# Synchronous CCSS Regulator

## Introduction
This application note is divided into four sections:

1. **Operating Principle**
   Overview of linear versus switched shunt regulators and the synchronous control technique used in the SR10.

2. **Design Guidelines**
   Procedure and equations to assist in the design of an SR10 power supply to meet specific requirements. Estimates of performance are also provided.

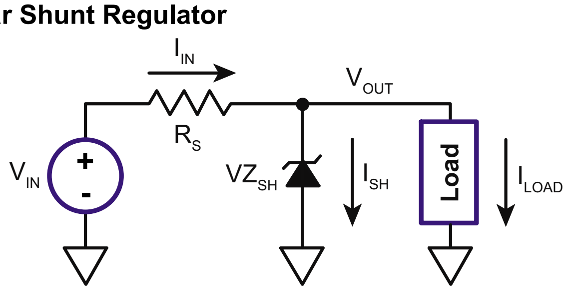
3. **Measurement Techniques**
   Due to the low real component of input power, special methods are required for measuring input power. Also provides setup for measuring conducted EMI.

4. **$C_S$ Table**
   Output current for various $C_S$ values, input voltage, and full-wave or half-wave rectification.

## 1. Operating Principle
Shunt regulators consist of two elements: a voltage regulator in parallel with the load (the shunt), and a series element between the supply and load to limit current. The parallel shunt regulates voltage by varying its conduction to maintain the desired voltage across the load. As the load current decreases, the shunt compensates by conducting more current. This results in high standby current consumption.

As depicted below, the simplest shunt regulator is a resistor to limit input current and a Zener diode to regulate the voltage across the load.

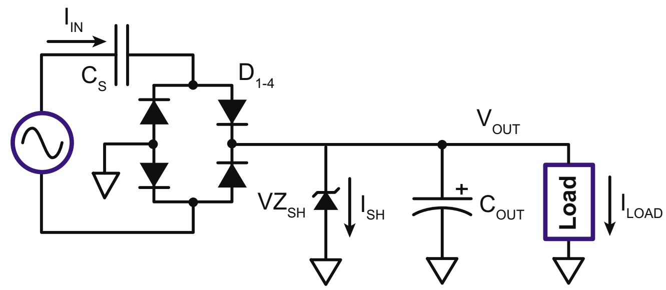
**Linear Shunt Regulator**




Input current is divided linearly between the shunt and the load. As output load increases, a portion of the input current is diverted from the shunt to the load. Since the linear shunt conducts current with voltage across it, it dissipates power and efficiency suffers, especially at light loads. No-load standby power is high. In addition, the resistor dissipates power, further decreasing efficiency.

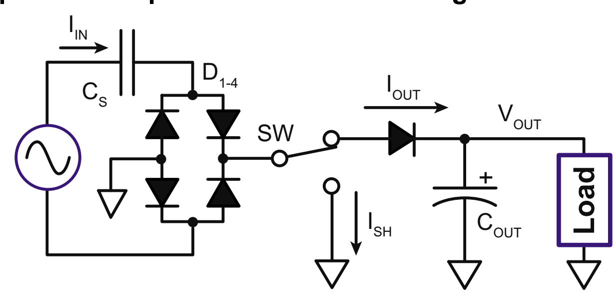
For regulators operating from the AC mains, the current-limiting element may be a capacitor as shown below. Capacitors have an AC impedance to limit current, yet the impedance is imaginary so no real power is dissipated.

**Capacitor-Coupled Shunt Regulator**




A series capacitor improves efficiency but the Zener shunt still dissipates power. The switched shunt solves this second problem.

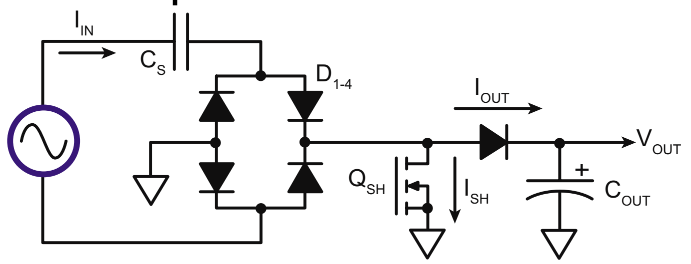
**Capacitor-Coupled Switched Shunt Regulator**




The switched shunt regulator operates similarly to a linear shunt regulator except current is proportioned between shunt and load in a switched (on/off) manner. When the switch is in the lower position it acts as a zero-ohm shunt. When in the upper position it diverts input current to the output. Since the switch is ideally zero ohms, it conducts current with no losses.

In an actual circuit, the switch in the upper position is implemented using a diode and in the lower position is implemented with a transistor.

## Practical Implementation




As with all shunt regulators, input current to a capacitor-coupled switched shunt (CCSS) regulator is constant regardless of load but varies with input voltage. Even under no-load conditions when the shunt is on, current will be drawn from the AC line. However, this current is mainly reactive with a small real component that represents load and losses. Input current can be approximated by: $I_{IN} = V_{IN} / X_C$.

Output voltage regulation is achieved by controlling the duty cycle of the switched shunt. The shunt turns off when $V_{OUT}$ is below the regulation point, diverting all the input current to the output. When $V_{OUT}$ exceeds the regulation point, the shunt is turned on, diverting all the input current away from the output to ground and back to the input. Output storage capacitor $C_{OUT}$ supplies the load when the shunt is on or when the input AC is near the peaks.

