How to Detect and Harden an Electricity Meter Against Tampering by Neutral Disconnection

Mekre Mesganaw
Systems Engineer
Grid Infrastructure
Texas Instruments

Energy theft poses a significant challenge in the utility industry and can financially impact both utility companies and end consumers

Accurately billing consumers for their electricity use requires that electricity meters measure energy consumption under normal operation and detect possible tampering to help prevent electricity theft.

Energy can be stolen through different meter tampering techniques to prevent meters from accurately registering consumption. One technique disconnects the neutral from a meter and connects the consumer's load to earth instead. Hardening electricity meters against this technique is a proactive approach to reduce tampering and help prevent theft. Electricity meters must be able to either detect neutral disconnections and other types of tampering, or be hardened to prevent energy theft.

Before going into the neutral removal tamper technique, it is important to understand how a smart electricity meter works and how it is connected. **Figure 1** shows an example connection of a single-phase electricity meter. The electricity meter is primarily powered from mains, which is provided between the line and neutral connections. In this configuration, the voltage between Line_In and Neutral_In and the current sensed across a shunt connected between Line_In and Line_Out calculate the energy consumption.

The sum of the voltage current product helps calculate the active power. Active power is also equivalent to the product of the root-mean-square (RMS) voltage and the RMS current multiplied by the cosine of the angle between the voltage and current. The meter accumulates active power over time to generate the active energy readings, which become the quantity for which the consumer is billed.
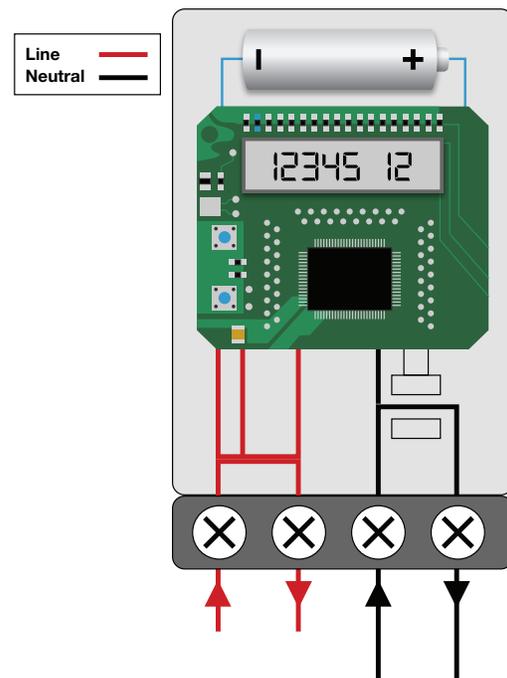

Figure 1. Example electricity meter configuration under normal operation.

Consumers can alter active energy readings in single-phase meters by disconnecting the neutral wire, as shown in **Figure 2** on the following page. If the neutral is disconnected, the voltage measured would be 0 V, which would lead to a 0-W measured value for active power. With the neutral missing, the main AC/DC is no longer functional, so the meter will require a backup power supply such as a coin-cell battery. Although the active power reading is 0 W because of the 0-V reading, there would still be current flowing through the line wire that could be

sensed. The presence of this line current can help identify a power outage from the neutral of a meter being disconnected.
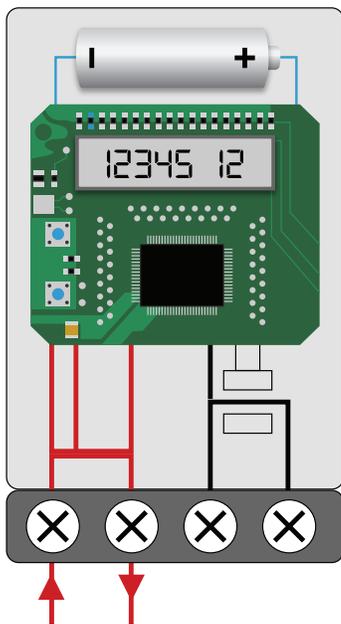

Figure 2. Example electricity meter configuration with neutral disconnected.

