Millisecond Rotation Pulsars as Next Generation Grid Timing Sources

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Abstract – *Time synchronized measurements of electric grid parameters provide a basis for overall system operation optimization. An examination of the use of a millisecond rotation pulsar as a grid measurement timing source is presented.*

Key Words: *electric grid, timing, pulsars*

1. Introduction

Wide-area synchronized measurement systems enable the monitoring of overall bulk power systems, such as the US transmission line network illustrated in Fig.1. Critical information is provided by such wide scale monitoring for understanding and responding to power system disturbances and cascading blackouts. An example of this critical information need arises when a significant power disturbance occurs, causing the frequency and phase angle of the power signal to vary in time and space, which, in many ways, exhibits the characteristics of electromechanical wave propagation.

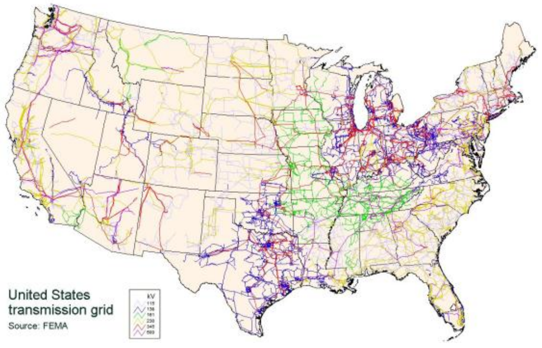

Fig. 1. Electric transmission lines (colors indicate varying voltage levels). (Source: FEMA)

According to IEEE standard C37.118.2011, the total vector error (TVE) of synchronized phasor measurements of the electric grid power waveform should be less than 1% [1]. In order to achieve measurement accuracy higher than the IEEE standard, precise time synchronization is essential for waveform sampling in grid sensors, most predominantly for Phasor Measurement Units (PMUs). Since Global Positioning System (GPS) can provide time accuracy better than 100 ns, in theory, via pulse per second (PPS) signals, it is currently used for the waveform sampling in PMUs [2,3]. Sharing a uniform time reference PPS signal enables PMUs across a wide geographical area to synchronize their clocks and therefore their measurements. Specifically, by demodulating the GPS signal, GPS receivers within PMUs can align their time with the GPS-provided time and then output a high precision PPS signal for waveform sampling. Fig 2 presents an illustration of the phase alignment situation present in a multibus electric grid. The number of devices and systems reliant on this time signal is proportional to the number of power plants (~7000) and substations (55,000) within the US electric grid [4].

Synchronized measurements of grid parameters - specifically voltage, frequency and phase – can provide the basis for optimization of overall grid operations.

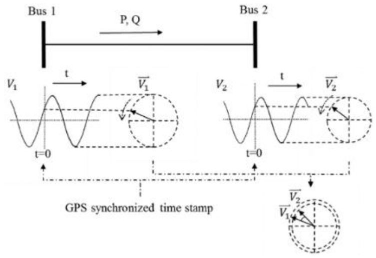

Fig. 2. Phase alignment of two grid buses.

Fig 3 illustrates the grid network architecture where automated reclosers are in use. Having the capability to accurately measure the phase of the electric signal being supplied from substations 1 and 2 (in Fig 3) allows the system operation to respond to outages via opening and closing such switches in an optimal manner.

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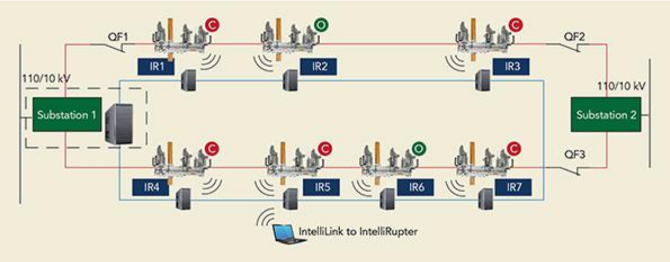


Fig. 3. "Standard" automated recloser network architecture.

The question arises as to appropriate time sources as replacements or back-ups to GPS.