Numerous control methods for regulating output voltage are possible, including hysteretic, integrating error amplifier, and synchronous to name a few. For reasons of low power loss and low external component count, the SR10 CCSS regulator is the synchronous type. The shunt is synchronized to turn on only when the voltage across it is low (cold-switching). This avoids the large voltage step that would otherwise be impressed across $C_S$ at shunt turn-on (hot-switching) if the regulator were asynchronous. Minimizing the applied voltage step across $C_S$ results in more efficient operation. The following diagram shows the operation of synchronous control from a timing perspective.

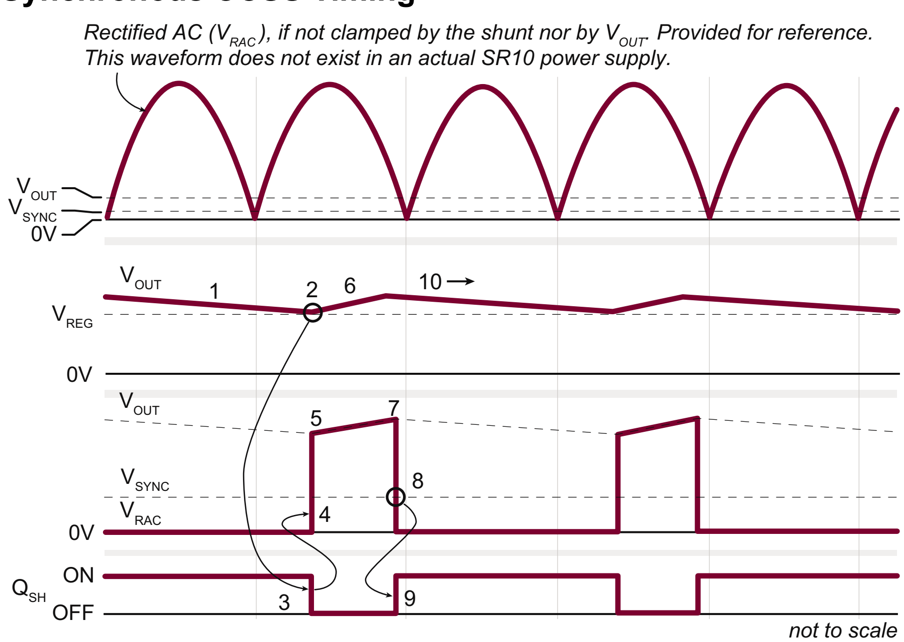
A side effect of synchronous operation is that the feedback signal cannot immediately turn on the shunt when $V_{OUT}$ exceeds the regulation point. Turn-on is delayed until the rectified AC falls below the synchronization threshold ($V_{SYNC}$). Since current continues flowing to the output after the output reaches the regulation point, overshoot occurs.

Higher input voltages impress more charge on $C_S$, resulting in more overshoot. The amount of overshoot may be minimized by using a large value $C_{OUT}$ or operating the regulator over a narrower input voltage range. The overshoot is like a inverted version of conventional output ripple

Short circuit current limiting is inherent in capacitor-coupled regulators. Capacitive reactance limits the current, even if the control circuitry ceases to function due to the output voltage collapsing under the short.

In a CCSS regulator, under normal operation, the only high voltage component in the supply is the $C_S$ capacitor. The highest voltage seen by the other components is one diode drop above $V_{OUT}$. This eases PCB layout and alleviates high voltage creepage concerns.

## Synchronous CCSS Timing




1. Output voltage decays under load until ...
2. it hits the regulation point which...
3. turns off the shunt...
4. freeing $V_{RAC}$ to rise until...
5. it is clamped by $V_{OUT}$ where...
6. input current flows to the output, causing $V_{OUT}$ to rise until...
7. $V_{RAC}$ falls below $V_{OUT}$.
8. When $V_{RAC}$ reaches $V_{SYNC}$...
9. the shunt is turned on, preventing current flow to the output and...
10. output voltage decays under load and the cycle repeats.

## 2. Design Guidelines

This section provides guidelines for designing an SR10-based off-line power supply. Design tasks consist of the following:

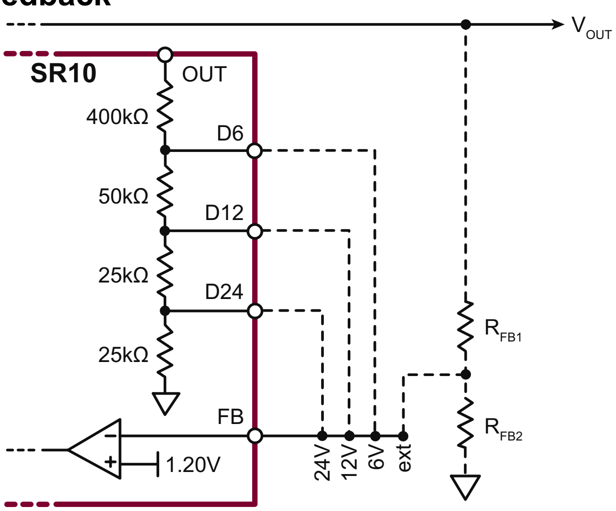
1. Feedback method to achieve desired output voltage
2. Half- or full-wave rectification and rectifier selection
3. Series limiting capacitor ($C_S$)
4. Output storage capacitor ($C_{OUT}$)
5. Bleed resistor ($R_{BLD}$)
6. Transient protection

Component values are given by simple equations. A Math CAD worksheet is also available. Contact the Supertex Apps group.