Power-supply considerations for missing neutral in a single-phase meter

In the event of a single-phase meter neutral disconnect, the meter's power supply should have a mechanism to automatically switch from the main AC/DC power supply to the backup power supply. This mechanism should kick in either when there is a power outage or when the neutral has been disconnected. One common way to enable automatic switching from the main power supply to the backup power supply is to use diodes to OR the AC/DC output with the backup power supply so that the higher-voltage power supply is used as the system's power source. Because the voltage from the backup power supply will gradually decrease over time until it falls below the minimum voltage needed to power the meter, the selected diodes should

have as low of a forward voltage drop as possible to extend the lifetime of the backup power supply. An ideal diode device like the **LM66100** provides this low voltage drop to maximize the lifetime of backup power supplies. The low voltage drop and low current consumption of the LM66100 enable a longer lifetime for a backup power supply than other types of diodes, such as a Schottky diode.

In addition to being able to automatically switch from the AC/DC power supply to a backup power supply, the meter should detect whether the AC/DC is about to fail. It can detect a potential failure by measuring the input voltage associated with the AC/DC's regulator, which would decrease due to either a power outage or someone disconnecting the neutral. The meter's microcontroller uses this early detection of AC/DC failure to finish any last-minute tasks before entering low-power mode in order to prolong the lifetime of the backup supply to which the meter will switch. A low-power voltage detector circuit and external voltage divider can together monitor the input voltage of the voltage regulator for this early detection.

A second option for the early detection of AC/DC failure is to use a power-supply device like the **TPS7A78**, which has a power-failure pin to provide this indication. The TPS7A78 also has a power good (PG) pin that indicates when the output voltage has ramped back up after a power outage. This indication enables the meter's microcontroller to trigger the system to exit low-power mode, since the system will eventually switch back to using the main AC/DC instead of the backup power supply.

Neutral removal anti-tamper technique: Estimating active power

One way to address the missing neutral is to calculate an estimate of the active power by

multiplying the RMS current (as measured from the line channel) by the region's nominal RMS voltage value (as an example, the nominal voltage is 230 V in India and many places in Europe). As I mentioned earlier, the actual active power is equal to the product of the RMS voltage and RMS current multiplied by the cosine of the angle between the voltage and current. Based on this equation for active power, the estimated active power includes the following assumptions:

- The actual RMS voltage applied to the customer's load doesn't deviate too far from the region's nominal RMS.

- The angle between voltage and current is 0 degrees, which corresponds to a perfectly resistive consumer load and is the maximum active power reading possible for a given RMS current and nominal RMS voltage.

When the neutral is missing, the meter is running off a backup power supply such as a battery. As a result, it is important for the meter to enter a minimal current-consumption state in order to prolong the life of the backup battery. If the missing neutral is handled by estimating the active power, the system current consumption should be reduced by lowering the sample rate of the ADC that is used to sense current. In addition, the metrology microcontroller and ADC should be configured from normal operating mode to a low power mode that will still enable the ADC to sense the line current.

For example, the **ADS131M04** standalone ADC has three power modes when in continuous conversion mode: high-resolution mode, low-power mode and very-low-power mode. High-resolution mode provides the best accuracy, while very-low-power mode provides the lowest current consumption. Based on these two modes, the ADS131M04 can be configured to be in high-resolution mode when the neutral is connected and the system is running off the meter's main power supply. Once

the neutral disconnects, the ADS131M04 allows the system to move from high-resolution mode to very-low-power mode to reduce the ADS131M04's current consumption.

Neutral removal anti-tamper technique: Current detection mode

Another way to address the missing neutral is to only detect the presence of current on the line. This method of dealing with the missing neutral consumes less current than estimating the active power. The reduced current consumption of this anti-tamper technique prolongs the lifetime of the backup power supply, which should at least equal the meter's expected lifetime.