2. Grid Applications and Timing Requirements

There are other parameters besides the phase of the electric signal that are measured directly (or computed based on measurements) for optimal grid operations. The timing requirements for a variety of such measurements are displayed in Fig 4. Note that as the electric grid operates at electromechanical speeds, there are potential applications that would be characterized as operating at electromagnetic speeds.

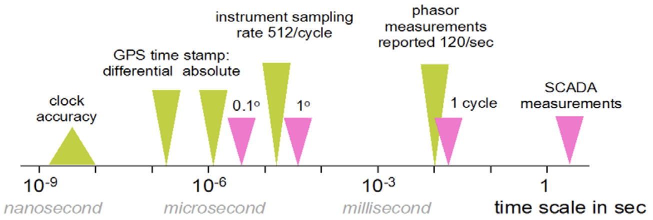


Fig. 4. Various timing needs for grid applications.

The measurement fidelity of a parameter wave moving through a location field, Fig 5, such as that associated with an operational electrical grid, is based on the measurements taken and mathematical analytical processes applied. The possibility of having sensor suites capable of measuring multiple parameters – with the requisite associated high resolution geolocation and time stamped information – gives rise to various application scenarios.

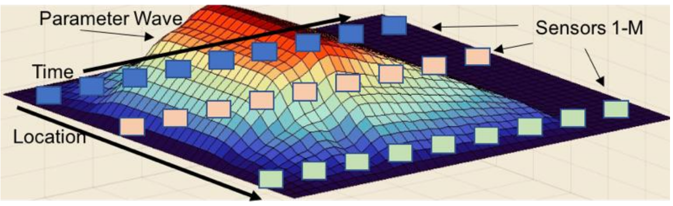
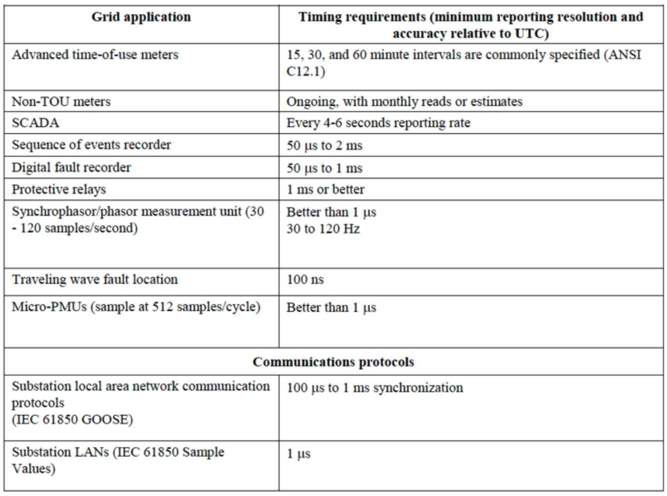


Fig. 5. A parameter wave moving across an array of sensors.

While the notion of correlating measurements taken at different times and locations is hardly new and crosses into the realm of sensor/data fusion[1] [5], having measurements with accurate geolocation and time stamped metadata provides a basis for a variety of mathematical tools to be applied in the analysis – both trends and predictions – of seemingly disparate information sets.

Table 1 presents a list of grid applications and the associated timing requirements. A detailed description of such – and related – applications is available [6].



Grid application	Timing requirements (minimum reporting resolution and accuracy relative to UTC)
Advanced time-of-use meters	15, 30, and 60 minute intervals are commonly specified (ANSI C12.1)
Non-TOU meters	Ongoing, with monthly reads or estimates
SCADA	Every 4-6 seconds reporting rate
Sequence of events recorder	50 µs to 2 ms
Digital fault recorder	50 µs to 1 ms
Protective relays	1 ms or better
Synchrophasor/phasor measurement unit (30 - 120 samples/second)	Better than 1 µs 30 to 120 Hz
Traveling wave fault location	100 ns
Micro-PMUs (sample at 512 samples/cycle)	Better than 1 µs
Communications protocols	
Substation local area network communication protocols (IEC 61850 GOOSE)	100 µs to 1 ms synchronization
Substation LANs (IEC 61850 Sample Values)	1 µs

Table 1. Grid applications and associated timing requirements [6].

Table 2 presents many of the same grid applications shown in Table 1, but adds the method of timing distribution as well as the timing source most frequently used.

