Development and Testing of Phasor Data Concentrators for a Wide-Area Control System

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I - Introduction

Research engineers at Hydro-Quebec have been studying for almost a decade the use of a Wide-Area Control System (WACS) to increase the angular and voltage stability of the power system using Phasor Measurement Units (PMU) and dynamic shunt compensators [1;2]. Previous work has shown that such control systems could significantly increase the power transfer limits on the main transmission corridors by increasing the inter-area oscillation damping and by supporting load voltage in extreme situations [3].

However, in order to catch the expected benefits, the wide-area control system has to act very fast despite the large distances involved. Transmission of data over up to 2000 km and concentration of measurements from various protocols represent the technology enablers of WACS with respect to classical control [4-6]. The maximum acceptable time delay for a wide-area power oscillation damping control is in the range of a hundred milliseconds [7]. In order to maximize the time allowed for measurement, which is critical for overall performance, a minimization of delay due to phasor processing and concentration is required.

At Hydro-Quebec, a wide-area monitoring system is in use since the 80's for energy management and post-event analysis [3]. This system can not be used for wide-area control since it can not fulfill the real-time constraint. Two types of custom phasor data concentrators were therefore designed for this specific application in order to get the maximum performances in terms of processing time and protocol translation capability.

In this paper, the development and testing of a centralized Phasor Data Concentrator (PDC) and a Substation Phasor Data Concentrator (SPDC) are presented. First, a description of application requirements is given. Then, the application developed in order to meet the specification is described. Finally, the performance test bench of Hydro-Quebec Research Institute is presented and test results are given.

II - Application Requirements

Wide-area control has the advantage over local control to make measurement location independent from control location. Power equipment location dictates the latter but these sites might present a low observability of the phenomenon to be controlled, leading to poor performance and low selectivity.

The use of GPS synchronization allows taking measurement at the same time in several distant locations. However, the transmission delays of the data to the control sites over long transmission paths might be different so measurements need to be resynchronized before they are used as control system input. The main objective of the PDC is to resynchronize data packets of simultaneous phasor measurements and process a resulting phasor difference used for real time control. The amount of information at the output is lower than at the input, minimizing the necessary bandwidth between PDC and control site. Other critical objectives of the PDC for control include the addition of measurements from SCADA system, operator commands and maintenance commands to the concentrated data packet.

Wide-area control relies on transmission of measurements over long distances and the availability of long transmission links may be lower than classical electrical links in the substation used for local control. The proposed strategy therefore uses a fallback control based on local measurements, giving a fraction of the benefit of those attainable with the WACS. In order to feed the control system with local measurements, the SPDC has to add local information from IEDs and relays to the remote measurements from the PDC and send it to Substation Synchronous Unit (SSU). The shunt compensator primary control is made of a Static Var Compensator (SVC) controlled by an Automatic Voltage Regulator (AVR). The secondary control is made of the SSU, which is responsible for the choice between local and global control, and the Power System Stabilizer (PSS). Figure 1 depicts the data flow in the application.

