

# Cap Drop Offline Supply for E-Meters

Akshay Mehta, Frank De Stasi

## ABSTRACT

This design idea provides a simple non-isolated AC/DC power supply for low power applications such as smart grid E-meter applications. The design uses a "capacitive-dropper" front-end combined with a LM46000 SIMPLE SWITCHER® buck regulator from Texas Instruments. The circuit provides 3.3 V at a minimum of 50 mA from a line supply of 90 VAC to 265 VAC. Theory of operation as well as design equations and performance results are given.

## Contents

|   |                                    |   |
|---|------------------------------------|---|
| 1 | Introduction .....                 | 1 |
| 2 | Theory of Operation .....          | 3 |
| 3 | Application Circuit and Plots..... | 5 |
| 4 | Conclusion .....                   | 9 |

## List of Figures

|   |   |   |
|---|---|---|
| 1 | Basic Schematic .....                                 | 2 |
| 2 | Voltage and Current Waveforms.....                    | 3 |
| 3 | Voltage Ripple at $V_{DC}$ .....                      | 6 |
| 4 | Application Schematic.....                            | 6 |
| 5 | Load Regulation.....                                  | 7 |
| 6 | Max Output Current vs Line Voltage .....              | 8 |
| 7 | Line Current Vs Line Voltage.....                     | 8 |
| 8 | Actual Power and Apparent Power Vs Line Voltage ..... | 9 |

## List of Tables

|   |                                |   |
|---|--------------------------------|---|
| 1 | Application Requirements ..... | 6 |
|---|--------------------------------|---|

## 1 Introduction

Many times a simple off-line power supply is required for low power applications such as E-meters. 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, and/or complexity. A better option is shown in [Figure 1](#).