### Output Voltage ($V_{OUT}$)

The SR10 is pin-programmable for output voltages of 6, 12, or 24V. For other voltages in the range of 6 to 28V, an external feedback divider may be used.

### Feedback




The internal feedback divider has 3 taps brought out to the DIV6, DIV12, and DIV24 pins for 6, 12, and 24V respectively. Simply connect the appropriate DIV pin to the feedback (FB) pin. Leave the unused DIV pins floating.

While the resistor ratios are tightly matched, the absolute tolerance of the internal feedback divider resistors is fairly loose. Therefore it is advisable to not parallel external resistors with the internal divider resistors to achieve other voltages.

For output voltages other than 6, 12, or 24V, an external feedback divider may be connected between the output and the FB input. The adjustable output voltage range is 6-28V. It is recommended that at least 25µA of bias current flow thru the divider. Output voltage is given by the following equations.

$$V_{OUT} = V_{FB}\left(1 + \frac{R_{FB1}}{R_{FB2}}\right)$$

$$R_{FB2} = \frac{V_{FB}}{I_{BIAS}}$$

$$R_{FB1} = R_{FB2}\left(\frac{V_{OUT}}{V_{FB}} - 1\right)$$

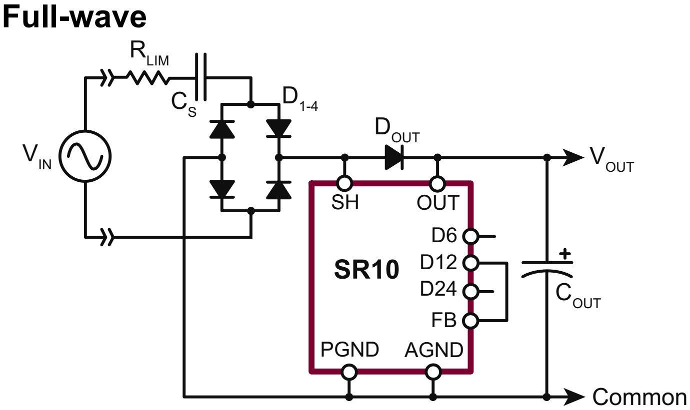
*where:* $V_{OUT}$ = *regulation point*
$V_{FB}$ = *feedback reference voltage = 1.2V nom*
$I_{BIAS}$ = *bias current thru feedback divider = 25µA min*

Output ripple will increase the DC average output voltage. Output voltage including dips must not go lower than the OCP threshold. Otherwise OCP may not trigger in the event of a transient.

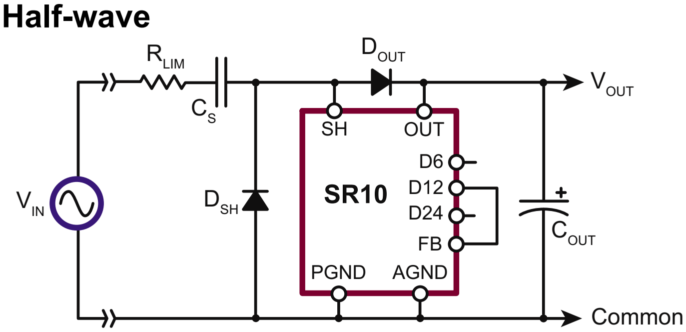
### Rectification

The SR10 may configured with a full-wave rectifier or a half-wave rectifier.

### Full-wave




### Half-wave



As would be expected, output current for half-wave is about half that of full-wave. On the plus side, standby power and efficiency are significantly improved since the losses associated with the bridge diodes of the full-wave are eliminated. Additionally, the internal shunt is capable of conducting in the reverse direction, reducing diode losses even further. An external rectifier across the shunt is still required for transient protection however.

Half-wave also allows circuit common to be directly connected to line-neutral.

## Full-Wave vs Half-Wave

| | Full-wave | Half-wave |
|---|---|---|
| Component count | Higher | Lower |
| Output current | Full | Half |
| Standby power | Higher | Lower |
| Efficiency | Lower | Higher |
| Circuit common | Floating | Line neutral |

Since low frequencies are involved, standard recovery rectifiers are acceptable. Reverse voltage on the rectifiers is only 1 or 2 diode drops greater than the output voltage, so high voltage rectifiers are not needed. Voltage rating should be appropriate for the output voltage. Under normal operation, rectifier current is low. However, during a transient they are subjected to high current. The requirements of recovery time, voltage rating, and surge current allow the use of inexpensive 1N4001 rectifiers or equivalent.

## AC Line Series Capacitor $C_S$

**Value**

Series capacitor $C_S$ is used to transfer charge from input to output. The amount of charge transferred per 50/60Hz cycle determines the load current capability. Approximate load current capability is given by the following equations. When using these equations, take worst case conditions into account: lowest anticipated AC voltage, capacitor tolerance, and output voltage tolerance. Additional losses may reduce output current up to 4%.