Some ADCs have a special low-power mode that detects current on the line channel while further reducing the system's current consumption. An example of this low-power mode for sensing line current is the current detection mode of the ADS131M04 standalone ADC, which is a special mode where the ADS131M04 asserts its ($\overline{DRDY}$) pin if a certain number of samples are above a user-defined threshold. By performing this current detection mode on the channel used to measure line current, the ($\overline{DRDY}$) notification will indicate that line current has been detected, which will differentiate power outage from a disconnected neutral. **Figure 3** on the following page shows the process specifically followed by the ADS131M04 in current detection mode.

To enter current detection mode, a command is sent to the ADS131M04 to enter standby mode, which is a low-power mode where the device is not converting samples. Once the ADS131M04 is in standby mode, a negative pulse on the SYNC pin will cause the device to enter current detection mode. A microcontroller timer can produce this negative pulse so that the microcontroller does not have to wake up if it is in a sleep mode. The
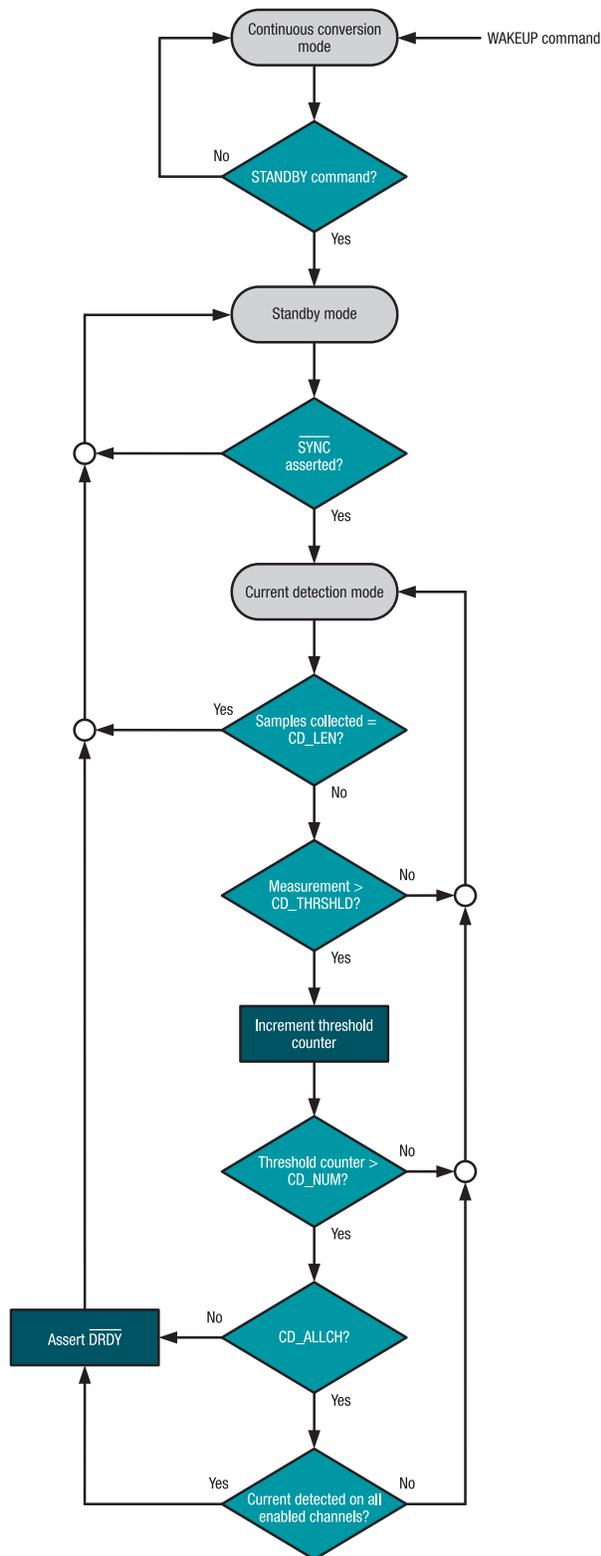
Continuous conversion mode ← WAKEUP command

No

STANDBY command?

Yes

Standby mode

$\overline{\text{SYNC}}$ asserted?

Yes

Current detection mode

Yes — Samples collected = CD_LEN?

