TERIDIAN SEMICONDUCTOR CORP.
A Maxim Integrated Products Brand

71M651x
Energy Meter IC

APPLICATION NOTE

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Current Shunt Meter Interface Using the TERIDIAN 71M6511

The 71M6511/6511H Demo Board is designed to use all combinations of sensors, i.e. current transformer (CT), current shunt/CT or single shunt resistor. When an isolation transformer is used, shunt/shunt configurations can be implemented. The Demo Code (Firmware revision 3.05) is designed to support all operating modes. **The 4-layer (round) Demo Boards are normally shipped in CT configuration. Some 2-layer (rectangular) Demo Boards are shipped in shunt configuration and complete with a shunt resistor and wire harness.**

With a few quick modifications, a 71M6511/6511H Demo Board configured for CT can be adapted to operation with a current shunt/CT or single shunt combination.

This application note describes how current shunts are connected to the 71M6511/6511H Demo Board, and what precautions have to be taken to ensure proper operation. Measurement results are presented for the single-shunt configuration with various shunt resistance values.

Safety Precautions

CAUTION

In shunt configuration, the whole Demo Board will be at line voltage! Touching the board or any components must be avoided!

CAUTION

It is highly recommended to isolate Demo Board and Debug Board (when used) and to provide separate power supplies for the Demo Board and Debug Board. Some 2-layer Demo Boards have the headers JP2 and JP3 for galvanic connection between the Demo and Debug Boards. Jumpers on these headers must be removed!

CAUTION

Emulators or other test equipment should never be connected to a live meter without proper isolation!

Shunt Configurations

The TERIDIAN 71M6511 can be used in CT, shunt, CT/shunt, CT/CT, and shunt/shunt configurations, as shown in Figure 1 and Figure 2.

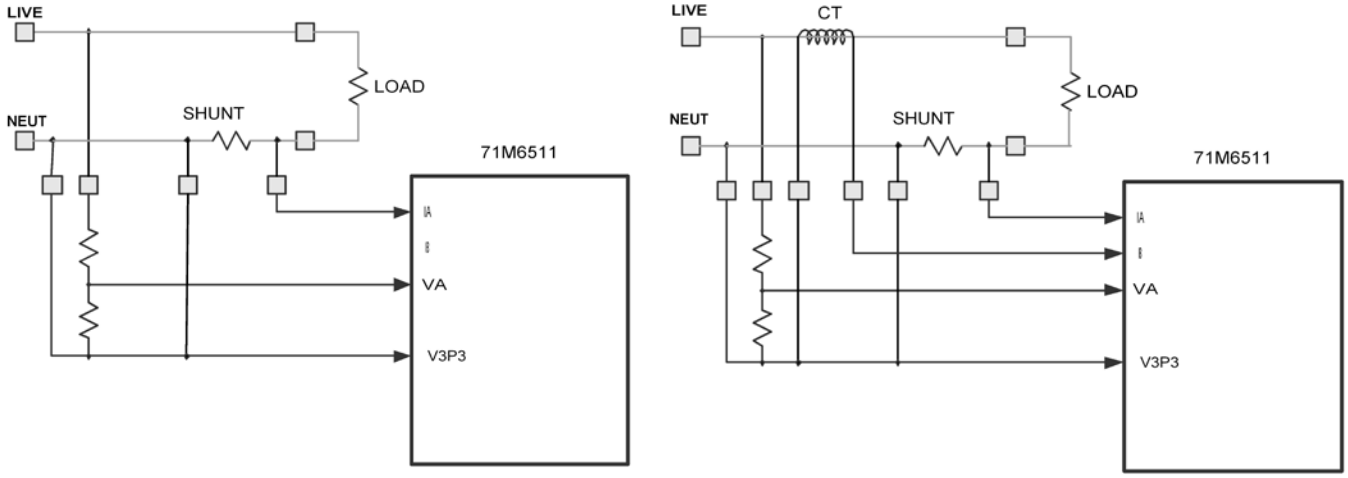


Figure 1: Topology for Shunt (left) and Shunt/CT (right)

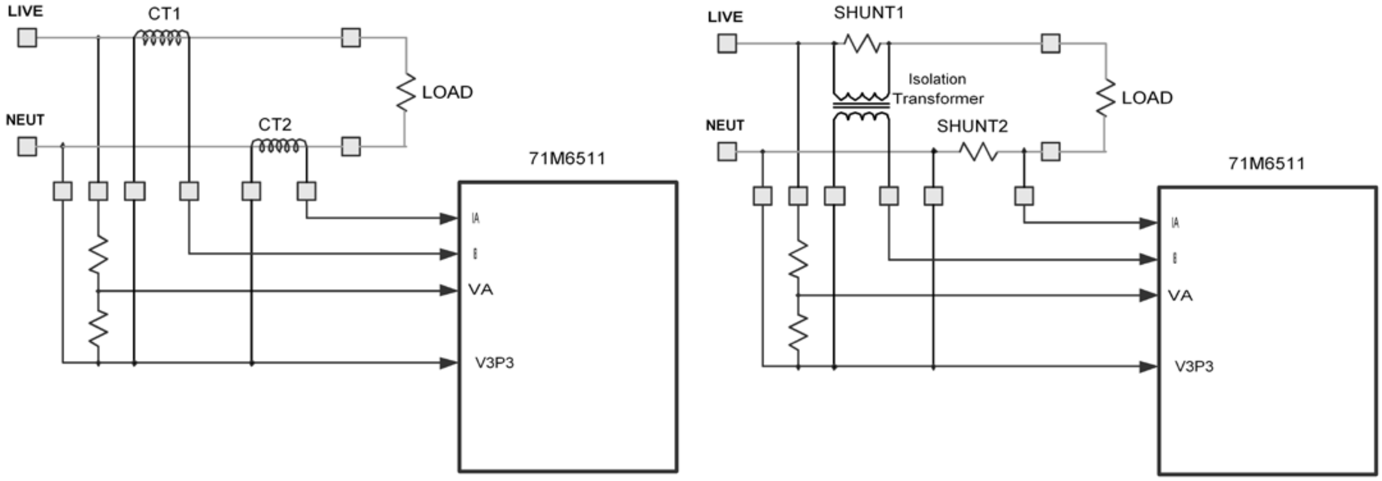


Figure 2: Topology for CT/CT (left) and Shunt/Shunt (right)

Note that the shunt/shunt configuration requires an isolation transformer. Without the isolation transformer, the LIVE and NEUTRAL wires would be shorted.

This application note describes the single-shunt and the shunt/shunt configurations. For a description of the shunt/CT configuration refer to the Demo Board User's Manual.

The diagrams above show general topology only. <u>For good measurement accuracy, the wiring rules laid out in the section "Wiring for Shunt Resistors" have to be followed</u>.