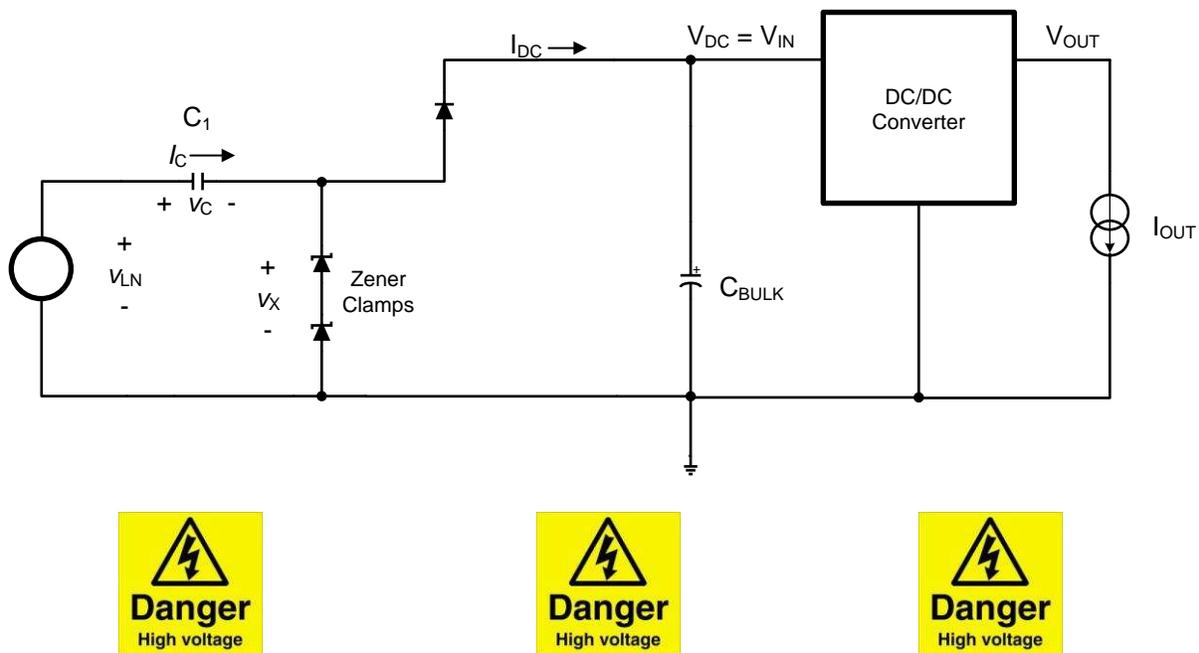


Figure 1. Basic Schematic

Here we first convert the line voltage to an intermediate unregulated DC rail ( $V_{DC}$ ) and then use a Wide  $V_{IN}$  range DC/DC converter to supply the load. The front-end is the well-known "capacitive-dropper". The Zener diodes clamp the input voltage to the DC/DC converter under no-load conditions. The input voltage to the DC/DC converter ( $V_{DC} = V_{IN}$ ) is set to a relatively high value, so that the current required from the "capacitive-dropper" can be kept low. For this design we use the [LM46000](#) as the DC/DC converter and  $V_{DC}$  is set to 48 V. The LM46000 converts this down to 3.3 V. For a line voltage range of 90 VAC to 265 VAC, this design can supply at least 50 mA to the 3.3 V load. The high step-down ratio, possible with the LM46000, allows the 50 mA load to appear as less as 5 mA load to the DC/DC. This permits a small value of  $C_1$  to be used. See also [SNVA733](#).

It is easy to see that this circuit is connected directly to the line supply and is not isolated. **EXTREME CAUTION** must be used when experimenting with this design. The user must ensure that the intended application for this power supply, including the load on the LM46000, is completely isolated from any contact with grounded entities; including people, animals and test equipment. All safety precautions must be observed when taking measurements. Test