choosing a specific DC power supply from amongst the many available alternatives.

How to Choose?
What's the process to follow?

- **When to select the power supply for your application**
  - **Don't wait! Start thinking about the requirements for the DC power supply, while the project is being defined.**
- **How to select a power supply?   Consider the 5 P's:**
  - **Power requirements**
  - **Performance characteristics**
  - **Protection features**
  - **Packaging density (switcher vs. linear)**
  - **Price**
- **Remember, all power supplies are not created equal**

Given the explosion of high technology, it's not surprising that the power supply, which seems like a very simple instrument, is the last thing that the test professional considers. However, there are a lot of aspects to consider in choosing the optimum power supply for a particular application, as you are learning. There are many tradeoffs that will need to be made in the selection process. Waiting until the project nears it's conclusion, when there is not much flexibility, virtually assures that some awkward compromises may have to be made to accommodate the power supply.   So, the first "best practice" is to START EARLY!.

Since there are so many things to consider, it's convenient to remember the major factors as the 5 P's of power supply selection.

* Power rating: Of course the first place to start is selecting the specific ratings that the DUT requires.

* Performance characteristics: We have already covered some key specs to be aware of.

* Protection features: We'll present a quick check list of things to be sure the power supply offers.

* Packaging density: Power supplies can be large, and hot! How much room will you need to house the power supply?

* Price: The purchase price is not the only aspect to consider.

Lastly, remember that there are many kinds of DC power supplies in the market, for a good reason. Agilent alone offers 150 models of DC power supplies. Each power supply has its own unique characteristics that differentiate it from other power supplies, and may make it ideal for your application requirements.

How to Choose?
Selecting power ratings for a DC Power Supply

- **First, what size power supply do I need? (Watts/size)**

- **The voltage and current need is (p =V x I) watts**

    - **Do I need flexibility? – Should I buy just enough power, or include some margin?**

    - **Don't "overbuy" power capacity because you may need to compromise other performance**

- **Is the DUT resistive, inductive or capacitive?**

    - **The type of load effects voltage programming response time**

- **Do I know the AC input requirement?**

    - **115/230V? Single or 3 phase? How much current will I need?**

Before jumping into a review of the specifications of comparative models, you should consider the requirements for the DUT(s) you need to test. Is it just one device, or will there be several? How stable is the requirement for power? Sometimes, it's amazing how much the power consumption of these devices can grow during the design process!

Of course, you probably know how much power is required for your DUT. But is the load primarily resistive or is there a capacitive or inductive component? Reactive components in the load can dramatically increase the current or voltage required especially during output transitions. Also, how much extra voltage or current is needed for any margin testing? To determine the power capacity you have to buy, be sure you consider the flexibility to accommodate all the devices being tested.

Be aware that these considerations lead to a tendency to "overbuy" power ratings, especially, if there is any doubt about the reliability of the power supply when operating near maximum ratings. However, a larger supply can also be slower, which affects test times, and may also have less resolution and less accurate measurement capability. Remember, that the DUT load characteristic can also effect the speed of DC power supply as was discussed previously. Choosing a power supply from a reliable vendor, ensures that you will be able to count on it to produce full power at the rated ambient temperature, while providing excellent reliability.

Another area to investigate is the AC power requirements for the power supply. Especially, if you need more than 500 Watts output, you should consider whether the power supply will operate on the AC line commonly available in your test area. Of course, available AC power can vary widely depending on the region. Will the power supply have to operate on 115Volts? Is there a high enough rated branch circuit available to accommodate the maximum input current of the power supply? For those supplies at or above 2kWatts, will 3-phase AC input be required, and is it readily available?

How to Choose?
Performance Characteristics

- **What is important in this application?**

    - **Requirements for basic characteristics?**

    - **Have I considered the frequently misunderstood characteristics as well?**

    - **Consider the reference material provided for further information**

- **Key decision:**
    Do I need a basic or a high-performance DC power supply?

Now, you need to review the features and specifications for DC power supplies. Most of the important characteristics were covered earlier, however there are additional characteristics that may be important in a given application.

The reference material on the CustomerCare CD that that you will receive provides extensive additional help. For example:

* The DC Power Supply Handbook (AN-90B) has a section on definitions and test circuits for the full range of specifications and characteristics.

* The Power Products Catalog has detailed application information, a glossary of terminology, and product specifications for over 150 power products.

* The Users Guides for the products include an extensive section on guaranteed specifications and supplemental characteristics that will cover virtually any requirement.

Here is a key point, where a decision will be helpful to narrow down the range of selection. Will a basic system power supply that offers the appropriate ratings, programmability, and reasonably good specs be adequate for this application? Some examples are automated bench testing in the R&D lab or testing in production where high throughput is not the primary concern.

Or are there specific performance requirements or throughput concerns that dictate a high-performance solution? Of course, the key example is the high volume production line, where the power supply will be counted on for achieving consistently high test quality AND high throughput.

Agilent Technologies offers a wide range of products in both categories from which to select.

How to Choose?
Protection Features

- **What kind of protection will the DUT require in this application?**
  - **over voltage protection (OVP); trigger an interrupt?**
  - **over current protection (OCP); with automatic shutdown?**
  - **over temperature protection; what is the ambient temperature**
- **In the event of failure of the DUT:**
  - **do you need to immediately shut down multiple outputs?**
  - **open an isolation relay connecting DUT to power source?**
- **Do you need need local lockout of front panel controls?**

Sometimes DUTs not only fail the test, but may do so in a catastrophic manner. It may be desirable to limit further damage or consequential damage to other equipment upon failure of the DUT. Clearly fast decisions need to be made. The power supply can't wait for a command from the computer.

Protection circuits in the power supply can limit the voltage or current to a preset level. Additionally, most power supplies have the capability to automatically shutdown the power supply when an over-voltage or over-current condition occurs. A good system power supplies should also have a down-programmer circuit which can quickly discharge the DUT. Another possibility, depending on the application, may be to have the power supply open a relay and isolate the DUT from the power source upon receiving a fault trigger. A system of fault triggers and remote shutdown terminals (RI/DFI) can provide a signal at hardware speed to shutdown multiple outputs in a test system, or to establish a pre-determined shut-down sequence.

Programmable wake up states can be utilized to protect the DUT in the event of an unexpected power failure to return the power supply to a know safe state. This would usually be 0volts and 0 amps, but could be defined differently for unique situations (for example: battery life cycling, where a 0v,0A state might drain the battery unexpectedly).

In some automated test set applications, local control of the power supply in the system is desirable during debug and troubleshooting. However, it may be desirable to limit accidental/unintended operator intervention during a test sequence. To protect against this, it is good to have the capability to select a local lockout mode for front panel controls.

How to Choose?
Packaging Density

- **Do I need:**
    - **Single range, multiple ranges or auto-ranging?**
    - **Single or multiple outputs?**
- **Do I need flexibility?**
    - **My test needs may change, can I add another power supply later? How much room is left in rack?**
    - **Half or full rack? How many U's high? (1 U = 44.5mm/1.75 in.)**
- **Higher power or more features frequently mean more space, more AC power, and more cooling**

There are many choices to satisfy your requirements for footprint on the bench -or- front panel area in a rack mount system. First, if you need full output at more than one voltage, you can select a power supply with a dual range output, I.e. which can deliver full power at two different voltages. Another possibility, for even more flexibility, is the auto-ranging capability some DC power supplies offer. An auto-ranging power supply offers constant power at any voltage between to endpoints.

Where more than 1 output is required for an application, it may be possible to save space on your lab bench or your test rack by choosing a power supply with multiple outputs. Boxes with 2, 3 or 4 DC power supplies instead of one are relatively common. These products not only save on physical space, but some of them offer multiple outputs programmed from one GPIB address. This can help conserve the number of addresses in a system with a lot of different equipment, all controlled by the computer. Of course, there are tradeoffs to consider. Multiple outputs in one box can reduce flexibility, limiting the number of separate displays and controls for each output to achieve a smaller package.

For the ultimate in flexibility, consider a modular power system that allows the user to select any combination of up to 8 outputs in one box. These modules can even be reconfigured quickly to test several different D.U.T.'s with one test system, or to satisfy different requirements for a future need.

Some power supplies are in half-rack width packages which can minimize the footprint on a bench, but may not rack mount as easily unless they are used in pairs, or matched with another half-rack instrument. Others, are full-rack packages that are primarily at home in a system rack. When multiple outputs, and or high power are required in a confined space, cooling requirements should be considered. Many higher power system supplies depend on a cooling fan to establish adequate airflow and reliable operation. Many of these do have fan speed control circuits to reduce noise when the ambient temperature permits (such as the lab environment). For best results, mount system power supplies at the bottom of the rack, where the air is coolest, and their heavy weight will help stabilize the rack.

