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High Performance Analyzer

PM180

Phasor Measurement Unit

Application Note

BG0637 REV.A3

REVISION HISTORY

A1	May 2021	Release
A2	Oct 2021	Added M performance class and unit specifications
A3	June 2022	Added positive sequence phasors, CFG-3 frame and spontaneous transmission of CFG frames

Table of Contents

1 General

This document describes the operation of the PM180 phasor measurement unit (PMU). For details on setting up the PMU and its communication options, see the product documentation listed below. Use the supplied PAS software tool to configure the PMU options in your device.

The PM180 phasor measurement unit provides synchrophasor and frequency measurements compliant with the IEEE C37.118.1/1a and IEC/IEEE 60255-118-1:2018 P and M performance classes, and real-time cyclic exchange of synchrophasor data with the substation phasor data concentrator (PDC) based on the IEEE C37.118.2 synchrophasor data transfer protocol or via the IEC 61850-9-2 sampled values (SV) service.

PMU features:

- IEEE C37.118.1-2011, IEEE C37.118.1a-2014 and IEC/IEEE 60255-118-1:2018 P and M class performance compliance
- IEEE C37.118.1 three-phase voltage and current phasor measurements synchronized to a common UTC time reference, e.g. GPS
- IEEE C37.118.1 synchronous frequency and rate of change of frequency (ROCOF) measurements
- Clock synchronization to a common UTC time reference using an IRIG-B timecode source or an IEEE 1588 PTPv2 master clock source
- IEEE C37.118.2 commanded client-server UDP and TCP data transmission and spontaneous UDP data transmission over IP protocol
- Optional IEEE C37.118.2 frame extensions with analog data (total active, reactive and apparent power and power factor) and digital status data (up to 32 inputs)
- Streaming of phasor data over Ethernet using the IEC 61850-9-2 multicast sampled value (SV) service with IEEE C37.118.2 compliant mapping of synchrophasor data upon IEC 61850-9-2 and IEC 61850-90-5 guidelines

Reference documents:

IEEE Std C37.118.1-2011, IEEE Standard for Synchrophasor Measurements for Power Systems

IEEE Std C37.118.1a-2014, IEEE Standard for Synchrophasor Measurements for Power Systems, Amendment 1: Modification of Selected Performance Requirements

IEEE Std C37.118.2-2011, IEEE Standard for Synchrophasor Data Transfer for Power Systems

IEC/IEEE 60255-118-1:2018, Measuring relays and protection equipment – Part 118-1: Synchrophasor for power systems – Measurements

IEC/TR 61850-90-5:2012, Communication networks and systems for power utility automation – Part 90-5: Use of IEC 61850 to transmit synchrophasor information according to IEEE C37.118

Product documentation:

BG0521 PM180 Installation Manual

BG0525 PM180 Operation Manual

BG0627 PM180 IEEE C37.118.2 Reference Guide

BG0523 PM180 IEC 61850 Reference Guide

BG0527 PM180 Modbus Reference Guide

Definitions and acronyms:

Phasor - a complex equivalent of a sinusoidal wave quantity such that the complex modulus is the cosine wave amplitude, and the complex angle (in polar form) is the cosine wave phase angle

Synchrophasor - a phasor calculated from data samples using a standard time signal as the reference for the measurement

APDU - application protocol data unit

APPID - application identifier

ASDU - application service data unit

ASN.1 - Abstract syntax notation number one

BER - ASN.1 basic encoding rules

PDC – phasor data concentrator

PMU – phasor measurement unit

SV - sampled value

2 PMU Installation

The PMU is implemented as an add-on card integrated in one assembly with the fast transient recorder module.

The PMU module may be located in any of the PM180 expansion slots.

Input voltages must be connected to the module terminals V1, V2, V3 and VN. Current signals are delivered from the common AC inputs via the PM180 backplane. Follow common grounding rules in the PM180 Installation Manual.

NOTE: Make sure you have the correct ABC phase sequence as frequency measurements are based on positive sequence signals. If you are using reverse CBA phase order, make the appropriate adjustment in the PM180 Basic Setup, otherwise the unit will not be able to measure frequency.

If an IRIG-B time source is used for UTC time synchronization, connect the IRIG-B signal wires to the 1pps/CM terminals on the PM180 CPU module.

