Design Guide: TIDA-010060
Off-Line (Non-Isolated) AC/DC Power Supply Architectures Reference Design for Grid Applications

Description

This reference design showcases three non-isolated AC/DC power supply topologies for line-powered applications such as residential circuit interrupters, circuit breakers, home automation equipment and appliances for < 100 mA. The three topologies are

- Off-line switcher using inductor
- AC line regulator using switched capacitor
- Capacitive-drop regulator

The trade-off between efficiency, start-up time and solution size is done across architectures for various input and output conditions. The design methodology, test data and comparison is included for system designers to quickly evaluate and customize their solution.

Resources

TIDA-010060	Design Folder
UCC28880	Product Folder
TPS7A78	Product Folder
LP2992	Product Folder

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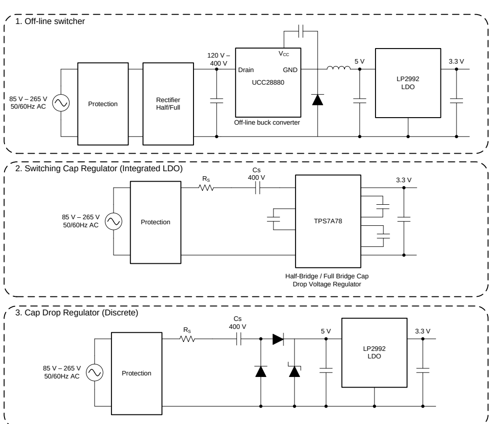
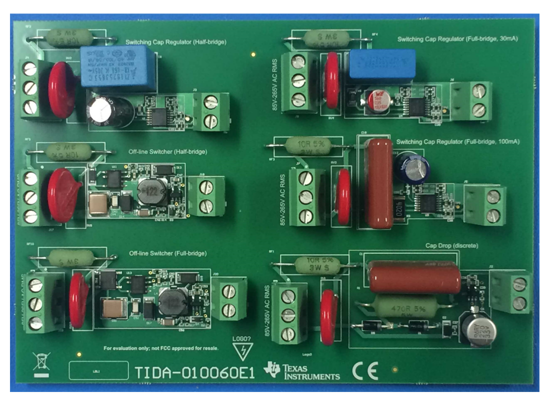
Features

- **Off-line switcher using the UCC28880**: High-efficiency architecture using a buck converter simplifies the design covering universal input voltage
  - Applications requiring fast startup (< 2 ms), small footprint or need to meet stringent surge requirements
- **Switching capacitor-drop regulator using the TPS7A78**: Inductor-less architecture customized for a narrow input voltage range
  - High efficiency solution for low current (< 30 mA) and a single chip solution with integrated active rectifier and LDO
- **Capacitor-drop regulator using an LDO**: Simplified solution with passive components and LDO
  - Low-cost solution with low efficiency, high startup time and large footprint

Applications

- Grid infrastructure: Residential breakers (AFCI, DFCI, MCB), Contactor, Branch Current Monitor (BCM), Grid asset monitoring, Electricity meter
- Building automation: Lighting and Thermostat control
- Appliances





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1 System Description

Applications in grid infrastructure, building automation, and appliances require a power converter to supply regulated DC voltage from AC mains. These include residential circuit breakers (AFCI, DFCI, MCB), electricity meters (e-meters), thermostats and so forth, that use a non-isolated DC supply which is optimized for space and size. Typical requirements for such applications include the ability to operate for wide input voltage from 85 VAC to 265 Vac to make them universal for both 110-V and 220-V systems, while providing a regulated 5-V or 3.3-V output. Output load current could vary from a few mA up to 100 mA depending on the application. As industrial electronics have advanced with more integrated features, the overall enclosure size has not grown, calling for smaller and efficient solution sizes over time.

The architectures today handle these requirements with trade-offs in efficiency, startup time, number of components, and so forth. They can be broadly classified under the following categories:

1. Low efficiency:
   a. For lower output currents (in the 10 mA range), a bridge rectifier and extra-wide input voltage linear regulator can be used. While this has smallest size, it has very low efficiency (< 10%).
   b. Another alternate approach is by using a combination of multiple discrete components such as rectifiers, MOSFETs (high voltage), Zener diodes, LDO, and so forth, which results in slightly better efficiency.
   c. One of the commonly-used architectures for slightly higher currents (up to approximately 30 mA) is a cap-drop power supply which introduces a high-voltage capacitor between the AC line and a Zener diode (acts as a DC clamp). **As shown in this design**, the bulky capacitor drops most of the line voltage while providing power to the load as needed. This helps keep the downstream bridge rectifier and conditioning circuits to lower voltage levels; thereby reducing its size. The current from the AC supply flows irrespective of whether the load demands it or not, as the Zener diode needs to be biased throughout; thus reducing efficiency. Though this architecture has the least number of active components and is easy to design, it has one of the slowest startup times and largest footprints.
2. High efficiency:
   a. The most efficient way of down-converting the AC line voltage is to use an off-line buck converter in conjunction with a downstream low-input voltage linear regulator **as shown in this design**. The converter can be designed to operate for universal wide input voltage meeting both 110-V and 220-V systems while providing DC power. Efficiencies in the range of 40% to 50% can be achieved within half a cycle of startup time. This solution, though efficient and capable of providing fast start-up time requires an inductor and a LDO, amongst other passive components. The inductor is susceptible to stray magnetic fields.
   b. Another unique topology that has an integrated active bridge rectifier, switched-cap network and an integrated LDO is **shown in this design.** Between the AC line and this chip is a current source capacitor that can be much smaller in size compared to an equivalent cap-drop power-supply capacitor. Applications requiring very low current (< 30 mA) and very high efficiency for narrow input voltage ranges (85 V–135 V or 195 V–245 V) can benefit from a switched-cap regulator such as the TPS7A78 device. Startup time can be 4 line cycles for full-bridge and 10 cycles for half-bridge configurations.

This design highlights the trade-off between three topologies (1c, 2a, and 2b). A comparison is shown for efficiency, startup time, footprint, and load regulation.

1.1 Grid Infrastructure: Circuit Breakers, E-meters

Circuit Breaker:

A circuit breaker is an automatic electrical switch that is designed to protect an electrical circuit from damage caused by faults. It detects a faulty condition and interrupts continuity to the electrical flow. Breakers or circuit interrupters are differentiated based on its capability to detect different types of fault conditions such as overcurrent, ground fault, arc fault, and so forth.. While a miniature circuit breaker (MCB) offers overcurrent protection, arc fault circuit interrupter (AFCI), and ground fault circuit interrupter (GFCI) are special-function breakers that interrupt during arc faults and ground faults, respectively.

These breakers and interrupters are line powered. Depending on the features that are available, the electronics inside them operate from 10 mA to 100 mA on 3.3 V. Another important requirement for these is minimal startup to meet fast fault clearance capability. Since their trip time can be as low as 30 ms, a fast start-up time capability for the electronic trip unit power supply is critical. With recent advancements in technology and the move toward a digital grid, the newer generation circuit breakers are designed with features such as wireless connectivity and monitoring power flow which is more like a smart meter or a smart breaker. This, in turn, places new requirements on system design: reduced component size to fit additional electronics in the same chassis, improved energy efficiency to perform within the same or lower thermal budget, and increased electrical and mechanical safety and reliability.

This reference design provides a solution for the previous use case.

E-meter:

Accurate measurement of power consumption is a key requirement for utilities and power distribution companies as it generates revenue. These companies are replacing conventional induction-type energy meters with electronic ones that can measure energy accurately over a wide voltage range, frequency, and temperature. These meters are available as single-phase or three-phase (tri-vector) meters.

A low-end single-phase meter used in residential complexes has a micro-processor that performs the current measurement and parameter computation. They, along with other semiconductor chips, consume very low power (approximately 10 mA–20 mA) and need a stable DC power supply to operate. The onboard power supply provides power to run the MCU, LED, and optional communication while remaining within the IEC power consumption specifications. Single phase meters are cost-sensitive and use a capacitive drop power supply that works without a transformer. It drops the voltage across a high-voltage capacitor (typically 200 nF to 680 nF) which is specially designed for a fixed input voltage (110 Vac or 220 Vac). While capacitive drop power supplies are small and more cost-effective than transformer-based or switch-mode based, the efficiency is low. Also for more advanced e-meters requiring higher load currents (approximately 100 mA), they are not practically feasible as they become bulky and lossy.

The TIDA-010060 design provides an off-line switcher that is highly efficient for loads up to 100 mA. Also a switched-cap regulator is shown that is highly efficient for low loads (< 30 mA) and is magnetically immure as it uses a capacitor instead of an inductor.

1.2 Building Automation

Building automation equipment commonly employs one or more sensors to monitor environmental conditions and irregular events. These devices are used for safety (heat, fire, and gas detectors), HVAC (thermostats, environmental sensors, and fault detectors) and security (motion and glass break detectors). Devices can also be fairly complex, such as electronic locks that require keypads, digital readers, and mechanical functionality.

Building automation developers face many challenges today. As with many applications, this places new requirements on system hardware: reduced component size to fit additional electronics in the same chassis, improved energy efficiency while increasing node intelligence, and integrating additional functionality to perform within the same or lower thermal budget and increased electrical and mechanical safety and reliability to reduce downtime. Additionally, the need for wireless connectivity to enable the Internet of Things (IoT) so devices can be controlled and managed remotely puts a further burden on developers to maintain low-power operation. Finally, developers must drive down manufacturing cost without compromising robustness or fail-safe mechanisms.

This reference design addresses all these challenges enabling the capability of choosing the right topology to achieve the best performance.

1.3 Appliances

A current trend in appliance development is to add new functionality into home appliances like having a washing machine send a message when the washing cycle is finished, or a refrigerator displaying what is inside it, either on a screen or by emailing a picture. These additional features need new subsystems like wireless communication, sensors, human-machine-interface (HMI), and lighting which all need power. “Get more from less” – that is always the goal and it is especially true for power consumption in appliances. As a designer, the goal is to get more current to power more subsystems while decreasing overall power consumption. At the same time, appliances must consume as little power as possible to limit their impact on the environment, reduce electricity costs for consumers, and successfully pass more and more stringent energy ratings. Additionally; cost, efficiency, and reliability are always key requirements.

This reference design addresses the key challenges of an appliance non-isolated AC/DC power supply design, that is, how to provide safe and reliable power while delivering high performance with low power consumption and low bill-of-materials (BOM) cost.