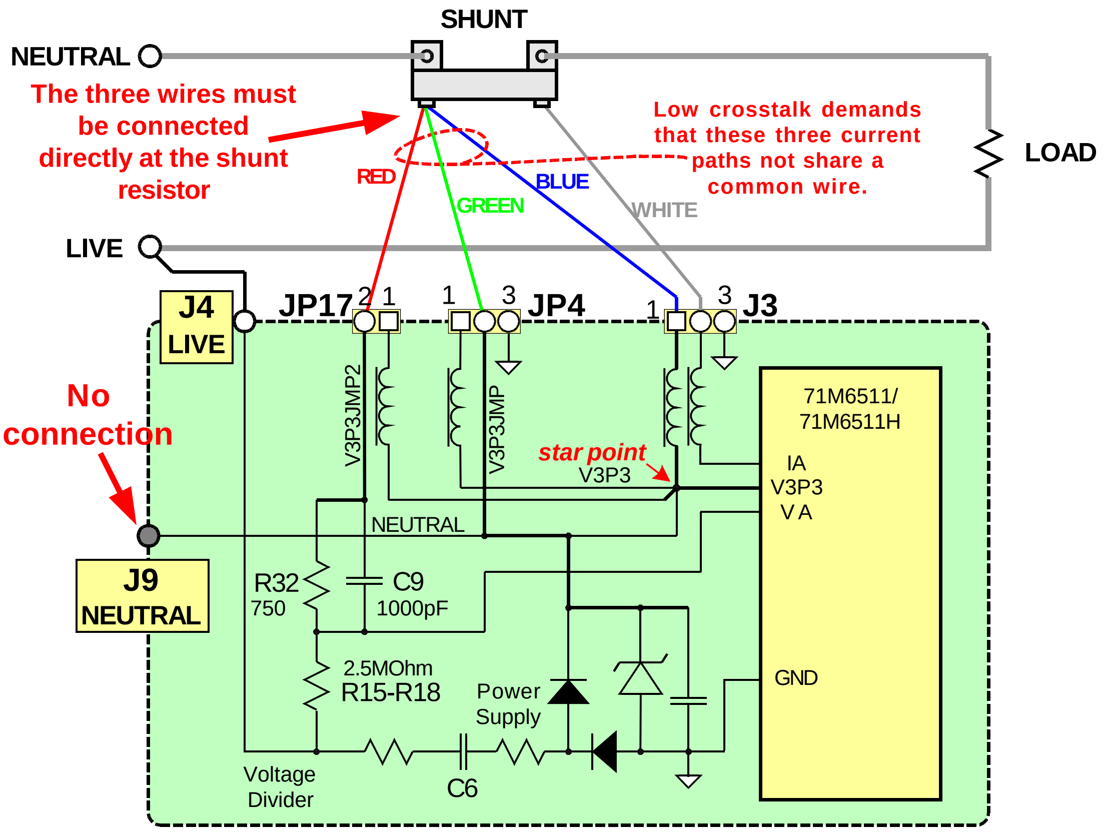
Single-Shunt Configuration

Wiring for Shunt Resistors

Figure 3 shows the general topology of the current shunt sensor operation. The voltage drop across the shunt resistor is fed into the IA input of the 71M6511/6511H device, with V3P3 being the reference. The voltage at the shunt is divided by a resistor divider R1/R2 associated with the voltage input and supplied to the VA input of the chip. The Demo Board generates the power for the 71M6511 chip by attenuating the voltage between NEUTRAL and LIVE through a network consisting of resistors, capacitors and diodes.

JP17 provides the NEUTRAL reference for the voltage divider used for VA. JP4 provides the NEUTRAL return path for the on-board power supply, and J3 provides both the reference and the signal for the voltage drop across the shunt resistor

Note that a separate path is provided for the power supply to the board and for the references of the measured signals.



71M6511/6511H Demo Board

Figure 3: Wiring for Current Shunt Mode (Shown for the 6511T4A7 2-Layer PCB)

Figure 4 shows the connections required at the shunt resistor itself.

It is important that three separate wires for V3P3 are attached at the shunt resistor as shown in Figure 4 and are routed to the 6511 Demo Board separately, as shown in Figure 3.

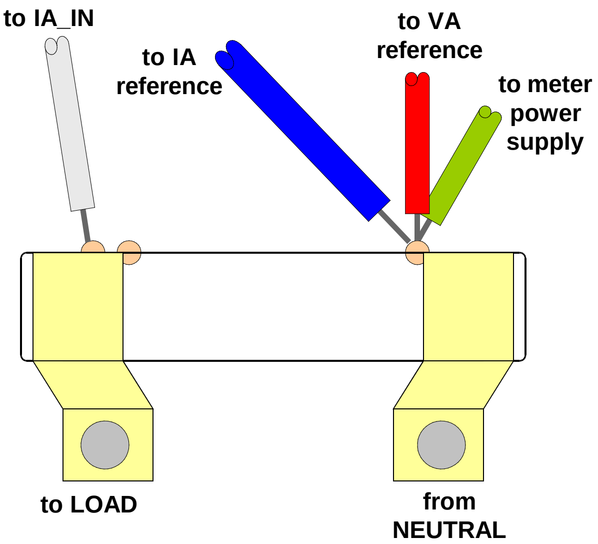


Figure 4: Recommended Shunt Connections

Shunt Connection Theory

This chapter is intended to illustrate and mathematically demonstrate the importance of proper shunt wiring.

The shunt resistors used for electricity metering tend to be in the order of few hundred micro-Ohms leading to small voltage outputs across the analog current input of the 71M6511 IC. The analog input measurements for the Teridian 71M6511 ICs are referenced to V3P3. Even though the input signal present at the current input is noise free, the contamination of the V3P3 reference for measurement can prevent achieving the desired accuracy, even with 22-bit ADC resolution.

The V3P3 signal used for the measurement contains the following sources of contamination:

- Noise from capacitive power supply.
- Noise contribution due to the voltage Reference V3P3
- Noise present in the signal conditioning circuit.

Capacitive Power Supply

The capacitive power supply circuit used for on Teridian 651x demo boards is as shown below in Figure 5.