equipment with grounded inputs can not be used with this circuit without proper isolation. The user is also responsible for any fusing, transient protection, and/or EMI filtering required on the input to this circuit.

## 2 Theory of Operation

The idea behind this circuit is that the series capacitor  $C_1$  acts as a lossless resistance and the reactance of the capacitor will set the maximum current that can be provided. Since a normal electrolytic capacitor cannot handle the stresses resulting from the line voltage, we use "X"-type capacitors which would be rated for the maximum line voltage in our range. From Figure 1 we can understand that the current  $i_C$  through the cap  $C_1$  would be flowing when there is a voltage differential across the capacitor. The capacitor current would steadily increase while  $v_{LN}$  is increasing. When the line voltage reaches the peak voltage,  $C_1$  stops charging, because the slope of the differential voltage across it goes to zero. Figure 2 shows the relevant waveforms; where we have the following definitions:

$v_{LN}$  = line voltage

$v_C$  =  $C_1$  voltage

$i_C$  =  $C_1$  current

$v_X$  = Voltage at input of bridge rectifier

$V_{LN}$  = RMS line voltage

$V_{DC} = V_{IN}$  = DC intermediate bus voltage and input voltage to DC/DC

$V_{OUT}$  = Output voltage of DC/DC

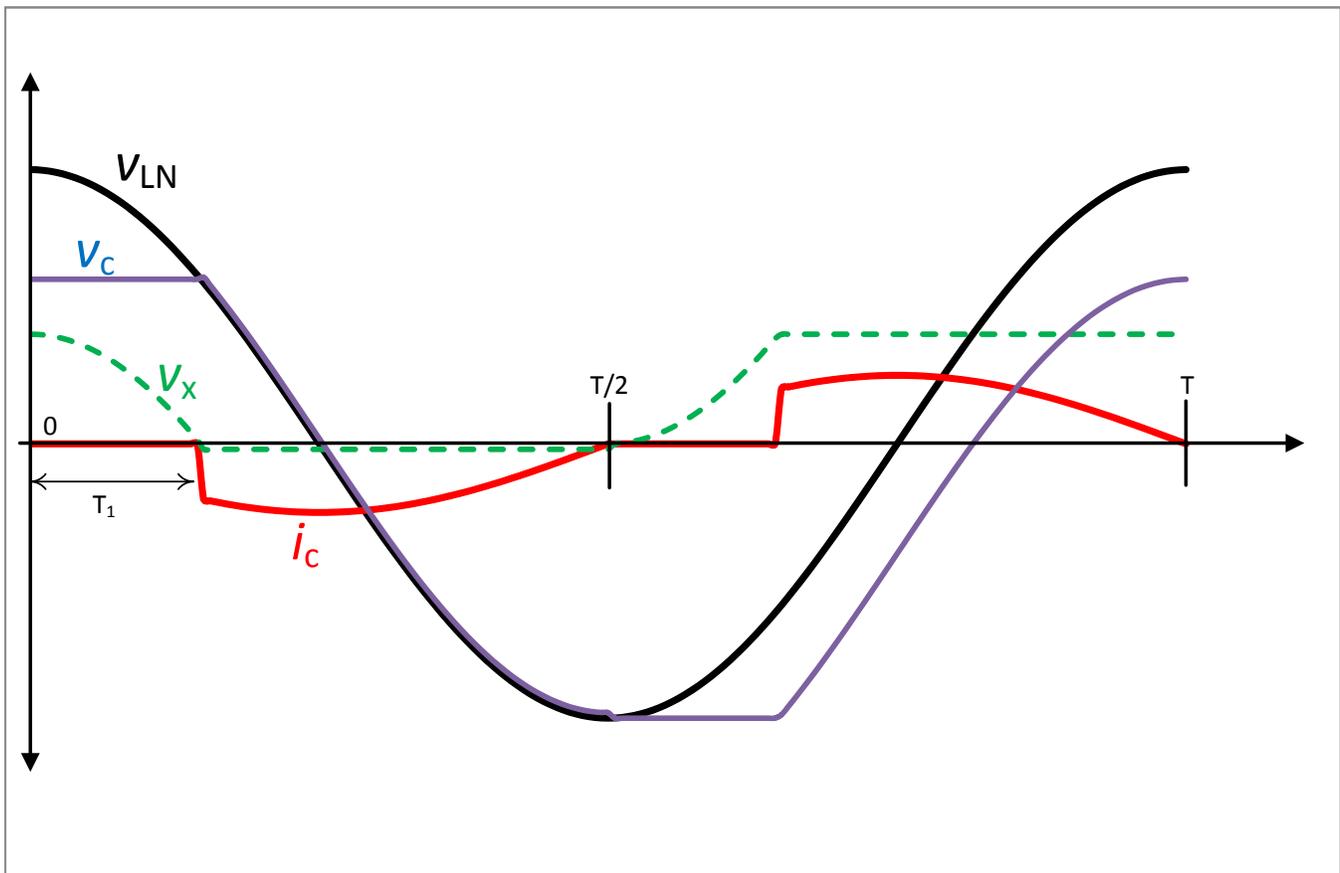
$I_{OUT}$  = Output current of DC/DC = user load current