1.4 Key System Specifications

Table 1. Key System Specifications

PARAMETER	SPECIFICATIONS			DETAILS
Output voltage	3.3 V DC or 5 V DC			Section 2.4
Isolation type	Non-isolated topology			
Architecture	**Cap drop regulator (30 mA)**	**Off-line switcher using inductor (30 mA, 100 mA)**	**Switching cap regulator with integrated LDO (30 mA, 100 mA)**	
Input voltage	85 Vac to 265 Vac at 50/60 Hz	85 Vac to 265 Vac at 50/60 Hz	85 Vac to 135 Vac at 60 Hz 195 Vac to 245 Vac at 50 Hz	
Output current	30 mA	30 mA, 100 mA	30 mA, 100 mA	
Peak efficiency	5%	49% (half-bridge, full-bridge)	43% (30 mA, Half-bridge), 57% (30 mA, full-bridge), 41% (100 mA, full-bridge)	Section 3.2.2.1
Overall footprint	1.6 in^2	0.643 in^2 (half-bridge), 0.806 in^2 (full-bridge)	0.76 in^2 (30 mA half-bridge), 0.64 in^2 (30 mA full-bridge), 0.77 in^2 (100 mA full-bridge)	Section 3.2.2.4
Startup time	350 ms	1.5 ms	217 ms (30 mA, half-bridge), 52 ms (30 mA, full-bridge), 51 ms (100 mA, full-bridge)	Section 3.2.2.3
Load regulation		15-mV change in output from no load to 100 mA	7-mV change in output from no load to 100 mA	Section 3.2.2.2

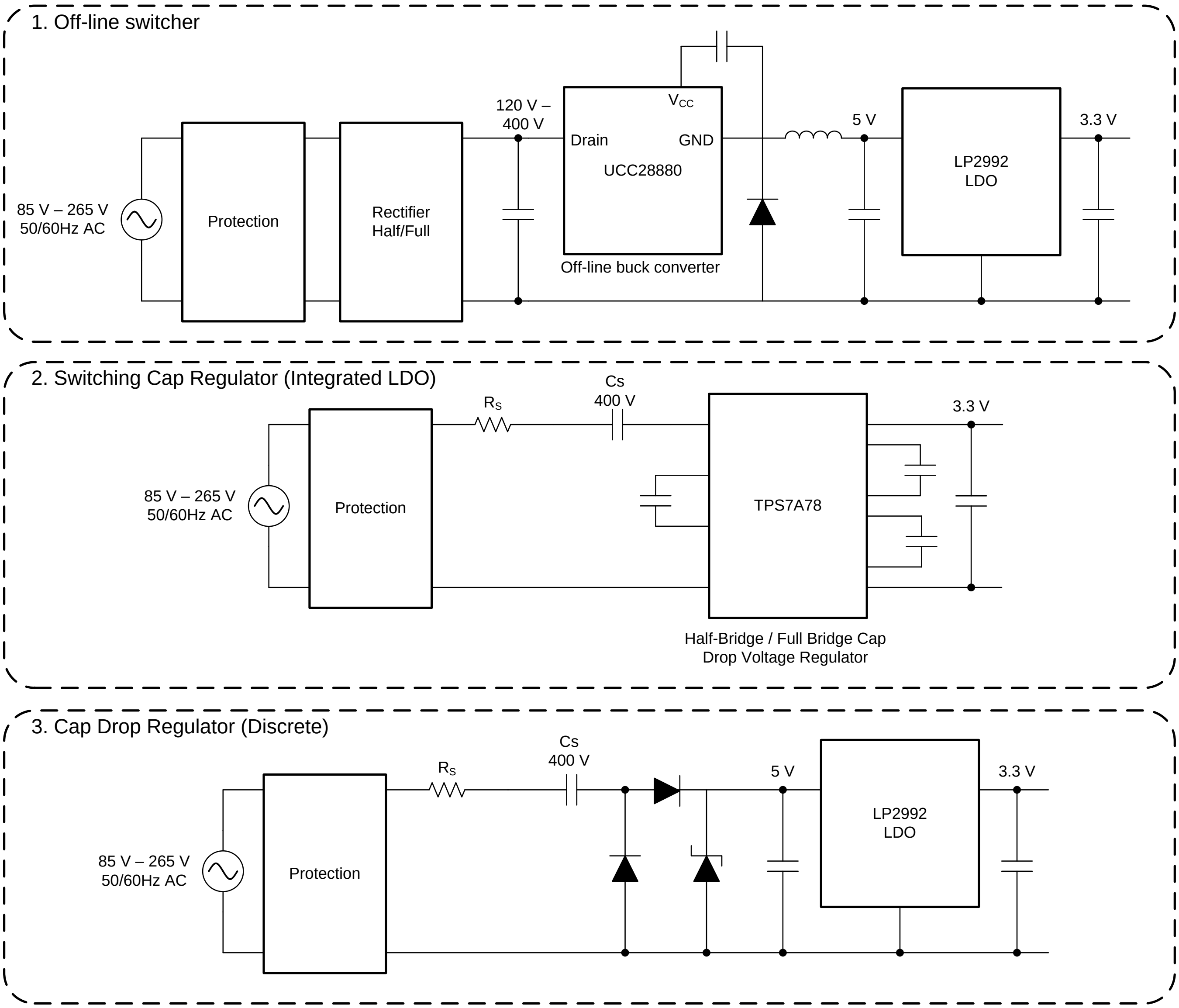
2 System Overview

2.1 Block Diagram

Figure 1 shows the block diagram of the reference design that has three different power-supply architectures.

- Off-line switcher using the UCC28880 device and LDO LP2992
- Integrated line power regulator using the TPS7A78 device
- Capacitor-drop (cap-drop) regulator followed by LDO LP2992

Figure 1. TIDA-010060 Block Diagram



2.2 Design Considerations

Some of the key considerations for design of the TIDA-010060 include:

- Maximize efficiency
- Reduce footprint
- Flexibility of using the design across a wide input voltage range (up to 265 Vac)
- Withstand voltage surges and transients

2.3 Highlighted Products

The following are the highlighted products used in this reference design. This section lists the key features for selecting these products. Refer to the respective product datasheet for more device details. For more information on each of these devices, see the respective product folders at www.ti.com.

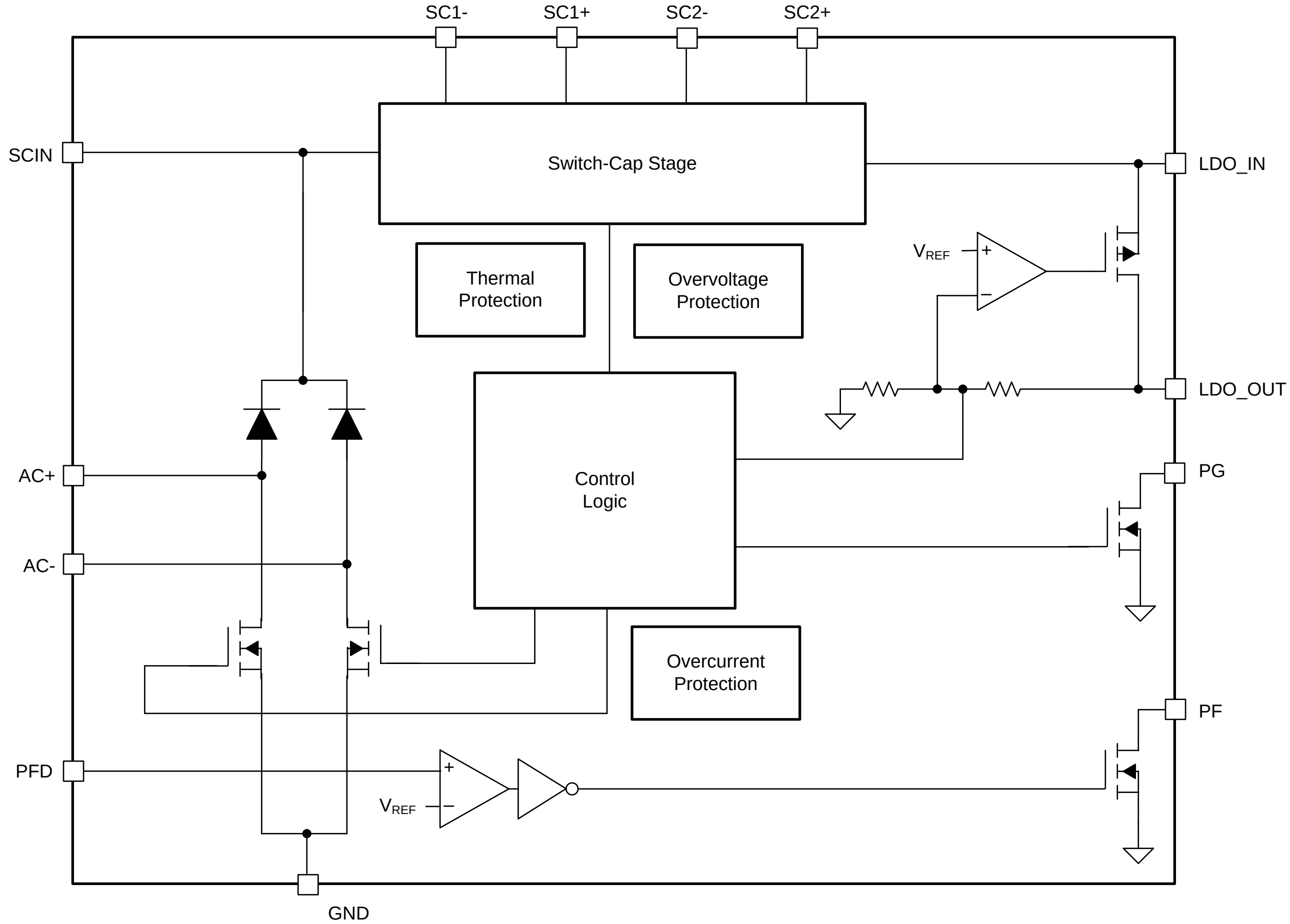
2.3.1 TPS7A78: 120-mA, Non-Isolated Line Power Voltage Regulator

The TPS7A78 device is a novel approach to improve overall efficiency and standby power in power supplies looking for an easy-to-use non-magnetic approach to AC/DC conversion. The TPS7A78 device is unique in that it uses an external capacitor to create a current source and it actively clamps the rectified voltage before regulating it down to the applications target operating voltage. Because of the unique architecture of the TPS7A78 device, the standby power can be reduced from several 100's of mW to just a few 10's of mW. The TPS7A78 device takes advantage of an innovative switched capacitor stage to reduce the clamped voltage down approximately one-forth the value which, in turn, multiplies the current by 4 ×. The upside of this architecture is that the current source capacitor can be much smaller in size which minimizes standby power, reduces solution size, and can lead to a lower system cost. The TPS7A78 device is optimized for e-metering applications where the power supply needs to be reliable and tamper-proof.