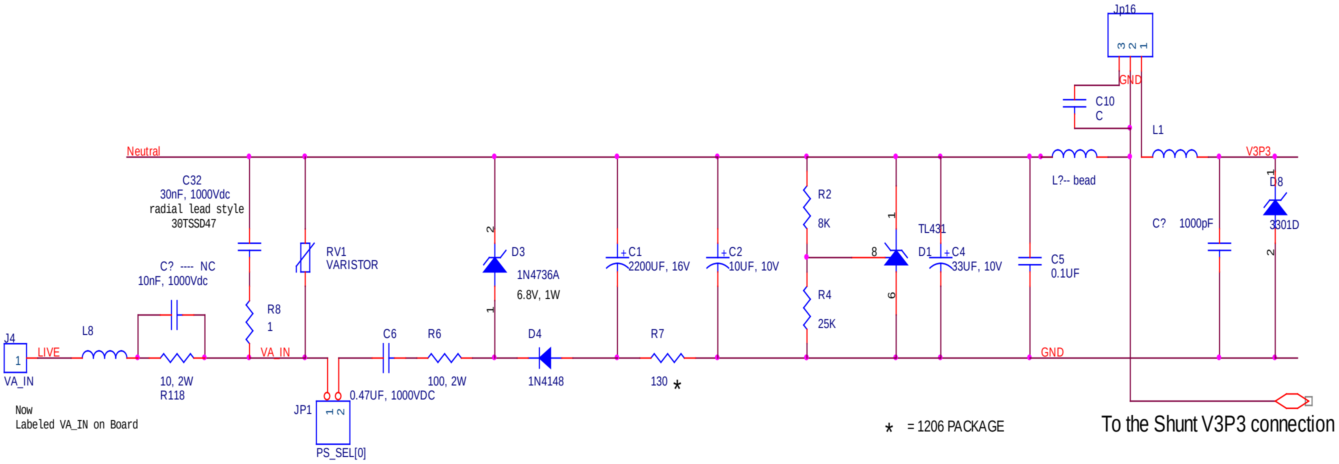


Figure 5: Typical Capacitive Power Supply

The output voltage of the above circuit (JP16, pin 2) will be 3.3VDC, along with the ripple caused by the 60Hz input signal. This output voltage can be expressed using the following mathematical equations:

$V_{out}(t) = V_a \cdot e^{\frac{-t}{RC}}$ for the duration of the discharge in a cycle.

$V_{out}(t) = V_a \cdot \cos(\omega t)$ for all other times in a cycle .

Based on the output voltage calculated above, the DC output can be mathematically represented as

$$V_{DC} = \frac{V_A}{2\pi}\left(\omega RC(1 - e^{\frac{-x}{\omega RC}} - \sin(x)\right) \qquad \text{EQU (1)}$$

The Voltage Measurement Circuit

The reference for the voltage measurement can pick up some of the noise coming from the analog signal conditioning circuit. This noise may not be as significant as the noise generated by the power supply circuit.

The Current Measurement Circuit

The signals present at the Shunt input are in the order of a few milli-volts to micro-volts Any noise present at the current measurement input can contaminate the whole power measurement, resulting in inaccuracies and repeatability issues.

The following example will clarify the role of noise in the current measurement circuits and connections:

Voltage applied: 240V, (240V sinωt), where $\omega = 2 * \pi * 60$ (or 50Hz if the fundamental is 50Hz).

Current applied: 5A for a 71M6511-based meter

Current sensor used: 400 µΩ shunt

Case 1 (Connection with one wire only):

The connection is made to the 6511 Demo Board with voltage applied at VA and Neutral, and the shunt resistor is connected at Ia_in and V3P3.

a) JP4, pin 1 and 2 are shorted.

b) JP17, pin1 and 2 are shorted.

This means that the V3P3 supply voltage is generated by the capacitive power supply with a modulated output as described by EQU (1). This output voltage is the reference for measurement, and the output ripple is present at the analog signals also.

The analog signal presented at VA_IN for voltage measurement is:

(240/600) * 176mV = 70.4mV ;

Mathematically, the signal present at VA_IN is:

(70.4 * cos (ωt) + V_{DC} (from EQU (1))

Please note that rms and peak are intentionally ignored for clarity.

The current output from the shunt resistor is:

(5/440) * 176mV = 2mV

Mathematically, the signal present at IB_IN is:

(2 Cos(ωt) + V_{DC} (from EQU (1))

The above calculations show that for low currents, the noise present on the V3P3 (V_{DC} output) is comparable to the shunt current input signals. The presence of this noise demands compensation via high QUANT values. However, high values for QUANT are not practical and can create low accuracy drifts with the applied voltage.

The power computed by the 71M6511 IC is:

P = (VA_IN) * (IA_IN), or

$$P = (V_a \cos(\omega t) + \frac{V_a}{2\pi})\left\{\omega RC(1 - e^{\frac{-x}{RC}}) - \sin(x)\right\} \cdot (I_a \cos(\omega t) + \frac{V_a}{2\pi}\left\{\omega RC(1 - e^{\frac{-x}{\omega RC}}) - \sin(x)\right\})$$

= (V_a * I_a) + unwanted signals.

Case 2 (Proper Connection):

The connection is made to the 6511 Demo Board with voltage applied at VA and Neutral and Shunt connected at Ia_in and V3P3:

- JP4, pin2 is directly connected to the shunt resistor.
- JP17, pin 2 is directly connected at the shunt resistor.
- The shunt resistor has a connection to the IA_IN and V3P3 inputs.

By wiring the connections in the way described above the ripple generated on the DC output voltage has a return path to V3P3 on the shunt.

Even though the EQU(1) holds good for this circuit also, the signal noise on the reference for the analog measurements is reduced because three separate wires are utilized. One of the wires carries the current used to power the Demo Board, and thus offers a return path for the noise, leaving the other wires mostly noise-free.

Figure 6 shows the top-level view of a two-layer 6511 Demo Board connected to a shunt resistor. As can be seen in Figure 6, the nets V3P3, V3P3J2, and V3P3_JUMPER are all connected at the shunt resistor.