How to Choose?
Do I need a linear or a switcher?

- **Linear**
    - **Large in size**
    - **Low in output noise**
    - **Fast(speed of control loops/up-down time)**
    - **Up to 500 watts**
- **Switcher**
    - **Smaller in size**
    - **Generally noisier output**
    - **Slower(speed of control loops/up-down time)**
    - **150 watts up**

From available DC power supplies in the market, there are primarily two different topologies. One uses linear circuits and the other is employs switching mode power control, usually called switchers for short. The debate over the merits of switchers versus linears for specific application have gone on for decades.

Linear power supplies can offer very high levels of performance. They generally have the lowest noise outputs, very fast transient response over the full range of output, and the highest programming speeds. They also can have much lower RFI noise outputs, and generally negligible common mode noise currents.

On the other hand, they are big, especially as the power approaches 500 watts. They also are inefficient, requiring more AC input power per unit output and, of course, more cooling air as a result. Another potential problem is a somewhat higher level of low frequency magnetic radiation, principally from their large power transformers. This latter characteristic makes it advisable to mount power supplies at some distance from oscilloscopes or computer monitors which are notoriously sensitive to magnetic radiation.

Switchers offer a lot of benefits in size, weight and output capacity, especially when the power is 150 watts and over. They are more efficient both in space and in energy usage. As a result, they do run cooler, and represent less of a drain on air conditioning resources in the test area. However, they generally have noisier outputs, their transient response is much slower and their programming speed is also slower. They do represent some additional noise sources, and it is wise to anticipate these potential problems in system design.

Recent design advances have enabled Agilent Technologies to offer switchers that have most of the performance of linears even at powers up to 5kWatts where linears are not available. With well controlled and characterized RFI and common mode current, there is little reason to hesitate to choose a linear where the power requirements make it the logical choice.

There are always trade-offs to consider when you select a DC power supply. Make sure to consider ALL your requirements carefully, rather than jumping to a conclusion based on topology or price.

How to Choose?
Price: All Power Supplies are not created equal

- **Generally, you prefer to buy "just enough capability"**
    - **The common saying is: "You get what you pay for...";
      but actually: "You don't get what you don't pay for!"**
- **Sometimes it does make sense to buy extra capability:**
    - **For the flexibility to accommodate multiple DUTs**
    - **For margin to accommodate future growth in DUT capability**
    - **To improve manufacturing yield / quality**
    - **To assure that a key specification will never be a problem**
- **Purchase price is not the only component...**
    - **Consider the total cost of ownership over test system life**

If you consider an analogy with cars, they all have four wheels on the ground and a steering wheel. But there the similarity ends. Cars are commonly available that offer similar functions but can differ in price by over a factor of 10x. You probably wouldn't expect to win the 24 hours GP of Le Mans with a Mazda Miata, nor would it be sensible to commute to work in a Ferrari GT. So it is with power supplies!
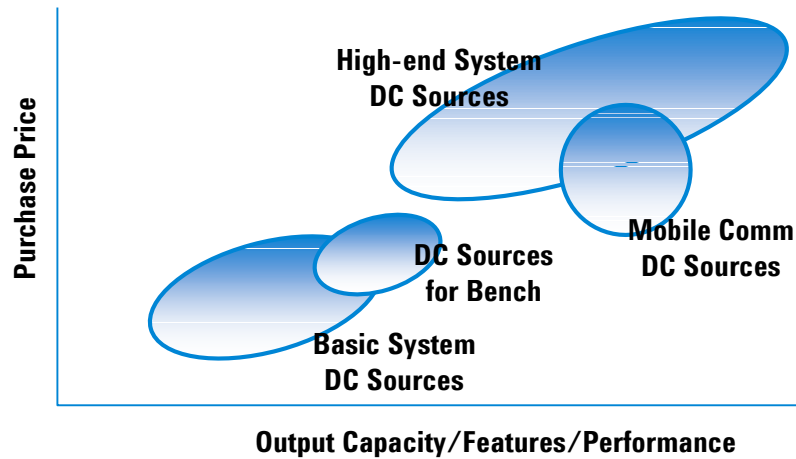
It's possible to get a 200 Watt GPIB programmable power supply with all the basic features and excellent performance for a very economical purchase price. Or you could spend twice as much to get a 200W system power supply that is capable of achieving very high throughput, while providing the ultimate in protection capability for the DUT. Both are excellent choices for certain applications.

No one wants to pay for features and capabilities they don't need. Hence, you should take the time to consider what your application requires and what you don't need before choosing a power supplies. You can not get the benefits if you decide the model to purchase based on just the output voltage/current ratings and the price. Especially in an automated test environment, the power supply probably represents less than 5% of the total system purchase price! Why risk problems in a mission critical system by choosing an inadequate supply with limited specifications.

When you consider the price, you should consider the "whole product experience" which includes cost for integrating a system, downtime for calibration or repair, and the cost to implement needed performance or protection features as an after thought.

For flexibility and future application changes, buying extra power supply capability now may save expensive redesign in the future and facilitate testing new DUTs or the margin to accommodate DUT product capability growth. With this extra capability, you could improve your yield and/or product quality for your current product.

How to Choose?
Offerings from Agilent

Purchase Price

High-end System
DC Sources

Mobile Comm
DC Sources

DC Sources
for Bench

Basic System
DC Sources

Output Capacity/Features/Performance

Agilent Technologies currently offers 150 different models of power products to meet your application needs. The price mainly depends upon the output capacity, the performance, and the features in the product, but their value is limited only by your ability to use them to solve tough application problems easily.

For more details about each model, you can refer to the Agilent web-site or the handy CustomerCare CD which we will after this presentation. Whichever media you use, the Power Products Catalog will provide a wealth of information on products, applications and more. For price and availability information, please contact your local Agilent Technologies sales office or call the local Call Center.

Back-to-Basics of Power Products
Agenda

- **Introduction**

- **Characteristics of DC power supply**

- **How to choose?**

- **How to use?**

  - **Digital Cell Phone Test**

  - **DC Power Supplies in ATE Applications (Base Station)**

  - **DC Charger Test with AC Source and DC load**

- **Further information**

As we switch focus to applications, we will cover a few popular applications today, which illustrate a variety of test requirements that are common to many applications.

First, let's look at a low powered application for testing a battery powered device. While we will choose a mobile phone as an example, the considerations could equally well apply to a host of high volume devices manufactured today.

Low Power Application
Digital Cell Phone Test

- **Digital mobile phones are an example of a battery powered device which draws significant power in bursts**
  - **talk mode: typically currents of 1-2 Amps for 600 uSec**
  - **standby mode: typically 200-300 mA for 100 mSec**
- **Production test environment frequently features automatic test sets which introduce significant challenges**
  - **long leads and relays can add up to 1-4 ohms of resistance and 6uH of inductance between dc source and the DUT**
- **Three challenges for the test engineer to meet:**
  - **sourcing pulsed currents with remote sensing**
  - **measuring current drain of DUT with pulsed waveforms**
  - **calibrating the battery management circuits**

Many of today's low power applications involve testing a device that is intended to be primarily powered by batteries. Of course, one obvious example is a mobile phone, but there are many more. Laptop or notebook computers, palmtops, pagers, GPS navigation aids and a variety of other personal digital assistants are also common. Just look around the average household to see the variety of entertainment devices, portable tools, cordless kitchen appliances, and more!
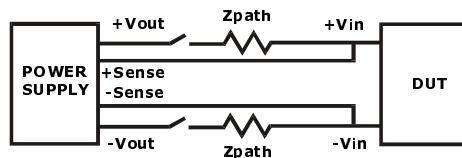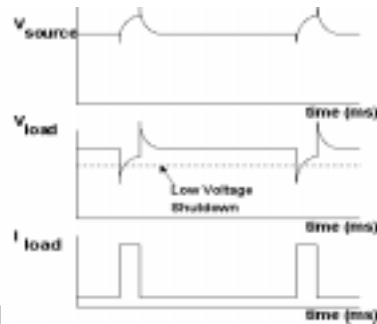
What these devices all have in common, in addition to being battery powered, is that battery life quickly becomes a key selling point to the end user. Thus testing to assure battery life frequently becomes a key objective for the test engineer. Often times, current is drawn from the battery in pulses to conserve battery life. Another key common characteristic is that most of these devices are manufactured in extremely high volumes. This in turn means that throughput is very important. Lastly, consumers can be very fickle. If a brand displays poor quality/reliability, there are many other equivalent brands that a customer can switch to. So, verifying that the manufacturing yield and quality are very high is of paramount importance.