Key features of this device include:

- Non-isolated power solution for VAC 70–360 VAC: achieving efficiency up to 70% for < 30 mA design
- Family of products supporting output voltages from 1.25 V to 5 V
- Can achieve approximately 10-mW standby power consumption
- Line voltage drop capacitor can be ¼th the size of traditional solutions
- Power fail detection and power good indication
- 1.5% precision voltage regulation over line, load, temperature

Figure 2. TPS7A78 Functional Block Diagram



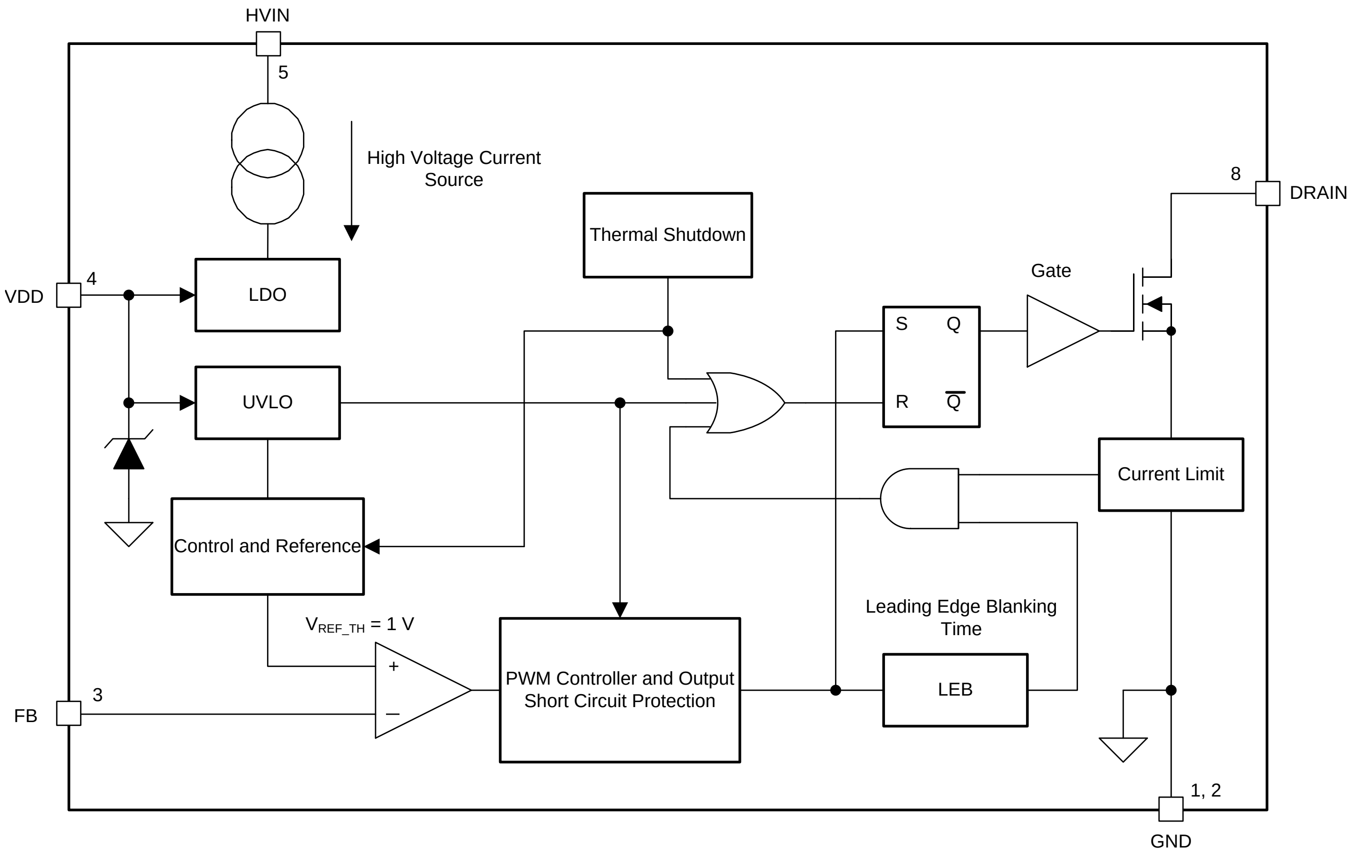
2.3.2 UCC28880: FET Integrated High Voltage Switcher

The UCC28880 device integrates the controller and a 700-V power MOSFET into one monolithic device. The device also integrates a high-voltage current source, enabling start up and operation directly from the rectified mains voltage. The low quiescent current of the device enables excellent efficiency. With the UCC28880 device, the most common converter topologies, such as buck, buck-boost, and flyback can be built using a minimum number of external components. The UCC28880 device incorporates a soft-start feature for controlled startup of the power stage which minimizes the stress on the power-stage components.

Key features of this device include:

- Integrated power MOSFET (switch) rated to 700-V drain-to-source voltage
- Integrated high-voltage current source for internal low-voltage supply generation
- Soft start
- Self-biased switcher (start-up and operation directly from rectified mains voltage)
- Supports buck, buck-boost, and fly-back topologies
- Robust performance with inductor current runaway prevention
- Thermal shutdown
- Protection: Current limit, overload, and output short circuit

Figure 3. UCC28880 Functional Block Diagram



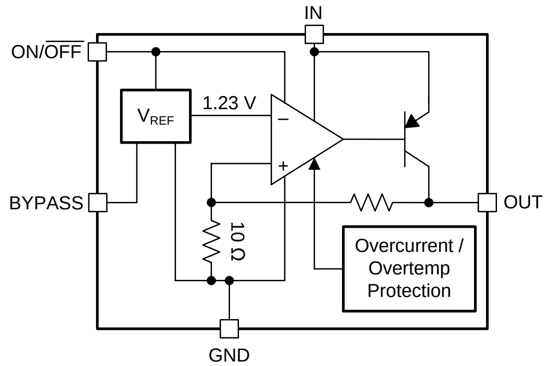
2.3.3 LP2992: 250-mA, Ultra-Low-Dropout Regulator

The LP2992 device is a 250-mA, fixed-output voltage regulator designed to provide ultra-low dropout and low noise in applications such as residential circuit breakers where micro-controllers require a regulated power supply. This provides regulated voltage from wider input voltage of up to 16 V. Using an optimized vertically integrated PNP (VIP) process, the LP2992 delivers unequaled performance in all specifications critical to such applications.

Key features of this device include:

- Input voltage range: 2.2 V to 16 V
- Output voltage range: 1.5 V to 5 V
- Output voltage accuracy 1% (A Grade)
- Ultra-low-dropout voltage: Typically 450 mV at 250-mA load and 5 mV at 1-mA load
- Stable With low-ESR output capacitor
- < 1-µA quiescent current when shut down
- Overtemperature and Overcurrent protection
- −40°C to 125°C junction temperature range
- Smallest possible size (SOT-23, WSON package)

Figure 4. LP2992 Functional Block Diagram



2.4 System Design Theory

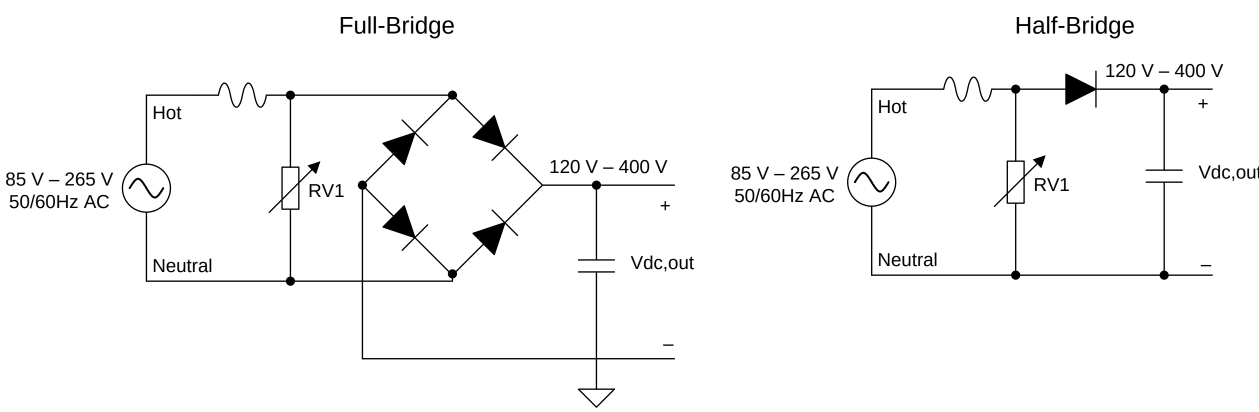
The TIDA-010060 reference design emphasis is on three different non-isolated AC/DC architectures for applications mentioned in Section 1 calling for low device count, small footprint, high efficiency, and high voltage surges and transients withstanding capability solutions. The following subsections detail the design procedure for each topology.

2.4.1 Half-Bridge and Full-Bridge Configuration

The first step in a non-isolated AC to DC power conversion is to rectify the high-voltage AC input to obtain unipolar voltage at the output. This is achieved by passing the AC input sine wave through either a full-bridge rectifier composed of four diodes or a single diode that blocks the negative part of the sinusoidal voltage.

Selection of the bridge configuration depends on the reference point for the output voltage as this powers the MCU or other analog circuit in the system. Figure 5 shows the two possible combinations for rectifying the AC waveform. In full-bridge configuration, the reference (negative terminal) for output voltage is floating depending on the line cycle whether it is in positive half cycle or negative half cycle. This architecture is mainly used in application where sensor input is isolated from the line and neutral supply such as current transformer (CT) or Rogowski coil. Conversely, for half-bridge configuration, the output reference is fixed and tied to neutral of the AC mains. These are typically used in applications with non-isolated sensors like shunt.

Figure 5. Full-Bridge and Half-Bridge Configuration



2.4.2 Off-Line Switcher

With the UCC28880 device, the most common converter topologies such as buck, buck-boost, and flyback can be built using a minimum number of external components. The UCC28880 device incorporates a soft-start feature for controlled startup of the power stage, which minimizes the stress on the power stage components. The UCC28880 device has been chosen for its integrated switching MOSFET and start-up current source, low standby power consumption (quiescent current consumption of less than 100 µA), and its internal current sense, which leads to a lower bill-of-materials (BOM) cost and board size.

In this reference design, it is configured as a high-side buck converter to obtain a regulated DC voltage of 5 V from the rectified AC line voltage. For this configuration, ultra-fast recovery high voltage diodes, inductor, and high-voltage capacitor at the input are designed to meet the design specifications. Figure 6 and Figure 7 show the schematic for half-bridge and full-bridge configurations.