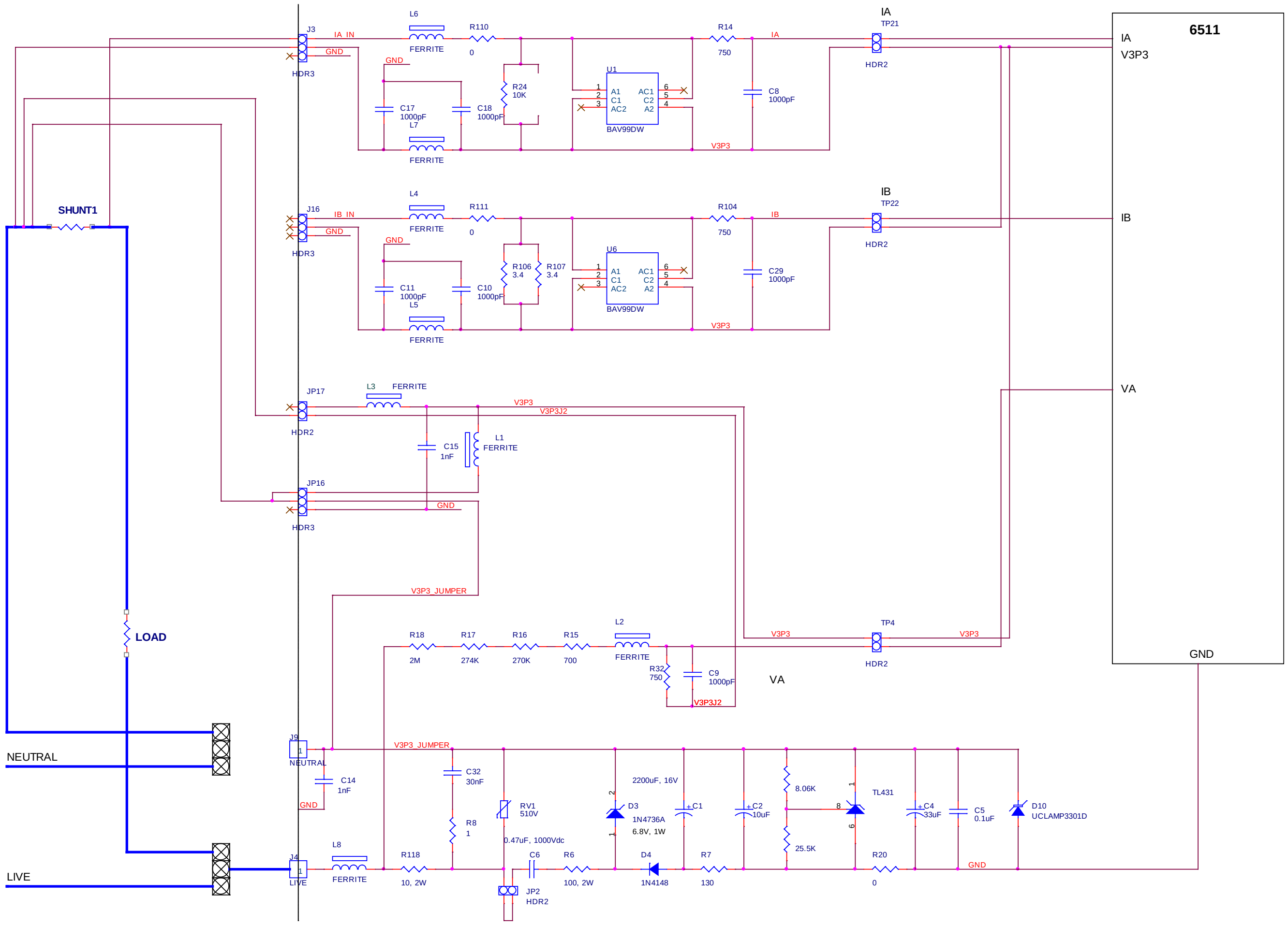


Figure 6: Top-level View of Shunt Connections (DB6511T4A7)

Current Shunt Input Schematic

Figure 7 shows an example for implementing a current shunt input on the TERIDIAN 71M6511 Demo Board.

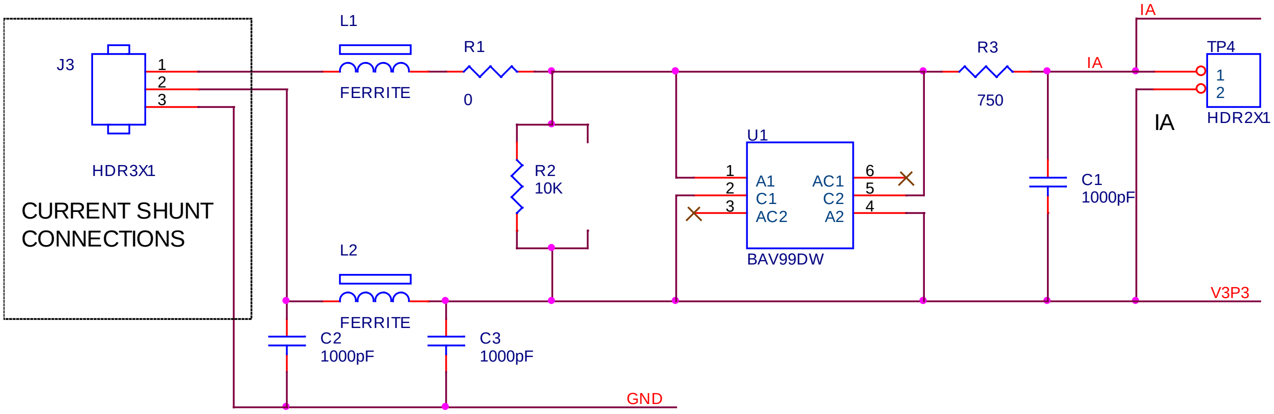


Figure 7: Current Shunts input signal conditioning circuit

Key EMI/EMC precautions for the input signal conditioning circuit are:

a. L1 and L2 are Ferrite beads that provide 600Ω impedance for signals above 100MHz (e.g. TDK MMZ2012S601A).

b. The combination of R3 and C1 provides a low-pass filter with cutoff frequency of around 212kHz.

c. The V3P3 trace connecting to the input signal conditioning circuit should be wide.

d. The J3 connector has a three-input pin provision to accommodate for the connection of a shield for the shunt cable. The shield may be connected to the digital ground to prevent high frequency noise entering through the shunt metal plate.

e. In environments with high electromagnetic radiation, R2 can be used at 10kΩ to prevent spurious measurements.

f. Unused current inputs should be properly terminated or shorted.

It is important to note that the routing of the input sensing traces and of the reference V3P3 to the voltage and shunt inputs is very critical. The circuit shown in Figure 8 provides the necessary information for routing the V3P3 net.

Software Adjustments

The ADC in the 71M6511/6511H chip is operating in 22-bit resolution mode. This means that both the control registers *CFIR* and *MUX_DIV* are set to 1.