In case the IEEE 1588 master clock is used as UTC source, connect the network cable directly to the PMU IEEE 1588 Ethernet port.

NOTE: The IEEE 1588 PMU port must be connected to an IEEE 1588 grandmaster clock through a PTPv2 peer-to-peer transparent clock switch compliant with IEEE Std 1588-2008.

PMU operation is indicated by the “PMU OK” LED on the front of the PMU, which flashes yellow ones a second when the PMU clock is not in sync with the UTC/IRIG-B clock, and flashes green when synchronized.

3 Measuring Techniques

3.1 Synchrophasor Estimation

The PMU calculates and reports synchrophasor estimates as defined and described in IEEE C37.118.1 Clause 4.

The estimates include three-phase voltage and current synchrophasors calculated from the input signal waveforms synchronized to an absolute time reference, followed by complex multiplication with the nominal frequency carrier, i.e., multiplication of the input by the quadrature oscillator (sine and cosine).

All measurements are made on a common time base and related to the system nominal frequency, so the phase angle measurements are directly comparable. Differences in the actual frequency are included in the phase angle estimation. A precise time reference clock is used to provide the UTC time to determine the phase angle.

3.2 Frequency and ROCOF Estimation

The frequency is computed as the first derivative of the synchrophasor phase angle, and ROCOF is computed as the second derivative of the same phase angle.

The frequency and ROCOF estimates are based on positive sequence synchrophasors calculated using the symmetrical components transformation. Since phase angle changes relative to the difference between the actual frequency and the nominal frequency, this approach yields the offset from nominal.

3.3 Reporting Rates

The PMU supports data reporting at sub-multiples of the nominal system frequency. The actual reporting rate is user selectable.

The available rates are listed in the following table.

Table 3-1 PMU reporting rates

System frequency	50 Hz						60 Hz											
Reporting rates (frames/s)	1	2	5	10	25	50	1	2	3	4	5	6	10	12	15	20	30	60

4 Time Synchronization

The PMU must be connected to a reliable and accurate GPS time source, that can provide time traceable to UTC so all measurements are synchronized to UTC time with accuracy sufficient to meet the requirements of IEEE C37.118.1.

The PMU clock can be synchronized to UTC using an IRIG-B timecode source or an IEEE 1588 PTPv2 master clock source.

4.1 IRIG-B Time Synchronization

When using an external IRIG-B time source, connect the IRIG-B signal wires to the 1pps/CM terminals on the PM180 CPU module.

The PM180 IRIG-B port uses an unmodulated (pulse-width coded) timecode signal (unbalanced 5V level) according to the IRIG 200-04 standard. It supports B000/B001 and B004/B005 timecode formats with time code extentions specified for the IRIG-B profle in Annex D of IEEE Std C37.118.1-2011.

The PMU IRIG-B port can synchronize to the IRIG-B timecode source with sub-microsecond accuracy.

To enable the IRIG-B port as a UTC source, select the IRIG-B time synchronization option in the IEEE C37.118.2 setup (see the PM180 IEEE C37.118.2 Reference Guide for details).

NOTE: The "PMU OK" LED on the PMU module flashes yellow ones a second when the PMU clock is not in sync with the UTC/IRIG-B clock, and flashes green when synchronized.

4.2 PTPv2 Time Synchronization

To use the IEEE 1588 master clock as UTC source, your PMU must be provided with the IEEE 1588 Ethernet port.

The IEEE 1588 PMU port must be connected to an IEEE 1588 grandmaster clock through a PTPv2 peer-to-peer transparent clock switch compliant with IEEE Std 1588-2008.

The IEEE 1588 PMU port implements the ordinary PTPv2 clock, complying with the IEEE Std 1588-2008 standard, and uses the following PTP profile:

1. PTP version 2.
2. PTP transport over Layer 2 Ethernet (IEEE 802.3), IEEE 1588-2008, Annex F.
3. Multicast addressing.
4. Peer-to-peer (P2P) path delay measurement mechanism.
5. Capable of working with one-step and two-step master clocks.
6. Responds to peer path delay requests with two-step peer delay responses (Pdelay_Resp, Pdelay_Resp_Follow_Up messages).

The IEEE 1588 PMU port can synchronize to the PTP grandmaster clock with sub-microsecond accuracy, which can be degraded by network topology, PTP switch accuracy, or transmission media asymmetry.