Figure 6. Off-Line Buck-Converter for Half-Bridge Configuration Schematic

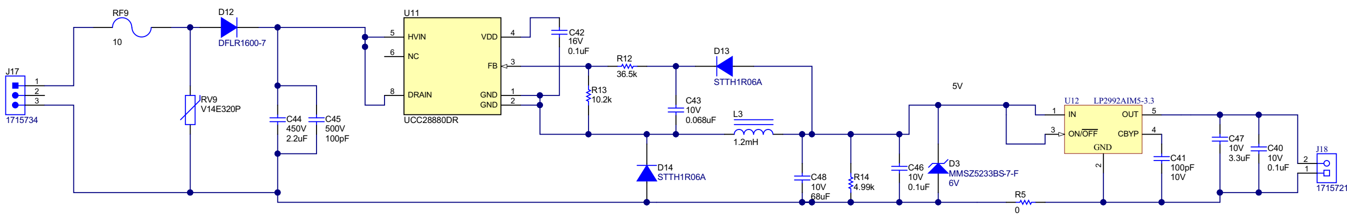
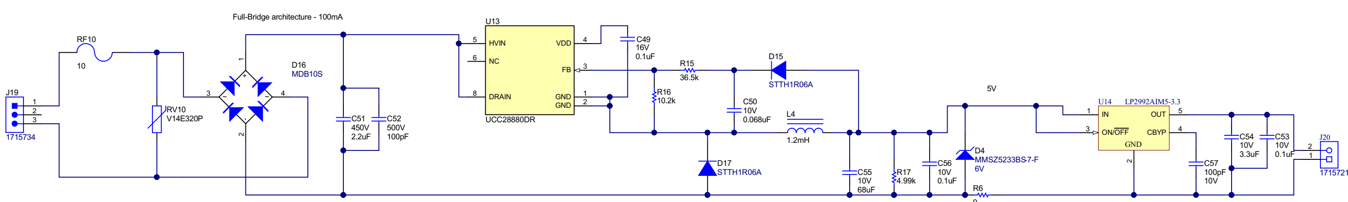


Figure 7. Off-Line Buck Converter for Full-Bridge Configuration Schematic



2.4.2.1 *Diode Selection (D13, D14, D15, D17)*

D13, D14, D15, and D17 are selected to have very small Q_{rr} and reverse recovery time t_{rr}, otherwise, catastrophic failures might occur. The *UCC2888x diode selection when configured as a high-side buck* application note that explains this in detail. In continuous mode operation, the diode reverse recovery time should be less than 35 ns (such as the STTH1R06A, which provides a 25 ns t_{rr}). If the device is being operated in discontinuous mode operation, a slower diode with a reverse recovery time of 75 ns, or less, can be used. Generally, using faster reverse recovery diodes, those that have a t_{rr} < 20 ns over the entire temperature range, is recommended since doing so provides additional design margin.

2.4.2.2 *Output Capacitor Selection (C48, C55)*

Proper sizing of the output capacitor is important in light of the impact it has on the output voltage ripple along with start-up time. To take into account both the capacitor value and the equivalent series resistance (ESR), a guide for sizing the output capacitor can be calculated using Equation 1 and Equation 2:

$$C_L > 4 \times \frac{I_{LIMIT} - I_{OUT}}{f_{SW,MAX} \times \Delta V_{OUT}} \tag{1}$$

$$R_{ESR} < \frac{\Delta V_{OUT}}{I_{LIMIT}} \tag{2}$$

A first-pass capacitance value can be selected and the contribution of C_L and R_{ESR} to the output voltage ripple can be evaluated. If the total ripple is too high, the capacitance value has to increase or the R_{ESR} value must be reduced. In our design, C_L is selected at 68 µF and it has an R_{ESR} of 3.494 mΩ. The formula that calculates C_L is based on the assumption that the converter operates in bursts of four switching cycles. The number of bursts per cycle could be different, but the formula for C_L can be used as a first approximation.

2.4.2.3 Inductor Value Selection (L3, L4)

For the UCC28880 device, the output inductor L3/L4 is selected to meet the following two requirements:

1. Inductance large enough to have peak inductor current smaller than I_{LIMIT} for supporting CCM operation at full load:

$$L > \frac{\left(V_{OUR} + V_D\right) \times \left(\frac{1}{f_{SW} - V_{IN,MAX}} - t_{ON\_VMAX}\right)}{\Delta I_L} \quad (3)$$

2. Inductor saturation current rating higher than the peak inductor current or the maximum current limit I_{LIMIT}(MAX) to avoid tripping the runaway current protection.

$$L > \frac{V_{IN,MAX}}{I_{LIMIT}} \times t_{ON\_TO} \quad (4)$$

For the given design requirements, the output inductor L3/L4 is sized to be about 1.2 mH. For 30-mA output current, 680-µH inductors are recommended in place of L3 and L4. For optimizing at lowest size or system cost, the *Operating UCC2888x offline buck in saturation for cost reduction* application report explains how to undersize the inductor to reduce its cost further while still enabling proper operation.

2.4.2.4 Voltage Control Loop (R12, R13, D13, C43 and R15, R16, D15, C50)

The feedback path consisting of resistors R12/R15 and R13/R16, diode D13/D15 and capacitor C43/C50, sets the output voltage to 5 V. The diode D13/D15 is identical to D14/D17, and their voltage drops compensate each other. The feedback is sampling the output voltage level to capacitor C43/C50 during the off state of the integrated HV FET of the UCC28880 device and the output voltage is set by the resistors R12/R15 and R13/R16 following the equation:

$$V_{OUT} = \frac{R_{13/16} + R_{12/15}}{R_{13/16}} \times V_{FB}$$

where

- V_{OUT} is the output voltage
- V_{FB} = 1.0 V is the voltage level at the feedback pin (5)

This provides a good starting point for the feedback parameters; however, it needs to be optimized for improved performance.

The value of bootstrap capacitor C43/C50, the impedance of feedback divider network R13/R16, R12/R15, and the output capacitor C48/C55 are especially critical. The RC time constant of the bootstrap capacitor and feedback resistor divider network influences the voltage on the FB pin, which in turn influences the burst pattern of switching pulses in the device. By adjusting these components the frequency of the burst pattern can be manipulated higher or lower. This is an effective way to address audible noise emanating from the magnetics and capacitors in the system. The *UCC28880, UCC28881 audible noise reduction techniques* application report provides more details on audible noise reduction techniques.

A higher RC time constant reduces the frequency of occurrence of burst pulses, which increases the output voltage ripple unless the value of the output capacitor is also increased alongside. A lower time-constant increases the frequency of the burst pattern but smaller resistor divider impedance increases the stand-by power consumption. These trade-offs have to be considered when designing the power supply.

2.4.2.5 Benefits of LP2992 as a Post-Regulator

Switching converters are necessary for efficiency; however, they have switching ripples on their output. Many devices like microcontrollers are very sensitive to power supply noise. A common practice is to have switching converters followed by an LDO to clean the supply. The LP2992AIM5-3.3 linear regulator has a very good PSRR which enables it to minimize the ripple using the bypass capacitor.

2.4.3 Switching Capacitor Regulator With Integrated LDO Using TPS7A78

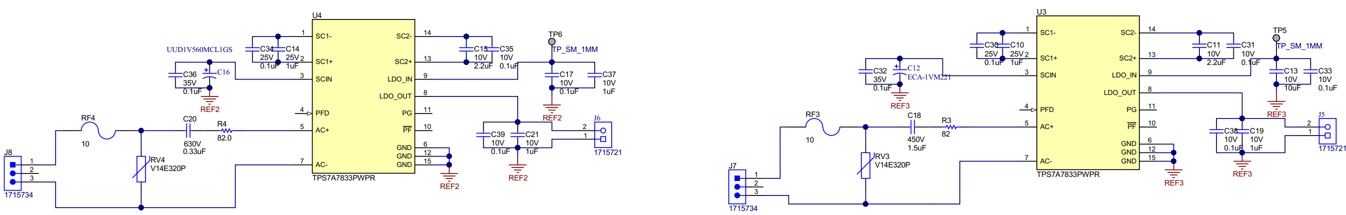
The TPS7A78 device is a non-isolated AC to DC solution capable of providing a maximum of 120 mA or 60 mA of load current with full-bridge or half-bridge configuration, respectively. Unlike typical AC to DC power topologies, the TPS7A78 device is an inductor-less solution which makes it an excellent choice for various applications by minimizing tampering and simplifying the design. The device uses a switching capacitor stage (charge pump) to reduce the AC voltage. Although the charge pump adds three external capacitors, they are low-voltage (< 16 V) rated ceramics, which do not significantly increase system size or cost. Additionally, by featuring an internally controlled active bridge rectifier with full-bridge or half-bridge configuration, the device does not require any external diode rectifier minimizing solution size along with system cost. Finally, an integrated LDO as output stage can provide regulated V_{OUT} and attenuate ripple avoiding any external regulator - the TPS7A78 device uses the LDO output voltage to set the clamp voltage for the best efficiency. Overall, this provides an integrated solution for AC/DC conversion with simplified design procedure.

There are two major design parameters that ensure functioning of the converter throughout its input and output specifications- cap-drop capacitor, C_S and series resistor, R_S. Selection of C_S is a function of the minimum input voltage and R_S is selected based on the maximum line voltage. Efficiency of the conversion for this architecture is optimal if it is designed for narrow input voltage range. Hence, in this design two separate designs are considered for 110 VAC and 220 VAC.

2.4.3.1 Full-Bridge and Half-Bridge Configuration

This device can be configured in half-bridge or full-bridge configuration. When using full-bridge configuration, the TPS7A78 device GND pin needs to be a floating GND: Full-bridge configuration disconnects neutral from TPS7A78 GND. Half-bridge configuration ties AC supply neutral line to the TPS7A78 device GND pin providing a fixed reference as shown in Figure 8.

Figure 8. Switching Capacitor Regulator With Integrated LDO Using TPS7A78



2.4.3.2 Recommended Capacitor Types

The device is designed to work with various kinds of capacitors such as ceramic and electrolytic capacitors. The device also requires AC mains capacitors such as a (safety-rated) class-X capacitor to be used for the cap-drop C_S. Use the minimum or larger than the minimum recommended capacitor size, voltage rating, and dielectric material for all the device capacitors to ensure optimum performance. Regardless of the capacitor type selected, the effective capacitance varies with operating voltage and temperature; as a rule of thumb, expect the effective capacitance to decrease by as much as 50%.