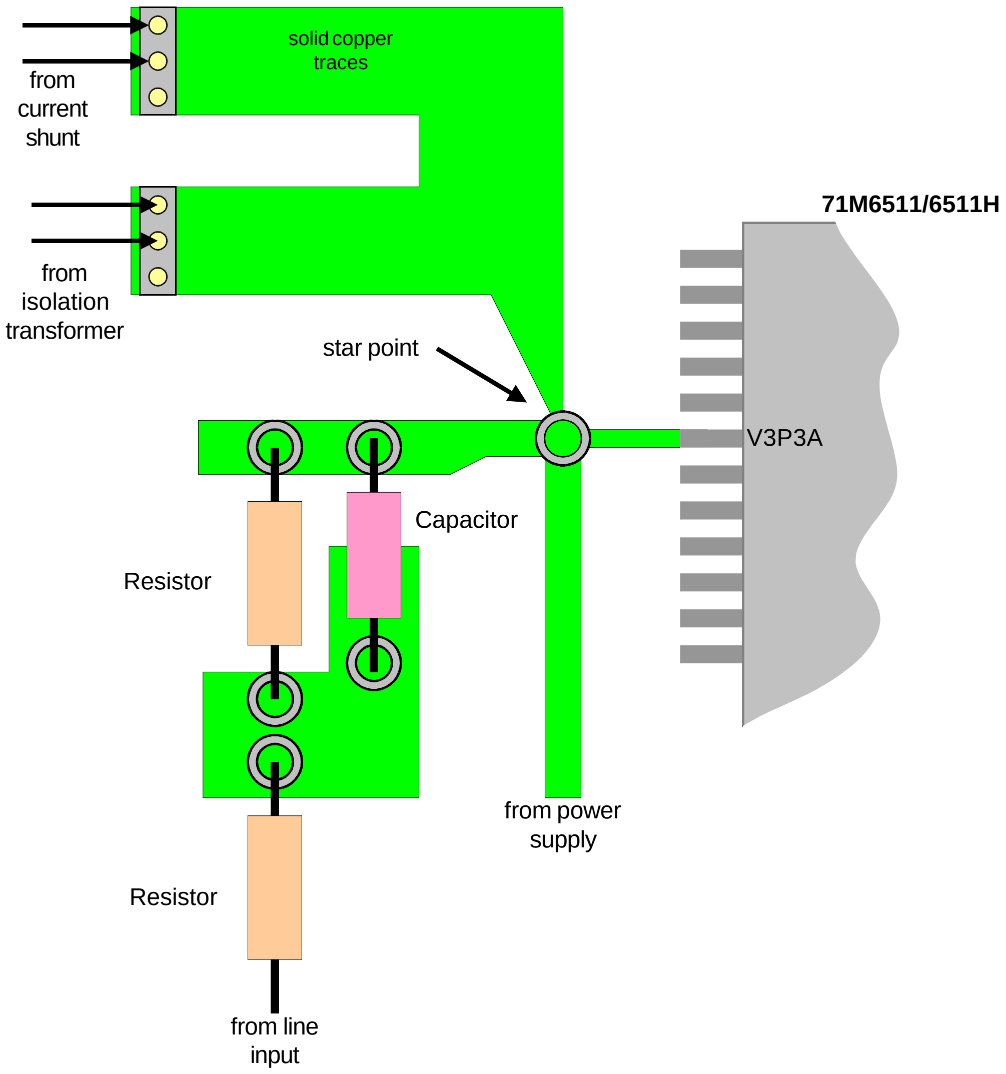


Figure 8: PCB Routing of the V3P3 Net

Required Modifications to the 71M6511 Demo Board for Current Shunt Sensor Connections:

The Demo board has provisions to incorporate the changes as pictured in Figure 6.

In order to operate the 71M6511/6511H Demo Board (D6511BT4A4 or D6511BT4A5) with a current shunt sensor, the following measures must be taken:

a. Remove the jumpers on JP4 and JP17.

b. Remove R24 and R25 if IA_IN is the input channel for the current shunt or remove R106 and R107 if IB_IN is the input channel for the current shunt.

c. Add a 10kΩ resistor at R24 if IA_IN is the input channel for the current shunt or add a 10kΩ resistor at R106 if IB_IN is the input channel for the current shunt. This resistor will provide noise termination and will suppress unwanted readings.

d. The LIVE line must be connected to the spade terminal J4 (bottom of the board).

e. One pair of wires from the shunt resistor must be connected to contacts 1 and 2 on J3 if IA_IN is the input channel or contacts 1 and 2 on J16 if IB_IN is the input channel.

f. Connect Pin1 of JP4 (pin closest to the regulator output, power supply pin) and pin 2 of JP17 (resistor divider output) together at the shunt, V3P3 terminal as shown in Figure 3.

g. Through the serial terminal (command line interface), the Demo Program can be set to run in current shunt mode. This is done by issuing the commands **`>]2A=1`** if IA_IN is connected to the shunt or **`>]2B=1`** for IB_IN connected to the shunt. This will cause the Demo Program to select the proper input channels and to apply the gain of 8 to the shunt input channel from the ADC output before processing for power measurement.

CAUTION

While connecting Neutral to VA_IN (J4), care should be taken to prevent shorting between LINE and NEUTRAL. Also note that no connection is required at J9 (NEUTRAL) since the LINE voltage from the shunt resistor becomes the reference for measurement.

On older Demo Boards and 4-layer Demo Boards, JP4 is labeled JP16.

Meter Performance with Shunt Connected

A Demo Board was used for testing the meter performance with Shunt resistor, using 71M6511 Demo Code revision 3.04. Meter accuracy or performance was verified for several test conditions by varying the input current gain and by using both internal and external power supply. Since the signals obtained from the Shunt resistor are small, it is better to integrate the inputs for a longer time (20 seconds) in order to ensure repeatability. Results are listed for 8x gain (Shunt_on), 1x gain (Shunt_off) and for operation with the internal power supply of the Demo Board (int_power). The results for internal supply were obtained with 1x gain (Shunt_off).

Measurement results are shown in Table 1and Figure 9.

						Test Results		
step	element	volt	amp	phase_angle	freq	Shunt_on	Shunt_off	Int_power
1	S	240	10	0	50	-0.0939	-0.1248	-0.1452
2	S	240	5	0	50	-0.0894	-0.1233	-0.1478
3	S	240	3	0	50	-0.1054	-0.1261	-0.1439
4	S	240	1	0	50	-0.0627	-0.1201	-0.1156
5	S	240	0.3	0	50	0.0002	-0.0697	-0.134
6	S	240	0.1	0	50	-0.1944	-0.1505	-0.0176
7	S	240	0.06	0	50	0.0407	-0.1743	0.1042