To enable the IEEE 1588 port as UTC source, select the IEEE 1588 time synchronization option in the IEEE C37.118.2 setup, and configure the port network addresses (see the PM180 IEEE C37.118.2 Reference Guide for details).

NOTE: The "PMU OK" LED on the PMU module flashes yellow ones a second when the PMU clock is not in sync with the IEEE 1588 grandmaster clock, and flashes green when synchronized.

The PMU comes with a Telnet server that can be used to check the PMU clock status and time accuracy. Connect with a Windows Telnet client to the PMU using the IP address of the IEEE 1588 PMU port, login with the password "1588" and enter "ptp". Figure 4-1 shows an example of the PMU clock status printout.

```
Telnet 192.168.0.204
grandmaster_identifier                 DFLT
grandmaster_priority_1                 128
grandmaster_priority_2                 128
grandmaster_clock_class                6
grandmaster_clock_variance             18465
grandmaster_clock_accuracy             0x21, time accurate within 100 ns
ptp_timescale                          true
time_traceable                         true
current_utc_offset                     37
utc_offset_valid                       true
leap_59                                false
leap_61                                false
epoch_number                           0
last_sync_sequence_number              197
last_origin_timestamp                  1614233543.259591937 s TAI
                                       2021-02-25 06:11:46 UTC

PMU clock
=========
port_state                             SLAVE
port_clock_identity                    00:05:f0:ff:fe:f0:00:05
port_id                                1
port_subdomain_number                  0
last_pdelay_request_sequence_number    65
last_pdelay_response_sequence_number   65
peer_mean_path_delay                   25 ns
offset_from_master                     -17 ns
clock_status                           locked to a UTC source

>_
```

Figure 4-1 PMU PTP clock status information

5 PMU Communications

5.1 IEEE C37.118.2 Communications

The PMU IEEE C37.118.2 protocol implementation is user configurable, making it easy to adapt for use in different installations. See the PM180 IEEE C37.118.2 Reference Guide for more details on operating and configuring IEEE C37.118.2.

To keep maximum interoperability with phasor data concentrators (PDC) and controlling stations, the PM180 supports all standard frame types for synchrophasor data interrogation and streaming.

The synchrophasor data is transmitted at a programmable reporting rate of 1 to 60 frames per second at sub-multiples of the nominal power line frequency.

The data stream ID number assigned to the PMU via the IEEE C37.118.2 setup uniquely identifies a synchrophasor data stream. Only requests with the matching data stream ID are responded by the PMU.

5.1.1 Unicast Commanded UDP and TCP Data Transmission

Commanded data transmission must be explicitly turned on by a command sent by a client to receive synchrophasor data via a unicast UDP or TCP connection.

The PM180 PMU provides 5 data streaming slots for continuous streaming synchrophasor data via unicast UDP or/and TCP connections.

5.1.2 Spontaneous UDP Data Transmission

Spontaneous synchrophasor data transmission is explicitly enabled and disabled by the user via the IEEE C37.118.2 setup. The destination UDP port and IP address are configurable.

Spontaneous UDP data transmission operates in unicast, multicast or broadcast mode depending on the specified destination IP address.

5.1.3 IEEE C37.118.2 Message Frames

Data Frames

Synchrophasor data frames transmit a time stamped set of measurements that include phasor estimates, frequency deviation from the nominal power line frequency and the rate of change of frequency. In addition, the data frame can be expanded to contain analog data (total active, reactive and apparent power, and power factor) and digital input status information (up to 32 inputs can be included).

The phasor data can represent single phase phasors (tree phase voltage and tree phase currents) or 3-phase positive sequence voltage and current, or both in a single frame.

The complex phasor values can be sent in a rectangular coordinates format (real and imaginary) or in polar coordinates (magnitude and angle). The phasor and frequency data can be represented in 32-bit IEEE floating-point format or as 16-bit scaled integer numbers. In case of using integer format, the data conversion factors are provided via the IEEE C37.118.2 configuration frames.

Configuration Frames

IEEE C37.118.2 configuration frames provide information about the synchrophasor data stream in binary format. The PM180 PMU supports CFG-1, CFG-2 and CFG3 configuration frames. The configuration frame contents correspond to the specification given by IEEE C37.118.2.