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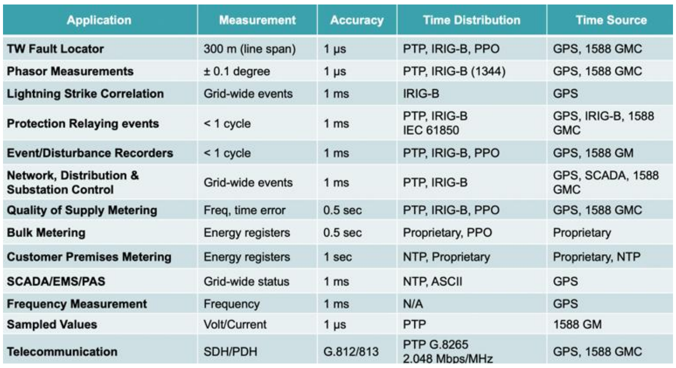
[1] The following data fusion description has been extracted from New World Vistas: Air and Space Power for the 21st Century, Chapter 3 (accessed at http://www.au.af.mil/au/awc/awcgate/vistas/vistas.htm): "…there is a greater demand to expand the dimensionality of sensed information acquired—driving the need for multiple sensors and the combination of that data. This demand to expand the time and space dimensionality of sensed data adds two important themes to New World Vistas: (1) sensors must be designed to be integrated and coordinated to maximize the overall system measurement process, and (2) processes are required to efficiently and accurately correlate and fuse data from a variety of sensors."



Application	Measurement	Accuracy	Time Distribution	Time Source
TW Fault Locator	300 m (line span)	1 μs	PTP, IRIG-B, PPO	GPS, 1588 GMC
Phasor Measurements	± 0.1 degree	1 μs	PTP, IRIG-B (1344)	GPS, 1588 GMC
Lightning Strike Correlation	Grid-wide events	1 ms	IRIG-B	GPS
Protection Relaying events	< 1 cycle	1 ms	PTP, IRIG-B IEC 61850	GPS, IRIG-B, 1588 GMC
Event/Disturbance Recorders	< 1 cycle	1 ms	PTP, IRIG-B, PPO	GPS, 1588 GM
Network, Distribution & Substation Control	Grid-wide events	1 ms	PTP, IRIG-B	GPS, SCADA, 1588 GMC
Quality of Supply Metering	Freq, time error	0.5 sec	PTP, IRIG-B, PPO	GPS, 1588 GMC
Bulk Metering	Energy registers	0.5 sec	Proprietary, PPO	Proprietary
Customer Premises Metering	Energy registers	1 sec	NTP, Proprietary	Proprietary, NTP
SCADA/EMS/PAS	Grid-wide status	1 ms	NTP, ASCII	GPS
Frequency Measurement	Frequency	1 ms	N/A	GPS
Sampled Values	Volt/Current	1 μs	PTP	1588 GM
Telecommunication	SDH/PDH	G.812/813	PTP G.8265 2.048 Mbps/MHz	GPS, 1588 GMC

Table 2. Grid applications and timing requirements. (PTP: Precision Time Protocol: 1588; 1588 GMC: Grand Master Clock; NTP: Network Time Protocol; SCADA: Supervisory Control Architecture and Data Acquisition)

Timing requirements in an industrial control system are similar to those for grid applications. A time source and distribution network is presented in Fig. 6. Note that in this architecture a layered approach, similar to that of ISA95 (Purdue Model), is used with appropriate cybersecurity safeguards embedded into the devices.

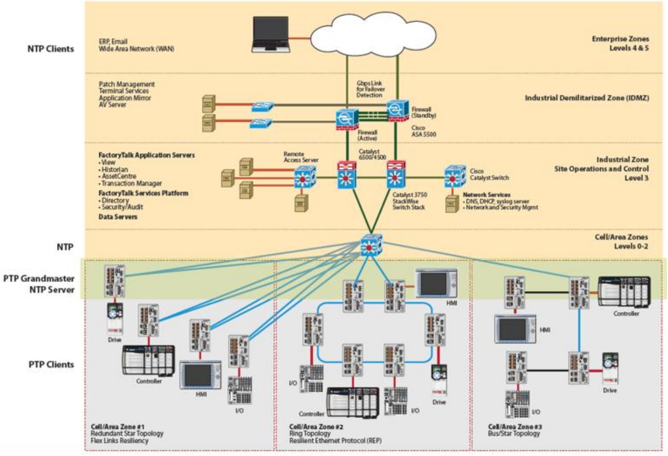


Fig. 6. Industrial automation time use and distribution network. (Source: [7])