High volume manufacturing with high throughput means automated production lines, and automated testing. Using a power supply to substitute for the battery is virtually universal. This creates three significant challenges for the test engineers in choosing the right power source.

1. Sourcing pulsed currents with remote sense requires attention to transient response at the DUT.

2. Measuring DUT operating currents is necessary to insure that every device will meet battery life specs.

3. Making sure that the DUT is able to use the full range of the battery from full charge to full discharge requires calibration and test of the DUT battery management circuits.

Low Power Application
Transient Voltage Drop at DUT - GP Power Supply

- **High series resistance causes poor transient response when remote sensing.**

- **Large voltage drop may trigger shutdown of DUT.**

- **Low-voltage performance testing is compromised.**

V_{source} time (ms)

V_{load} Low Voltage Shutdown   time (ms)

I_{load} time (ms)

POWER SUPPLY   +Vout   Zpath   +Vin   DUT
+Sense
−Sense
−Vout   Zpath   −Vin

When choosing a power source, it may seem like any reasonably good low power programmable power supply will be adequate. However, experience shows that this often is not the case. The lead lengths and relay contacts between power source and DUT for a typical ATE system will introduce substantial series resistance. Thus it is normal to use remote sense to eliminate the resultant voltage drops and control the voltage at the actual DUT.

Furthermore, with many products, one or more operating modes may cause load current to be drawn in a pulsed mode, for example talk mode on a mobile phone, or disk startup on a laptop. Testing is generally done at high line (fully charged battery) and low line (below which battery voltage the DUT is forced to shut down). Especially in the latter case, any significant deviation from the programmed voltage level could result in termination of the test due to premature DUT shut down. A typical goal therefore might be to hold deviations to no more than 100 mV. As indicated by the graph, with general purpose power supplies, the initial instantaneous voltage drop for a pulsed load, even with remote sensing, could result in substantial spikes. These can be an order of magnitude larger than our desired goal of 100 millivolts. In a typical example, the voltage drop could be over 2 volts, easily triggering the mobile phone's low voltage shutdown, and disrupting the testing.

A general purpose power supply simply does not have the required response speed to source the fast pulse current drain of a digital mobile phone with out significant transient voltage drop. One approach taken to compensate for the transient voltage drop is to run low voltage testing at a higher setting than desired. This compromises the accuracy of the low voltage testing.

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Low Power Application
Common Work Around: Add a Large Filter Cap

+Vout Zpath +Vin
POWER SUPPLY
+Sense
-Sense
C
Rc
DUT
-Vout Zpath -Vin
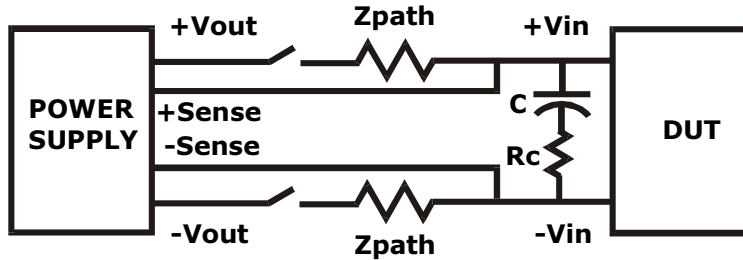
- Note: carefully consider current measurements before choosing a bypass capacitor

- Alternatively, consider all steps to minimize path impedance first

A common work around is to place a large electrolytic capacitor across the terminals of the DUT at the test fixture. For a typical mobile phone ATE test environment / configuration, adding a 3,000 microfarad capacitor, limited the transient amplitude to 100 millivolts. There are, however, some drawbacks to this solution:

1. Electrolytic capacitors of this magnitude are large and may be difficult to mount at the test fixture, close to the cell phone, and can impose limitations on flexibility.

2. In many test applications for mobile phones, we want to measure the phone's standby and off state current. In some cases, the leakage current of a large electrolytic capacitor may be too great in comparison to the phone's off or standby current. Further, the leakage current of an electrolytic is a function of time, voltage, and temperature.

3. If we want to measure the magnitude of the pulse current of the mobile phone, we find that a large capacitor at the DUT terminals can corrupt this measurement because the capacitor, and not the power supply, is providing the pulse current.

4. A large capacitor impacts test time two ways. First it can slow down low level measurements due to long settling time; second it can add time for the source voltage to reach its final value during powering up or powering down.

When any of these factors is important in the application, adding a capacitor at the DUT is not a practical solution. To optimize performance, it is always a best practice to minimize the wiring path inductance and resistance. We can accomplish this with the following steps.

1. Use larger gauge wire and reduce distance between the power source and fixture as much as possible.

2. Always use twisted pair wires to minimize inductance.

3. Eliminate or minimize use of relays and connectors, or select low contact resistance devices. Always consider the end of life resistance specifications as well.

Low Power Application
Types of Battery Drain Currents Measured

- **Talk-mode pulsed current drain**
  - **Pulsed characteristic**
  - **DC average and pulse parameters**
- **Standby-mode current drain**
  - **Pulsed (slotted mode) and continuous**
  - **DC average value**
- **Off-mode current drain**
- **Charge mode current**

The second challenge facing the test engineer is measuring the current drain for different operating modes to assure that the customer will receive the full specified battery life. For a mobile phone, talk mode current drain is the heaviest drain on the battery, and thus is the most fundamental current measurement, to assure the device has adequate talk time. However, the pulsed current drain characteristic can be challenging to measure accurately.

Long standby-mode operation is also extremely desirable, allowing devices to receive incoming calls for many days before recharging the battery. DC average current drain for standby is also a very fundamental measurement in production test of a mobile phone. Standby current may either be continuous or pulsed, as is the case for slotted mode standby operation on digital phones. Accurate average measurement of slotted mode pulsed current drain is even more challenging than for talk mode .
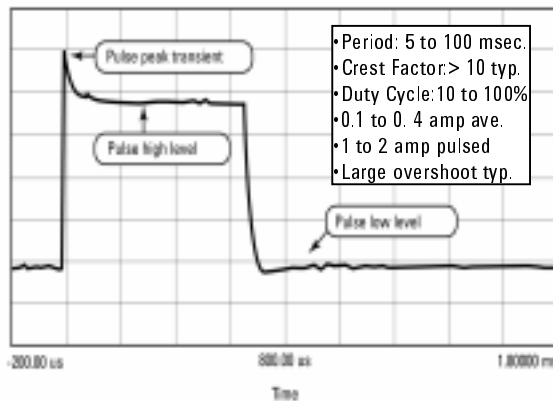
If off-mode current drain is high, it can quickly and unexpectedly drain the battery, leading to user dissatisfaction, as well as being systemic of potential latent failure mechanisms. Here, the measurement challenge is simply being able to resolve very low currents with reasonable accuracy.

Finally, charge mode current is measured at both rapid charge and trickle charge levels to accurately calibrate the DUT's internal battery current monitoring circuits.

Low Power Application
Talk-Mode Pulsed Current Drain Characteristics

- Key current measurement considerations:
  - Pulse crest factor
  - Max. to Avg. ratio
  - Pulse period (may not be known precisely)

Figure annotations:
- Pulse peak transient
- Pulse high level
- Pulse low level

Box:
- Period: 5 to 100 msec.
- Crest Factor:> 10 typ.
- Duty Cycle:10 to 100%
- 0.1 to 0. 4 amp ave.
- 1 to 2 amp pulsed
- Large overshoot typ.

Time
-200.00 us   600.00 us   1.80000 ms

Pulsed current drain characteristics need to be taken into consideration when making any measurements. In our example of a digital mobile phone, the pulse rate can vary from 5.67 msec for GSM, to 10 msec for TDMA & CDMA, and up to 90 msec for iDEN/Nextel mobile phones.

The transmit burst current drain can easily exceed a crest factor of 10. Duty cycles range from 1/8th for GSM to 1/3rd for TDMA, and between 1/4th to 1 for CDMA. CDMA duty cycle depends on speech activity.

The average and maximum (burst) current drain values depend on the maximum transmit power for a given format and the battery voltage. Most formats output up to 0.6 watts RF power, while handheld GSM can be as high as 1watt RF power. Battery voltage is usually between 3.6 and 6.0 volts and the trend is to go to even lower voltages. The resulting average current usually ranges between 0.1 to 0.4 amps, with pulsed levels of 1 to 2 amps. The pulse top may be relatively flat, as is the case with GSM, or it may vary in shape with other transmission formats.

Many times the DC average current measurement is incorrect, or erratic, because the pulse characteristics were not taken into consideration, for ex.: the high crest factor was not considered and exceeds the test instrument's capability. The measurement may end up erroneously low, allowing defective products to pass. The high pulse level, but low DC average level, dictates milli-ampere level measurement accuracy over a full 2 to 3 ampere measurement range.

