AN2317
Application Note

STPM01 Programmable, Single-Phase Energy Metering IC External Circuits

Introduction

The STPM01 is implemented in an advanced 0.35µm BCD6 technology. It is designed for active, reactive, and apparent energy measurement, including Root Mean Square (V_{RMS} and I_{RMS}), instantaneous, and harmonic voltage and current.

This application note describes the STPM01 external circuits which are comprised of:

- a crystal oscillator,
- a power supply circuit,
- a voltage sensing circuit, and
- two current sensing circuits.

Note: *This document should be used in conjunction with the STPM01 datasheet.*

Contents

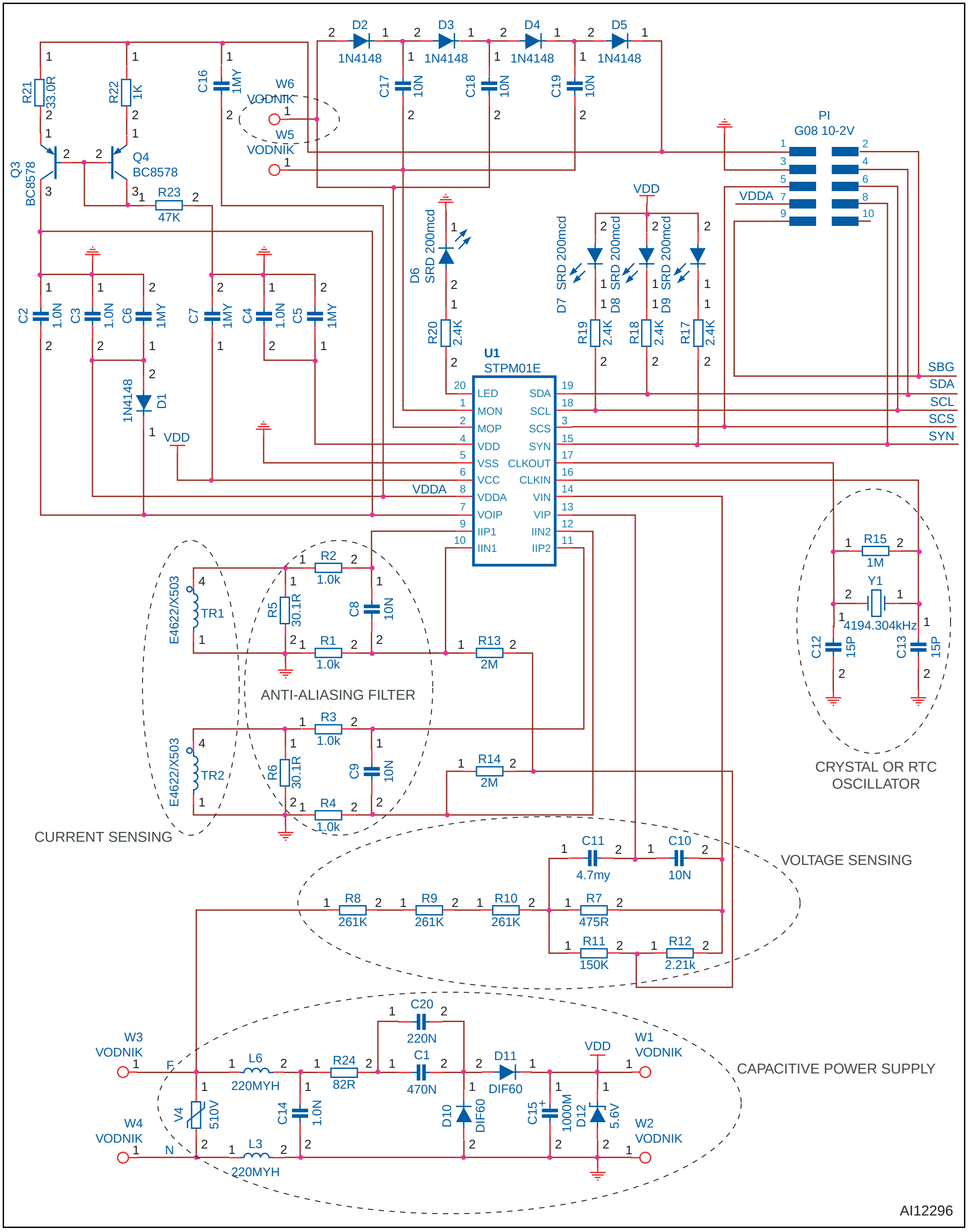
List of Figures

1 External Circuit Design

Figure 1 on page 5 shows an implementation example of the STPM01 in a simple Stepper Counter Connector design. The main external circuits include:

- a *Current Sensing Circuit*,
- an *Anti-aliasing Filter on page 11*,
- a *Voltage Sensing Circuit on page 15*,
- a *Capacitive Power Supply Circuit on page 18*, and
- a *Clock Generation on page 24* (RC oscillator, quartz, or external clock).