2.4.3.3 Capacitive-Drop Capacitor C_S

The use of the capacitive-dropper, or cap-drop, is not new in the realm of low-power applications. The safety rated X class cap-drop C_S acts as a lossless resistance where its reactance limits the maximum AC current that is used to charge the bulk capacitor C_{SCIN}. The voltage rating of C_S capacitor is determined by the minimum peak AC supply voltage of the application, that is, 85 Vac for 110 VAC input and 195 VAC for 220 VAC input. The size of the C_S capacitor is determined by many factors related to the solution such as the AC line voltage, AC line frequency, load current, output voltage, and bridge configuration of the device, that is, full-bridge or half-bridge.

Although largely oversizing the C_S capacitor is not desirable due to apparent-power limitation in some applications, it is recommended for other applications that require faster start-up time for the whole solution. Slightly oversizing the capacitor may be desirable to swap out long term degradation for high-voltage, low-power applications such as e-meters.

As C_S size increases, the maximum AC charging current also increases leading to a faster charging to the bulk capacitor C_{SCIN} and maintaining the headroom between V_{LDO_IN} and V_{LDO_OUT} under heavy load conditions.

Use Table 2 for proper selection of C_S capacitor given the various usage conditions:

Table 2. Components Selection Table for Various Usage Conditions

AC SUPPLY V_{RMS} (Hz)	R_S MIN (Ω)	I_{OUT}	V_{LDO_out}	C_S FB/HB (nF)	C_{LDO_in}	C_{LDO_out}
120 (60)	68	10	3.3, 3.6, 5	100, 220	10 µF	1 µF
		30		330, 470		
		60		560, 1000		
		90		820, -		
		120		1000, -		
240 (50)	131	10	3.3, 3.6, 5	47, 100	10 µF	1 µF
		30		150, 330		
		60		330, 560		
		90		470, -		
		120		560, -		

For our design requirements, at 30-mA load current and 85 Vac minimum input voltage, C_S = 680 nF for half-bridge configuration and C_S = 330 nF for full-bridge configuration. For different configurations and input voltage ranges, C_S values are tabulated in Table 3.

2.4.3.4 Hot Plug Resistor R_S

The minimum value of the hot plug current-limiting resistor $R_{S,min}$ is determined by the peak AC supply voltage of the application. The value can be easily calculated using Equation 6:

$$R_{S,min} = \frac{V_{AC,MAX}}{i_{SURGE}} \tag{6}$$

where

- $V_{AC,MAX}$ is the maximum peak AC supply voltage for the application
- i_{SURGE} is the maximum AC transient current that the TPS7A78 pin AC– or AC+ can tolerate, which is 2.5 A

where .

The maximum AC supply voltage is bound by the availability of the high-voltage cap-drop capacitor C_S. As for surge resistors, R_S value shall be << $1/(2\pi f \times C_S)$. If R_S value is comparable or higher than the reactance of C_S, then the max output current will be limited by both components rather than just by C_S. For 110 VAC input, R_S value of 82 Ω is used considering maximum AC voltage of 135 VAC. Similarly for 220-V input, a resistor of more than 139 Ω is used.

2.4.3.5 Input and Output Capacitor Requirements

The device requires a fair number of input and output capacitors and all the capacitors seen in the schematic are required for proper operation of the device. For switching caps C_{S1} and C_{S2}, use the required capacitor values along with their voltage rating as specified in the recommended operating conditions table of the *TPS7A78 120-mA, smart AC/DC linear voltage regulator* data sheet.

Oversizing switch caps is not recommended since it will have an adverse effect on the start-up time of the whole solution. It will also lengthen the time taken by the overvoltage clamp to recover from an overvoltage event. Keep the switch caps as close to the device as possible to eliminate any unwanted trace inductance. For bulk capacitor C_{SCIN}, use a minimum voltage rating of 35 V for C_{SCIN} to account for bias-voltage capacitor derating. Place the capacitor as close as possible to the device.

As for C_{SCIN} size, Equation 7 is used for full-bridge 60-Hz input AC supply:

$$C_{SCIN,MIN} = 0.0014 \times I_{LOAD} \quad (7)$$

Equation 8 is used for half-bridge 60-Hz input AC:

$$C_{SCIN,MIN} = 0.0035 \times I_{LOAD} \quad (8)$$

Use Equation 9 and Equation 10 for full-bridge 50-Hz input AC supply and for half-bridge 50-Hz input AC supply, respectively.

$$C_{SCIN,MIN} = 0.0017 \times I_{LOAD} \quad (9)$$

$$C_{SCIN,MIN} = 0.0041 \times I_{LOAD} \quad (10)$$

It is acceptable to round down the value calculated from the previous equations to the nearest available standard capacitor value as long as it is with 10% or less, otherwise round up. It is also recommended to oversize C_{SCIN} and upscale its voltage rating to account for relatively low life expectancy, especially when an electrolytic capacitor is used.

If your application requires a hold-up time, you can increase the size of the C_{SCIN} capacitor or C_{LDO_IN} capacitor accordingly without exceeding the max C_{LDO_IN} capacitor specified in the recommended operating conditions table of the *TPS7A78* data sheet. Note that vastly oversizing C_{SCIN} or C_{LDO_IN} has an adverse effect on the startup time of the solution. Use the minimum capacitors value specified in the recommended operating conditions table of the data sheet if your application does not require a hold-up time. As for C_{LDO_OUT} size, it is recommended to maintain 10:1 ratio between C_{LDO_IN} and C_{LDO_OUT} for applications using close to the maximum load current. For optimum device performance, place the capacitors as close as possible to the device.

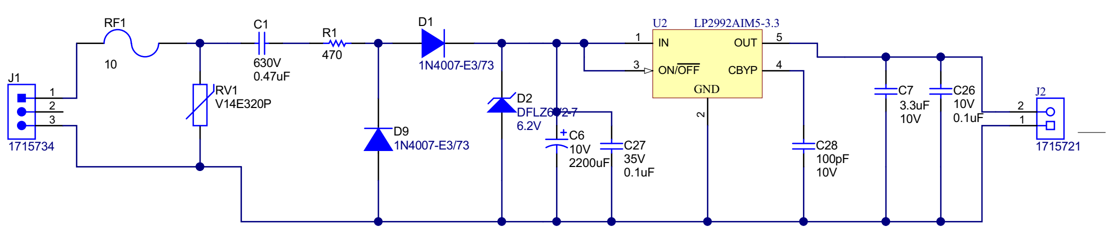
Table 3. C_S and R_S Values for 110-V and 220-V Systems

INPUT VOLTAGE	$C_{S,\ min}$			$R_{S,\ min}$
	HALF-BRIDGE, 30 mA	FULL-BRIDGE, 30 mA	FULL-BRIDGE, 100 mA	
85 VAC - 135 VAC	680 nF	330 nF	1.5 µF	76 Ω
195 VAC - 245 VAC	330 nF	150 nF	560 nF	139 Ω

2.4.4 Capacitor-Drop Regulator

Many times a simple off-line power supply is required for low-power applications such as e-meters, battery chargers, and so forth. Typically, the need is to convert the line voltage to a small DC value such as 3.3 V or 5 V. This can be done with a line frequency power transformer or a complex AC/DC off-line power supply. Both approaches have well-known disadvantages of weight, size, or complexity, or a combination of these. A better option is a half-wave capa-drop circuit which has a lesser number of active components.

Figure 9. Capacitive Drop Regulator in 30-mA Half-Bridge Configuration Using LP2992AIM5-3.3 Schematic



2.4.4.1 Input Resistor

As a result of powering up an AC/DC power supply, one can observe an inrush current at the input of the power supply during power up transient. If the inrush current is too large (where the power supply sunk too much energy in a short period of time), components in the power supply might be damaged. To prevent high inrush currents, a small resistance is usually placed in series with C1. The resistance should be small enough that it does not generate much heat, but should be large enough that it limits inrush currents to acceptable levels. For the inrush current to remain less than 1 A, then R1 = V_{pk} / 1 A = 374 Ω, works well.. In this design, a 470-Ω resistor is used to keep some margin.

$$i_{INRUSH,MAX} = \frac{V_{pk}}{R_1} \tag{11}$$

The steady-state power loss (as heat) incurred by this additional resistance is based on the maximum output current of the supply.

$$P_{R_1} = i^2_{OUT,MAX} R_1 \tag{12}$$

For capacitive-drop power supplies, there is a tradeoff between reducing inrush current and reducing power consumed by the resistor. In this design, the resistor power rating has been selected based on the 30-mA output current.

The dropping capacitor C1 is sized for the lowest line voltage, that is, 85 VAC, thus ensuring that the load current is maintained even at the worst case. For our design requirements and according to the *Improved load current capability for cap-drop off-line power supplies for e-meter using the TPS5401* application report, capacitor C1 is sized to be about 0.47 µF rated at 630 V:

$$C_1 = \frac{I_{RMS}}{(VRMS \times 2 \times \pi \times f)} \tag{13}$$

Do not oversize this capacitor. Oversizing this capacitor increases the load current hence the standby power loss along with the apparent power drawn from the mains.

Since the capacitor C1 is sized for 85 VAC, when the capacitive-drop power supply operates at higher input voltages like 120 VAC or 230 VAC, higher current is drawn from the line, further reducing the efficiency. This capacitor must be capable of handling positive and negative voltage (so an aluminum electrolytic cannot be used!). To meet UL safety requirements, the capacitor must be rated for use in series with the mains, which is typically a poly-film capacitor.

With 50/60 Hz AC input voltage, the output capacitor has 50/60 Hz ripple for a half-wave rectified circuit, and 120-Hz ripple for a full-wave rectified circuit. For the same rated output current, the full-wave rectified circuit will have half as much output ripple as the half-wave rectified circuit. The peak voltage of the ripple will be at the Zener voltage, which should be taken into consideration when observing maximum and minimum voltage thresholds of the load. The magnitude of voltage ripple will vary directly with the amount of load current; more load current will result in a higher magnitude of voltage ripple. Simulation is recommended to determine whether the expected ripple is acceptable. For applications which generate greater-than-desired ripple, the output can be conditioned with the LP2992AIM5-3.3 device providing power supply ripple rejection (PSRR). When using an LDO, the Zener diode should be about 1 V to 2 V above the LDO output voltage to ensure that the minimum dropout limit is met.

In the half-wave implementation shown in Figure 9, the LP2992AIM5-3.3 is rated for a maximum input voltage of 16 V and a load current of 250 mA. Therefore, the input voltage can be clamped at a voltage of 6 V through the Zener diode. It is important to size the Zener diode for the right power requirement.