If the relationship between the DUT's pulse period and the measuring instrument's "sampling" window is overlooked, the result will be jittering or erratic measurements. If the period is known precisely, the window needs to be accurately set for one or more periods. If not precisely known, the test equipment should provide alternate means for accurate measurements, typically setting the window for many periods to reduce error. However, this can dramatically increase overall test time, reducing throughput.
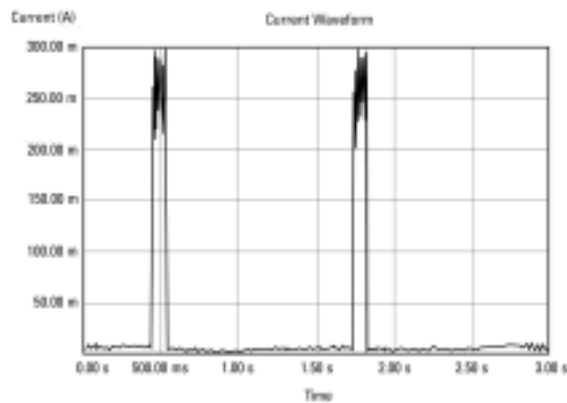
Continuous standby current drain is typically tens of milliamperes, providing about two days of standby time. In slotted-mode standby operation the mobile phone "wakes up" every few seconds to check for incoming calls, drawing 100's of milliamperes and then drops back into a sleep mode drawing a few milliamperes. This uses less average current, thus providing even longer standby time.

Sub milliampere measurement accuracy is needed for standby mode current drain measurement. Slotted mode current measurement is extremely challenging to make to this level of accuracy in presence of such high peak currents. It is further complicated because the measurement window of most test equipment does not adequately handle seconds-long pulse periods, low duty cycles, and/or crest factors of 100.

Low Power Application
Additional DUT Current Measurements

- **Off-mode (leakage) current drain:**
    - **Benefits: Battery life, latent failure mechanisms**
    - **Accuracy: <10 uA for 50-100 uA levels**
    - **Test system errors: Electrolytic caps, leakage paths**
- **Charge current:**
    - **Benefits: Proper battery charging circuit calibration**
    - **Accuracy: <3 ma or 0.5%, trickle & rapid charge rates**
    - **Polarity: negative**

Again, if off mode leakage current is high, it can quickly and unexpectedly drain the battery, leading to user dissatisfaction. It may also be indicative of a problem in the DUT that represents a potential latent failure mechanism. Production testing catches random manufacturing and component defects. As leakage current is around 50 to 100 uA, a separate measurement range with 10 uA accuracy is adequate. Test system leakage currents need to be watched. If an electrolytic filter capacitor was used to reduce transient voltage drops at the DUT, it can easily have 100's of uA leakage or higher, introducing significant error to the measurement.

In most newer designs, the charger current is monitored and controlled by the device itself. The DUT is typically charged at tens of milliamperes trickle charge current levels as well as ampere rapid charge current levels. Measurement accuracy of < 3 ma or 0.5% is sufficient.

Low Power Application
Mobile Phone Battery Charging Configuration

Battery Pack — Mobile Phone — AC to DC Adapter

"Constant Voltage" "Typically Constant Current"
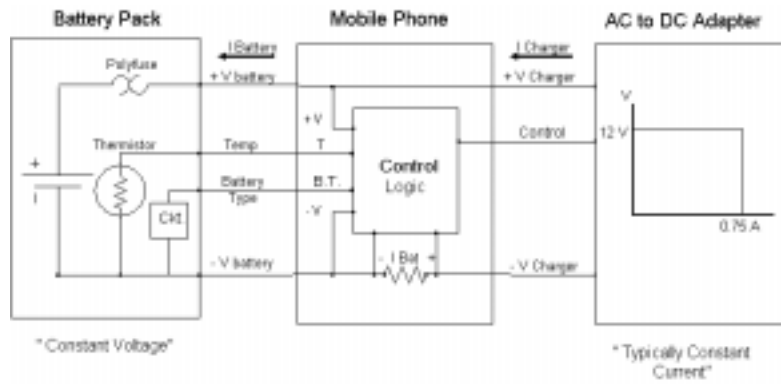
A mobile phone provides an excellent example of key considerations here. The block diagram illustrates a typical mobile phone battery charging system. There are three parts, the battery pack, the measurement and control in the mobile phone, and the charging power source or adapter. All parts are critical in making the battery charging system work.

The mobile phone has Analog to Digital converters to measure the battery voltage, current, and temperature. Typically a combination of these parameters are used to determine the charge status of the battery. The control logic in the Mobile phone in turn controls the power output of the AC to DC adapter.The AC to DC adapter is a compact switching power supply with universal AC input. It has well regulated and controllable current and/or voltage limits.

In this case, the battery is actually a battery pack, which has over-current protection, temperature sensing, and identification. Batteries are basically constant voltage devices with low output impedance. In the case of NiCad or NiMH batteries they are charged with a constant current. When they reach full charge, the current is turned off. In the case of Li-Ion batteries they are charged with a constant current until they reach a float voltage, where the charger then switches to a constant voltage (CV) mode for the final charging. This is much like the charging of the Lead Acid battery in your automobile.

Newer mobile phones are designed to automatically accommodate any battery technology.

Low Power Application
Charger Testing: Test System Configuration

- **Objective: Calibrate Cell Phone Battery V & I Read back Circuits**
- **Battery Source Considerations:**
  - **CV load operation mode**
  - **Max. charge (sink) current**
  - **Wiring reverse V drop**
  - **OC, OT, Open Sense lead**
- **Charger Source Considerations:**
  - **Adequate V& I range**
  - **Basic V & I read back**
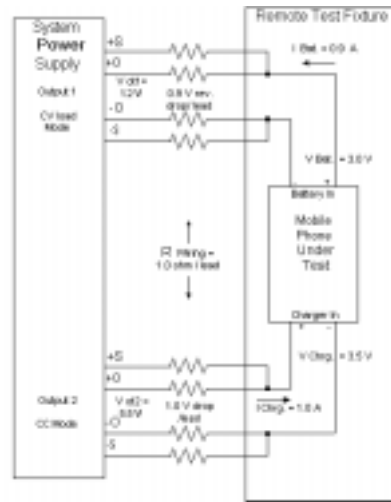
In production test, the objective of battery charger testing is to calibrate the mobile phone battery voltage and current monitoring A to D converters for proper battery charging function. There are a few test system and power supply considerations:

First, the battery source supply must first be able to sink the full charge current and maintain an accurate (0.05%) constant voltage at the DUT battery port to emulate the conditions of a battery under charge. This is called CV load operation. The power supply operates as a large, programmable zener diode. Since this is not a standard capability in most system power supplies, an electronic load may be needed to provide this function.

Next, assuming a power supply with suitable CV load capability has been selected, the test system wiring voltage drop needs to be considered. The result is the power supply output terminal voltage can be lower than the DUT battery port voltage. At low battery voltage operation the power supply can possibly drop out due to insufficient voltage across the power supply terminals. As shown, output 1 terminals are at only 1.2 volts.

Protection against faults should not be overlooked in this CV load operating mode. The power supply should be protected against over current and over power at a minimum.

Protection against open or broken sense leads is another key fault mode to consider. Under these conditions most system power supplies revert to local sense mode operation. The fault will not be detected. The remote voltage accuracy will degrade due to wiring voltage drops The DUT will be mis-calibrated leading to improper battery charging in actual use.

In most cases the charger source requirements are adequate voltage and current programming range to simulate the voltage and current limits of the actual charger. Basic voltage and current read-back capability is sufficient, if used.

Low Power Application
General Purpose Test Equipment Limitations

- **GP Power Supply:**
  - **Transient response may not be acceptable in remote sense**
  - **One current measurement range, insufficient accuracy**
  - **Short, fixed aperture time causes high measurement jitter**
  - **May not have current sinking for battery charging test**
- **GP Power Supply, DMM, and Electronic Load:**
  - **Limited measurement aperture time setting and resolution, inadequate for full range of pulsed measurement needs**
  - **Multiple boxes, integration problems**

General purpose power supplies simply do not have adequate source and measurement capabilities for this application. The typical accuracy of tens of milliamperes for the one current measurement range is not suitable for standby and off-mode current drain measurements.

The current measurement is really designed to measure DC average values for DC loads, not pulsed loads. The short, fixed measurement aperture will usually track the pulsed load, causing unacceptably high measurement jitter.

The most common approach in many mobile phone test systems is to add a low cost DMM to augment the test system current measurement capabilities. The DMM's current measurement ranging addresses accuracy for low level currents. The measurement aperture time is programmable, in PLC's (power line cycles) making a DMM useful for measuring pulsed talk mode current.