Configuration frames CFG-2 or CFG-3 can be sent spontaneously without the explicit user command. If enabled, the configuration frame is sent once before start of transmission in unicast UDP/TCP modes, and periodically every 30 s in multicast/spontaneous UDP mode.

Phasor and channel names are listed in Table 5-1.

Table 5-1 Phasor and channel names

Channel name	Description
VA	V1 phase phasor
VB	V2 phase phasor
VC	V3 phase phasor
IA	I1 phase phasor
IB	I2 phase phasor
IC	I3 phase phasor
V1	Positive sequence voltage phasor
I1	Positive sequence current phasor
P	Active power analog channel
Q	Reactive power analog channel
S	Apparent power analog channel
PF	Power factor analog channel
DI1	Digital channel 1
DI2	Digital channel 2
…	
DI32	Digital channel 32

Header Frame

A header frame gives information about the synchrophasor data stream in human-readable format.

5.2 IEC 61850 Communications

5.2.1 PMU Data Model

Synchrophasor data transfer in the context of IEC 61850 uses IEEE C37.118 to IEC 61850 mapping mechanism defined in IEC 61850-90-5.

PMU is modeled as a dedicated logical device within the PM180 IED. The detailed PMU data model is shown as a part of the ICD definition file provided with your device.

The PMU logical device is responsible for the publishing of the synchrophasor measurements as defined in IEEE C37.118.2. It includes:

a) MMXU measurement logical node that represents voltage and current synchrophasor data, frequency and ROCOF measurements; the new data object of HzRte is added to the MMXU logical node to accommodate the ROCOF data.

b) LTIM time management logical node that gives indication of the local time configuration and status, like offset of local time from UTC and the flag indicating if daylight saving time is in effect.

c) LTMS time master supervision logical node that is used for supervision of the time synchronization function; it indicates the current time source and time synchronization status according to IEC 61850-9-2.

5.2.2 Encoding Phasor Data in Multicast SV APDU

IEEE C37.118.2 synchrophasor data stream is mapped to IEC 61850-9-2 sampled values APDU (application protocol data unit). The sampled values dataset is user configurable. Encoding of the sampled values APDU frame is shown in Figure 5-1.