Figure 1. STPM01 External Circuit Schematics



1.1 Current Sensing Circuit

The STPM01 has two external current sensing circuits (see *Figure 1 on page 5*):

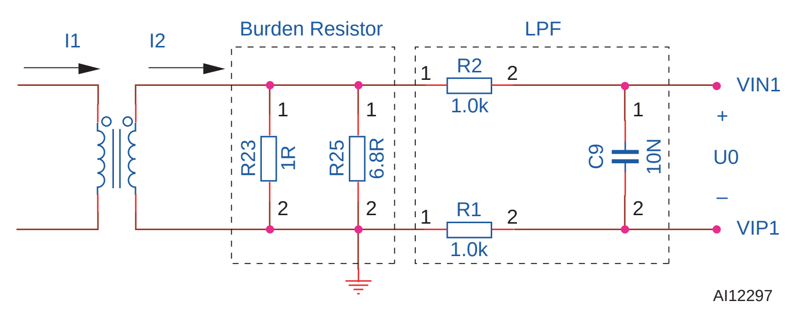
1. Primary channel, and
2. Secondary channel.

1.1.1 Primary Current Sensing

The primary channel uses a current transformer to couple the mains current (see *Figure 2*).

The Burden resistor is used to produce a voltage between V_{IN1} and V_{IP1}. The Low-pass filter (LPF) is used to filter out the high frequency interference and has little influence on the voltage drop between V_{IN1} and V_{IP1}.

Figure 2. Primary Current Sensing Circuit



Primary current sensing is calculated as follows:

Equation 1

$$I_2 = \frac{N_1}{N_2} \cdot I_1$$

Equation 2

$$U_0 \approx U_A = I_2 \cdot \frac{R_{23} \cdot R_{25}}{R_{23} + R_{25}} = \frac{N_1}{N_2} \cdot I_1 \cdot \frac{R_{23} \cdot R_{25}}{R_{23} + R_{25}}$$

Assuming I_{1PEAK}, the calculation will proceed as:

Equation 3

$$\frac{I_{1PEAK}}{I_{2PEAK}} = \frac{N_2}{N_1} = \frac{2000}{1}$$

Equation 4

$$I_{2PEAK} = \frac{I_{1PEAK}}{2000} = 3mA$$

Equation 5

$$U_{0PEAK} = U_{APEAK} = I_{2PEAK} \cdot \frac{R_{23} \cdot R_{25}}{R_{23} + R_{25}} = 2.6mV$$

The maximum differential input voltage between V_{IN1} and V_{IP1} is dependent on the Programmable Gain Amplifier (PGA) selection. For the purposes of this application, use 8x as the gain value, then $U_{0PEAK} = 0.15V$.

Equation 6

$$U_{APEAK} = U_{0PEAK} = 0.15V$$

Equation 7

$$I_{2PEAK} = U_{APEAK} \cdot \frac{R_{23} + R_{25}}{R_{23} \cdot R_{25}} = 172mA$$

Equation 8

$$I_{1PEAK} = 2000 I_{2PEAK} = 344A$$

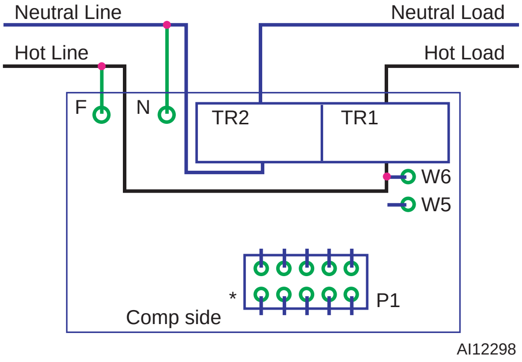
Equation 9

$$I_{1RMS} = \frac{I_{1PEAK}}{\sqrt{2}} = 243A$$

The primary current sensing circuit can be connected to mains as follows (see *Figure 3*):

1. The hot line voltage wire must be connected to pin F of the module.
   Normally, this wire is also connected to the hot line current wire. However, during production or to verify phases, this wire may be connected to some other line voltage source.
2. The neutral line voltage wire must be connected to pin N of the module.
   This wire is also connected to the neutral line current wire.
3. The hot line current wire must be placed through the current transformer TR1 hole (becoming the hot load wire).
   Use insulated 4mm^2 copper wire.
4. The neutral line current wire must be placed through the current transformer TR2 hole.
   Use insulated 4mm^2 copper wire.

Figure 3. Current Sense Transformer-to-Power Line Connections



1.1.2 Secondary current sensing

The secondary channel uses shunt resistor structure (see *Figure 4*). The 420µW shunt resistor is used to maximize the use of the dynamic range of the current sensing circuit. However, there are some important considerations when selecting a shunt structure for energy metering applications.

- The power dissipation in the shunt must be minimized.