$V_D$  = One diode drop

$F$  = line frequency =  $1/T$

$\eta$  = Efficiency of LM46000

$T_1$  = Time during which the diode is forward biased.



**Figure 2. Voltage and Current Waveforms**

The peak capacitor current can be obtained as follows:

$$I_P = 2\pi \cdot F \cdot C_1 \cdot V_{LN} \cdot \sqrt{2} \quad (1)$$

Where,

$I_P$  = Peak  $C_1$  current

In the half wave implementation of the capacitive dropper circuit, the diode D1 will be turned off during the negative half cycle of the line voltage. During that time the Zener diode will act as a regular diode and will allow current flow. During the positive half cycle, the Zener diode will clamp the line voltage which is held by the bulk capacitor. Since the negative half cycle of the line voltage is completely ignored, the current delivered to the DC/DC regulator would be half that of the full wave implementation. E-Meter applications using the cap drop implementation have an upper limit on the apparent power being pulled from the mains. This app note uses 8 VA as the upper limit. The approximate value of capacitor  $C_1$  can be obtained from that relationship as shown:

$$C_1 \cong \frac{VA}{2\pi \cdot F \cdot V_{LN}^2}$$

where

- $VA = V_{RMS} \cdot I_{RMS}$  (2)

At time  $T_1$  the Zener conducts current in the opposite direction acting as a regular diode. From observing the waveforms in [Figure 2](#), we can evaluate time  $T_1$  as follows:

$$T_1 = \frac{1}{2\pi \cdot F} \cdot \cos^{-1} \left( 1 - \frac{(V_{DC} + V_D)}{V_{LN} \cdot \sqrt{2}} \right) \quad (3)$$

$I_{RMS}$  is the AC current flowing through the  $C_1$  capacitor. Substituting that and using the time  $T_1$  we can calculate a more accurate equation for capacitor  $C_1$  as shown:

$$C_1 = \frac{VA}{2 \cdot \sqrt{2} \cdot F \cdot \pi \cdot V_{LN}^2 \cdot \sqrt{0.5 - T_1 \cdot F + \frac{1}{4\pi} \cdot \sin(4\pi \cdot T_1 \cdot F)}} \quad (4)$$

Since the value of  $C_1$  is limited, the max current that can be delivered to the input of the DC/DC regulator will also be limited. It is shown as follows:

$$I_{MAX} = 2 \cdot \sqrt{2} \cdot F \cdot C_1 \cdot V_{LN} \cdot \left( 1 - \frac{V_{DC}}{2 \cdot \sqrt{2} \cdot V_{LN}} \right) \quad (5)$$

### 3 Application Circuit and Plots

#### WARNING

**CAUTION MUST BE USED IN THE CONSTRUCTION, TESTING, AND USE OF THE CIRCUITS FOUND IN THIS DOCUMENT.**

**LETHAL VOLTAGES ARE PRESENT IN THESE CIRCUITS THAT MAY CAUSE INJURY.**

**THE USER MUST ENSURE THAT SAFETY PROCEDURES ARE FOLLOWED WHEN WORKING ON THESE CIRCUITS.**

Let's look over some BOM calculations for the capacitor dropping circuit.