However, a general purpose DMM aperture time setting and resolution is usually not adequate for the long pulse period of pulsed standby mode current measurement.

Adding a DMM also creates test system integration problems, adding wiring, switching, and a shunt, resulting in additional wiring path resistance.

- **Choose a solution-tailored power supply which offers:**
  - special operating modes deliver fast rise current pulses with remote sense to improve transient response
  - extensive measurement capabilities including a digital sampling mode and filters for accurate pulsed current measurement
  - multiple outputs, with current sinking to emulate battery/charger functions when testing battery management subsystems
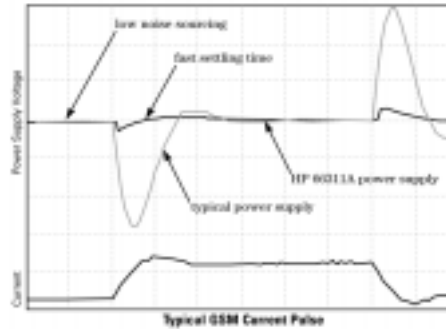
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This waveforms above illustrate the results of using a power source, such as the Agilent Technologies 66319B Mobile Communications DC Source, with fast dynamic response characteristics. While developed to meet the needs of digital mobile phone testing, it can be used to advantage in other battery powered device test applications as well.

This unique Agilent Mobile Communications DC Source can respond to the speed of the load change, compensating for the wiring voltage drop. The net result is a reduction of the transient voltage at the DUT to well within acceptable limits, well below our desired goal of 100 mV for a 3.6 volt mobile phone. There is no need to have a large capacitor at the test fixture, with the associated drawbacks.

The Agilent Mobile Communications DC Source uses a unique high speed DSP based digitizing measurement system, much like that of a digital oscilloscope. There are three DC current ranges to provide fast and accurate talk, standby, and off mode current measurements, specially tailored for digital mobile phone testing. The digitizing measurement system is further supported by our Device Characterization Software, a graphical user interface that provides digital oscilloscope like measurement capability without having to do any programming, This is a very useful tool for R&D, production repair, and service depots.

Agilent Mobile Communications DC Source operates over two quadrants for CV load capability for testing and calibrating the mobile phone battery charging circuits. In addition they feature full protection features, including open sense lead detect, to assure reliable product testing without any concerns.

The dual output models provide a second programmable output with voltage and current read-back to replace the charger power source in the production test system. All in the same size package to optimize valuable production floor space!
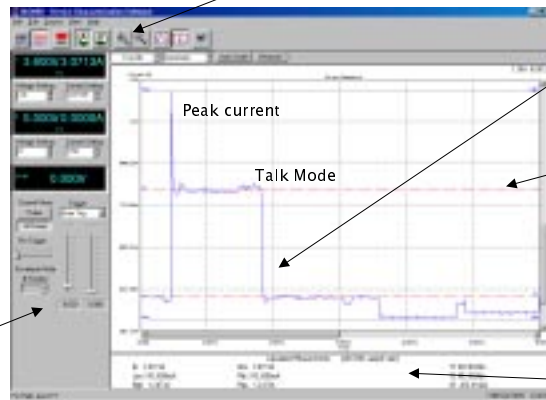
Low Power Application
Device Characterization Software

Easy to use, no programming required!

Zoom capability

Oscilloscope-like view of battery current profiles

Peak current

Markers for fast analysis

PS Output control

Talk Mode

Standby mode

Off mode

Measurement setup control

Calculated Measurements

Useful R&D and Repair/Service Tool

The Mobile Communications DC Sources have a very complete set of features for accurate measurement of pulsed waveforms. The 14565A Graphical User Interface allows the R&D Engineer to have full access to the features and controls of the Mobile Comms dc Source. It also facilitates making sophisticated dynamic current measurements accurately, using the internal digital filters.
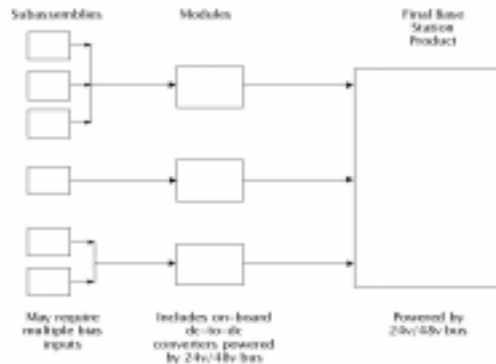
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Back-to-Basics of Power Products
Agenda

- **Introduction**
- **Characteristics of DC power supply**
- **How to choose?**
- **How to use?**
    - **Digital Cell Phone Test**
    - **DC Power Supplies in ATE Applications (Base Station)**
    - **DC Charger Test with AC Source and DC load**
- **Further information**

Sometimes it seems that DC power supplies are just volts and amps.   But in reality, the way you choose and use DC power supplies can affect your time to market, time to volume, and time to profit. This next application, mobile communications base station testing, will illustrate some of the subtle aspects of system power supplies, and how to get the most value from the features available.

DC PS in ATE Applications
Example: Base Stations

Base Station Test Process

Subassemblies   Modules   Final Base
                                                Station
                                                Product

May require   Includes on-board   Powered by
multiple bias   dc-to-dc   24v/48v bus
inputs   converters powered
                     by 24v/48v bus

There are certain concerns that are common to most high volume electronics manufacturing. Let's use base station manufacturing as an example to illustrate some of these. The typical manufacturing process includes testing the product at 3 different stages of assembly.

A base station in the field must operate properly under a wide variety of input power conditions, thus a full test includes verification of operation across the full range of possible input voltage variations. This testing is usually done as early as possible in the manufacturing process on the module or even subassembly level. This way, full operational confidence has been achieved before the final base station integration and customization phase.

The overall process starts with a wide variety of subassemblies that are combined into modules, which then are configured into the complete base stations. Modules are the separate instruments that compose the base station. This would include such categories as power amplifiers, transceivers, and digital control and I/O. Many of the Modules are composed of subassemblies which will require separate testing.

This functional testing, conducted at subassembly and module stages, uses DC power supplies to substitute for the main base station DC bus, and other bias voltages which are required. While the assembled base station will run off of either a 24 or 48 volt DC bus, dc to dc converters are incorporated into the modules to provide the correct bias voltage levels. Since the subassemblies will not yet be joined with their dc to dc converters, multiple bias inputs during test will be required when they are tested.

The final base station test is the last testing before the base station is deployed in the field. All of the components are assumed to be functional before this point. Here the system is customized and module interaction is verified.

DC PS in ATE Applications
Subassembly Test Needs

- **Test platform must be very flexible**
    - **test a wide range of subassemblies**
    - **many subassemblies require multiple bias inputs**
    - **some +/- bias pairs needed (i.e. +/-12Vdc)**
    - **must adapt to new assemblies easily**
- **Multiple bias input subassemblies may require specific timing delays during turn-on**
- **Subassemblies which do not pass tests will be repaired**
    - **bias supplies should turn off if damage is detected**

Flexibility is the key, for both present and future needs.

The base station modules are designed to be powered by the main base station dc bus, however, on the subassembly level, other voltage levels exist. Dc–to-dc converters are incorporated into each module, to convert the main bus voltage to whatever the circuit components require. When the module is broken down into its composite subassemblies, these dc-to-dc converters might not be included in a particular subassembly. Therefore, the test system for these subassemblies must provide whatever assortment of bias inputs each subassembly requires.

The test platform must be able to provide as many different bias supplies as required. This generally includes both positive and negative bias voltages, such as +/- 12 volts. This requirement could quickly produce the need for a great number of power supplies, taking up a lot of space.

When doing bias margin testing on a subassembly which requires a number of different bias voltage levels (i.e. 3.3V, 5V, +/-12V), you would of course vary all bias inputs. However, sending programming commands to all of those power supplies takes valuable test time. It would be desirable to be able to program all of these power supplies with only one command. Choosing a power supply that allows pre-loading of bias supply voltages in a list, which can then be triggered by a single command saves valuable test time.

An additional requirement is the desire to repair and retest any subassembly which fails test. If the failure is caused by a shorted component, however, an excessive amount of current might start to flow and the dc power to the subassembly must be immediately shut down to prevent damage to major components and printed circuit boards. We will discuss use of the appropriate protection features shortly.

Finally, subassemblies with multiple bias inputs sometimes require a particular order to the powering up of the bias voltages, because one circuit needs to be powered up first to ensure the correct operation of another circuit.