3. Possible Space-Based Time Sources

The notion of augmenting GPS, whose satellite constellation is stationed in low earth orbit (LEO), with other space-based timing sources operating in medium earth orbit (MEO) or geosynchronous orbit (GEO) is an active endeavor. The US Federal Aviation Administration's (FAA) Wide Area Augmentation Service (WAAS) has a number of satellites in geosynchronous orbit [8]. Further studies have examined placing time source satellites in quasi-stable Earth-Moon LaGrange points L1 and L2, Fig 7.

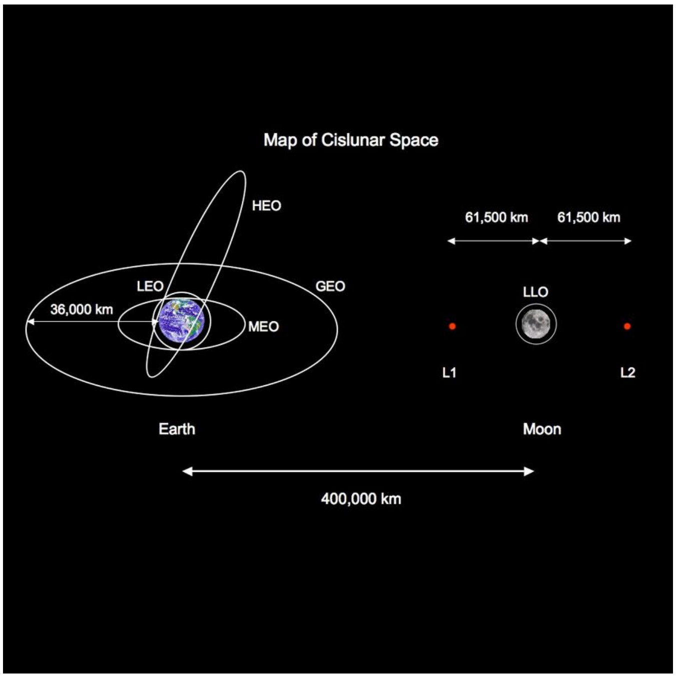


Fig. 7. Representation of satellite earth orbits and earth-moon LaGrange Points. (LEO: low earth orbit; MEO: medium earth orbit; GEO: geosynchronous earth orbits; L1 and L2 are gravitational null LaGrange points. [9]

NASA's Station Explorer for X-ray Timing and

Navigation Technology (SEXTANT) project placed an X-ray receiver onto the International Space Station (ISS), Fig 8, for determining if x-ray pulsar sources could be used for space-based position and navigation applications. SEXTANT relied on the instrument Neutron-star Interior Composition Explorer (NICER) to "*demonstrate real-time, on-board X-ray pulsar navigation, which is a significant milestone in the quest to establish a GPS-like navigation capability that will be available throughout our Solar System and beyond* [10]."

Fig. 8. Photograph of SEXTANT on the ISS. [10]

A 2016 presentation [11] described the possibility of using a multitude of LEO satellites as navigational sources. From [11]: "*New players are coming with proposals to build* *constellations of hundreds and even thousands of satellites in low Earth orbit (LEO). Their aim is delivering Internet to the world by providing global broadband coverage. We focus on how such constellations could be leveraged to carry a hosted payload, allowing them to act as navigation satellites.*". Such a situation is illustrated in Fig 9.

Fig. 9. Depiction of a grid-array of satellites. [12]

As compact and highly magnetized rotating neutron stars, pulsars emit electromagnetic radiation as they rotate [13-15]. The magnetic axis of a pulsar inclines to the rotation axis as illustrated in Fig 10, and it acts like a cosmic lighthouse emitting radio pulses that can be detected once the beam is directed towards the Earth per rotation.