  The maximum rated current for this design element is 20A, so the maximum power dissipated in the shunt is calculated as follows:

  $$(20\text{A})^2 \times 420\mu\Omega = 168\text{mW}$$

- The higher power dissipation may make it difficult to manage the thermal issues.

  Although the shunt is manufactured from manganin material, which is an alloy with a low thermal resistance, an apparent error may occur when it reaches a high temperature.

- The shunt should be able to resist the shortage of the phase circuit.

  This reduces the shunt resistance is much as possible.

  The design values used are:

  - Mains voltage = 220V_{RMS},
  - Ib = 2A, and
  - Shunt resistance = 420µΩ.

  The remaining design elements calculated from these values are as follows:

  - Voltage across shunt:

    $$2\text{A} \times 420\mu\Omega = 0.00084\text{V}$$

  - Mains power dissipation:

    $$220\text{V} \times 2\text{A} = 0.44\text{kW}$$

  - Error:

    $$1.68 \times 10^{-3} / 0.44 \times 10^{-3} \times 100\text{percent} = 0.0004\text{percent}$$

The secondary current sensing circuit can be connected to the mains as shown in *Figure 4*:

1. The hot line voltage wire must be connected to pin N of the module.

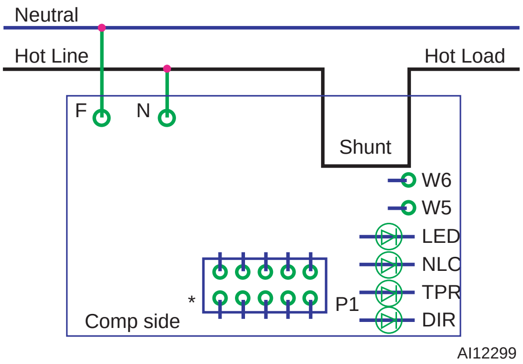
   Normally, this wire is also connected to the hot line current wire. However, during production or to verify phases, this wire may be connected to some other line voltage source.
2. The neutral line voltage wire must be connected to pin F of the module.

   This wire is also connected to the neutral line current wire, which passes by the module.
3. The hot line current wire must be connected to the Shunt pole which is close to pin N of the module.

   Use insulated 4mm^2 copper wire.
4. The hot load current wire must be connected to the Shunt pole which is close to the edge of the module.

   Use insulated 4mm^2 copper wire.

Figure 4. Shunt Module-to-Power Line Connections



1.2 Anti-aliasing Filter

The anti-aliasing filter (*Figure 5*) is a low-pass filter. It reduces high frequency levels which may cause distortion due to the sampling (aliasing) that occurs before the analog inputs of an analog-to-digital converter (ADC) are introduced into the application (see *Figure 6*). Filtering is easily implemented with a resistor-capacitor (RC) single-pole circuit which obtains an attenuation of –20dB/dec.

Figure 5. Anti-aliasing Filter

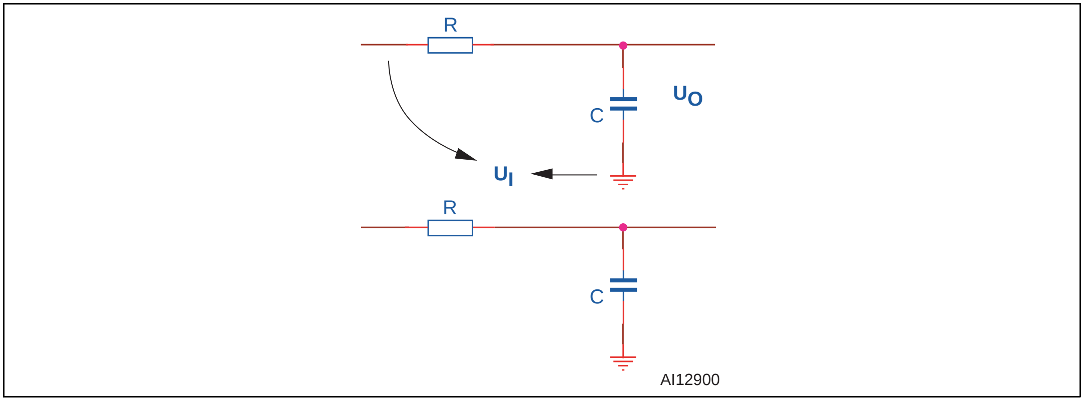
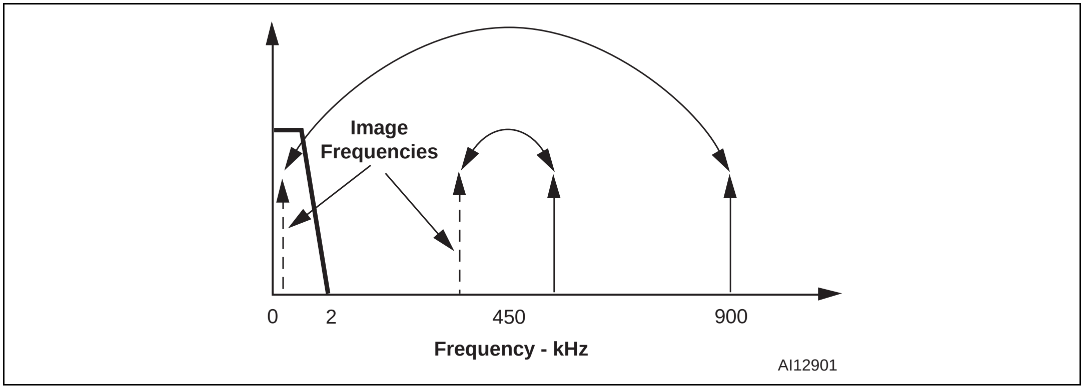