No

Measurement > CD_THRSHLD? — No

Yes

Increment threshold counter

Threshold counter > CD_NUM? — No

Yes

Assert $\overline{\text{DRDY}}$ ← No — CD_ALLCH?

Yes

Yes — Current detected on all enabled channels? — No

Figure 3. *The current detection mode flow chart of the ADS131M04.*

microcontroller does not have to output an external clock for the sampling to occur in current detection mode (like it does for continuous conversion mode); thus, the microcontroller can enter a low-power sleep mode. The ADS131M04 runs off an internal oscillator when in current detection mode so that the ADC can function independently of the metrology microcontroller, enabling the microcontroller to enter sleep mode and reduce system current consumption.

In current detection mode, the ADS131M04 collects a configurable number of samples (CD_LEN) at 2.7 ksps and compares the absolute value of the results to a programmable threshold (CD_THRSHLD). If a configurable number of the samples (CD_NUM) within the sample window (CD_LEN) exceed the threshold (CD_THRSHLD), the ADC's assertion of its ($\overline{\text{DRDY}}$) pin notifies the host metrology microcontroller. The ADC then immediately goes back to standby mode after the ($\overline{\text{DRDY}}$) pin assertion, as shown in **Figure 4** on the following page. If the configurable number of samples within the sample window does not exceed the threshold, the ADS131M04 goes back to standby mode after the ADS131M04 collects the full sample window.

In TI's "**One-phase shunt electricity meter reference design using standalone ADCs**," the ADS131M04's current detection mode distinguishes a missing neutral from a power outage condition by following the sequence of events shown in **Figure 5** on the following page. The reference design uses a TPS7A78 capacitive-drop AC/DC power supply, which monitors the voltage at its PFD pin. This pin will drop when there is a power outage or neutral disconnection. Once the voltage at the PFD falls below a threshold, the PF pin indicates when there is a power failure either from an outage or neutral
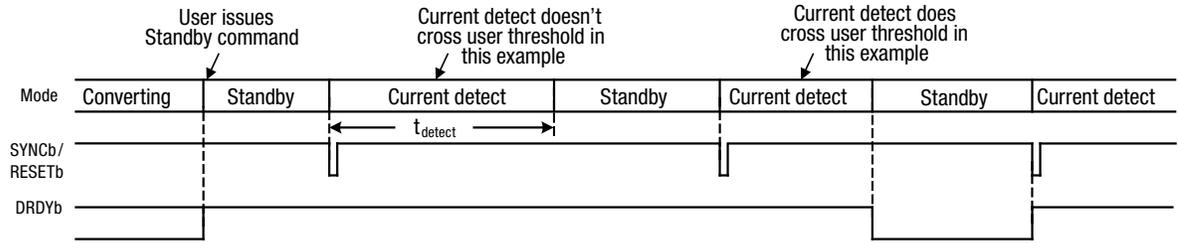
Figure 4. *ADS131M04 current detection mode examples.*

removal, which triggers the microcontroller to put the ADS131M04 into standby mode and start a timer output to regularly trigger a shift from standby mode to current detection mode. When in current detection mode, the ADS131M04 asserts its ($\overline{DRDY}$) pin if line current is detected, indicating that the source of the power failure was the removal of the neutral instead of an outage. Sometime after the power failure, the output of the AC/DC will drop until it triggers the system to run off of its backup power supply.

If the source of the power failure was from an outage, the system should configure itself back for normal operation when power is restored. In the one-phase shunt reference design, the TPS7A78's PG pin provides an alert when power is restored. When the PG pin is asserted, the design's microcontroller reverses what was done to enter current detection mode in order to return to normal operation. **Figure 6** on the following page shows the sequence of events after restoring power.