Eq 1a: Full-wave

$$I_{OUT} \approx 4 \cdot f_{IN} \cdot C_S\,(V_{IN}\sqrt{2} - V_{OUT} - 3V_D)$$

Eq 1b: Half-wave

$$I_{OUT} \approx f_{IN} \cdot C_S\,(2V_{IN}\sqrt{2} - V_{OUT} - 2V_D)$$

*where:* *$I_{OUT}$ is the maximum output current*
*$f_{IN}$ is the AC line frequency*
*$C_S$ is the series cap on the AC line*
*$V_{IN}$ is the RMS AC line voltage*
*$V_{OUT}$ is the DC output voltage*
*$V_D$ is the diode forward voltage*

To allow easier selection of $C_S$, Eq 1 may be rearranged.

Eq 2a: Full-wave:

$$C_S \geq \frac{I_{OUT}}{4f_{IN}\,(V_{IN}\sqrt{2} - V_{OUT} - 3V_D)}$$

Eq 2b: Half-wave:

$$C_S \geq \frac{I_{OUT}}{f_{IN}\,(2V_{IN}\sqrt{2} - V_{OUT} - 2V_D)}$$

**Ripple Current Rating**

The $C_S$ capacitor should be AC rated. DC rated capacitors generally have higher ESR and may overheat when subjected to AC current. Ripple current is at the line frequency. Its RMS magnitude is given by the following equation:

$$I_{RPL} = V_{IN} \cdot f_{IN} \cdot 2\pi \cdot C_S$$

**Voltage Rating**

$C_S$ should be AC rated for the maximum expected AC line voltage.

**Safety Rating**

$C_S$ should be rated X2.

## Input Voltage and Current

With a light load, the shunt is on almost all of the time. Since the shunt acts as a low impedance switch, the effective load on the AC line is only the $C_S$ capacitor. The input current waveform is therefore a continuous sine wave 90° out of phase to the line voltage.

Eq 3:

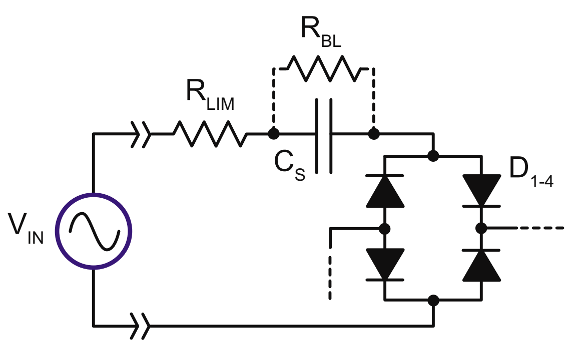
$$I_{IN(RMS)} = \frac{V_{IN(RMS)}}{X_C} = V_{IN(RMS)} \cdot 2\pi \cdot f_{IN} \cdot C_S$$

$$I_{IN(PK)} = I_{IN(RMS)} \cdot \sqrt{2}$$

Since the input current is a direct function of line voltage, to limit input current to reasonable values the power supply should be designed for either 120VAC or for 230VAC. A power supply designed for universal applications (120/230VAC) will have high standby power and high output overshoot (see below) when designed for the low-line 90VAC but operated at the high-line 265VAC. This higher current is due to the nature of capacitor-coupled shunt regulators, whether linear or switching. The $C_S$ capacitor must be selected large enough to supply the load at low-line. But at high-line, the $C_S$ capacitor causes high input current. If the input voltage doubles, the input current doubles and is independent of load. A supply designed for the range 90-275VAC has an input current range of over 3:1. The high-line current flowing thru the rectifiers and shunt resistance creates increased power losses. In addition, the peak current must not exceed the SR10's shunt current rating nor the peak current ratings of the external diodes.

**Bleed Resistor $R_{BL}$**

When disconnected from the wall outlet, the $C_S$ capacitor may hold a charge at high voltages. If the unit employing the SR10 can be unplugged and the prongs are accessible, there is the risk of electrical shock. For safety reasons it is advisable to parallel a high-value resistor across $C_S$ to bleed-off the charge on $C_S$. For self-contained units, such as utility meters, the bleed resistor may not be needed.




The addition of a bleed resistor introduce a small degree of power loss. The power loss may be approximated by:

$$P_{BL} \approx \frac{V_{IN}^2}{R_{BL}}$$

## Output Capacitor $C_{OUT}$

Output capacitor $C_{OUT}$ acts as energy storage, supplying the output when the rectified AC falls below the output voltage on when the shunt is turned on. $C_{OUT}$ is recharged when the shunt FET is turned off. Larger values reduce voltage ripple and overshoot (see next section).

$C_{OUT}$ serves a second function in absorbing line transients. Depending on the magnitude of the transient, the value of $R_{LIM}$, and the value of $C_{OUT}$, output voltage will rise as the transient energy is absorbed. Consideration must be given to transients when selecting both the voltage rating and value of $C_{OUT}$, the larger the better.