Figure 6. Anti-aliasing Effect



The anti-aliasing filter magnitude and phase response can be calculated as follows:

Equation 10

$$\overline{A_u} = \frac{\overline{U_O}}{\overline{U_I}} = \frac{\frac{1}{j\omega c}}{R + \frac{1}{j\omega c}} = \frac{1}{1 + j\omega RC}$$

Note: The cutoff frequency is expressed as:

$$f_p = \frac{1}{2\pi\tau} = \frac{1}{2\pi RC}$$

So *Equation 10* can be changed to:

Equation 11

$$\overline{A_u} = \frac{1}{1 + j \cdot \frac{f}{f_p}} = \frac{1}{1 + j \cdot \frac{f}{f_p}}$$

Equation 12

$$\left|\overline{A_u}\right| = \frac{1}{1 + \left(\frac{f}{f_p}\right)^2}$$

The phase is expressed as:

Equation 13

$$\varphi = -\text{arc}\ \tan\frac{f}{f_p}$$

In the module:

$R = 2 \bullet 10^3 K\Omega$ and

$C = 10nF$, so then

$$f_p = \frac{1}{2\pi RC} = 7961.8Hz$$

According to *Equation 12* and *Equation 13 on page 12*, the filter's magnitude and phase response can be seen in *Figure 7* and *Figure 8 on page 14*.

- When f = 50Hz:

Equation 14

$$\varphi = -0.35^{\circ}$$

and

Equation 15

$$\left|\overline{A_u}\right| \approx 1$$

- When f = 60Hz:

Equation 16

$$\varphi = -0.43^{\circ}$$

and

Equation 17

$$\left|\overline{A_u}\right| \approx 1$$

Assume that the current lags the voltage by a phase angle, δ. After an anti-aliasing filter, a phase error (φ) is introduced into the STPM01. The power factor (PF) error is calculated as:

Equation 18

$$\text{error}_{PF} = \frac{\cos\delta - \cos(\delta + \varphi)}{\cos\delta} \cdot 100\text{percent}$$

When,

$\delta = -60°$ (PF = –0.5), and

f = 50Hz,

according to *Equation 14*, a phase error, $\varphi = -0.35^{\circ}$ has occurred:

Equation 19

$$\text{error}_{PF} = \frac{\cos(-60^{\circ}) - \cos(-60^{\circ} - 0.35^{\circ})}{\cos(-60^{\circ})} \cdot 100\text{percent} = 1\text{percent}$$

This indicates that even a small phase error will translate into a significant measurement error at a low power factor. Thus correct phase matching is required in this situation.

Figure 7. Anti-aliasing Filter Magnitude Response

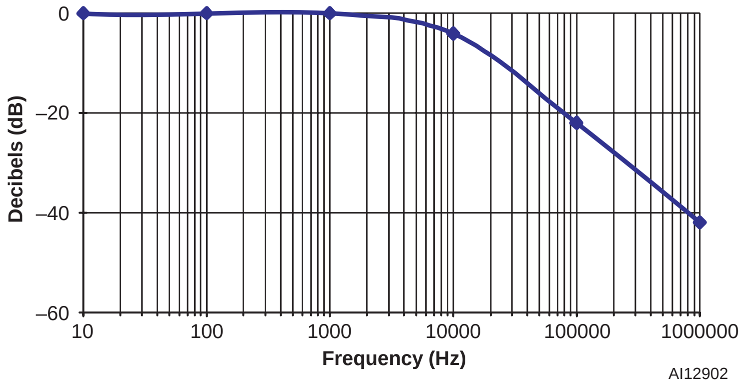
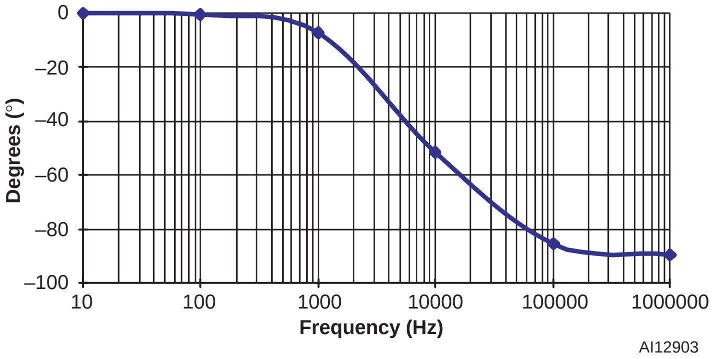