#### 3.1 *Dropping Capacitor*

The dropping capacitor  $C_1$  is sized for the lowest line voltage thus ensuring that the load current is maintained even at the worst case. For our design requirements and from [Equation 4](#) the cap  $C_1$  is sized to be about 0.39  $\mu\text{F}$  rated for 375 VAC. Care must be taken to not oversize this capacitor. Oversizing this capacitor would increase the apparent power drawn from the mains. This capacitor must be rated for the highest peak line voltage.

#### 3.2 *Zener Diodes*

In the half wave implementation as shown in the schematic, The LM46000 is rated for a maximum input voltage of 60 V and a load current of 500 mA. Therefore  $V_{\text{DC}}$  can be clamped at a high voltage of 48 V. The Zener voltage established  $V_{\text{DC}}$ . As shown in the schematic two Zener diodes of 24 V each have been used in series to obtain a clamping voltage of 48 V. It is important to size the Zener diodes for the right power requirement.

In this implementation, the Zener current will be equal to the  $I_{\text{MAX}}$  current. At higher line voltages, the  $I_{\text{MAX}}$  increases and so does the Zener current. The power dissipating in the Zener will be a product of  $I_{\text{MAX}}$  and  $V_{\text{DC}}$ .

#### 3.3 *Bulk Capacitor*

A bulk electrolytic capacitor of 680  $\mu\text{F}$  is used to hold the 48 V with low ripple voltage. Keeping the ripple voltage on the intermediate rail low will also help with keeping the output voltage ripple low. Having enough bulk capacitance is also important to maintain enough voltage at the input of converter in case of a fast load transient at the output of the converter. A range of 470  $\mu\text{F}$  to 680  $\mu\text{F}$  was tested to be appropriate. [Figure 3](#) shows the voltage ripple at the input of the LM46000. The 680  $\mu\text{F}$  cap results in about a 200 mV ripple at 60 Hz. Since the ripple at  $V_{\text{DC}}$  is at a relatively low frequency, it is important to keep the ripple low because it cannot be filtered effectively by the inductor and the output capacitor of the LM46000.

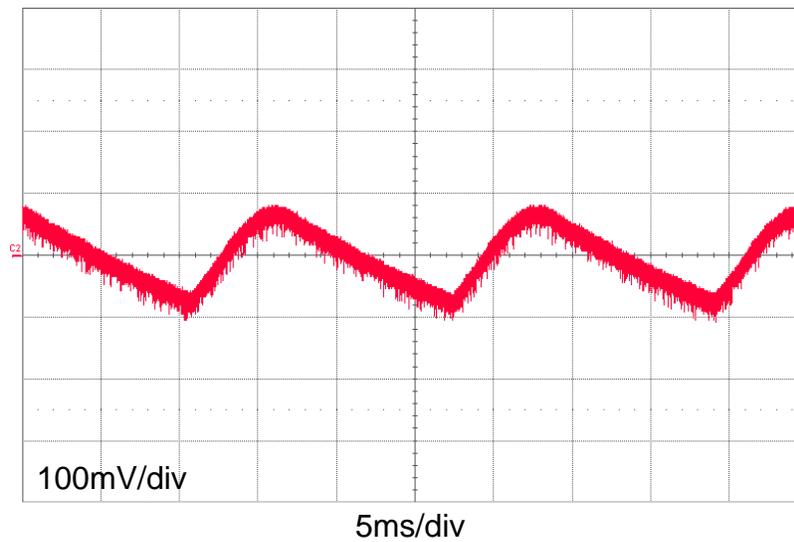


Figure 3. Voltage Ripple at  $V_{DC}$

The newly released LM46000 Wide  $V_{IN}$  DC/DC converter was interfaced with the "capacitive drop" front-end to obtain the schematic as shown in Figure 4.