## Output Overshoot

To achieve high efficiencies, the SR10's synchronization circuit only allows the feedback signal to turn on the shunt when the voltage across the shunt falls below the $V_{SYNC}$ threshold. This minimizes losses by minimizing the near-instantaneous application of voltage across $C_S$. The feedback signal turns on the shunt immediately when the $V_{OUT}$ falls below the regulation point, but turn-on is delayed until the start of the next conversion cycle. Since the $V_{OUT}$ feedback signal is delayed from turning on the shunt when $V_{OUT}$ rises above the regulation point, a certain amount of output voltage overshoot will occur. The maximum overshoot is given by:

$$V_{OS} = (\sqrt{2} \cdot V_{IN(RMS)} - V_{OUT}) \frac{C_S}{C_{OUT}}$$

*where:* $V_{OS}$ *= amount of overshoot*

This is the theoretical maximum overshoot — actual overshoot will generally be lower. Output overshoot may be minimized by increasing $C_{OUT}$, using as low a $C_S$ as practical, or by designing the power supply only for 120VAC operation or only for 230VAC operation.

Consideration must also be given to line transients in selecting $C_{OUT}$, since $C_{OUT}$ absorbs the surge energy. See the subsection on transients below.

## Short Circuit/Overload Protection

Overload and short circuit protection is inherent in a cap-coupled regulator. The reactance of CS limits the current during a short or overload on the output. This protection is present even when the control circuitry is rendered non-functional by lack of supply voltage caused by the short. Short circuit current is given by equation 1 above.

## Transient Protection

Transient protection is afforded by 3 means: over-current protection, absorption by $C_{OUT}$, and a limiting resistor. While following the guidelines will contribute towards a robust design, the final circuit, including the PCB, must be tested to assure transient survivability. If cost of the surge generator is an issue, they are widely available for rent, or testing at an outside lab.

**Overcurrent Protection (OCP)**

An overcurrent protection (OCP) circuit is employed for protecting the regulator during line transients. If a line transient occurs when the shunt is turned on, the output voltage will be impressed across the shunt while it is conducting. High currents would then flow thru the shunt, potentially damaging it. The OCP circuit quickly shuts off the shunt when the voltage across it reaches the OCP threshold ($V_{OCP}$).

If the output voltage is less than the OCP threshold at the time of the transient, clamping will occur below the OCP threshold, preventing OCP from activating. Care must be taken to ensure the output voltage does not drop below the OCP threshold.

### Limiting resistor $R_{LIM}$

To limit surge current during line transients, a limiting resistor in series with the AC line is recommended. Greater immunity from transients is afforded by higher resistances but at the expense of higher power loss. Since input current is constant regardless of load, power loss remains constant from no load to full load.

$$P_{LIM} = I_{IN}^2 \cdot R_{LIM}$$

*where:* $P_{LIM}$ = *power loss in the* $R_{LIM}$ *resistor*
$I_{IN}$ = *input current as calculated in Eq 3*
$R_{LIM}$ = *limiting resistor value*

For additional protection, $R_{LIM}$ may be fusible.

## PCB Layout

### High voltage creepage

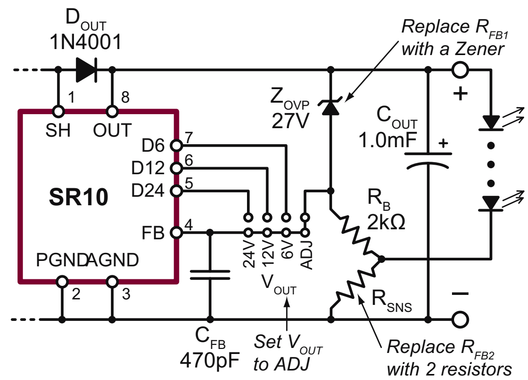
For safety reasons, RLIM should be fusible and the most upstream component.

The shunt ground (PGND) and control ground (GND) should be connected together as close as possible the SR10.

## Driving LEDs

The SR10 can be configured to provide a constant-current output to drive LEDs. A current sense resistor ($R_{SNS}$) is used to convert LED current to the 1.2V feedback voltage required by the SR10.