DC PS in ATE Applications
Module Test Needs

- **Usually only one bias input**
    - **could be 24Vdc or 48Vdc nominal**
- **Subassemblies which do not pass tests will be repaired**
    - **bias supplies should turn off if damage is detected**

The requirements for dc power supplies for module test are a little different in that they generally require only one bias input either 24 volts nominal or 48 volts nominal. So either two power supplies are required, or one very large one or one with multiple ranges.

There is no definitive industry standard for dc bus voltage range. Typically the actual level of a 24 volt bus is 27 volts, with a normal expected operating range of 24 volts to 28 volts. Typically, the actual level of a 48 volt dc bus is 54 volts, with a normal expected operating range of 48 volts to 56 volts.

For 24 volt systems, 21 volts is typically considered the worst case low line condition. For 48 volt systems, 42 volts is typically considered the worst case low line condition. Low line is the minimum dc bias level that the module or subassembly is specified to operate at. For 24 volt systems, 30 volts is typically considered the worst case high line condition.

For 48 volt systems, 60 volts is typically considered the worst case high line condition. There are two reasons to test at higher than nominal line. First, correct operation needs to be verified. Second, the higher input voltage might accelerate the failure of weak components

A test plan might include repetitions of sections of the functional tests at a few dc input levels to have full confidence.

Module test has the same requirements as subassembly test for dc power supply protection features, because the modules will also be repaired and re-tested after having failed a test.

DC PS in ATE Applications
Maximizing Production Yield

- **Some subassemblies and modules will**
    - **fail during manufacturing test**
    - **be repaired if possible and retested**
- **If a component shorts**
    - **excessive current might flow**
    - **additional damage might occur**
    - **repair cost becomes higher**
    - **damage might mean loss of the assembly**

We have talked about using some of the basic features of an ATE power supply for maximum flexibility. Now lets talk more about how to use the protection features of a system power supply to address a common manufacturing concern - maximize your production yield.

During the testing process, it is inevitable that a few subassemblies and modules will fail some aspect of their tests. Hopefully, the failed assembly can be repaired so that the value of the materials and labor can be salvaged. However, if the failure involves a shorted component, excessive current may begin to flow through the assembly. This current might then cause additional damage, increasing the cost of repair. In some cases a circuit board can be damaged from excess heat, to the point of making the assembly unrecoverable.

Fortunately the proper application of current limit circuits in the power supply can protect the DUT from consequential damage. There are a number of tools in a good system power supply that the test engineer can utilize to minimize potential loss off work in process.

DC PS in ATE Applications
Goal: Limit current flowing into a failed assembly

- **Types of current limit controls:**
    - **Fixed current limit**
    - **Programmable current limit**
    - **Programmable current limit with automatic shutdown**
    - **Programmable current limit with delayed shutdown**
    - **Active downprogrammer**
    - **Discrete fault indicator / remote inhibit**
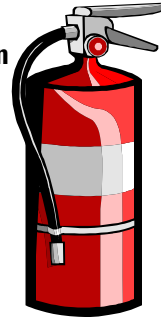
There are actually many different approaches to this problem. In some cases, the cost of the subassembly is such that it is not deemed cost effective to attempt repair. In these situations, some testing is still performed with bias voltages provided by very basic power supplies, such as fixed output OEM supplies. These may offer only a fixed current limit, whereas most modern system supplies offer a programmable current limit. As we will see, this offers very poor protection against consequential damage from a shorted component.

If recovering failed assemblies is important in your process, then it is important to choose dc power supplies that have the appropriate protection features, and then to make use of them to best advantage. Actually, there can also be some disadvantages to some of the approaches that can cause problems in normal testing. And where multiple supplies are involved for testing a sub-assembly, it may be necessary to shut down all supplies at once, or in a prescribed sequence. So, there are a fair amount of details to consider, for such an apparently simple topic.

Let's go through a simple example that will be helpful to illustrate the different results with each of the above approaches.

DC PS in ATE Applications
Current Limit Example

You are testing a subassembly which requires 6 amps; the dc power supply has a rating of 10 amps. The assembly fails with a shorted component

What happens?

- **Fixed Current Limit: 10 amps flow**

- **Programmable Current Limit: 6 amps flow**

- **Programmable Limit w/Automatic Shutdown: 6 amps flow, then immediately zero amps flow !**

In this example, we are testing a subassembly which normally draws up to 6 amps maximum. The power supply we are using has a maximum current capability of 10 amps.

Consider what happens when a major component on the assembly shorts. The current begins to increase rapidly. What will happen next?

If the power supply has only a fixed current limit, the maximum output current of the supply would be 10 amps, or slightly higher than the rated value. This current will continue flowing until the power supply is turned off or disconnected. Generally only the most basic power supply has this type of current limit.

With a variable current limit, you can set the current at the appropriate level for the specific assembly being tested. So, in this case we might set it for 6 amps, or maybe a little higher to allow some margin. (Perhaps you might use 6.3 amps to allow for variations in tolerance of components, however, we'll stick with 6 volts to keep the numbers simple.) Then, when a component shorts, that lower value of current would continue to flow until the power supply is either turned of or disconnected.

If your power supply has a programmable current limit with automatic shutdown, and you enable it, then when the component shorts, the current could still increase to 6 amps. But now, as soon as 6 amps is reached, the protection feature would trip, and the power supply would program down to zero volts, quickly reducing the current to the failed assembly. This automatic shutdown feature can protect the assembly under test from extended damage due to continuous current flow. Sometimes this type of current limit is called Over-current Protection (similar to Over-voltage protection), or in some cases, Current Fold-back.

DC PS in ATE Applications
Current Limit Example, continued

- **Programmable current limit with delayed shutdown:**
    - **inrush current can cause unwanted tripping of shutdown**
    - **allows the current limit to be set tighter for most of the test**
    - **example: set a 20 ms delay**
    - **not necessary for some subassemblies and modules**

Now lets fine tune our protection strategy.

At power-up, some assemblies exhibit a phenomenon called inrush current. This means that upon initial turn-on, the current into the assembly is significantly higher than it will be under normal operation. This is caused mostly by the need to charge filter capacitors at the input to the assembly, intended to reduce voltage spikes, etc.

If you have set your current limit close to your normal current demand, then the inrush current might trip the Over-current Protection. Since this will interrupt the test, we need a way to delay the onset of current fold-back. You can measure the delay empirically, or you could calculate it knowing the size of the capacitor and the value of the current limit setting, from $t = (CV)/I$.

Many system power supplies allow just such a delay to be set, usually programmed in milliseconds. After this delay time the Over-current Protection feature will then take affect. This allows time for the normal inrush current to subside. Thus, you can accommodate the inrush current, and still have a tight current limit in effect to protect circuitry in the DUT.

DC PS in ATE Applications
Current Limit Example, continued

Active downprogrammer:

- **most dc power supplies have capacitors at their output**

- **output capacitors could discharge into your DUT**

- **active downprogrammer draws the energy out and minimizes how much the DUT receives**

- **speeds normal downprogramming, so it increases test throughput too!**

As a normal part of the design, most dc power supplies have significant size capacitors at their output to provide the lowest possible noise. So when a failure occurs, that triggers the current limit, and the power supply output is programmed to zero volts, the energy in the output capacitor will continues to flow into the DUT until the capacitor is discharged to 0 volts. Clearly, this delays the complete shutdown of the power to the DUT.

Active downprogramming can dramatically reduce the time required to bring the output to 0 volts. It is accomplished by a circuit in the power supply that bleeds off this energy. By the way, this energy could come from either the power supply output capacitor OR the DUT's input capacitor.   This will minimize the amount of energy that would be dumped into the failed assembly. Note that there is no way to completely avoid some energy transferring into a shorted DUT

This downprogrammer circuitry is not a feature that needs to be enabled; if the power supply has this capability, it is always in operation.

Another valuable feature of this downprogrammer circuit is that it also helps the power supply to make negative going voltage transitions faster, during normal testing. This can significantly decrease test time, thereby increasing overall throughput.

DC PS in ATE Applications
Inhibit (INH) / FAULT (FLT)

Daisy-Chain of Three Power Supplies for Emergency Shutdown

Power Supply A   Power Supply B   Power Supply C
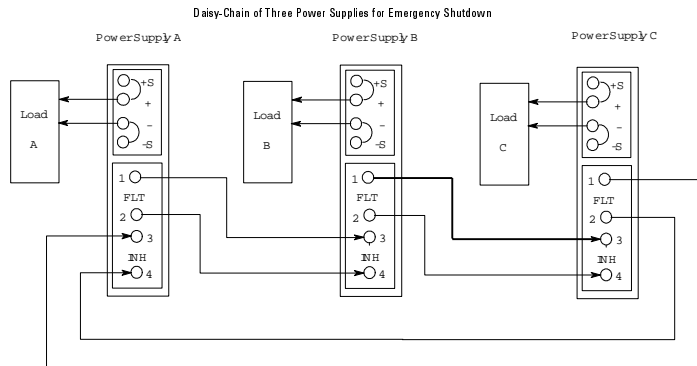
- **For multiple bias input subassemblies, if one bias supply senses a failure, all should be shut down**
- **TTL Input/Output**
- **Fault definition defined by system controller at set-up**

Lets complete our example. Earlier, we had mentioned that there would likely be multiple voltages for subassembly test. It would be unwise to leave other supplies powering up the DUT, if a failure that triggered Over-current protection was detected on one output. It really would be best if all the power supplies could be automatically programmed to 0 volts in this case.