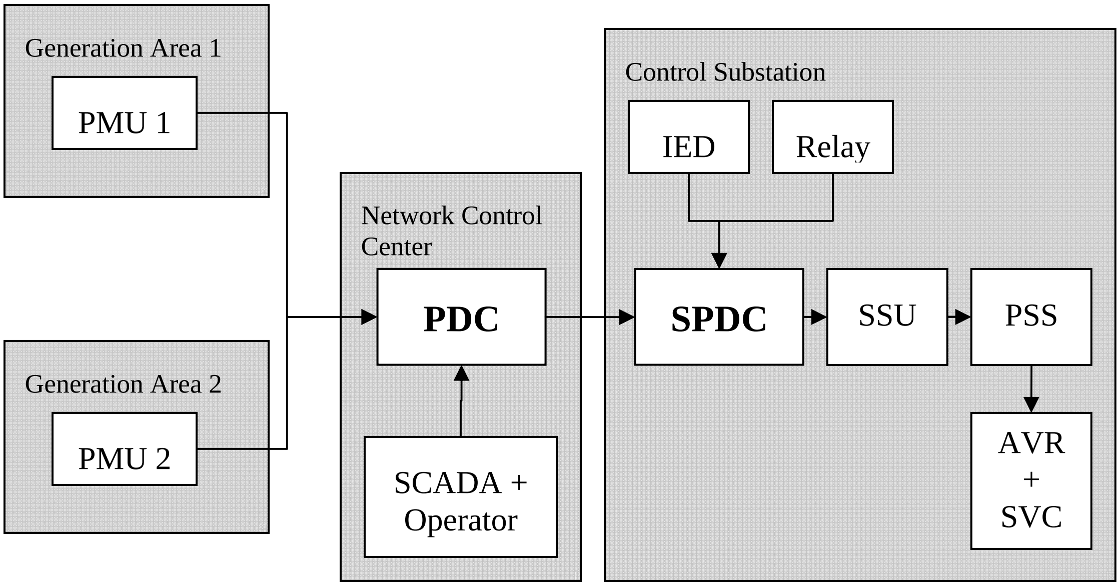

Figure 1 : Data flow in the Wide-Area Control System

Measurements from existing systems (SCADA, IED, Relays) are sent in different protocols, the PDC and SPDC must therefore be able to translate them all to IEEE C37.118 as shown in table 1.

Table 1 : Data types and sample rate in the specific application

Sending device	Receiving device	Protocol	Sample rate
Phasor Measurement Unit	Central Phasor Data Concentrator	IEEE C37.118	60 samples / sec
SCADA measurement	Central Phasor Data Concentrator	IEC 60870	6 samples / sec
Operator commands	Central Phasor Data Concentrator	IEC 60870	On demand
Central Phasor Data Concentrator	Substation Phasor Data Concentrator	IEEE C37.118	60 samples / sec
Substation Relays	Substation Phasor Data Concentrator	IEC 61850	60 samples / sec
Substation IED	Substation Phasor Data Concentrator	IEC 60870	2 samples / sec
Substation Phasor Data Concentrator	Substation Synchronous Unit	IEEE C37.118	60 samples / sec

PDC Description

Phasors from PMUs received in the PDC are stocked in a memory with a capacity of 6 phasors per PMU, thus leaving the ability to conciliate phasors with identical time tags received 100 ms apart due to telecommunication delay difference. The calculations made in the PDC are the angle and frequency differences between PMUs located at large generation areas. The phasor difference calculation is triggered by the arrival of the second phasor with an equal time tag as the one already into PDC’s memory. Then, load voltage measurements from SCADA are included to the data packet before it is sent to SPDCs (see Figure 2). The maximum allowed processing time for PDC is 10 ms. In case of loss of a PMU phasor stream for more than 100 ms, the PDC is able to autonomously send phasors with SCADA measurement spaced by 1/60 second, even if the phasors differences from PMUs are not available.