In the worst-case scenario (when the load current is zero) the maximum current for the capacitive-drop power supply is being passed through the Zener diode. The power dissipation in the Zener diode will be the Zener voltage multiplied by the rated output current of the power supply. Thus, higher the Zener voltage, the higher is the power rating of the supply which generates more heat in the Zener diode.

$$P_{ZENER,MAX} = V_{ZENER} I_{OUT,MAX} \tag{14}$$

It is critical to note the thermal properties of the Zener diode to ensure it meets desired performance at the temperature during its operation. If necessary, the Zener power dissipation can be reduced by using multiple Zener diodes in series, but this comes at the cost of increased part count and board space.

A bulk electrolytic capacitor of 220 µF is used to hold the 6 V with low ripple voltage. Keeping the ripple voltage on the intermediate rail low also helps keep the output voltage ripple low. Having enough bulk capacitance is also important to maintain enough voltage at the input of the voltage regulator in case of a fast load transient at the output of the LDO.

2.4.5 Design Considerations for Surge

Since this power converter is connected to the AC mains, it has to withstand voltage surges and transients in some of the applications. The input stage consists of fusible resistance and varistor. The input resistance, RF1, provides two important functions:

- Acts as a fuse in case of any short in the power supply
- Controls the inrush current going into the bulk capacitor

Flame proof and film type resistance or WWR surge resistance is recommended since this design must be able to perform these two functions. For designs up to 2 W of output power, 8.2–10 Ω, 3 W is recommended for RF1.

Regulation IEC 61000-4-5 defines the surge immunity test as high-power spikes are caused by large inductive devices in mains. The input of the power supply is coupled to a short duration (1.2/50 µs) but high voltage (up to 4 kV) pulse. The surge pulse causes high inrush current, quickly charging the storage capacitor in a standard power supply. The major risk is then overvoltage and inrush current that can damage the input components - rectifier diode, fusible resistance in series in the input section, and so forth.

Typically, the varistor is used to absorb part of the energy and clamps the voltage across it to protect the rest of the circuit. Since the input AC voltage can go as high as 265 VAC, a 320 VAC, 14-mm varistor, RV1, is recommended for the design for surges up to the 4-kV level. If the application requires surge immunity up to higher levels, then choose appropriate values and an appropriate diameter of the varistor along with the input resistance.

3 Hardware, Software, Testing Requirements, and Test Results

3.1 Required Hardware

This section provides information on evaluating this reference design for functional and performance testing. Designers can set up this platform to compare different powering architectures for the performance metrics such as line and load regulation, efficiency, BOM and surge tests for the required specifications and load profiles.

3.1.1 Hardware

The following setup is required for the functional testing of the TIDA-010060:

- Tested TIDA-010060 board
- Programmable AC voltage source capable of varying between 85 V to 265 V and a frequency of 50 Hz and 60 Hz
- Electronic load for testing the power supply output (3.3 V and up to 100 mA)
- Digital multimeter for measuring the DC or AC voltages with true RMS measurements
- Digital oscilloscope for capturing startup and shutdown time
- Power analyzer for input AC current and power measurement

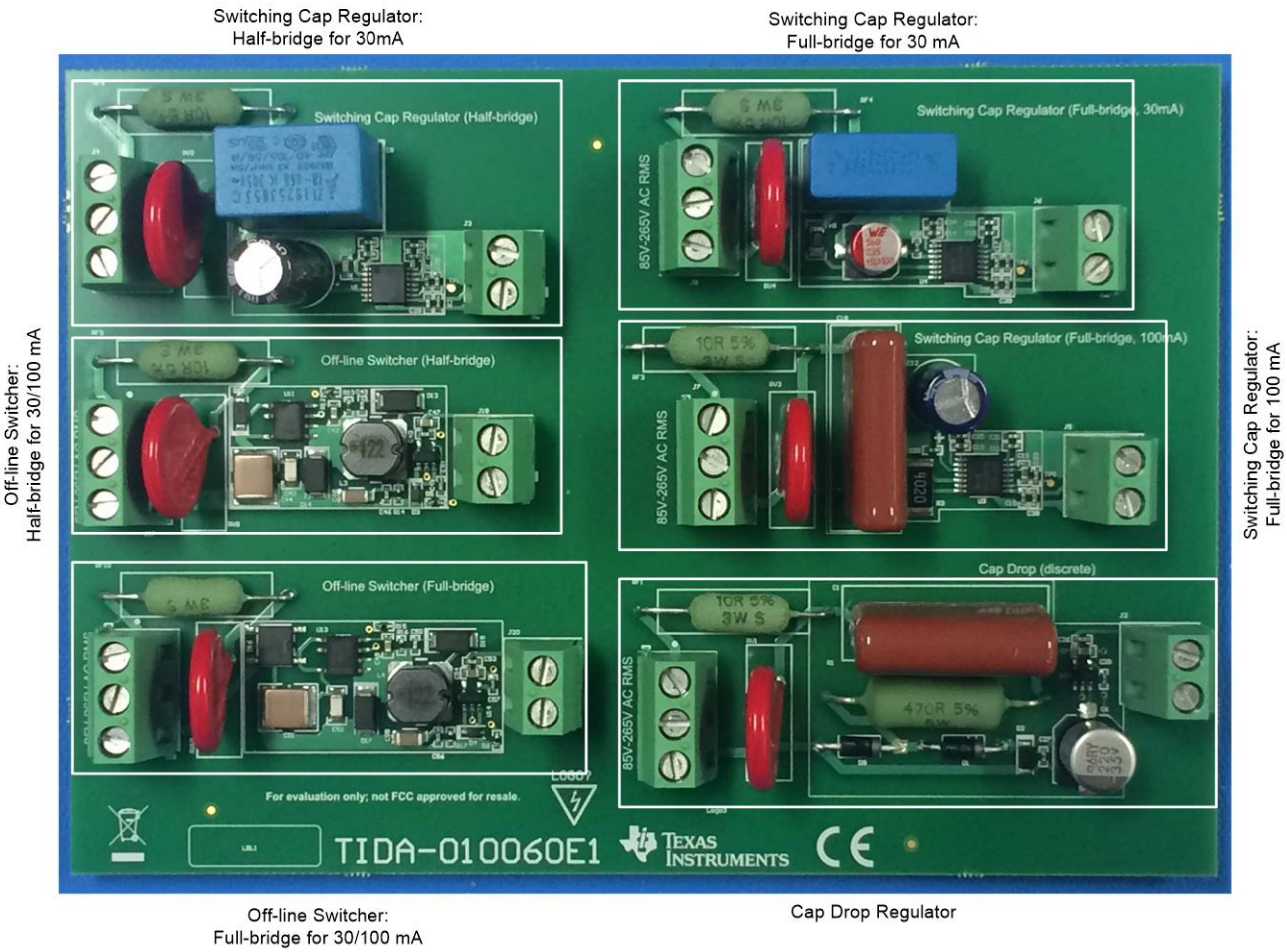
3.2 Testing and Results

Figure 10 shows the board layout for the TIDA-010060 used for testing and validating its performance. The board is sectionalized based on the implementations of various architectures and output current levels. Individual connectors are provided for plugging AC voltage source and DC output to the corresponding sections.

The test board has the following configurations and results are captured for these six variants:

- Off-line switcher: Half-bridge, full-bridge configurations for 100 mA
- Switch-cap regulator: Full-bridge configuration for 100 mA (Half-bridge maximum load support is only up to 60 mA)
- Switch-cap regulator: Half-bridge, full-bridge configuration for 30 mA
- Cap-drop regulator: Half-bridge configuration for 30 mA

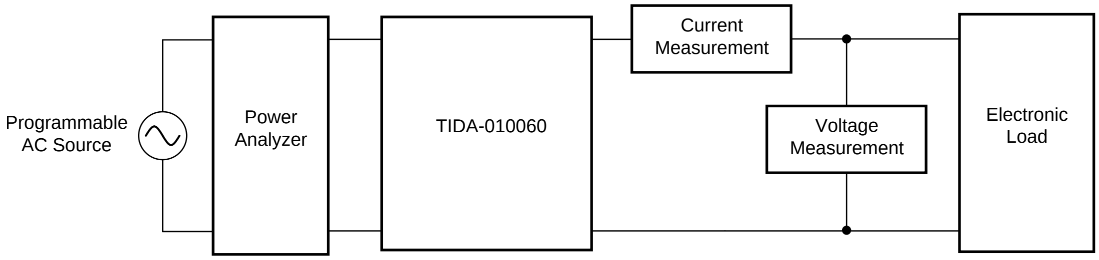
Figure 10. TIDA-010060 Board Setup



3.2.1 Test Setup

Figure 11 shows the test setup used for evaluating and comparing three different architectures. A programmable AC source is used which can be used to sweep the input voltage between 85 VAC to 265 VAC along with 50-Hz and 60-Hz variation. A converter is loaded using an electronic load where output current can be accurately varied between 0 to 100 mA. For capturing efficiency, input power is measured using a power analyzer, output power is calculated from the output voltage, and output current is measured through two multimeters.

Figure 11. Test Setup



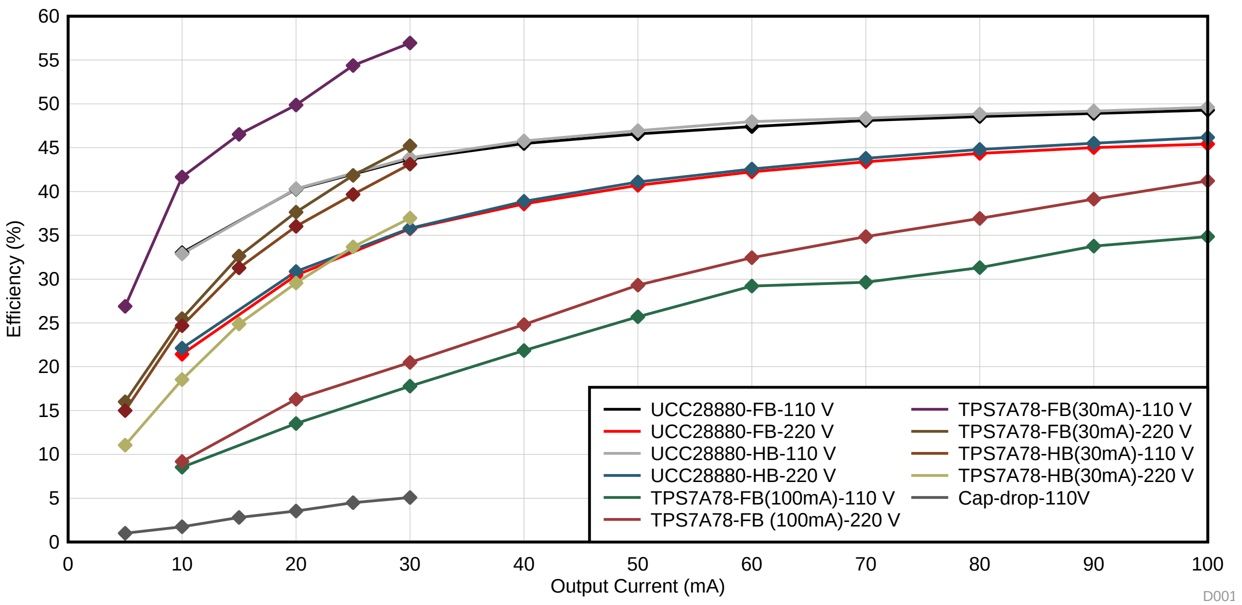
3.2.2 Test Results

This section provides details of the functional and performance tests done with the TIDA-010060 reference design and observations made from the results.