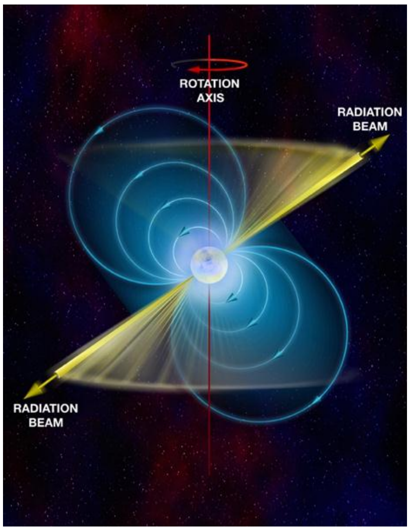


Fig. 10. A rotating neutron star, a Pulsar, functions similarly to a fast rotation lighthouse beacon.

The rotation periods of most pulsars are between 0.001 and 1.0 seconds with a deviation of less than 10^{-15} seconds per second with certain pulsars exhibiting a rotation period variation of less than 10^{-18} seconds [16-26]. This makes pulsars a viable timing signal source - a natural cosmic clock - in terms of precision and long-term stability as shown in Fig. 11 [27].

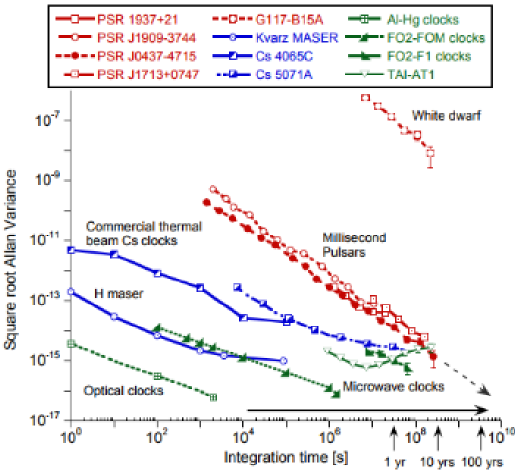


Fig. 11. Comparison between pulsar timing and other clocks [28].

Of particular note are millisecond rotation pulsars (MRPs) for these fast rotation neutron stars radiate a highly repeatable signal. The signal-to-noise ratio (SNR) guiding the detection of the MRP signal with period P and pulse width W is provided as Equation 1.

$$SNR_{avg} = \frac{S_{av}\,A_{eff}}{k\,T_{sys}}\,\frac{P}{W}\,\sqrt{B\tau_s}\,\sqrt{N_p} \qquad \text{Eq.1}$$

Where Sav is the time average flux being detected using a radio telescope of effective aperture A_{eff}. T_{sys} is the system temperature, using bandwidth B and time constant τ_s, width N_p pulses being measured [29].

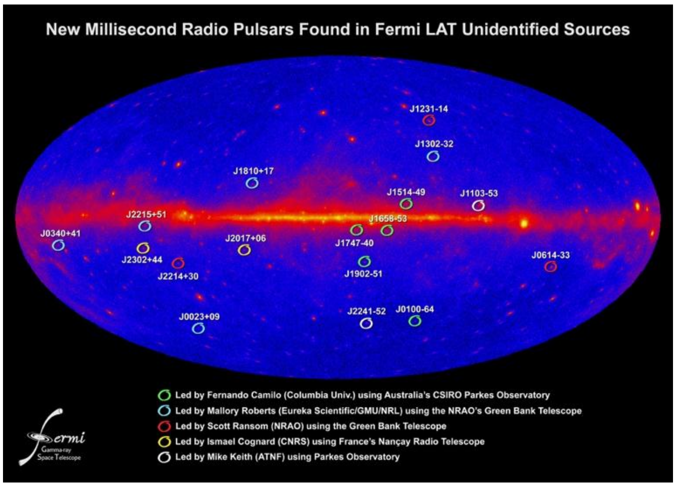


Fig. 12. Map of MRPs discovered by NASA's Fermi X-Ray observatory. [30]

The National Radio Astronomical Observatory (NRAO) 20m Skynet automated radio telescope has provided recorded signals from MRP J1939+2134. A representative waveform is presented as Fig 13. The timing signal with the waveform is highlighted.