Figure 8. Anti-aliasing Filter Phase Response



1.3 Voltage Sensing Circuit

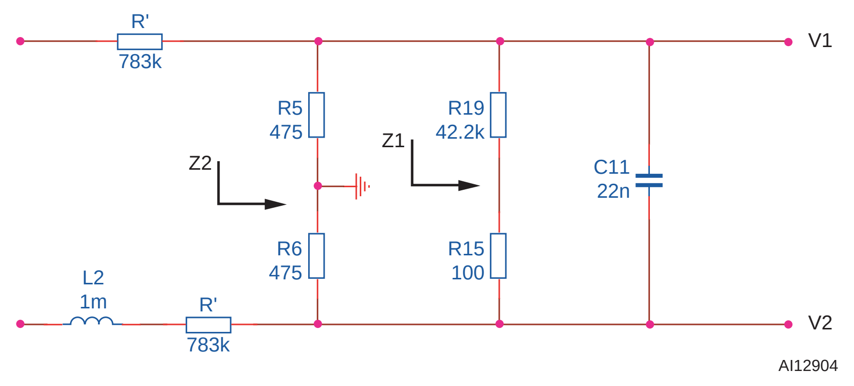
The STPM01 normally uses a resistor divider as voltage input channel (see *Figure 9*). The 783kΩ resistor is separated into three 261kΩ, in-series resistors (see *Figure 1 on page 5*), which ensure that a high voltage transient will not bypass the resistor. These three resistors also reduce the potential across the resistors, thereby decreasing the possibility of arcing.

The following resistors are used as the resistor divider when the mains voltage is present:

- R' = 783KΩ, and
- R_5=475Ω.

C11 and (R_{19}+ R_{15}) create a filter which prevents Electromagnetic Interference (EMI) created by the circuit from migrating onto the Line or Neutral busses (see *Equation 20* through *Equation 24 on page 16*).

Figure 9. Voltage Sensing Circuit



Equation 20

$$Z_1 = (R_{19} + R_{15}) = 42.3K\Omega$$

Equation 21

$$Z_2 = \frac{(R_5 + R_6) \cdot Z_1}{R_5 + R_6 + Z_1} = 930\Omega$$

Equation 22

$$U_1 = -U_2 = \frac{\frac{Z_2}{2}}{2R' + Z_2} \cdot V_{mains} = \begin{cases} V_{mains} = 110\sqrt{2}V, U_1 = 0.046V \\ V_{mains} = 220\sqrt{2}V, U_1 = 0.092V \end{cases}$$

Equation 23

$$U_0 = U_1 - U_2 = \frac{\frac{Z_2}{2}}{R' + \frac{Z_2}{2}} \cdot V_{mains} = \begin{cases} V_{mains} = 110\sqrt{2}V, U_0 = 0.092V \\ V_{mains} = 220\sqrt{2}V, U_0 = 0.185V \end{cases}$$

Z1 has little influence on the U_0, thus:

Equation 24

$$U_0 \approx \frac{R_5}{R' + R_5}$$

Note: *For a specific U_0, choose an appropriate combination of resistors (R_5 and R') to get that particular U_0 value.*

1.4 Crosstalk Cancellation Network

The voltage front end handles voltages of considerable amplitude, which makes it a potential source of noise. Disturbances are readily emitted into current measurement circuitry where it will interfere with the actual signal to be measured. Typically, this shows as a non-linear error at small signal amplitudes and non-unity power factors.

At unity power factor, voltage and current signals are in phase and crosstalk between voltage and current channels merely appears as a gain error, which can be calibrated. When voltage and current are not in phase, crosstalk will have a non-linear effect on the measurements, which cannot be calibrated.

Crosstalk is minimized by means of good PCB planning and the proper use of filter components in the crosstalk network. Recommended filter components are shown in *Figure 10*. The network subtracts a signal proportional to the voltage input from the current input. This prevents crosstalking within the STPM01. The signal subtraction is calculated in *Equation 25* and *Equation 26*.

Equation 25

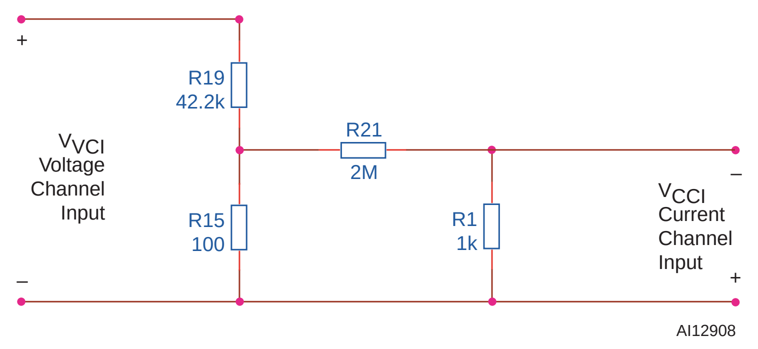
$$V_{R15} = \frac{R15}{R19 + R15} \cdot V_{VCI} \cong \frac{R15}{R19} \cdot V_{VCI}$$