So, let's consider a subassembly which we are testing actually has THREE bias voltages, not just one one. When a component shorts, and causes one of the three bias power supplies to go into current limit, we want to use its Over-current protection trip as a signal to feed to other outputs.

This can be easily done if you use power supplies with digital I/O connections that provide a REMOTE INHIBIT input and a DISCRETE FAULT INDICATOR output signal, (RI/DFI). Using these connections, the power supply which exhibits the predefined error condition activates it's DFI line. This is then connected to the next power supply's FAULT INHIBIT input, and the second power supplies DFI. This scheme is continued to connect all of the power supply's in a daisy chain.

As you can see, the signal will quickly pass around to all the power supplies. Of course, you must program the definition of what condition will constitute a Discrete Fault Indicator output, with the system controller during system set-up, (and after a power failure).

This input can also be used with any external TTL signal. For example, as a safety feature in the test set, you may want to program the power supplies down if someone opens the test rack door. This type of configuration can easily be implemented using an appropriate micro-switch. As another example, if the temperature in then rack were to exceed a safe level due to failure of a cooling fan, the RI/DFI feature could be used to shutdown the outputs to the DUT and interrupt the test.

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DC PS in ATE Applications
When should current limit protection be used?

- Probability of failure decreases as the base station integration process proceeds
- Regret of failure increases

So current limit protection should be taken into account at all stages of the manufacturing process!

When in the manufacturing process is it appropriate to consider current limiting?

It is much more likely to have such a component failure in the early phases of product integration, such as subassembly test. As subassemblies are combined into modules, and modules combined into the final base station, confidence in the correct operation of the electronics increases with each step. So as the base station components step through the manufacturing process, they are less likely to have a failure that would cause excessive current to flow. However, the regret factor of such a failure and the potential expense associated with repair of such a failure grows rapidly due to the extra process time and material invested as the product gets closer to completion.

For this reason, it is advisable to utilize current limiting effectively in all stages of the manufacturing process.

DC PS in ATE Applications
Flexibility for Subassembly Test

- **66000A Modular Power System**
- **Up to eight 150 watt modules**
- **Polarity reversal/disconnect relays**
- **Protection features to bring down bias fast in the event of a failure**
- **Output sequencing**
  - **simultaneous or with specified delays**
  - **reduce test time with List feature**
  - **download power supply parameters**

Lets take a brief look at some Agilent dc power supplies that are well suited to the needs of the flexible manufacturing test system platform.

For a test system that must test a wide variety of multiple input assemblies, the Agilent 66000A is a good match. You can configure the mainframe with up to eight 150 watt dc power supply modules. Modules can be added at any time

There are also polarity reversal and disconnect relays.

The 66000A MPS also provides extensive protection features.

The power supply outputs can be controlled separately or together, and sequenced to turn on simultaneously or with programmed delays.

Test time can be minimized using the List feature of the 66000A. The output voltage levels, current limits, and other parameters can be downloaded to each power supply module. The List can be stepped through either based upon preloaded dwell times, or with one trigger command. The benefit of using the List feature is that there is no command processing time and minimal computer interaction during test run time, saving valuable test time.
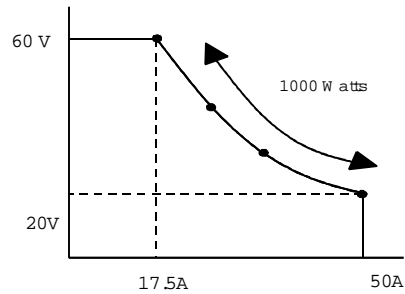
DC PS in ATE Applications
Flexibility for Module Test

- **Getting full power at two different voltages:**
  - **two power supplies**
  - **one with two ranges**
  - **an autoranging power supply**

- **The 6032A 1000 Watt Autoranging Power Supply:**
  - **offers full power at any voltage between 20 and 60 volts**

60 V

1000 Watts

20V

17.5A   50A

When only one bias input is necessary, but the system must be able to provide for different voltages for each item to be tested, such as the 24 or 48 volt modules used in base stations, you might buy multiple power supplies, or one very large one. Or if a power supply with multiple ranges provided the needed ratings, that would work.

But a more flexible solution is autoranging. This example here would use the 1000 watt 6032A, which would work well for both the 24 volt and 48 volt base station modules. This type of output characteristic allows for full power to be drawn at any voltage between 20 and 60 volts. This accommodates the full range of limit testing required for today's base stations (and other products, as well).

Back-to-Basics of Power Products Agenda

- **Introduction**

- **Characteristics of DC power supply**

- **How to choose?**

- **How to use?**

  - **Digital Cell Phone Test**

  - **DC Power Supplies in ATE Applications (Base Station)**

  - **DC Charger Test with AC Source and DC load**

- **Further information**

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Charger Testing
Using Power Products to Test Chargers

- **Chargers are, fundamentally, Constant Current (CC) ac-dc power sources**
- **They can be "smart" (includes battery sense and control) or basic**
- **Functional test goals are focused on ensuring the charger:**
  - **operates properly for worlswide ac mains conditions: 115 -230V, 50/60 Hz**
  - **provides the appropriate current for each charge state of the battery**

Originally, battery chargers were little more than rectifier/filter assemblies with some simple internal circuits to limit the maximum voltage and current. However, today's increasingly mobile society has given rise to a bewildering array of mobile, cordless, portable devices to make our lives easier and more productive. Almost as ubiquitous as the remote control devices for controlling entertainment equipment, is the charger which is needed to re-charge the batteries in this portable equipment, and in some cases to enable operation on the AC line when it is available.

To gain a competitive advantage, manufacturers have sought methods to charge batteries faster, and of course more safely. No manufacturer wants to be responsible for causing "rapid battery disassembly", better known as an "explosion". As a result, " smart " chargers have been developed that can detect when the battery is fully charged. For chargers without built-in circuitry, the needs to change to a different modes, such as trickle or cut-off mode, is sensed via a control line which monitors charge level or temperature of the battery pack.

Today's chargers are more likely to be small high frequency switching power supplies with CV and CC modes of operation. They also provide automatic AC line ranging over the full worldwide requirements of voltage and frequency. This represents additional capability that can be tested using system power products.

- **Full Charge Test**
    - **Tests charger's full output charge current.**
- **Trickle Charge Test**
    - **Tests charger's trickle charge or charge cutoff output current**
- **Start Up Test**
    - **Tests charger's ability to turn on with a load already in place**
- **Shorted Battery Test**
    - **Test charger's ability to limit its full output charge current to a safe level when connected to a shorted battery**

There are several conditions that the manufacturer needs to test:

Full Charge Test

Manufacturers need to test the charger to regulate current. During full load testing, the load emulates the lower constant voltage (CV) characteristic of a low/discharged battery.

Trickle Charge Test

Here the load emulates the higher constant voltage characteristic of a fully charged battery. When a battery reaches its fully charged voltage. The charger knows to cut back so that it won't damage the battery.
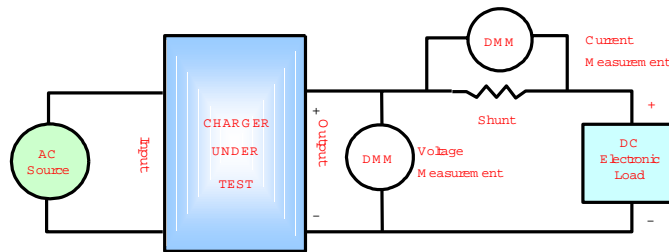
Start Up Test

In this test, there is a need to emulate the loading of a fully or over discharged battery with resistive loading. The start up test is a desired by many manufacturers.

Shorted Battery Test

The load emulates the very low resistance of a battery. Manufacturers will either short an electronic load or place the load in CR mode to test charger.