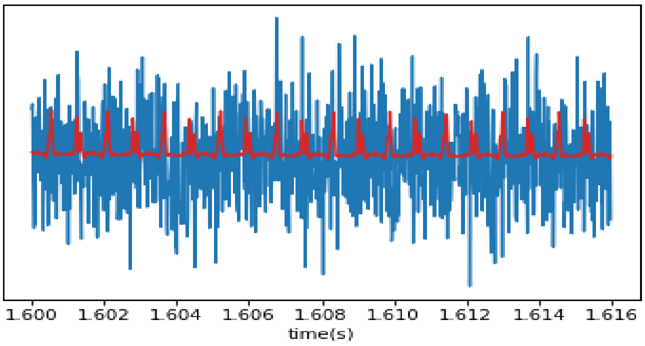


Fig. 13. MRP J1939+2134 received waveform.

Signal reception and timing pulse extraction follows the process illustrated in Fig 14. Utilization of the generated and distributed time signal may be by phasor measurement units (PMUs), power systems controllers, or other systems performing grid applications.

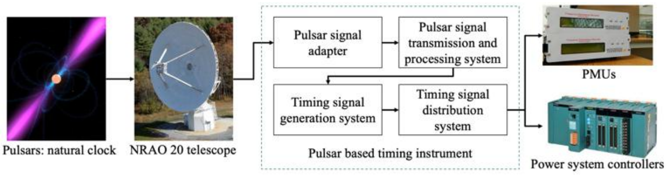


Fig. 14. Process for extracting the timing information from a MRP signal.

4. Practical Considerations

With the process of receiving, extracting and distributing time signals based on MRP signals defined and demonstrated, the question of an implementation at an electric utility's substation arises. While there is no standardized size for all such substations, a representative one in Chattanooga TN has been used to determine if an adequately sized radio telescope could be deployed within the substation's fence line (physical boundary). In the case of using a 20m radio telescope, similar to the NRAO Skynet 20m, a simple overlay of 20m diameter shows that it could "fit" within this substation's boundary, Fig 15.

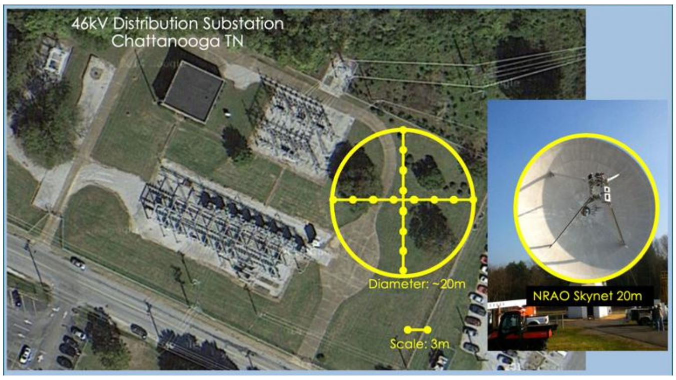


Fig. 15. Deployment of a 20m radio telescope within an electrical substation.

5. Summary

Millisecond rotation pulsars may serve as reliable time sources for electrical grid applications. While the example of placing a radio telescope within a substation has been presented, the time pulse may serve as an input into a 1588 (or similar) network for time distribution. In such a case the radio telescope does not require to be within the substation, although the associated signal processing and time signal generation must be network connected. Such integration into an envisioned electric utility time distribution network is presented as Fig. 16 [31].

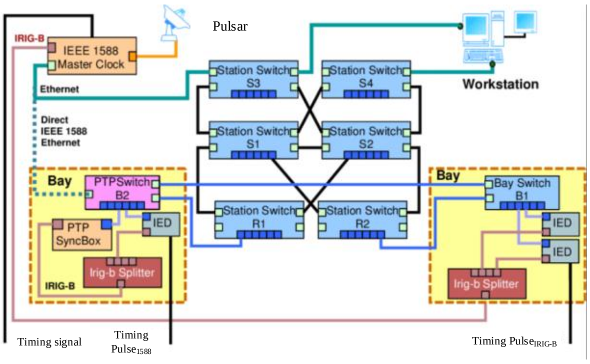


Fig. 16. Time distribution utilizing a millisecond rotation pulsar source.

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