$$I_{LED} = \frac{1.2V}{R_{SNS}}$$

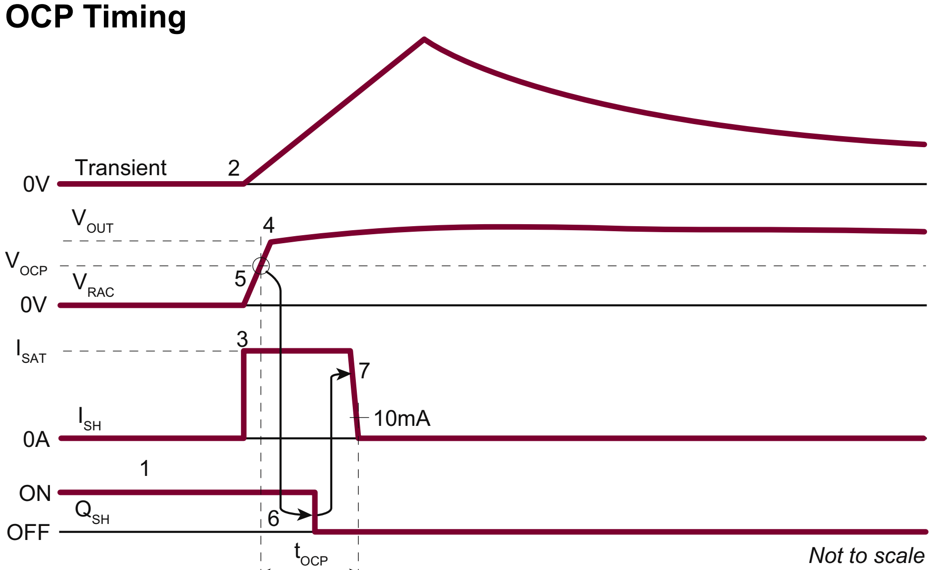



When operated over a wide supply voltage range, a small $C_{OUT}$ can result in overcharging at higher line voltages. It may take several cycles for the voltage to drop back down to the regulation threshold. This may cause visible flicker. The remedy is to increase $C_{OUT}$.

To protect against open LEDs, an overvoltage protection (OVP) circuit is employed. The OVP level is set by the value of the OVP Zener. $R_B$ limits the current thru the Zener.

$$V_{OVP} = V_Z + 1.2V$$

## OCP Timing




1. Shunt is on, clamping $V_{RAC}$ to ground.
2. The line transient hits, causing...
3. the shunt FET to saturate, raising $V_{RAC}$ until...
4. clamped by $V_{OUT}$.
5. Meanwhile, when $V_{RAC}$ exceeds the OCP threshold...
6. the shunt is turned off, causing...
7. $I_{SH}$ to fall, reducing power dissipation.
8. OCP resets when $V_{RAC}$ falls below $V_{SYNC}$ (not shown).

## 3. Measurement Techniques

Measurements of SR10 performance fall into two general categories: time-domain and frequency-domain. Time-domain measurements include load regulation, standby power, output ripple, et cetera. Frequency domain measurements include line current harmonics and conducted EMI.