Using the reference design, I measured the ADS131M04 average current consumption with current detection mode enabled using these test settings:
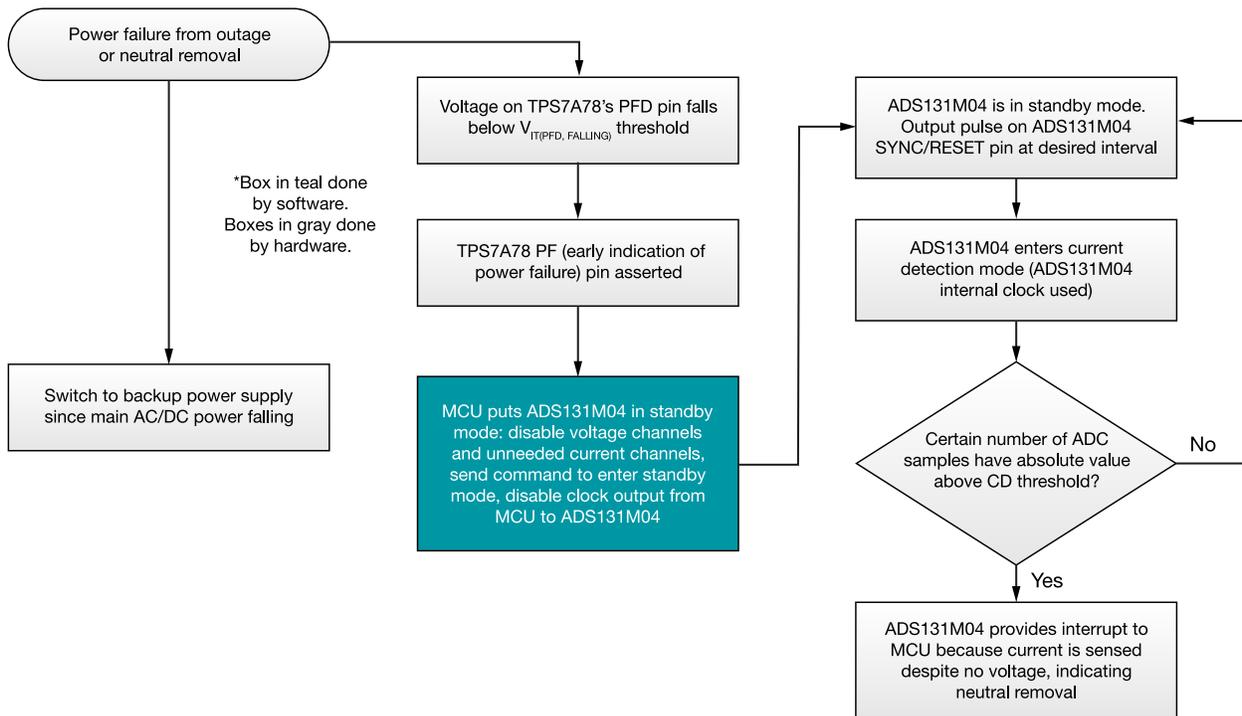
Figure 5. *Sequence of events after power failure.*
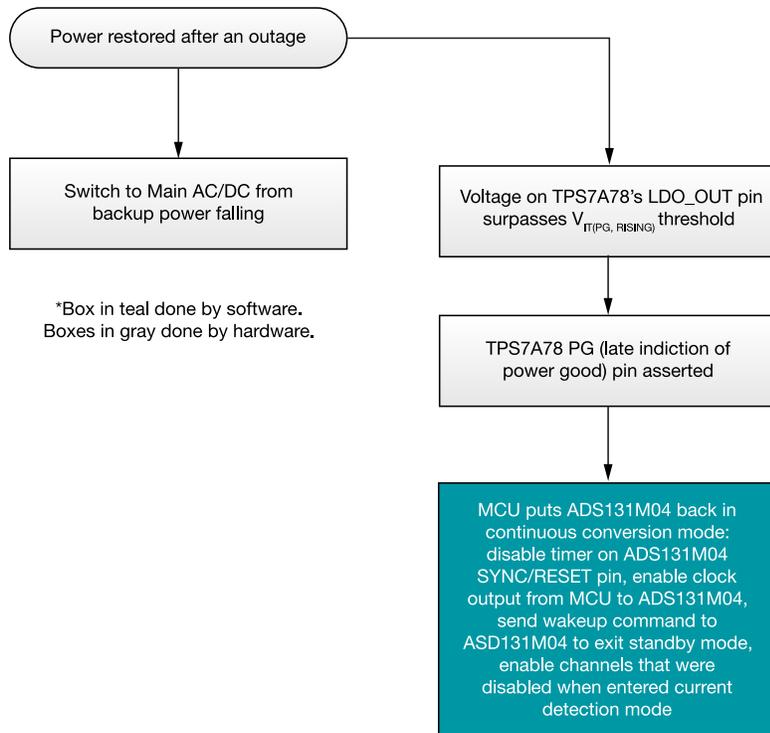
Figure 6. *Sequence of events after power restoration.*