Table 1: Shunt Measurement Results

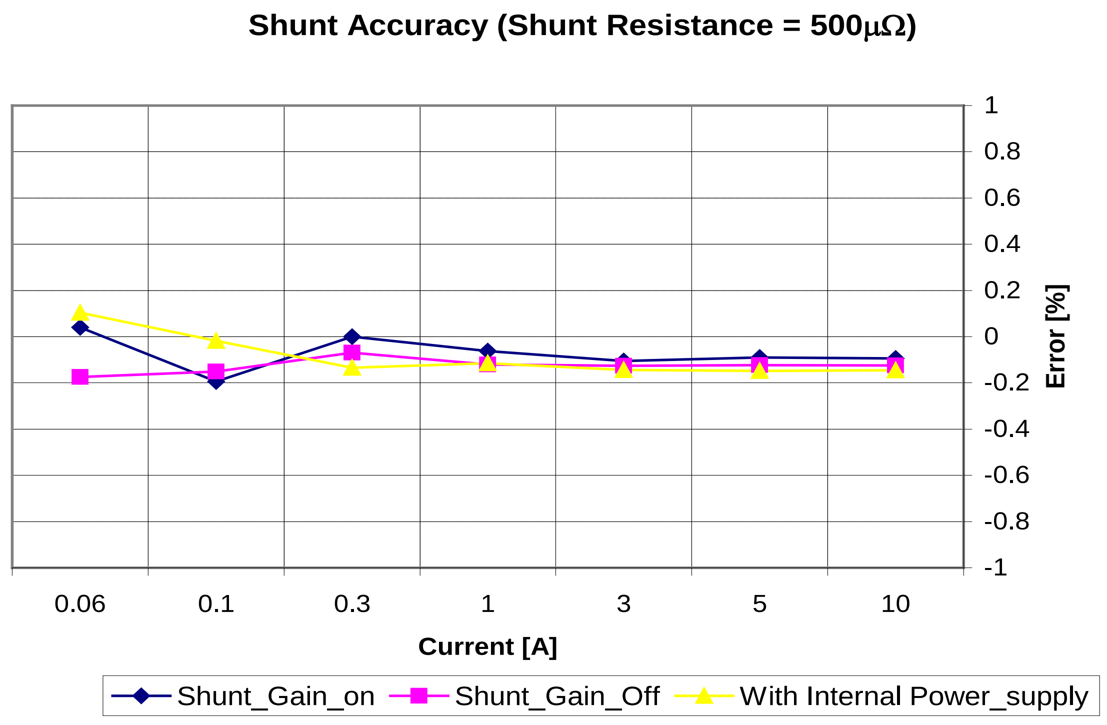


Figure 9: Shunt measurement results

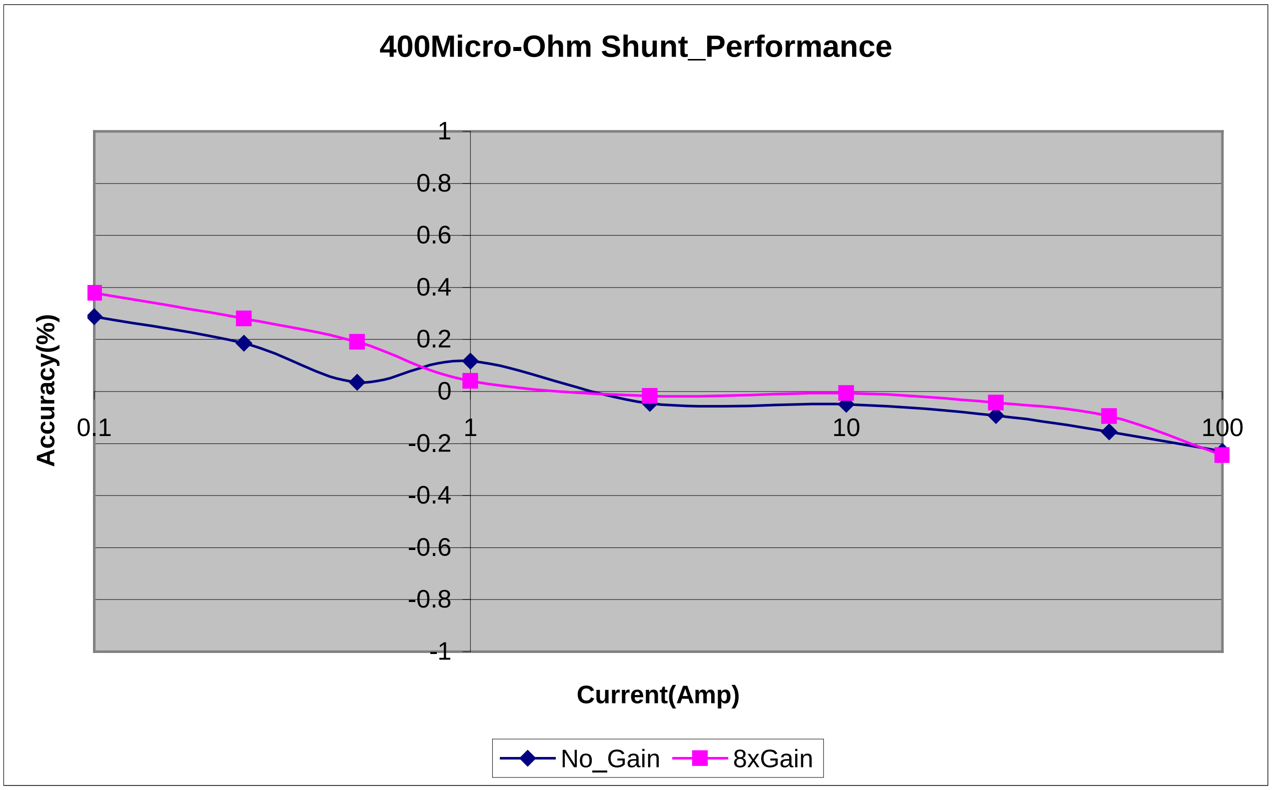
Measurement Results with Various Shunt Resistors:

400µΩ Shunt Performance

TERIDIAN 71M6511 B03 Demo Board accuracy was tested with a 400 µΩ Shunt. The shunt resistor was connected to the 71M6511 demo board as per the instructions provided in this application note.

The measured data and performance curve are given below:

step	volt	amp	revs	freq	No_gain	with 8x gain
2	240	100	100	60	-0.23	-0.2453
3	240	50	50	60	-0.1547	-0.0949
4	240	25	25	60	-0.0917	-0.043
5	240	10	10	60	-0.0491	-0.0066
6	240	3	3	60	-0.0459	-0.0178
7	240	1	1	60	0.1166	0.0409
8	240	0.5	1	60	0.0355	0.1906
9	240	0.25	1	60	0.1862	0.2799
10	240	0.1	1	60	0.2876	0.3789

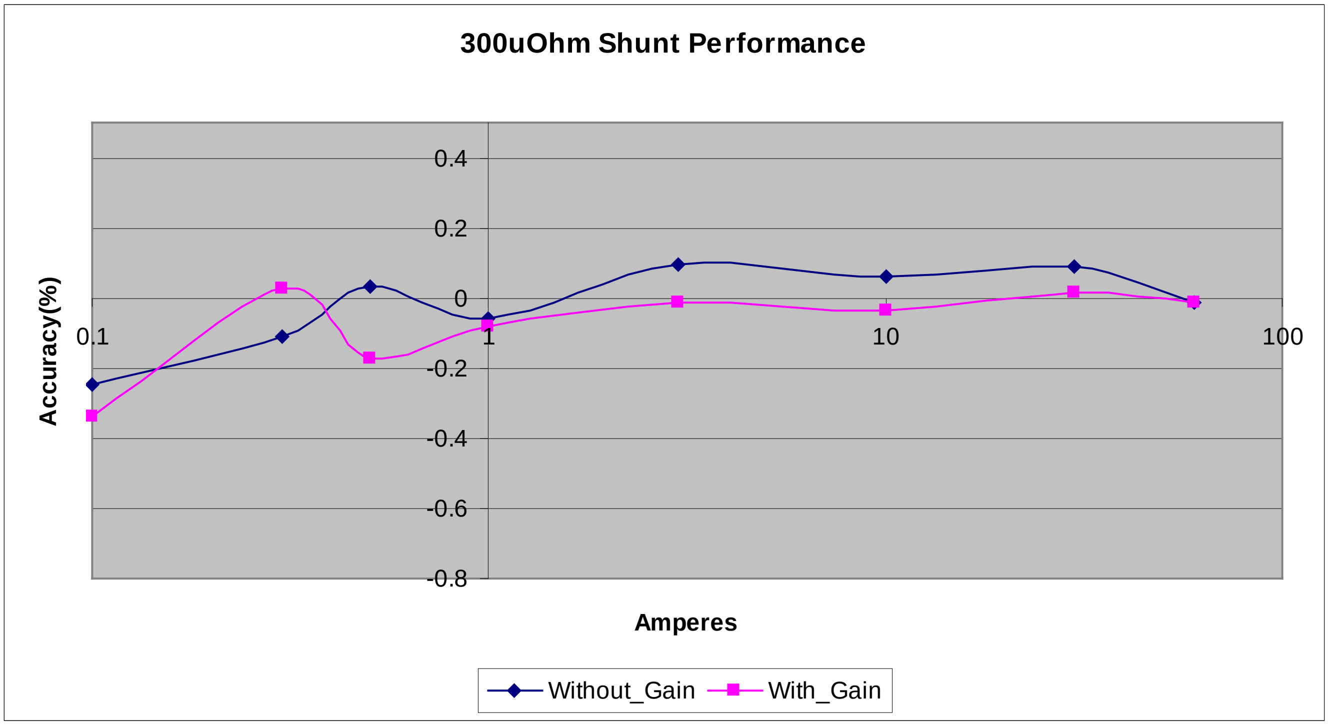


300μΩ Shunt Performance

TERIDIAN 71M6511 B03 Demo Board accuracy was tested with a 300μΩ shunt. The shunt resistor was connected to the 71M6511 demo board as per the instructions provided in this application note.