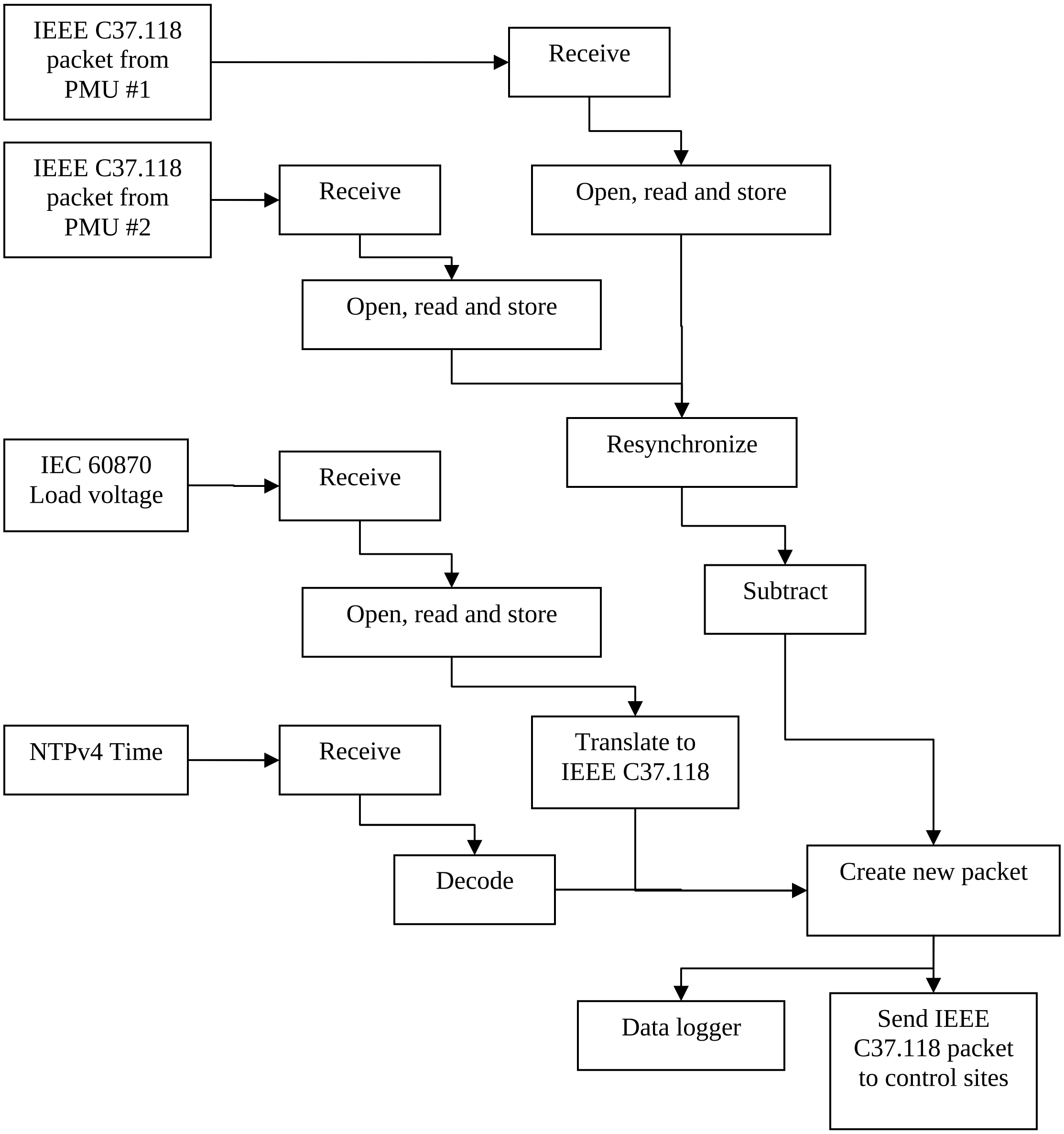

Figure 2 : PDC processing for phasor data

PDC is also used to translate operator commands and configuration commands originally in IEC 60870 into IEEE C37.118 protocol (see Figure 3). These packets are sent asynchronously with respect to the control ones, on operator demand.