Equation 26

$$V_{CCI} = \frac{R1}{R21 + R1} \cdot V_{R15} \cong \frac{R1}{R21} \cdot V_{R15} = \frac{R1}{R21} \cdot \frac{R15}{R19} \cdot V_{VCI} \cong 1.18e^{-6} V_{VCI}$$

Note: *This network must be applied to every STPM01 design, from the voltage channel to each current channel.*

Figure 10. Crosstalk Network

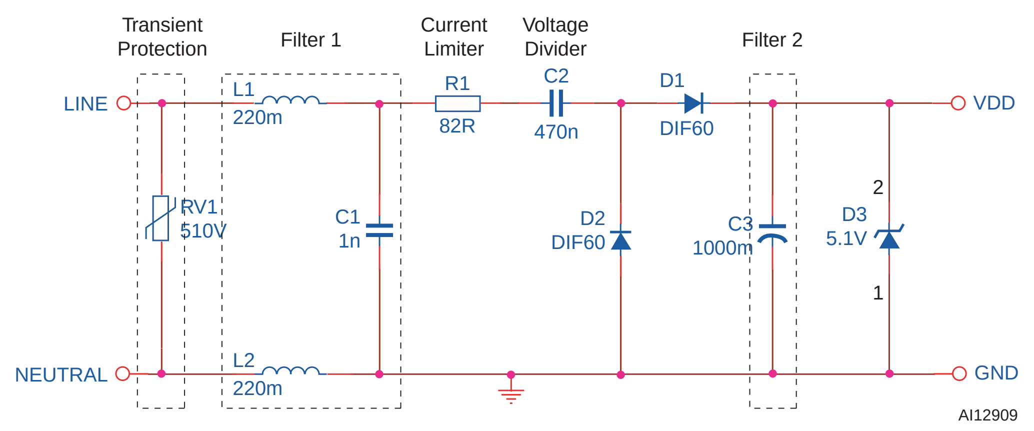


1.5 Capacitive Power Supply Circuit

The capacitive power supply circuit is shown in *Figure 10* and includes:

- a varistor,
- the capacitive power supply, and
- the Electromagnetic Compatibility (EMC) filter.

Figure 11. Capacitive power supply (with EMC Filter)



1.5.1 Varistor

The varistor is a surge protection device that is connected directly across the AC input. When a power surge or voltage spike exceeding a specified voltage (varistor voltage) is sensed, the varistor's resistance rapidly decreases, creating an instant shunt path for the overvoltage, thereby saving the sensitive control panel components. The varistor and the line fuse are subject to damage or weakened because the shunt path creates a short circuit.

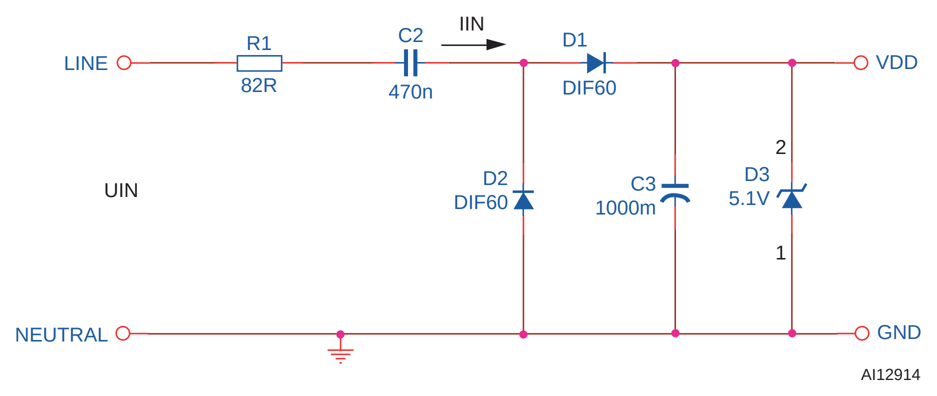
An essential point of varistor selection is that the varistor can handle the peak pulse current, which is 110% of the maximum current at which the varistor voltage does not change. If the peak pulse current rating is insufficient, then the varistor may be damaged. The main voltage is $220V_{RMS}$, and sometimes the maximum will reach $265V_{RMS}$.Thus, an MOKS K10*300V varistor is chosen for this application.

1.5.2 Capacitive Power Supply

There are several ways to convert AC voltage into the DC voltage required by STPM01. Traditionally, this is done with a transformer and rectifier circuit. There is also switching power supply solution. However, these two solutions are expensive and take up a considerable amount of PCB space.

To provide a low-cost, alternative solution, a transformerless power supply can be used (see *Figure 12*).