Charger Testing
Test Set Configuration

- **Requires control of the AC input voltage, frequency, and waveform**
- **Requires an Electronic Load that can operate in multiple modes**

AC Source | Input | CHARGER UNDER TEST | Output | DMM Voltage Measurement | DMM Current Measurement | Shunt | DC Electronic Load

When we covered testing mobile phones, we discussed using special features of the power supply to test circuitry in the phone that monitors and controls the battery charging process. However, in testing a charger, we need a dedicated electronic load to provide suitable loading for the charger current. Both an expanded range of V/I characteristics and a more complete set of operating modes are required.

Also an AC source is needed to provide controlled input power to the charger.

While the diagram above shows the use of DMMs for measurements, however these measurement needs can be met in most cases with the internal measurement capabilities of the AC source and Electronic Load.

Let's explore some of the basics of each of these types of power products in the context of this application.

Charger Testing
Powering the charger with an AC Sources

- AC sources simulate what comes out of an ac outlet, but with the ability to control various parameters (e.g. V_{rms} and frequency)

- The most sophisticated ac sources allow the user to...
    - simulate "real life" ac mains disturbances that can affect the operation of connected electronic products such as a charger
    - perform ac power measurements and analysis

- For charger testing, the ac source needs to operate at the specific ac mains voltage and frequency required for the test

We could use the AC mains voltage directly from the wall outlet for basic functional testing. However, there is no way to vary the line voltage or frequency to simulate worldwide conditions. Also, if it is desired to be able to simulate some of the line disturbances which are becoming an all too frequent part of everyday life, again, there are no capabilities.

However, we can use an electronic AC source to simulate what comes out of the ac outlet, both on a good day, and a bad day as well!.

It is used to power the charger, providing low and high ac line voltages, low and high frequencies, and ac power on/off control. It can also simulate brownout conditions, line drop-out, or any type of line distortion, such as flat-topping. This latter condition can be caused by too many switched mode devices drawing power simultaneously from the peak of the line voltage.

Furthermore, an AC source has extensive measurement capability so it can also make ac power and current measurements on the charger under test. Examples include, inrush current, total input power, and more.

Charger Testing
AC power terms and what they mean

- RMS = Root Mean Square
    Equivalent to the constant value that will produce the
    same average power dissipation in a given resistor
- PF = Power Factor
    PF = Watts/VA
    Always between 0 and 1
- VA = VoltAmperes = apparent power
    VA = Vrms * Irms
- Watts = real power
    Watts = $1/(2\pi) * \int v(t) * i(t)\, dt$
- VAR = Reactive Power
    VAR = $\sqrt{[(VA)^2 - Watts^2]}$
- Crest factor = waveform peak / waveform rms

To do a good job of choosing an AC sources, there are some specifications that you need to become more familiar with.

The rms term, we discussed in the context of noise voltage for DC power supplies. However, with AC sources, which are capable of some fairly complex wave-shapes, it becomes and increasingly important term in discussing the total energy content in an AC waveform.

With AC waveforms and reactive components, the possibility arises that voltage and current waveforms may not be in phase. Thus the concept of power factor is used to describe the degree of difference in phase. In fact it is defined as the cosine of the phase angle between the two. Where they are in phase (i.e. a resistive load), PF = 1. In this case the phase angle is 0 and they cosine of 0 is 1. Where they are completely out of phase (such as for the input of a power supply with a large capacitor to be charged), the phase angle is 90 degrees and the cosine of 90 is 0.

PF can also be expressed as the ratio of the real power in watts to the apparent power in volt-amperes.

Finally, the crest factor can be defined as the ratio of the peak waveform voltage to the rms voltage. We came across this term also previously in the presentation, when we discussed the measurement capability of a DMM to accurately measure current waveforms in a mobile phone with a high peak content.

Charger Testing
AC Source Graphical User Interface

Included for Free !

An easy way to control the AC source
- Easy to use soft panel
- Control output /measurements
- View actual output waveforms
- View harmonic content
- Easily generate complex transients by clicking the mouse
- View Instrument commands
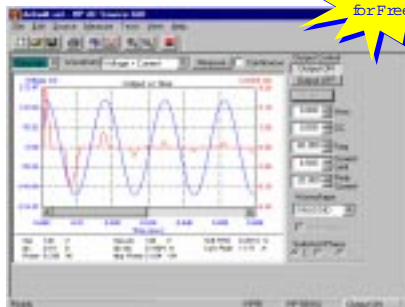
A full featured AC Source has a lot of flexibility and measurement capability built in. One easy way to set up the AC Source test conditions, and to view the actual test waveforms, is via a graphical user interface (GUI). This tool is especially handy in R&D and in service for troubleshooting defective units.

All Agilent AC sources come with a Each product includes a software GUI. This makes it much easier for the user to establish complex waveforms for special test requirements, and to analyze waveforms for harmonic content.

Charger Testing
DC Electronic Load Modes

- **For charger testing, the dc electronic load simulates a charging battery in a portable device, such as a cell phone or lap top**

- **The battery behaves as a Constant Voltage (CV) device, so the electronic load must operate in CV and CR mode when testing chargers**

Mode	Application
Constant Current (CC) Regulates current flow through itself	Testing a dc power supply in CV mode Discharging a battery for capacity testing
Constant Voltage (CV) Regulates voltage drop across itself	Testing current sources Testing a dc power supply in CC mode
Resistance (CR) Acts as a power resistor	Power supply current limit detection Mode crossover

Most charger outputs are effectively a current source (I.e. a power supply operating in the constant current (CC) mode).   To properly test all the aspects of a charger, the load will be required to function in several operating modes. Let's take a look at these different modes.

First, the Electronic Load is primarily used to accept power from a voltage source at a specified level. Either a power supply operating in the CV mode or a battery being discharged are good examples. These applications are most easily accomplished using the constant current (CC) mode of the Electronic Load. Here, the desired output current can be programmed and will be maintained within the limits of voltage compliance that the load is capable of.

Most typical power supplies can also operate in the constant current CC mode, to simulate a true constant source. A load operating in the CV mode can be programmed for a specific voltage and will maintain this voltage within the limits of its current compliance.

In the CR mode, the load acts as a power resistor, and will maintain a specified ratio of voltage and current within its range of compliance for both variables. This latter mode is useful for testing certain unique output states of power supplies, and at the cross over between different power supply operating modes.

 Lastly, it should be noted that unlike power supplies, which have automatic mode crossover from CV to CC depending on load conditions, Electronic Loads must be deliberately switched between operating modes by the user.

**Charger Testing
Electronic Load Operation**

CV

V

I
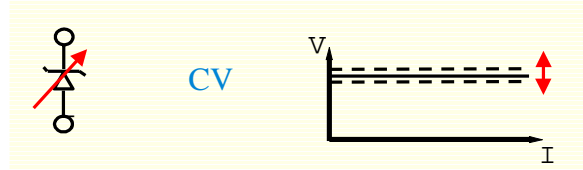
- **The dc electronic load should be operated in Constant Resistance (CR) mode, then Constant Voltage (CV) mode for charger testing to simulate the battery**

- **An initial electronic load setting in CR mode may be necessary to allow the charger to "start up" (the charger is a switching power supply!)**

- **Tests include:**

  Full Charge Test   **Start Up Test**

  Trickle Charge Test   **Shorted Battery Test**

In production test of a charger, the Electronic Load behaves like a battery. The battery is a constant voltage device that has no current limit. When the load, operating in CV mode, is placed across the charger, the charger is forced to operate in CC mode, providing the appropriate charge current, typically 1 Amp.   Lower voltage simulates a discharged battery. Higher voltages simulate charged batteries.

When a fully discharged battery needs to be charged, the charger is called upon to turn-on under a heavy load. Many chargers are now switching supplies, which typically have difficulty turning on into a load. So, manufacturers may test to see if the charger will turn on by placing the electronic load in CR mode initially, and then switching to the normal CV load.

One of the failure modes for a battery is for it to be essentially shorted. Occasionally, a charger is called upon (inadvertently) to charge a shorted battery. As a protection in these cases, the charger generally has a built-in current limit circuit. To test this charger current limit, it is also convenient to use the CR mode.

In production test, manufacturers may force the charger into the trickle charge mode with an electronic load in one of two ways. For smart batteries that adjust their operating mode based on voltage level, simply setting the load voltage close to the level of a fully charged battery should be sufficient to engage this mode.   For those battery packs that do not have built-in circuitry, there may be a control line that indicates a high temperature or some other condition that the charger senses to change modes. This same signal can be used to switch modes in the load when necessary.

Back-to-Basics of Power Products Agenda

- Introduction

- Characteristics of DC power supply

- How to choose?

- How to use?

- **Further information**

Agilent Technologies

Back-to-basics of Power Products
Further Information

- **Web-sites**

    - http://www.agilent.com/find/power

- **Easy to use CustomerCare CD-ROM**

    - **Power products catalog**

    - **User's guides**

    - **Application notes**

    - **and more!**