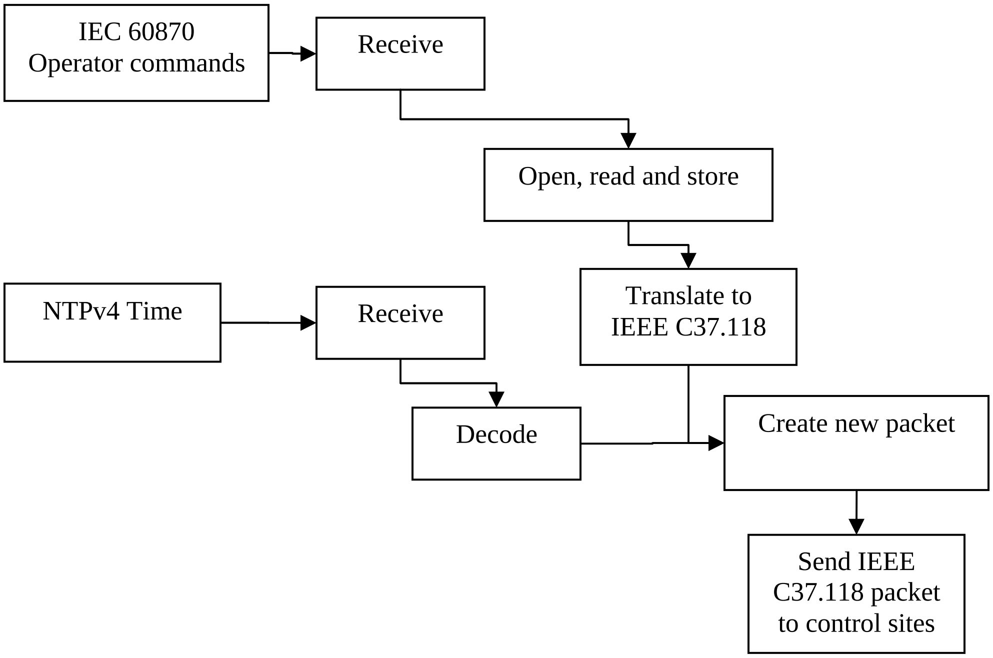

Figure 3 : PDC processing for operator commands

Monitoring of the control system should also be implemented to measure its availability and analyze its performance after an event. This post-event monitoring is based on transient recordings from the PMUs acquired in the PDC and transient recordings from the IEDs and Relays acquired in SPDCs. All records from the SPDCs can be retrieved by the PDC and made available to the power system analyst.

SPDC description

The SPDC does not make any calculations; it translates and includes the data from substation IED and Relays into the data packet from PDC, triggered by the arrival of such a packet. A maximum of 16 ms is allowed to perform data concentration in SPDC. Like the PDC, SPDC is able to autonomously send IED and Relays measurements after a 100 ms loss of the phasors stream from PDC.

III – Application Description

The PDC’s functionalities have been incorporated into the vendor’s standard gateway to provide the required functionalities presented in table 1.

The overall system allows personnel to view in real-time the different pieces of information (including operator commands) being received from other systems and/or transmitted to other attached systems. Some of these systems are presented below:

- Typical measurements received and displayed in real-time
    - phasor measurement units (from PMUs)
    - SCADA (load voltage magnitude)
    - protection relays (voltage, current and frequency)
    - operators (command actions)

A real time view of PDC data is shown at figure 4. The two frequencies from PMUs, emulated by a personal computer as shown on figure 5, are subtracted in the PDC and sent to the SPDC. The emulated measurements reproduce data from a simulation of a short circuit on a transmission line.