3.2.2.1 Efficiency

Figure 12 shows the efficiency for the three architectures.

Figure 12. Efficiency Across Load Variations for Different Architectures



The efficiency of the discrete cap-drop regulator for 110 VAC input while sweeping the output current from 5 mA to 30 mA is in the range of 1–5%. Most of the power is dissipated in series resistor R_S, and a Zener diode which results in poor efficiency of the converter. There is a standby power loss of 1.8 W which is present independent of the load requirement.

In the case of the off-line switcher using the UCC28880 device, efficiencies for full-bridge and half-bridge configurations are similar for the given line voltage. Efficiencies are in the range of 40–50% (for 20-mA to 100-mA load currents) and it is higher for 110-V input as compared to 220 V.

For switch-cap line regulator in half-bridge mode, the efficiency is in the range of 15-45%. R_S of 82 Ω and 150 Ω are used for 110-V and 220-V inputs, respectively. Losses in R_S are going to be higher for 220 V, resulting in lower efficiency. Efficiency boosts above 50% for the same power level in the case of full-bridge configuration. Full-bridge configuration is efficient as compared to half bridge, since a lower value of C_S is needed for the same output current which reduces the standby current consumption.

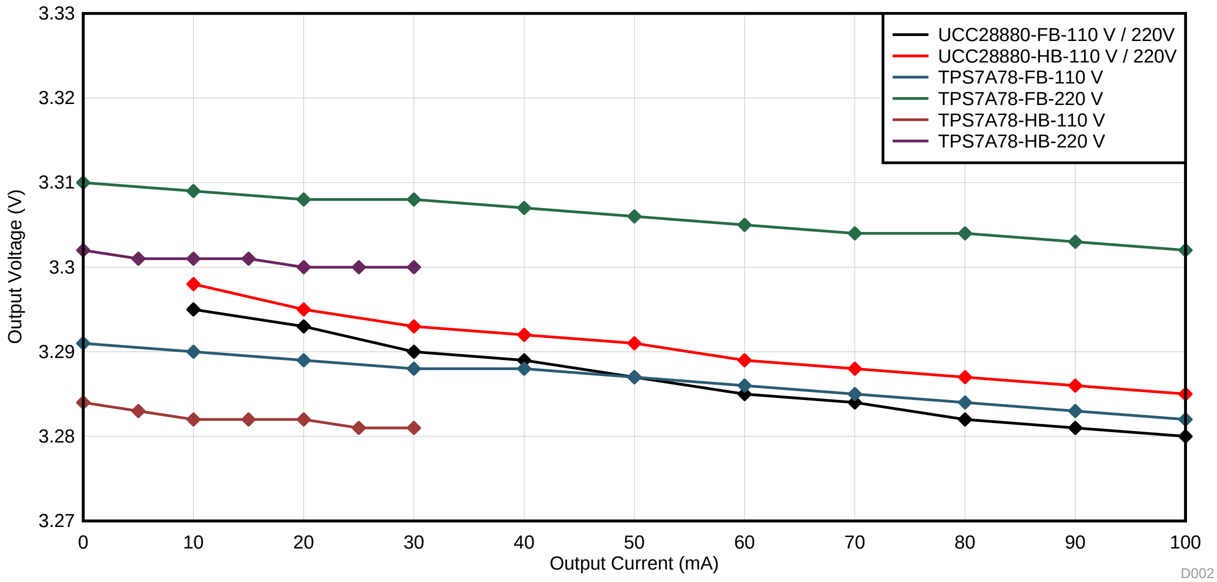
For a 100-mA design, the efficiency for the switch-cap line regulator has a peak efficiency of 41% at full load condition with a standby power loss of 335 mW.

3.2.2.2 Load Regulation

In this section, load regulations are shown for all the configurations in Figure 13.

A load regulation of 15 mV and 13 mV are obtained for the off-line switcher configured in full bridge and half bridge, respectively. Output voltages are independent of input line voltage. The TPS7A78 device has an internal voltage regulator which provides stable output and eliminates the need for external LDO. For half-bridge, a load regulation of 2 mV is obtained for 0–30 mA variation. Similarly, for full-bridge, the load regulation is found to be less than 10 mV.

Figure 13. Load Regulation for Different Architectures



3.2.2.3 Startup Time

To capture the startup time, an oscilloscope is probed on to the input voltage and output voltage. The time taken between the start of AC voltage and the instant when the output voltage reaches the nominal value is measured.

Figure 14. Startup Time for Half-bridge Cap-Drop Regulator

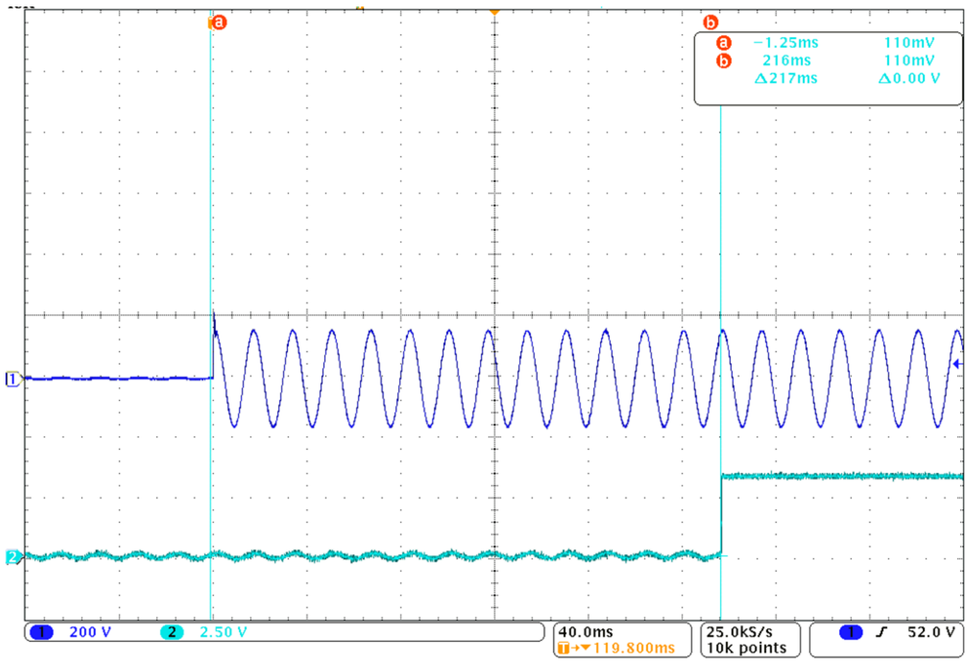


Figure 14 shows the startup time for the cap-drop regulator when 110 Vac is applied. It has the largest startup time of 350 ms to reach from 0 to 3.3 V.

The off-line switching regulator has the fastest startup of all with less than 1.5 ms as the full-bridge configuration in Figure 15 shows. However, in the case of half-bridge configuration, the startup delay is dependent on the angle at which input voltage is at the startup. It is going to start within 1.5 ms from the raising zero crossing of the line voltage as Figure 16 shows. Hence, it could be as long as 11.5 ms if the input voltage is at falling zero crossing when the supply is powered.

Figure 15. Startup Time for Full-Bridge Off-Line Switcher

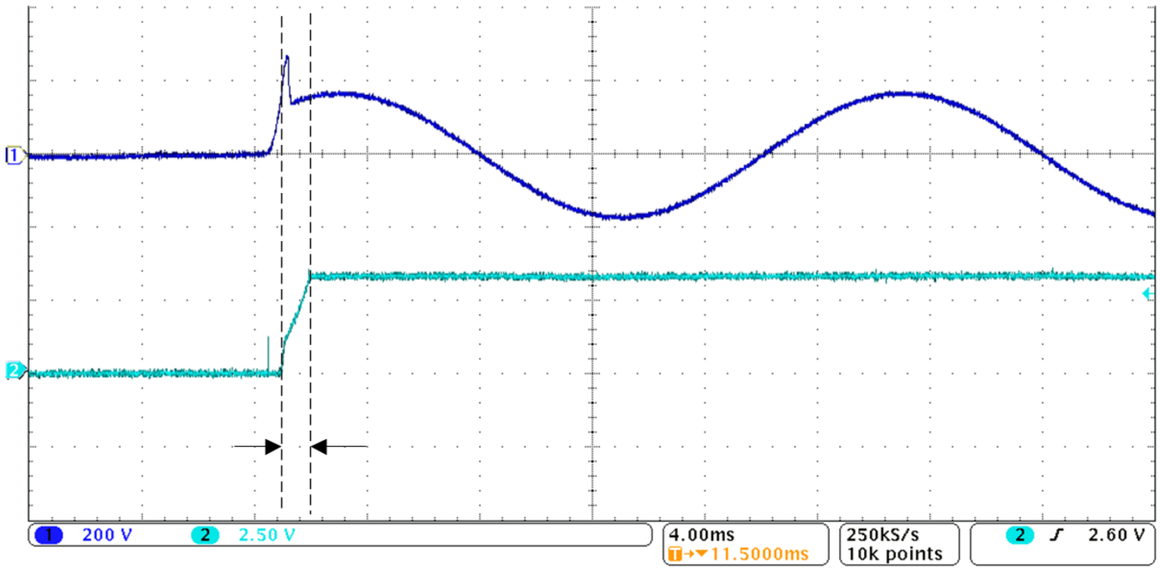
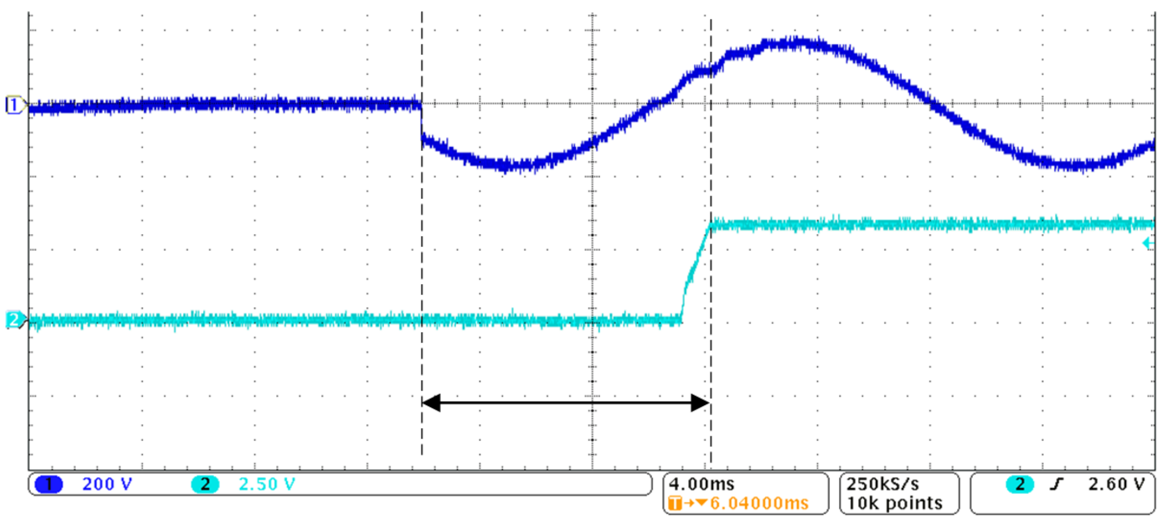