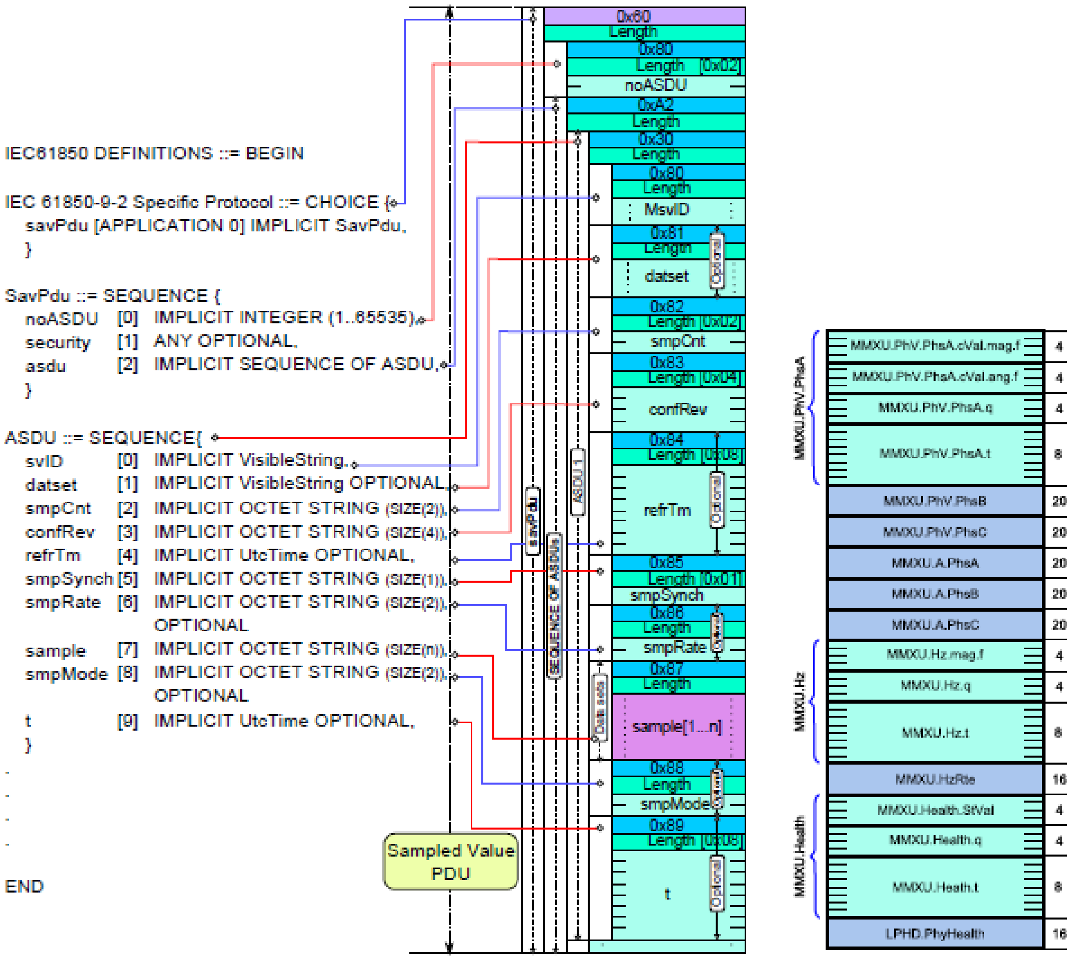

Figure 5-1 Encoding of the SV APDU frame and synchrophasor data

The APDU contains a single ASDU (application service data unit), which is encoded using ISO/IEC 8825-1 ASN.1 basic encoding rules (BER) with context-specific field tag octets listed in IEC 61850-9-2, Table 14.

Unlike other APDU attributes, a sequence of sampled phasor data is encoded as a compact block without ASN.1 tag triplets. The dataset members are encoded in their basic forms using fixed-length basic data type encoding rules listed in IEC 61850-9-2 Table 15.

The following picture shows an example of the multicast sampled values frame that carries a synchrophasor data stream over an Ethernet LAN.