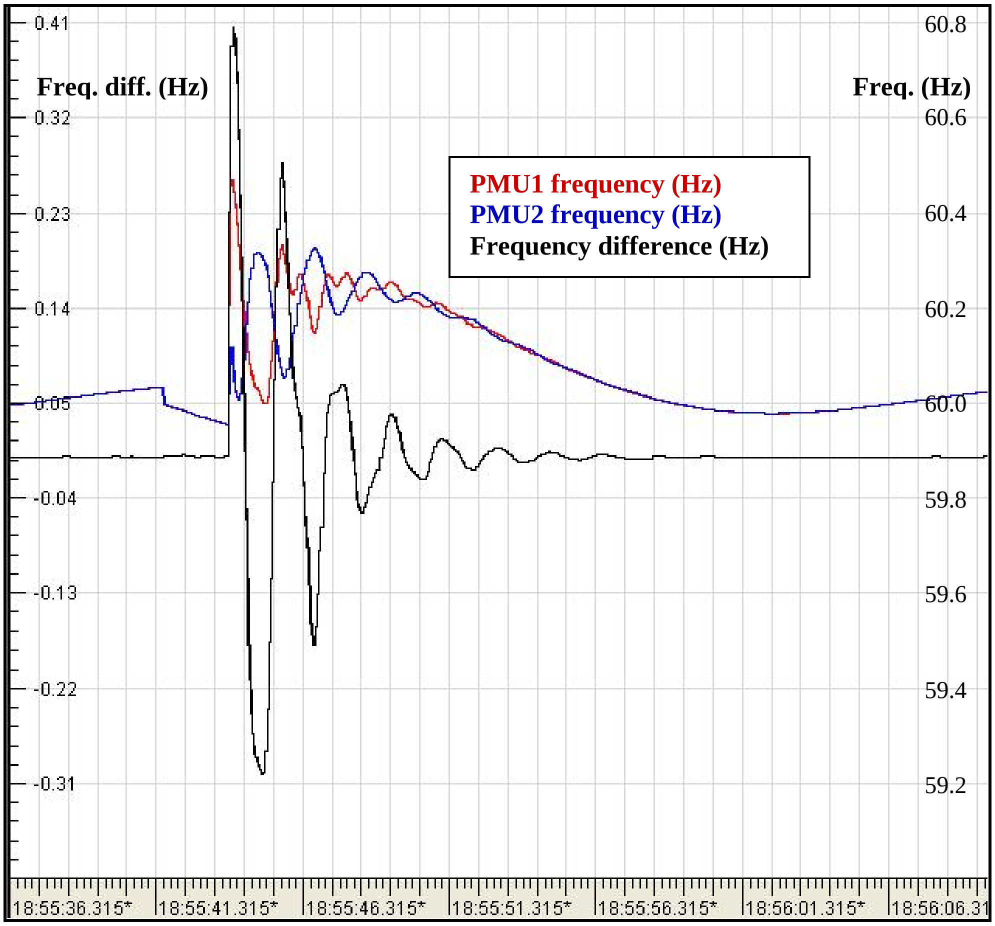

Figure 4 : Example of PDC calculations for simulated data

Requirements where identified in regards to being able to record information when an event is detected so that the information would be available for post event analysis. This data recorder functionality runs at high speed in the system and the user can select any point in the system to be part of the recording (PMU data, relay information, SCADA data including potential control information from the operator). When an event is detected, the recorder will store in the flash memory the information that has been collected in the memory buffers into a Comtrade format file. The system allows the user to define how many seconds before and after an event that should be recorded for the creation of the Comtrade file with the user being capable to use any signal desired in the system as the event trigger. In this application 6 simultaneous recordings can be active in parallel at any point in time.

Another interesting addition has been the PMU generator, allowing any information in the system to be part of a new PMU stream where the user can define how the information will be incorporated in its PMU stream, providing an interesting way to make data available to other systems.

Since Hydro-Quebec is part of NERC, the use of the standard gateway with its PDC functionalities fulfilling CIP standard requirement from its basic functionalities ensure native NERC-CIP compliance.

The platform also allows IREQ engineers to be able to access from remote the event Comtrade files stored by the data recorder functionality. Another use of the system from remote is to access the different configuration files within the relays themselves with the different native vendor tools using the built-in passthrough functionality.

IV – Test Bench Description

A test bench has been deployed at Hydro-Quebec research Institute to validate the performances of the PDC and SPDC. Since PMU, SCADA, IED and Relay measurements are not available at Research Institute site, they were emulated in their native protocols. A representation of the test bench is shown at figure 5.