Figure 16. Startup Time for Half-Bridge Off-Line Switcher



In the case of switch-cap regulator, startup time depends mainly on the passive elements around TPS7A78 since all the capacitors need to be charged to the specific value to start generating output voltage. Figure 17 and Figure 18 shows startup of the half-bridge and full-bridge configurations for the values mentioned in the Section 2.4.3. The half-bridge has more than two times the startup time as the full-bridge since it rectifies the input voltage in only half of its cycle.

Figure 17. Startup Time for Half-Bridge Switch-Cap Regulator

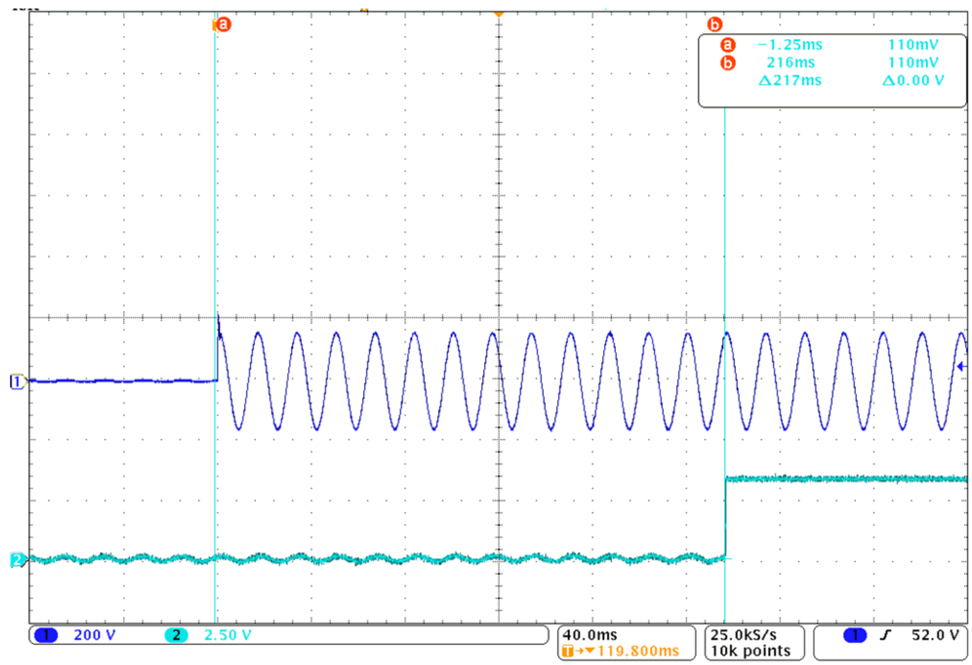
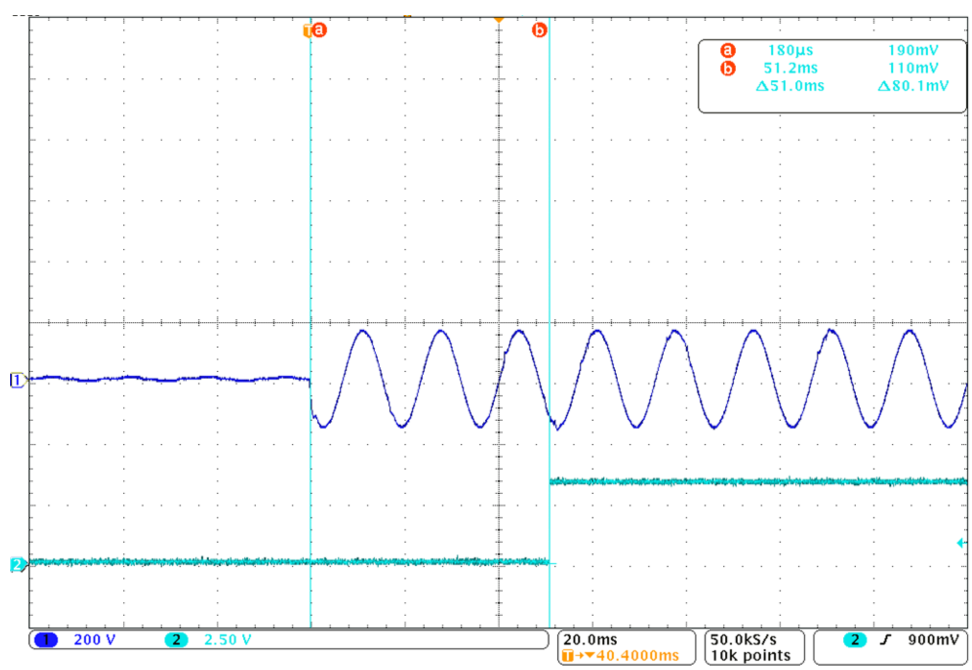


Figure 18. Startup Time for Full-Bridge Switch-Cap Regulator



3.2.2.4 Solution Footprint

Table 4 shows the overall solution size in inch^2 for different architectures. Cap-drop has the largest footprint of all, with cap-drop capacitor and resistor occupying most of the size. For an off-line switcher using the UCC28880 device, full-bridge configuration needs an external rectifier as compared to half-bridge which increases its area size while comparing with the switch-cap regulator of a similar rating.

Table 4. Board Area (in inch^2) for Different Power Conversion Architectures

	OFF-LINE SWITCHER (UCC28880)		SWITCH-CAP REGULATOR (TPS7A78)		CAP-DROP REGULATOR
	HALF-BRIDGE	FULL-BRIDGE	HALF-BRIDGE	FULL-BRIDGE	HALF-BRIDGE
30 mA	0.543	0.706	0.757	0.636	1.559
100 mA	0.643	0.806	-	0.766	-

3.2.3 Summary

3.2.3.1 Recommendations

Is the input voltage range universal?

If the input voltage range is universal, then off-line switching regulator architecture is recommended since efficient single configuration can be designed to meet across the wide input voltage range. A switched-cap regulator is going to have lower efficiency for a wide input range since C_S and R_S are designed for lowest input voltage and highest input voltage, respectively.

Is the output current more than 30 mA?

An off-line switcher is recommended for more than 30-mA load current if faster startup and higher efficiency is needed for the application. This has higher efficiency for > 30 mA as compared to a switched-cap regulator. If the application demands immunity to magnetic interference, then a switched-cap regulator is preferred. For lower current designs such as < 30 mA, a switched-cap regulator is going to be much more efficient than an off-line switcher.

Is faster startup needed?

If the application requires a faster startup such as 1 ms to 2 ms, then an off-line switcher is recommended as a switched-cap regulator has more than 2–3 times the cycle startup time.

4 Design Files

4.1 Schematics

To download the schematics, see the design files at TIDA-010060.

4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-010060.

4.3 PCB Layout Recommendations

4.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-010060.

4.4 Altium Project

To download the Altium Designer® project files, see the design files at TIDA-010060.

4.5 Gerber Files

To download the Gerber files, see the design files at TIDA-010060.

4.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-010060.

5 Software Files

To download the software files, see the design files at TIDA-010060.

6 Related Documentation

1. Texas Instruments, *UCC28880 700-V Lowest Quiescent Current Off-Line Switcher*
2. Texas Instruments, UCC2888x Diode Selection When Configured as a High-Side Buck
3. Texas Instruments, Operating UCC2888x Offline Buck in Saturation for Cost Reduction
4. Texas Instruments, UCC28880, UCC28881 Audible Noise Reduction Techniques
5. Texas Instruments, TPS7A78 120-mA, smart AC/DC linear voltage regulator
6. Texas Instruments, LP2992 Micro-power 250-mA Low-Noise Ultra-Low-Dropout Regulator
7. Texas Instruments, Improved Load Current Capability for Cap-Drop Off-Line Power Supplies for E-Meter Using the TPS5401

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7.1 Acknowledgments

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1. Work Area Safety:
   a. Keep work area clean and orderly.
   b. Qualified observer(s) must be present anytime circuits are energized.
   c. Effective barriers and signage must be present in the area where the TI HV EVM and its interface electronics are energized, indicating operation of accessible high voltages may be present, for the purpose of protecting inadvertent access.
   d. All interface circuits, power supplies, evaluation modules, instruments, meters, scopes, and other related apparatus used in a development environment exceeding 50Vrms/75VDC must be electrically located within a protected Emergency Power Off EPO protected power strip.
   e. Use stable and non-conductive work surface.
   f. Use adequately insulated clamps and wires to attach measurement probes and instruments. No freehand testing whenever possible.
2. Electrical Safety:

   As a precautionary measure, it is always good engineering practice to assume that the entire EVM may have fully accessible and active high voltages.

   a. De-energize the TI HV EVM and all its inputs, outputs and electrical loads before performing any electrical or other diagnostic measurements. Revalidate that TI HV EVM power has been safely de-energized.
   b. With the EVM confirmed de-energized, proceed with required electrical circuit configurations, wiring, measurement equipment hook-ups and other application needs, while still assuming the EVM circuit and measuring instruments are electrically live.
   c. Once EVM readiness is complete, energize the EVM as intended.

WARNING

While the EVM is energized, never touch the EVM or its electrical circuits, as they could be at high voltages capable of causing electrical shock hazard.

3. Personal Safety
   a. Wear personal protective equipment e.g. latex gloves or safety glasses with side shields or protect EVM in an adequate lucent plastic box with interlocks from accidental touch.

Limitation for safe use:

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