The measured data and performance curve are given below:

Step	Volt	Amp	NoGain	8xGain
1	240	60	-0.0128	-0.0128
2	240	30	0.09	0.0141
3	240	10	0.0617	-0.0341
4	240	3	0.0938	-0.016
5	240	1	-0.0615	-0.083
6	240	0.5	0.0303	-0.1756
7	240	0.3	-0.1086	0.0294
8	240	0.1	-0.2453	-0.3387



Performance with 180µΩ Shunt

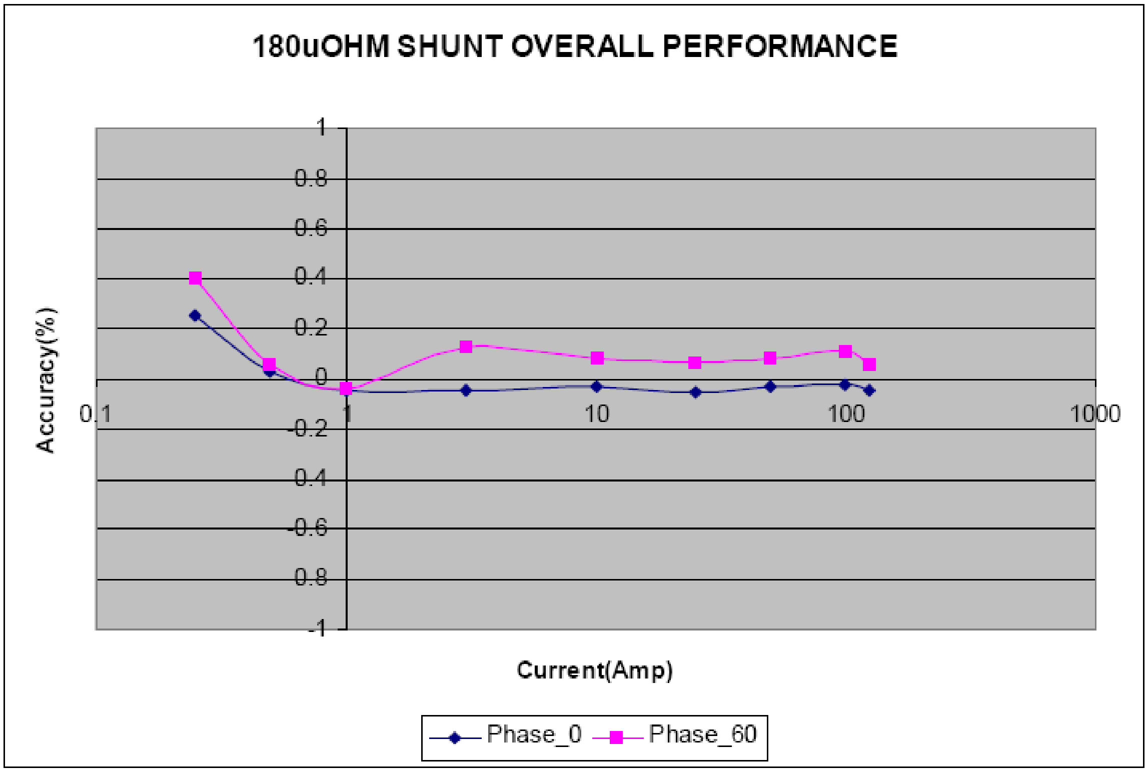
A 180µΩ shunt resistor was connected to the 71M6511 Demo Board as per the instructions provided in this application note. The following parameters were used:

- PHADJ_A = -1850
- QUANT = +1200 (CE QUANT variable)
- WRATE = 7933 for kh = 1.0Wh/pulse
- IMAX = 10420 (set for 1042A)

The theoretical computation based on 180µΩ provides only 950A. However, when measuring the shunt resistor, the resistance appeared 10% lower than specified, which is 168µΩ.

The measured data and performance curve are given below.

step	volt	amp	Phase_0	Phase_60
1	240	125	-0.0479	0.0628
2	240	100	-0.0232	0.1123
3	240	50	-0.0332	0.08
4	240	25	-0.0511	0.067
5	240	10	-0.0335	0.0857
6	240	3	-0.0453	0.1298
7	240	1	-0.0466	-0.0358
8	240	0.5	0.029	0.0634
9	240	0.25	0.2532	0.4062

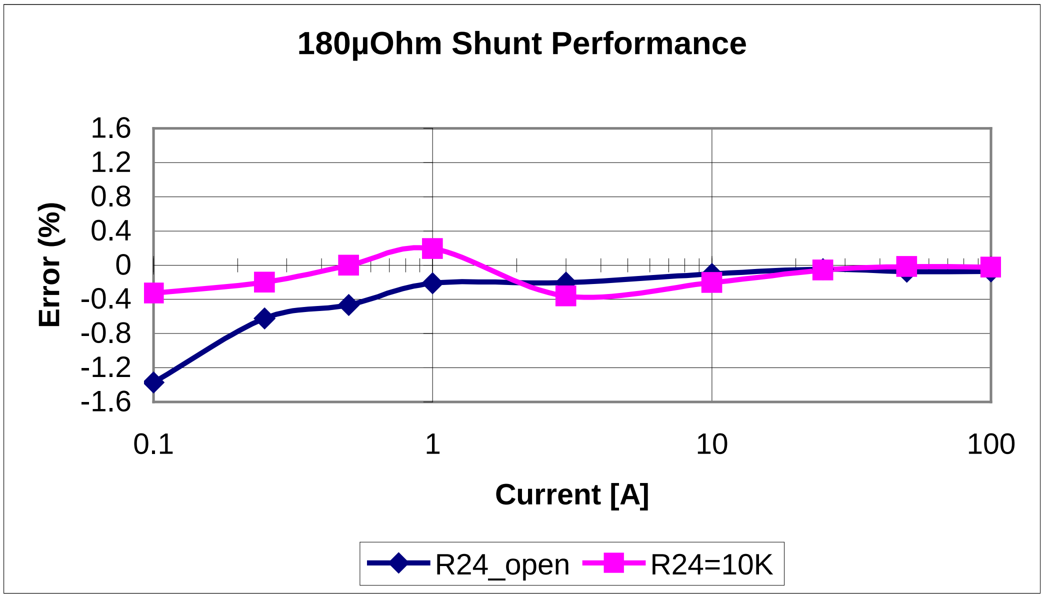


Importance of Proper Termination

A 6511 Demo Board was tested with a shunt resistor of 180µΩ. Measurements were taken with a 10kΩ termination resistor installed at position R24 and with R24 open.