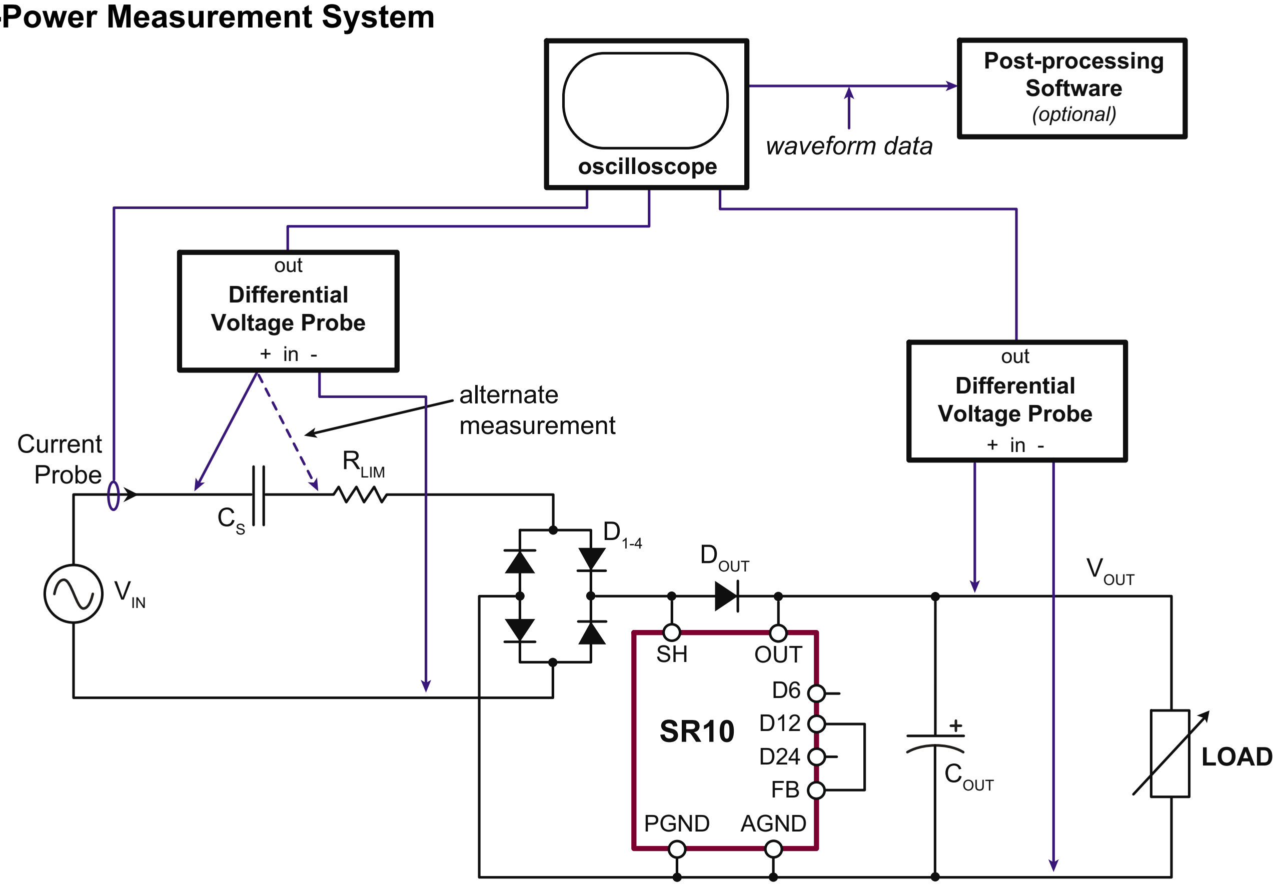
### Time-Domain Measurements

With the goal of reducing standby power to the milliwatt range, measuring input power at these low levels becomes problematic. Specialized AC power analyzers frequently are unable to resolve milliwatts. Compounding the problem, the load presented to the AC line by the SR10 is mainly reactive due to the $C_S$ capacitor. Therefore input power is mainly imaginary, with a small real component representing losses and the load. The ratio between the real component and the imaginary component can be several orders of magnitude. The combination of milliwatt-range real power and the low real/imaginary ratio makes measurement of real power difficult.

Real-power measurements entail measuring input voltage and current and multiplying on a time-point basis. One way to improve the real/imaginary power ratio is to configure the input voltage measurement to exclude the $C_S$ capacitor. This eliminates the reactive component of the $C_S$ capacitor, improving the real/imaginary ratio. The downside of this technique is that any real losses in $C_S$ avoid measurement. However, X2 rated film capacitors are high quality and exhibit very low ESR, so $C_S$ may be ignored with little impact on real-power measurements. For measurements that require the full imaginary component, such as power factor, the voltage must be measured directly at the input (across the AC source).

The measurement setup shown below can be used to make real-power measurements. High voltage differential probes are used to measure input and output voltages and provide isolation from the high voltage AC source. A clip-on current probe is used to measure input current, again providing isolation. Current probe sensitivity may be increased by looping the current-carrying wire multiple times thru the probe. The number of passes thru the probe is the increase in sensitivity. Don't forget to compensate for the increased sensitivity, either at the scope or in the post-processing software. The locations of $C_S$ and $R_{LIM}$ must be as shown.

### Real-Power Measurement System



Since the current drawn from the AC source by the SR10 may skip cycles of the line frequency, the sample window should be long enough to average-out the pulse-skipping. In general, at least 20 cycles of the input frequency should be captured. The window need not be an integer number of cycles, as the post-processing software can truncate the waveform data to an integer number of cycles.

The AC line may be used as the source. A variable transformer (Variac) my be used to simulate high/low line conditions. An AC power supply is more flexible, allowing testing at different line frequencies as well as voltages.

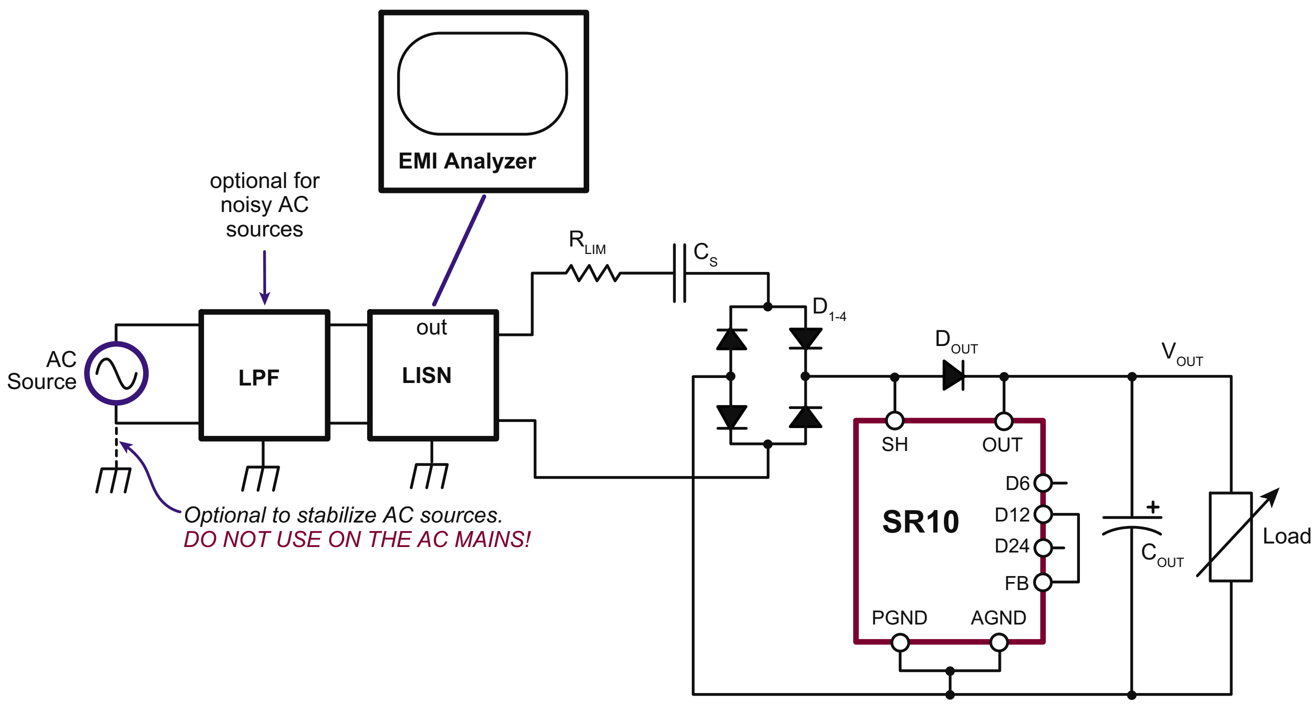
Post-processing software written in MathCAD is available from the Supertex Applications group. It was written for the Lecroy 6000 series oscilloscopes, but may be modified by the user to accommodate waveform file formats of other oscilloscopes.