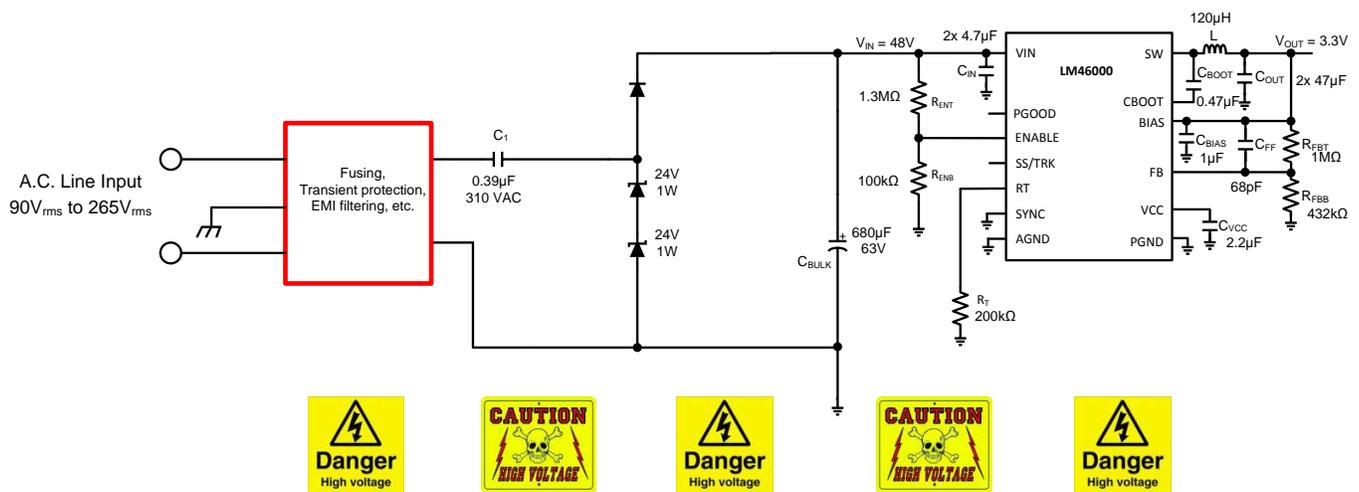


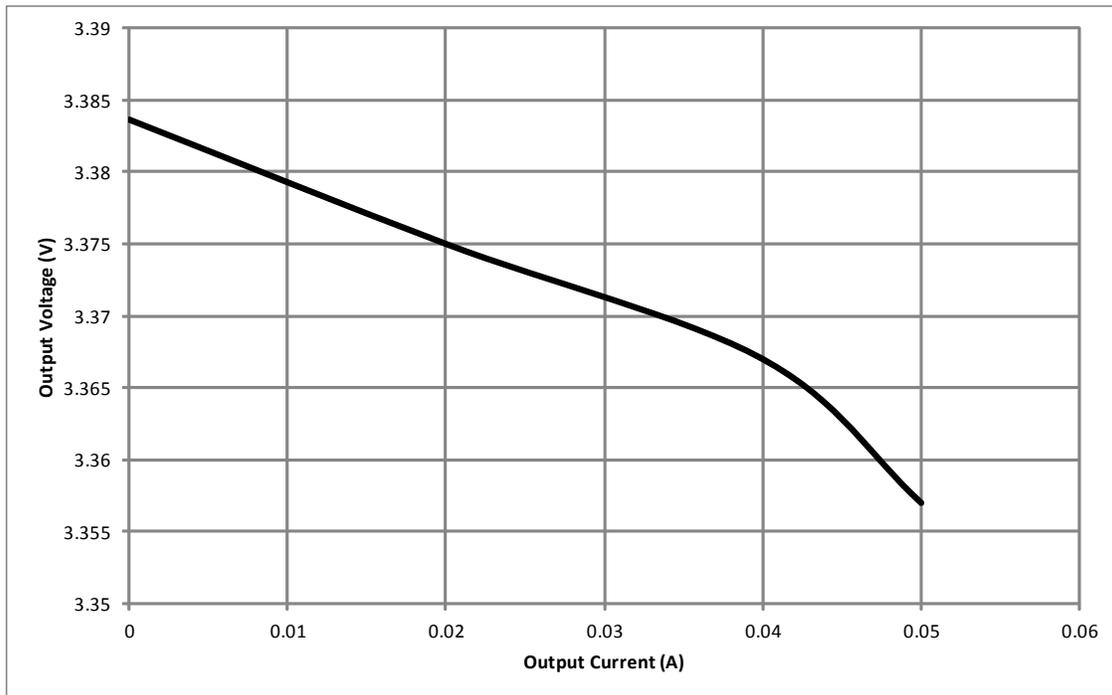
Figure 4. Application Schematic

Table 1. Application Requirements

| Parameter                      | Value             |
|--------------------------------|-------------------|
| $V_{LN}$                       | 90 VAC to 265 VAC |
| $V_{OUT}$                      | 3.3 V             |
| $I_{OUT}$                      | 50 mA at 120 VAC  |
| $\eta$ at 120 VAC and 50 mA    | 53 %              |
| $I_{RMS}$ from line at 120 VAC | 16.5 mA           |