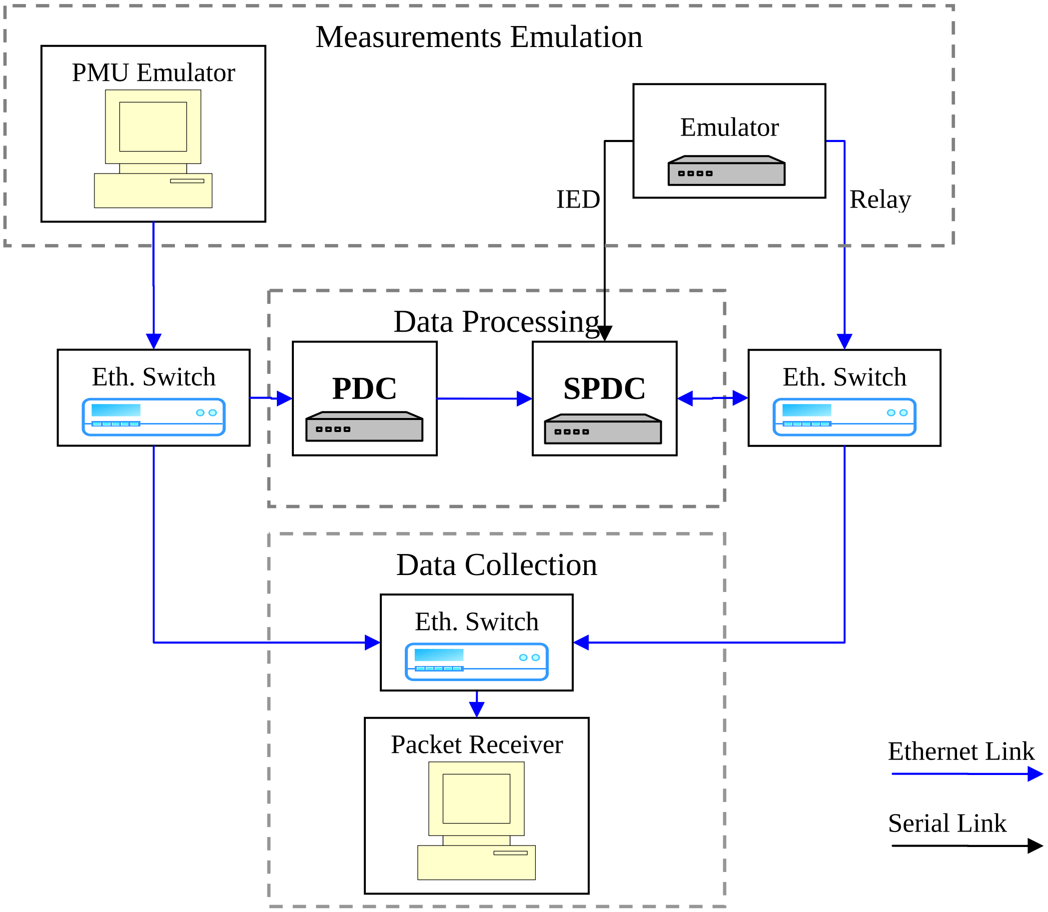

Figure 5 : Data flow in the test bench

The test setup performs duplication of the phasor streams at PDC input and at SPDC output using Ethernet switches (mirroring function). The two streams are then put onto the same Ethernet connection, using another switch, to be sent to the packet receiver located in a PC in which specific software is used to time tag and log all received data packets into a file. Then, a Matlab program finds the transmission and concentration delays from the time tags of the input-output phasors. This program, for each PMU sampling time, subtracts the time of arrival of the phasor from the slowest communication channel from the output time and determines the delay generated by the PDC for processing.

Precise time synchronization of all equipments in the test setup is not critical because PDC input packets and SPDC output data packets are time tagged in the same packet receiver. The drift of the clock of the packet receiver is considered negligible between transmission and reception of a packet since the elapsed time is maximum 26 ms according to the specification. The PMU emulator sends predefined measurements with a predefined time tags which are not the actual time of measurement.

V – Test results

First, buffering of PMU data packets and association of phasor measurements taken at the same time is tested. Figure 6 shows the reception time in the PDC (PMU1 input and PMU2 input) and transmission time from the SPDC (output) for the ten first samples of a typical test.