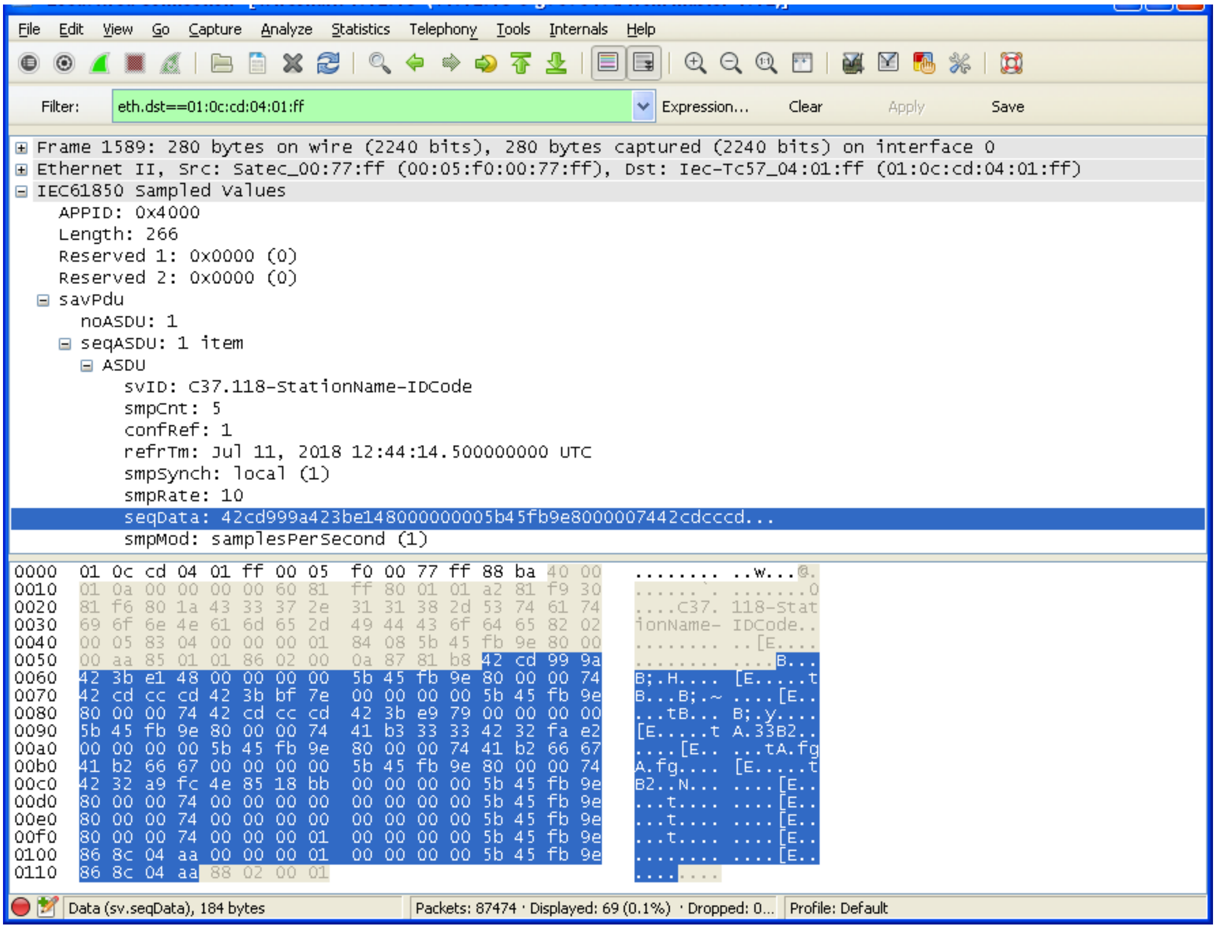

Figure 5-2 Captured synchrophasor multicast sampled values frame

5.2.3 IEC 61850 SV Publisher

The PM180 multicast SV publisher is responsible for publishing of the synchrophasor data over Ethernet. The SV publisher options and the sampled values dataset can be configured using the supplied PAS configuration software tool as described in the PM180 IEC 61850 Reference Guide.

5.3 Modbus Communications

Modbus communications is used to configure PMU parameters and monitor synchrophasor data measurements using the PAS configuration software tool or client software application.

The PM180 provides a dedicated synchrophasor data set listed in Table 5-2. For convenience of monitoring and verification, synchrophasor data is given in both polar format (magnitude and angle in arc-degree) and rectangular format (real and imaginary parts of a complex magnitude).

The bitmapped PMU time quality and frame status attributes are detailed in Table 5-3 and Table 5-4.

See the PM180 Modbus Reference Guide for the location of the synchrophasor data registers. Refer to the PM180 Operation Manual for more information on configuring datasets for monitoring with the PAS configuration tool.

Table 5-2 Modbus synchrophasor dataset

Label	Description
FrmNo	Frame number
Tm	Frame timestamp, UTC seconds since 1/1/1970
Tmmcs	Frame timestamp, fractional second
TmQual	Time quality, bitmap
IDCode	Data source/stream ID number
Stat	Frame status, bitmap
FREQ	Frequency deviation from nominal, Hz
DFREQ	Rate of change of frequency (ROCOF), Hz/s
V1 mag	V1 phasor magnitude
V1 ang	V1 phasor angle
V2 mag	V2 phasor magnitude
V2 ang	V2 phasor angle
V3 mag	V3 phasor magnitude
V3 ang	V3 phasor angle
I1 mag	I1 phasor magnitude
I1 ang	I1 phasor angle
I2 mag	I2 phasor magnitude
I2 ang	I2 phasor angle
I3 mag	I3 phasor magnitude
I3 ang	I3 phasor angle
V1 Re	V1 phasor, Real
V1 Im	V1 phasor, Imaginary
V2 Re	V2 phasor, Real
V2 Im	V2 phasor, Imaginary
V3 Re	V3 phasor, Real
V3 Im	V3 phasor, Imaginary
I1 Re	I1 phasor, Real
I1 Im	I1 phasor, Imaginary
I2 Re	I2 phasor, Real
I2 Im	I2 phasor, Imaginary
I3 Re	I3 phasor, Real
I3 Im	I3 phasor, Imaginary
V1seq mag	Positive sequence voltage phasor magnitude
V1seq ang	Positive sequence voltage phasor angle
I1seq mag	Positive sequence current phasor magnitude
I1seq ang	Positive sequence current phasor angle
V1seq Re	Positive sequence voltage phasor, Real
V1seq Im	Positive sequence voltage phasor, Imaginary
I1seq Re	Positive sequence current phasor, Real
I1seq Im	Positive sequence current phasor, Imaginary