The results are shown in the table and graph below.

Current [A]	**Error [%]**	**Error [%]**
	R24 = Open	R24=10k
100	-0.074	-0.023
50	-0.0751	-0.0162
25	-0.0474	-0.0589
10	-0.104	-0.2052
3	-0.2051	-0.3606
1	-0.2118	0.1935
0.5	-0.466	-0.001
0.25	-0.6235	-0.1996
0.1	-1.3725	-0.327



As can be seen, installing the 24kΩ resistor brings significant improvements in accuracy at low currents.

Shunt-Shunt Configuration

For the purpose of tamper detection, two current sensors are sometimes used, one in the LIVE connection to the load, and the other one in the return connection from the load to NEUTRAL, as shown in Figure 2.

Connections Required for the Shunt-Shunt Configuration

If two CTs or one CT and one shunt are used, no isolation issues occur. If two shunt resistors are used, isolation has to be provided by an isolation transformer. Figure 10 shows the necessary connections.

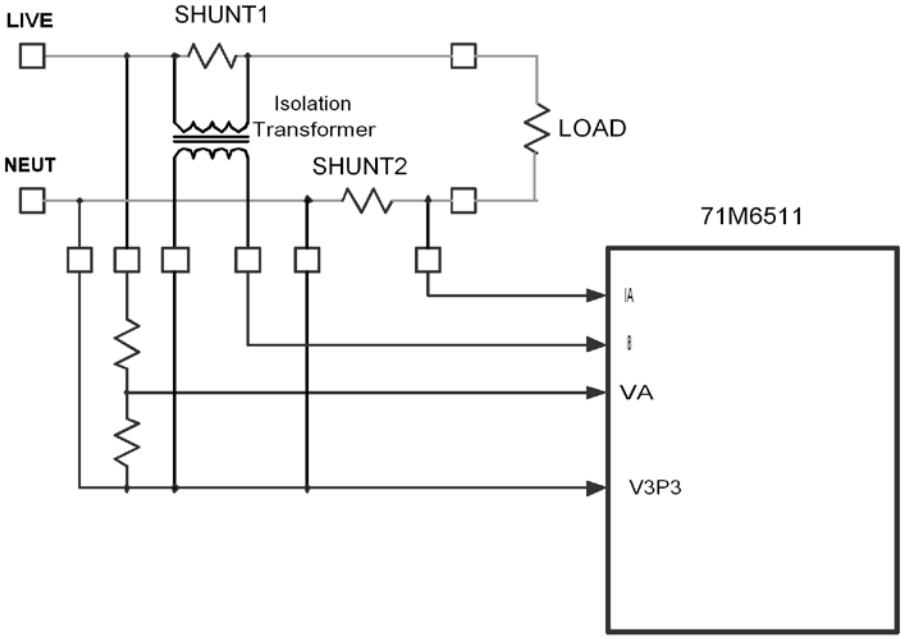


Figure 10: Shunt/Shunt Configuration

The connections from SHUNT 1 to the isolation transformer should be made using a twisted-pair cable. This cable should be shielded if severe EMI conditions are encountered.

Since the isolation transformer does not have to carry the primary current (as a CT would have to) but only the small current caused by the voltage drop at SHUNT 1, it can be significantly smaller than a comparable CT. Therefore, the isolation transformer will be easier to shield against magnetic fields than a comparable CT.

Determining IMAX for the Shunt-Shunt Configuration

For the channel measuring the current via the isolation transformer, IMAX is determined using the following formula:

$$IMAX = \frac{176mV}{N \cdot R_S}$$

Where:

N = winding ratio of the isolation transformer (secondary over primary)

R_S = shunt resistance

With a winding ratio of 10 and a shunt resistance of 160µΩ, IMAX will be 110A.

Phase Compensation

The isolation transformer will introduce a phase shift, which will have to be compensated with the calibration factors of the CE (PHADJ_A, PHADJ_B). This phase compensation factor is determined just like the compensation factor for a regular CT, using the methods described in the Demo Board User's Manual. The various calibration procedures found in the calibration spreadsheets provided by TERIDIAN can also be used to easily determine the phase compensation factors.

Termination on the Meter PCB

Unlike a CT that needs a burden resistor to drop a voltage proportional to the scaled voltage, the isolation transformer provides a voltage proportional to the primary voltage (i.e. the voltage drop across its associated shunt resistor). This means that no burden resistor is required.

However, just as in the case of a directly connected shunt resistor, a high-value termination resistor will help to suppress unwanted current readings. This resistor as shown as R2 in Figure 11.

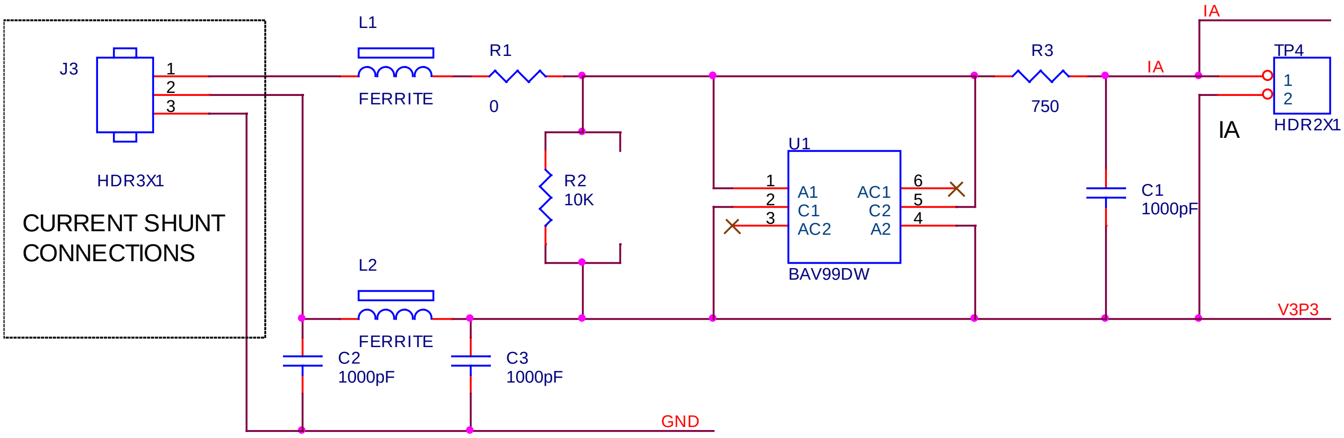


Figure 11: Input Circuit for Shunt/Shunt Configuration

Ferrites (L1, L2), capacitors (C1, C2, C3), and diodes (U1) for EMI suppression are recommended.

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