## Frequency-Domain Measurements

Since the SR10 operates from the AC line, it must meet certain conducted EMI standards, which vary by country. Conducted EMI measurements are generally performed using the test setup shown below.

Some AC power supplies are unstable with capacitive loads. Others may introduce significant EMI themselves. Sometimes both. An L-C low pass filter (LPP) on the output of the AC supply can help isolate the capacitive load and reduce injected noise. Earth-grounding one of the AC outputs can sometimes help stabilize the AC power supply (*DO NOT attempt this when using the AC mains!*).

## EMI Test Setup



## 4. $C_S$ Table

The following table is based on the previously provided equations for $C_S$. Actual output current may be less due to losses (~5% less). AC line voltage is assumed to be 90 - 135VRMS @ 60Hz or 190 - 275VRMS @ 50Hz. Slashed cells exceed recommended operating conditions for peak shunt current at 85°C.

For universal 120V and 240V operation choose $C_S$ based on 120VAC and make sure that operation at 240VAC does not fall in a slashed cell. The relevant cells are adjacent to each other. For example, if 50mA at 12V is needed and full rectification used, a $C_S$ capacitor of 2.2µF ± 10% provides 53.8mA at 120VAC (90VAC low line). But at 240VAC, the cell to the right (240VAC column) is slashed, and universal operation is not possible. This assumes 120VAC low line is 90VAC and 240VAC high line is 275VAC. For other high/low voltages use the equations.

### Output current capability (mA)

| $C_S$ | $C_S$ Tol | 6V Output | | | | 12V Output | | | | 24V Output | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Half | | Full | | Half | | Full | | Half | | Full | |
| | | 120V 60Hz | 240V 50Hz | 120V 60Hz | 240V 50Hz | 120V 60Hz | 240V 50Hz | 120V 60Hz | 240V 50Hz | 120V 60Hz | 240V 50Hz | 120V 60Hz | 240V 50Hz |
| 220nF | 10% | 2.9 | 5.2 | 5.7 | 10.3 | 2.9 | 5.2 | 5.4 | 10.1 | 2.7 | 5.1 | 4.8 | 9.6 |
| | 20% | 2.6 | 4.7 | 5.0 | 9.2 | 2.5 | 4.6 | 4.8 | 9.0 | 2.4 | 4.5 | 4.3 | 8.5 |
| 330nF | 10% | 4.4 | 7.9 | 8.5 | 15.5 | 4.3 | 7.8 | 8.1 | 15.1 | 4.1 | 7.6 | 7.2 | 14.4 |
| | 20% | 3.9 | 7.0 | 7.6 | 13.8 | 3.8 | 6.9 | 7.2 | 13.4 | 3.6 | 6.8 | 6.4 | 12.8 |
| 470nF | 10% | 6.3 | 11.2 | 12.1 | 22.0 | 6.1 | 11.1 | 11.5 | 21.5 | 5.8 | 10.8 | 10.3 | 20.5 |
| | 20% | 5.6 | 10.0 | 10.8 | 19.6 | 5.4 | 9.9 | 10.2 | 19.1 | 5.2 | 9.6 | 9.1 | 18.2 |
| 680nF | 10% | 9.1 | 16.2 | 17.5 | 31.9 | 8.9 | 16.0 | 16.6 | 31.2 | 8.4 | 15.7 | 14.9 | 29.7 |
| | 20% | 8.1 | 14.4 | 15.6 | 28.4 | 7.9 | 14.3 | 14.8 | 27.7 | 7.5 | 13.9 | 13.2 | 26.4 |
| 1.0µF | 10% | 13.3 | 23.9 | 25.7 | 46.9 | 13.0 | 23.6 | 24.4 | 45.8 | 12.4 | 23.0 | 21.9 | 43.7 |
| | 20% | 11.9 | 21.2 | 22.9 | 41.7 | 11.6 | 21.0 | 21.7 | 40.7 | 11.0 | 20.5 | 19.4 | 38.8 |
| 1.5µF | 10% | 20.0 | 35.8 | 38.6 | 70.4 | 19.5 | 35.4 | 36.7 | 68.7 | 18.6 | 34.6 | 32.8 | 65.5 |
| | 20% | 17.8 | 31.8 | 34.3 | 62.5 | 17.4 | 31.4 | 32.6 | 61.1 | 16.5 | 30.7 | 29.1 | 58.2 |
| 2.2µF | 10% | 29.4 | 52.5 | 56.6 | 103.2 | 28.6 | 51.9 | 53.8 | 100.8 | 27.2 | 50.7 | 48.1 | 96.1 |
| | 20% | 26.1 | 46.6 | 50.3 | 91.7 | 25.5 | 46.1 | 47.8 | 89.6 | 24.2 | 45.1 | 42.7 | 85.4 |

*= Exceeds Recommended Operating Limits*



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