Figure 12. Capacitive Power Supply



The input current (I_{IN}) is limited by R_1 and the capacitive reactance of C2 (see *Equation 28* and *Equation 29*), and is expressed as:

Equation 27

$$I_{IN} = \frac{V_{IN(RMS)}}{X_{C2} + R_1}$$

where,

X_{C2} = C2 reactance.

Note: R_1 is used to limit inrush current, but it dissipates power.

By adding a low-cost half-wave rectifier, current is allowed to be supplied by the source during the positive half, where,

- V_{INRMS} = RMS voltage of the half-wave AC waveform, and is expressed as follows:

Equation 28

$$V_{IN(RMS)} = \frac{1}{2} \cdot \frac{V_{PEAK} - V_Z}{\sqrt{2}}$$

where,

V_{PEAK} = mains peak voltage (i.e. United States = 115V/60Hz and Europe = 220V/50Hz), and

V_Z = the voltage drop across D_1 and D_3.

- X_{C2} = Capacitor reactance, and is expressed as:

Equation 29

$$X_{C2} = \frac{1}{2\pi f C_2}$$

By substituting the values expressed in *Equation 27* with those in *Equation 28* and *Equation 29*, the results are as follows:

Equation 30

$$I_{IN} = \frac{V_{PEAK} - V_Z}{2\sqrt{2}(X_{C2} + R_1)} = \frac{\sqrt{2}V_{mains} - V_Z}{2\sqrt{2}(X_{C2} + R_1)}$$

Assuming that the voltage drop across each diode is 0.7V, then the total voltage drop is expressed as:

Equation 31

$$V_Z = V_{D1} + V_{D3} = 5 + 0.7 \cdot 2 = 6.4V$$

When these application parameters are considered:

$V_{mains} = 220V_{AC}$,

f = 50Hz, and

$V_Z = 6.4V$ (see *Equation 31*), the calculated I_{IN} would be:

Equation 32

$$I_{IN} = 15.7mA$$

Selecting components in the circuit is a critical consideration. As a general rule, components should be sized at twice the maximum power calculated for each device.

For example, by using the I_{IN} value in *Equation 32* and V_{DD} = 5V to choose an appropriate Zener diode, the results required to make the selection are expressed as follows:

Equation 33

$$V_{DD} = I_{IN}^2 \cdot R_1 = 0.02W$$

and

Equation 34

$$P_{D3} = V_{D3} \cdot I_{IN} = 5.1 \cdot 0.0157 = 0.08W$$

Thus, a ZMM SOD 80*5.1V G Zener Diode is used.

1.5.3 EMC Filter

EMC has become an important power supply parameter. In order to deal with common and differential mode noise, a two-part AC filter is added (see *Figure 11 on page 18*).

- Differential filter (Filter 1)

  Inductors L_1/L_2, and C_1 represent a differential filter for DM (differential mode) noise trying to enter the power supply. DM noise is produced by current flowing along either the Line or Neutral conductor, and returning by the respective other. This produces a noise voltage between the Line and Neutral conductors.

  The filter will be designed for at least 10 times the line frequency, thereby resulting in a frequency of 600Hz. The indication is then, that the cutoff frequency (f_C) must not be below 600Hz.

  Capacitor C_1 is X Class capacitor, used to reduce differential noise. To ensure that C_1 does not fail because of the surge or short circuit current, it must be able to withstand twice the mains voltage value. Keeping this requirement in mind, f_C is calculated as follows:

Equation 35

$$f_C \approx \frac{1}{2\pi\sqrt{(L_1 + L_2) \cdot C_1}} = 7.59\text{Hz}$$

Note: Generally, a specific f_C value is chosen, then the inductors are tuned to that value.

- Capacitor filter (C_3, Filter 2)

  Capacitor C_3 is used as a filter. Considering load R_L, the size of C_3 must satisfy the requirements expressed in *Equation 36*:

Equation 36

$$R_L C = (15 \sim 25)T$$

In fact, considering that the charge stored in the capacitor is:

Equation 37

$$I_L T = Q$$

where,

I_L = the load current, and

T = the AC sine wave period, and

the output ripple voltage is expressed as:

Equation 38

$$\Delta V = \frac{Q}{C}$$

then the capacitor C value can be calculated by using a fixed voltage ripple value:

Equation 39

$$\Delta V = \frac{I_L T}{C}$$

then, fixing our ripple to ΔV=200mV we can calculate C value accordingly.

For the purposes of this application, C is calculated as follows:

Equation 40

$$C = \frac{10\text{mA}}{200\text{mV} \cdot 50\text{Hz}} = 1000\mu\text{F}$$

The STPM01 power supply (V_{CC}) configuration range is from 3.3V to 6V. While it seems to be enough to change the D3 diode (see *Equation 34*) from the previously selected ZMM SOD 80*5.1V G Zener Diode, if the output current is too high, then the C_2 value must be reduced.