The BOM for the [LM46000](#) can be calculated for  $V_{IN}$  of 48 V to  $V_{OUT}$  of 3.3 V. The design can be obtained from the datasheet for LM46000. The datasheet has detailed calculations for the entire BOM. The rising UVLO threshold on the LM46000 was set to about 30 V. This helps with limiting the inrush currents and potential voltage crash at the input of the converter. The resulting falling UVLO threshold is about 25 V.

For the application circuit shown in [Figure 4](#) load regulation test was performed at 120 VAC line voltage. At light loads, the LM46000 enters the PFM mode. In this mode the switching frequency is folded back to improve the efficiency. In PFM operation, a small positive DC offset is required at the output voltage to activate the PFM detector. This can be seen in [Figure 5](#). Please refer to the datasheet for more information.



**Figure 5. Load Regulation**

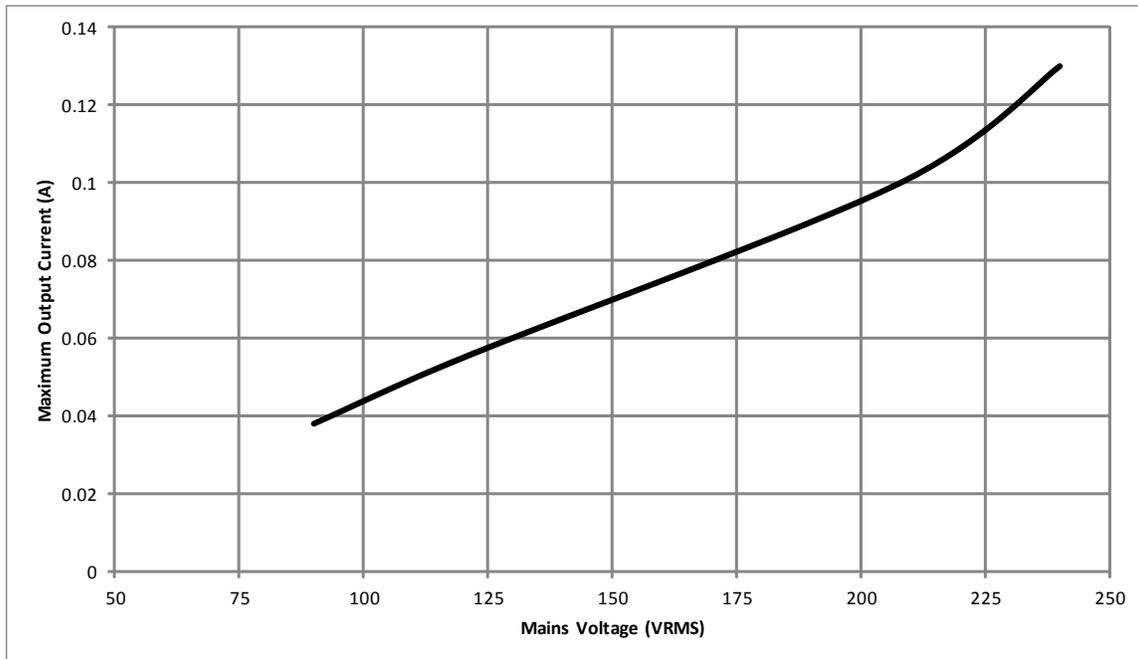


Figure 6. Max Output Current vs Line Voltage

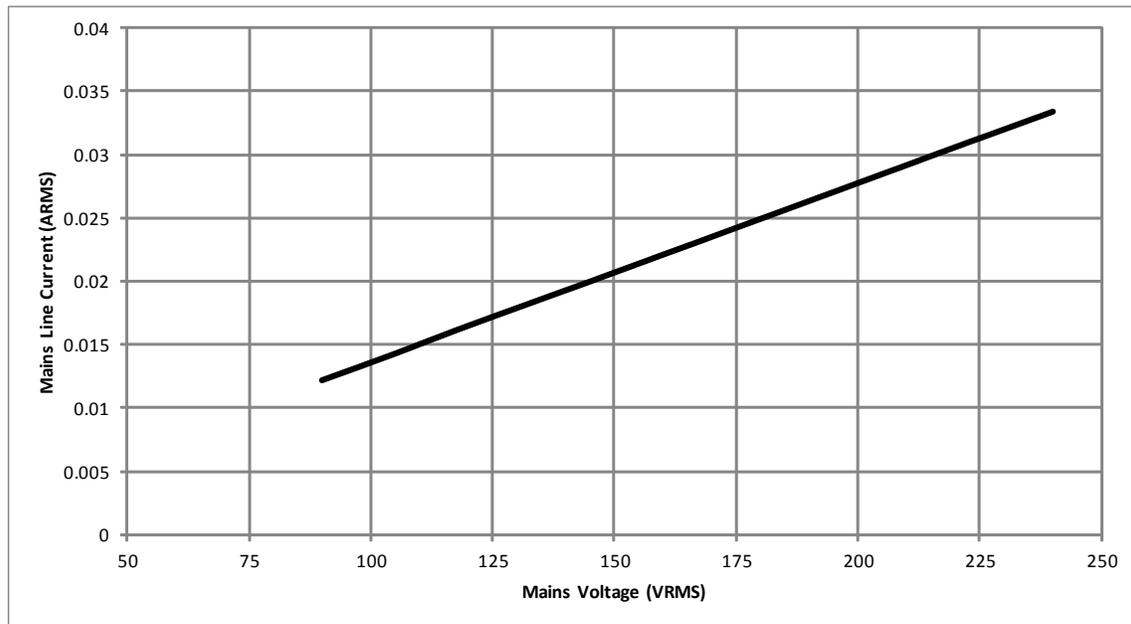


Figure 7. Line Current Vs Line Voltage

Because the capacitor  $C_1$  value is limited the max load that can be pulled is also limited. Figure 6 shows the chart for the max load current capability of the design. Figure 8 shows the actual power and the apparent power drawn from the mains for this design.