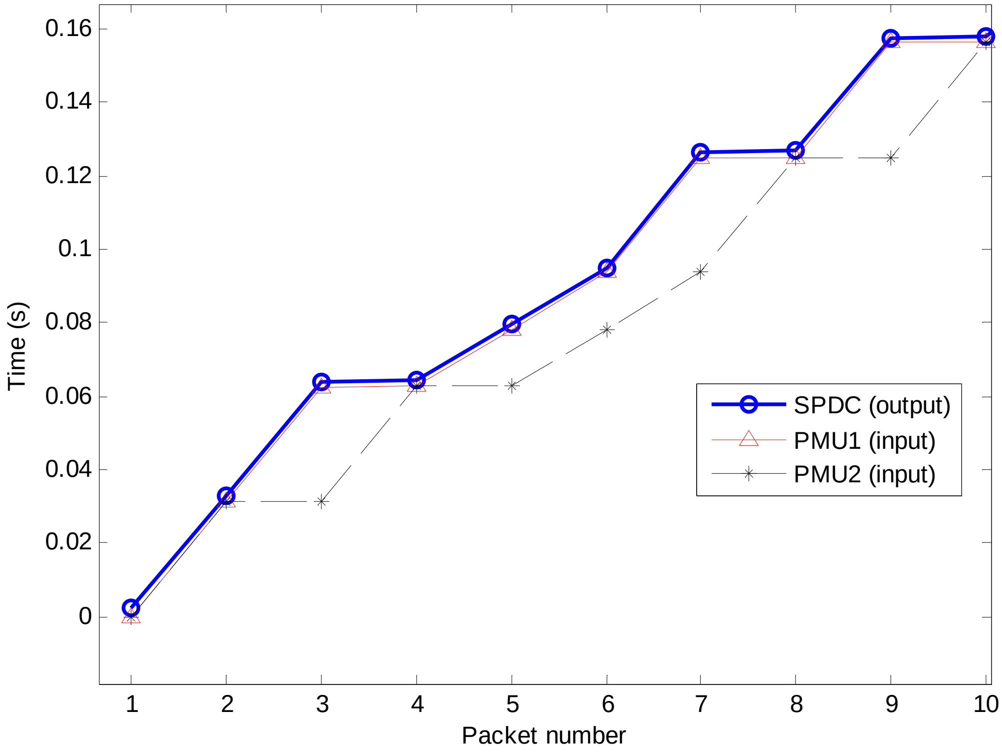

Figure 6 : Reception time of inputs and transmission time of output

On figure 6, the latest input phasor arriving for a given sampling time is always from PMU1. After the reception of PMU1 phasor (red curve), the output (bold blue curve) is then sent. Some phasors are received in groups of two due to queuing in PMU measurement emulator, a behavior that simulates queuing in the routers of the telecommunication system. For example, samples 2 and 3 from PMU2 and samples 3 and 4 from PMU1 are received in a very short amount of time. Figure 7 shows the detail of the reception of samples 2 and 3.

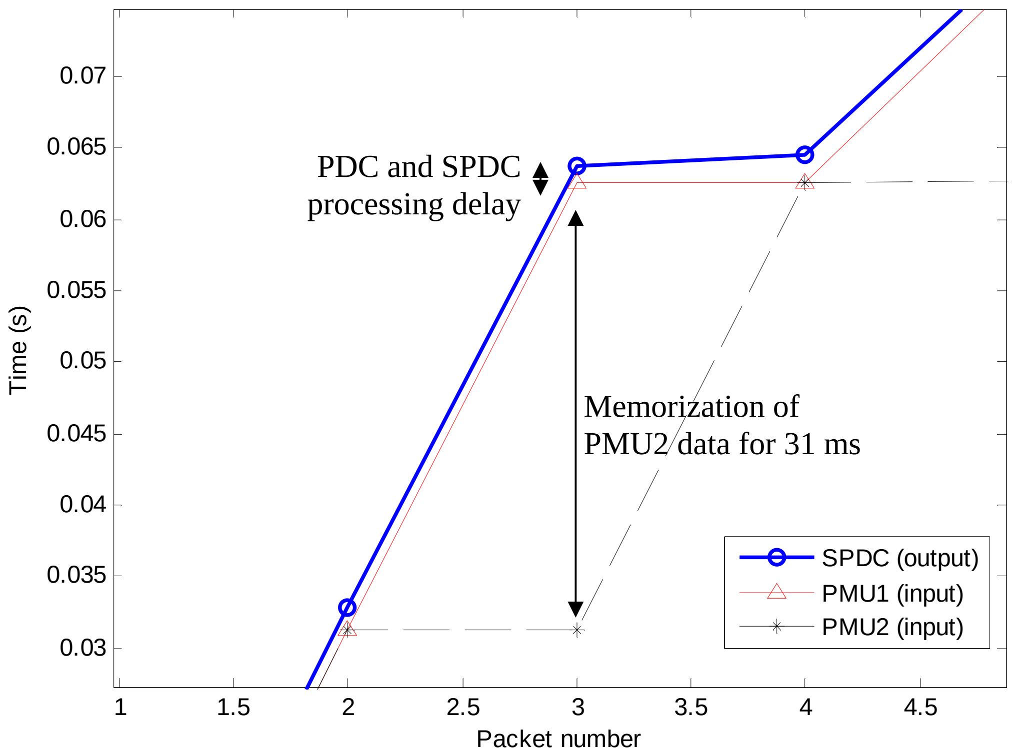

Figure 7 : Example of delay calculation for queuing of two samples in PMU measurement emulator

On figure 7, once sample 3 from PMU2 has been received, it is kept in memory for 31 ms until corresponding sample from PMU1 is received. Then, the processing takes 1.1 ms to output the difference phasor. For sample 4, data from PMU1 and PMU2 is received with 0.02 ms time difference and the total processing time is 2.0 ms.

Some packets have a longer processing time due to multitasking in the PDC and the SPDC. Figure 8 shows an example of packets that present longer processing time (packets 365-366).