Note: *Usually it is not necessary to use resistor R1 in the circuit.*

1.6 Clock Generation

All of the STPM01 internal timing is based on the CLKOUT oscillation signal. This signal can be generated in three different ways:

- RC (see *Figure 13*)

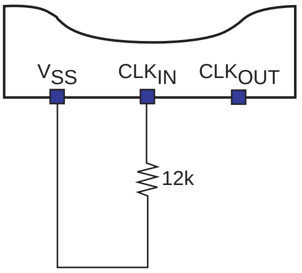
  This oscillator mode can be selected using the RC configuration bit. If RC = 1, then the STPM01 will run using the RC oscillator. A resistor connected between CLKIN and Ground will set the RC current.

Note: For 4MHz operation, the suggested settling resistor is 12k.

- Quartz (see *Figure 14*)

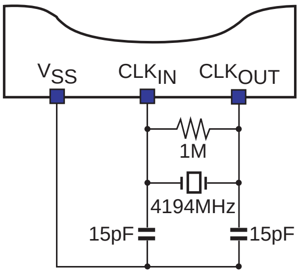
  The oscillator will work with an external crystal.

Figure 13. Internal RC Recommended Connections



AI12915

Figure 14. Quartz Recommended Connections



AI12916

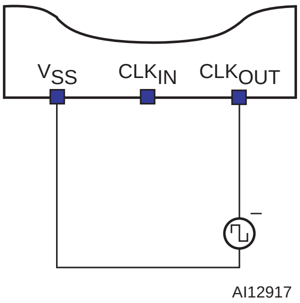
- External Clock (see *Figure 15*)

  The clock generator is powered from analog supply, and is responsible for two tasks:

  a) to retard the turning on of some of the function blocks after Power-on Reset (POR) in order to help smooth start the external power supply circuitry and keep all major loads off of the circuit, and

  b) to provide all necessary clocks for the analog and digital parts. Two nominal frequency ranges are expected,(1) from 4.000MHz to 4.194MHz, or (2) from 8.000MHz to 8.192MHz.

Figure 15. External Clock Source Recommended Connections



2 Revision History

Table 1. Document revision history

Date	Revision	Changes
14-Apr-2006	1	Initial release.

Please Read Carefully:

Information in this document is provided solely in connection with ST products. STMicroelectronics NV and its subsidiaries (“ST”) reserve the right to make changes, corrections, modifications or improvements, to this document, and the products and services described herein at any time, without notice.

All ST products are sold pursuant to ST’s terms and conditions of sale.

Purchasers are solely responsible for the choice, selection and use of the ST products and services described herein, and ST assumes no liability whatsoever relating to the choice, selection or use of the ST products and services described herein.

No license, express or implied, by estoppel or otherwise, to any intellectual property rights is granted under this document. If any part of this document refers to any third party products or services it shall not be deemed a license grant by ST for the use of such third party products or services, or any intellectual property contained therein or considered as a warranty covering the use in any manner whatsoever of such third party products or services or any intellectual property contained therein.

UNLESS OTHERWISE SET FORTH IN ST’S TERMS AND CONDITIONS OF SALE ST DISCLAIMS ANY EXPRESS OR IMPLIED WARRANTY WITH RESPECT TO THE USE AND/OR SALE OF ST PRODUCTS INCLUDING WITHOUT LIMITATION IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE (AND THEIR EQUIVALENTS UNDER THE LAWS OF ANY JURISDICTION), OR INFRINGEMENT OF ANY PATENT, COPYRIGHT OR OTHER INTELLECTUAL PROPERTY RIGHT.

UNLESS EXPRESSLY APPROVED IN WRITING BY AN AUTHORIZE REPRESENTATIVE OF ST, ST PRODUCTS ARE NOT DESIGNED, AUTHORIZED OR WARRANTED FOR USE IN MILITARY, AIR CRAFT, SPACE, LIFE SAVING, OR LIFE SUSTAINING APPLICATIONS, NOR IN PRODUCTS OR SYSTEMS, WHERE FAILURE OR MALFUNCTION MAY RESULT IN PERSONAL INJURY, DEATH, OR SEVERE PROPERTY OR ENVIRONMENTAL DAMAGE.

Resale of ST products with provisions different from the statements and/or technical features set forth in this document shall immediately void any warranty granted by ST for the ST product or service described herein and shall not create or extend in any manner whatsoever, any liability of ST.

ST and the ST logo are trademarks or registered trademarks of ST in various countries.

Information in this document supersedes and replaces all information previously supplied.

The ST logo is a registered trademark of STMicroelectronics. All other names are the property of their respective owners.

© 2006 STMicroelectronics - All rights reserved

STMicroelectronics group of companies

Australia - Belgium - Brazil - Canada - China - Czech Republic - Finland - France - Germany - Hong Kong - India - Israel - Italy - Japan - Malaysia - Malta - Morocco - Singapore - Spain - Sweden - Switzerland - United Kingdom - United States of America

www.st.com