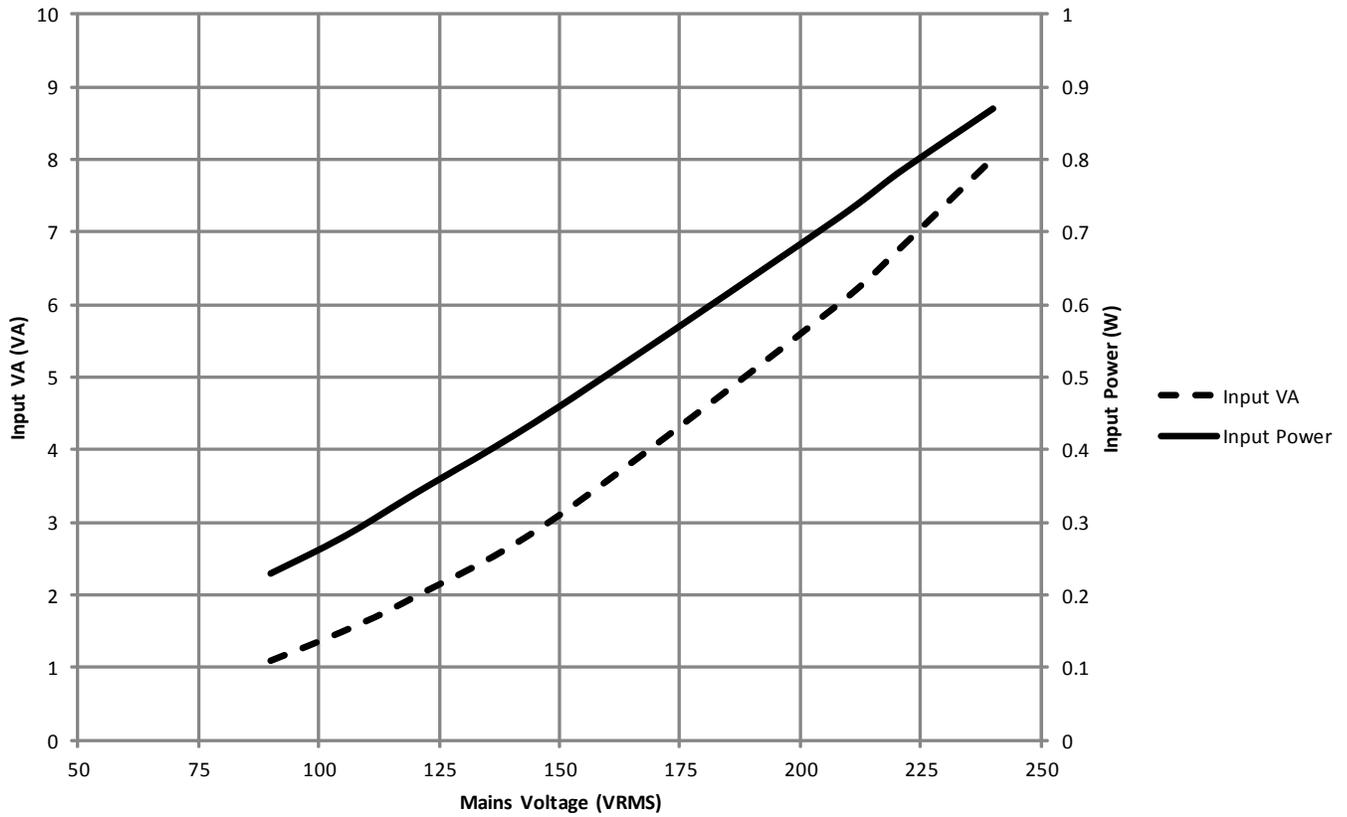


Figure 8. Actual Power and Apparent Power Vs Line Voltage

#### 4 Conclusion

The cap drop circuit is an easy cost effective approach for low load AC-to-DC conversion. Interfacing with a Wide  $V_{IN}$  DC/DC converter can be further useful to draw relatively higher loads at the output while keeping the current drawn from the line low. A maximum of 130 mA can be obtained from the output of the LM46000 at 240 VAC line voltage. While this circuit is easy to make, utmost care should be taken to create a bench prototype and appropriate filtering and protection circuit should be added.

## IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as "components") are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI's terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers' products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers' products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI's goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or "enhanced plastic" are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have **not** been so designated is solely at the Buyer's risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

### Products

|                              |  |
|------------------------------|--|
| Audio                        | <a href="http://www.ti.com/audio">www.ti.com/audio</a>                               |
| Amplifiers                   | <a href="http://amplifier.ti.com">amplifier.ti.com</a>                               |
| Data Converters              | <a href="http://dataconverter.ti.com">dataconverter.ti.com</a>                       |
| DLP® Products                | <a href="http://www.dlp.com">www.dlp.com</a>   |
| DSP                          | <a href="http://dsp.ti.com">dsp.ti.com</a>   |
| Clocks and Timers            | <a href="http://www.ti.com/clocks">www.ti.com/clocks</a>                             |
| Interface                    | <a href="http://interface.ti.com">interface.ti.com</a>                               |
| Logic                        | <a href="http://logic.ti.com">logic.ti.com</a>                                       |
| Power Mgmt                   | <a href="http://power.ti.com">power.ti.com</a>                                       |
| Microcontrollers             | <a href="http://microcontroller.ti.com">microcontroller.ti.com</a>                   |
| RFID                         | <a href="http://www.ti-rfid.com">www.ti-rfid.com</a>                                 |
| OMAP Applications Processors | <a href="http://www.ti.com/omap">www.ti.com/omap</a>                                 |
| Wireless Connectivity        | <a href="http://www.ti.com/wirelessconnectivity">www.ti.com/wirelessconnectivity</a> |

### Applications

|                               |  |
|-------------------------------|--|
| Automotive and Transportation | <a href="http://www.ti.com/automotive">www.ti.com/automotive</a>                         |
| Communications and Telecom    | <a href="http://www.ti.com/communications">www.ti.com/communications</a>                 |
| Computers and Peripherals     | <a href="http://www.ti.com/computers">www.ti.com/computers</a>                           |
| Consumer Electronics          | <a href="http://www.ti.com/consumer-apps">www.ti.com/consumer-apps</a>                   |
| Energy and Lighting           | <a href="http://www.ti.com/energy">www.ti.com/energy</a>                                 |
| Industrial                    | <a href="http://www.ti.com/industrial">www.ti.com/industrial</a>                         |
| Medical                       | <a href="http://www.ti.com/medical">www.ti.com/medical</a>                               |
| Security                      | <a href="http://www.ti.com/security">www.ti.com/security</a>                             |
| Space, Avionics and Defense   | <a href="http://www.ti.com/space-avionics-defense">www.ti.com/space-avionics-defense</a> |
| Video and Imaging             | <a href="http://www.ti.com/video">www.ti.com/video</a>                                   |

### TI E2E Community

[e2e.ti.com](http://e2e.ti.com)