- Channels with current detection mode enabled = Channel 1 (neutral current channel with current transformer) and Channel 2 (line current channel with shunt). ADC offset subtracted out on both of these enabled channels; Channels 0 and 3 disabled.

- Threshold (CD_THRSHLD) = 80,000 ADC units.

- Sample window (CD_LEN) = 256.

- Number of samples that require an absolute value greater than the threshold for ($\overline{DRDY}$) to be asserted (CD_NUM) = 8.

Figure 7 shows the measured ADS131M04 current consumption when current detection mode is triggered once every 10 seconds ($t_{CD\_mode\_period}$ = 10 s) and once every 64 seconds ($t_{CD\_mode\_period}$ = 64 s). When triggering current detection mode once every

10 seconds, the average current consumption over this 10-second duration was 7.51 μA. When triggering current detection mode once every 64 seconds, the average current consumption over this 64-second duration was 2.399 μA. For both trigger rates, the system is only in current detection mode for a maximum time of 95.453 ms. The rest of the time, the ADS131M04 is in standby mode.

For the results in **Figure 7**, current detection mode enters on both the line current and neutral current channels. The number of channels used in current detection mode affects the current consumption of the device in current detection mode. If enabling current detection mode only on one ADC channel— specifically the line current channel—the average current consumption in **Figure 7** could be reduced further (as shown in **Figure 8** on the following page). In addition, the sample window in **Figure 7** is set to 256, which corresponds to more than

	Current consumption	Duration estimate
Standby mode	1.452 μA	$t_{CD\_mode\_period}$ − 95.453 ms
Current detection (CD) mode	636.155 μA	95.453 ms
Average current consumption when $t_{CD\_mode\_period}$ = 10 s	7.510 μA	Standby duration = 9,904.548 ms CD duration = 95.453 ms
Average current consumption when $t_{CD\_mode\_period}$ = 64 s	2.399 μA	Standby duration = 63,904.548 ms CD duration = 95.453 ms

Figure 7. *Average current consumption in current detection mode.*

Current detection mode: Current consumption vs. number of enabled channels

Channels enabled	Current detection mode current	Average current estimate at $t_{CD\_mode\_period} = 10$	Average current estimate at $t_{CD\_mode\_period} = 64$
2 (ch 1 and 2)	626.822 µA	7.421 µA	2.385 µA
2 (ch 0 and 1)	565.645 µA	6.837 µA	2.293 µA
1 (ch 2)	386.59 µA	5.128 µA	2.026 µA
1 (ch 1)	397.716 µA	5.234 µA	2.043 µA
1 (ch 0)	391.505 µA	5.175 µA	2.034 µA

Figure 8. Current consumption in current detection mode vs. number of enabled channels.

four mains cycles of data for a line frequency of 50 Hz. If the sample window length changes from 256 samples to the minimum value of 128 samples, the time spent in current detection mode would also decrease, thereby decreasing the average current consumption as well.

The results in **Figure 7** and **Figure 8** show that the ADS131M04's current detection mode is low power, which enables the distinction of a power outage from neutral removal without significantly draining the backup power supply. By using this mode, the meter can detect one form of tampering, and alert utilities about the tamper attack so that customers are billed accurately.

For more details on how to deal with other tamper techniques, or the current detection implementation on the one-phase shunt reference design, watch these training videos:

- "Anti-tamper techniques to thwart attacks on smart meters."
- "How to design 1-phase shunt electricity meters using standalone metrology ADCs."