Table 5-3 PMU time quality

Bits	Description
0:3	0xF = clock failure, time not reliable 0xB = time within 10 s 0xA = time within 1 s 0x9 = time within 10 s 0x8 = time within 0.1 s 0x7 = time within 0.01 s 0x6 = time within 1 ms 0x5 = time within 0.1 ms 0x4 = time within 0.01 ms 0x3 = time within 100 ns 0x2 = time within 10 ns 0x1 = time within 1 ns 0x0 = locked to UTC traceable source
4	Leap second pending
5	Leap second occurred
6	Leap second direction, 0 = add, 1=delete

Table 5-4 PMU frame status

Bits	Description
0:3	Trigger reason
4:5	Unlocked time: 0 = sync locked or unlocked time < 10 s (best quality) 1 = unlocked time < 100 s 2 = unlocked time <= 1000 s 3 = unlocked time > 1000 s
6:8	PMU time quality (see F39)
9	1 = data modified by post processing, 0 = otherwise
10	Configuration change, set to 1 for 1 min to advise configuration will change, and cleared to 0 when change effected
11	1 = PMU trigger detected, 0 = no trigger
12	Data sorting, 0 = by timestamp, 1 = by arrival
13	0 = PMU in sync with a UTC traceable time source
14-15	Data error: 0 = good measurement data 1 = PMU error (no information about data) 2 = PMU in test mode or absent data tags inserted (do not use values) 3 = PMU error (do not use values)

6 Measurement Specifications

Table 6-1 Input ratings

Inputs	Parameter	Value
Voltage	Rated voltage	100-120 V phase-to-phase/57.7-69.3 V phase-to-neutral
	Measurement range	1-480 V phase-to-neutral
Current	Rated current	1 A or 5 A (upon order)
	Measurement range	0.1-400 % (4x) rated current

Table 6-2 Measured frequency range

Performance class	Nominal frequency	Data reporting rate (Fs), frames/s	Frequency range
P	50 Hz	1, 2, 5, 10, 25, 50	50 +/-2 Hz
	60 Hz	1, 2, 3, 4, 5, 6, 10, 12, 15, 20, 30, 60	60 +/-2 Hz
M	50 Hz	1, 2, 5, 10	50 +/-2 Hz
		25, 50	50 +/-5 Hz
	60 Hz	1, 2, 3, 4, 5, 6, 10	60 +/-2 Hz
		12	60 +/-2.4 Hz
		15	60 +/-3 Hz
		20	60 +/-4 Hz
		30, 60	60 +/-5 Hz

Table 6-3 P class accuracy, under steady-state conditions (80% to 120% rated voltage, 10% to 200% rated current, at 23° C)

Parameter	Conditions	Value
Frequency	Over frequency range	< 0.0005 Hz
	Over temperature range 0-50 °C	0.001 Hz
TVE, voltage	At nominal frequency	0.05%
	Over frequency range	0.1%
	Over temperature range 0-50 °C	0.2%
TVE, current	At nominal frequency, > 40% rated current	0.05%
	Over frequency range	0.1%
	Over temperature range 0-50 °C	0.2%
Phase	At nominal frequency	0.025 degree
	Over frequency range	0.05 degree
	Over temperature range 0-50 °C	0.1 degree

Table 6-4 M class accuracy, under steady-state conditions (10% to 120% rated voltage, 10% to 200% rated current, at 23° C)

Parameter	Conditions	Value
Frequency	At nominal frequency, > 40% rated voltage	< 0.0005 Hz
	Over frequency range	0.001 Hz
	Over temperature range 0-50 °C	0.001 Hz
TVE, voltage	At nominal frequency, > 60%/50Hz, > 40%/60Hz rated voltage	0.05%
	Over frequency range	0.1%
	Over temperature range 0-50 °C	0.2%
TVE, current	At nominal frequency, > 40% rated current	0.05%
	Over frequency range	0.1%
	Over temperature range 0-50 °C	0.2%

Parameter	Conditions	Value
Phase	At nominal frequency	0.025 degree
	Over frequency range	0.05 degree
	Over temperature range 0-50 °C	0.1 degree