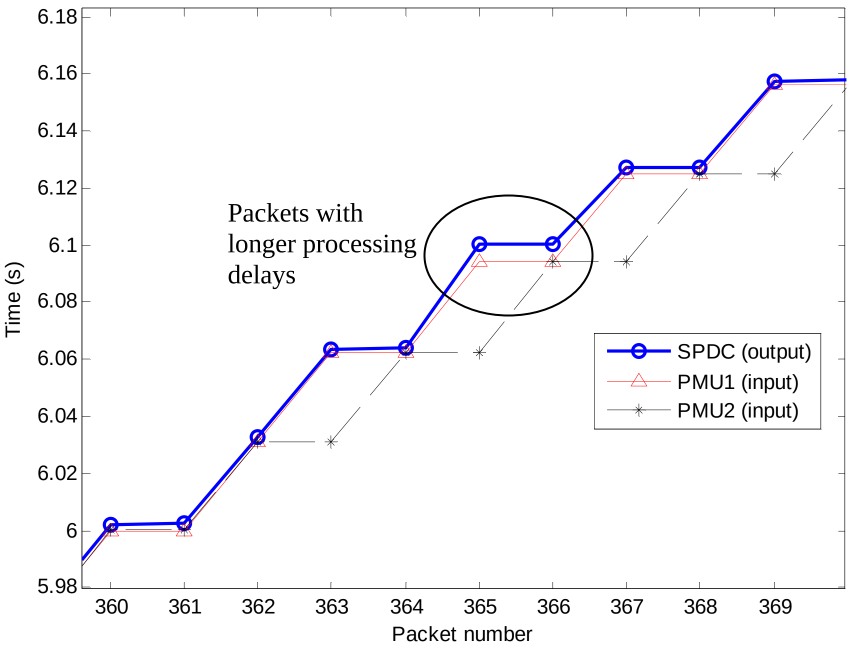

Figure 8 : Transmission time of inputs and output for longer delays

To get the statistical distribution of time delay, data is collected over several minutes. The time delay characteristics are given at table 2.

Table 2 : Test duration and time delay characteristics

Test duration	5.8 minutes
Number of output packets	20837
Average time delay	1.675 ms
Variance of time delay	0.54 ms
Maximum time delay	13.9 ms

The probability distribution of the total time delay corresponding to data given at table 2 is shown at figure 9.

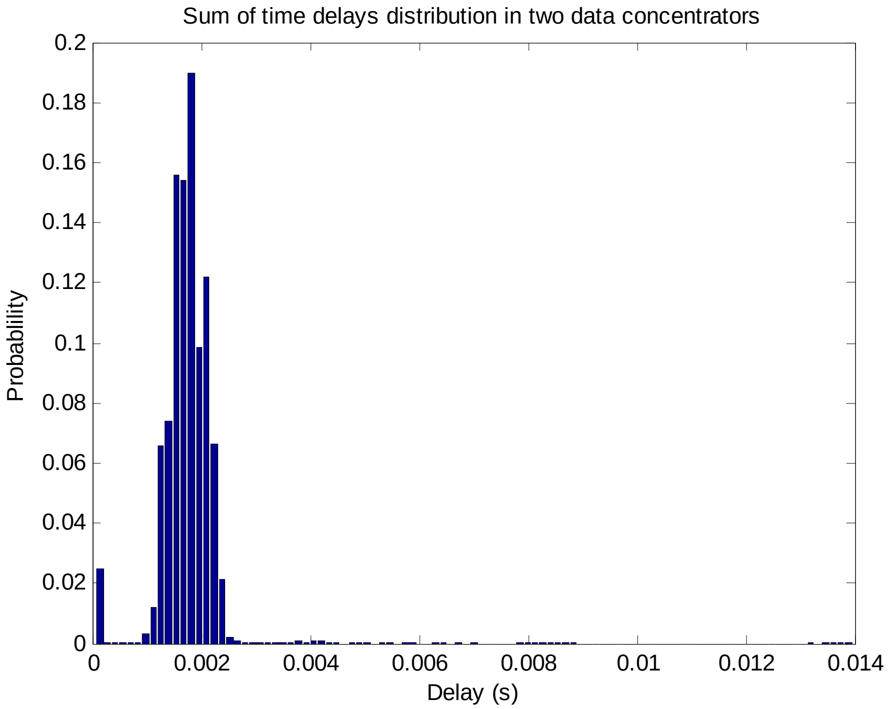

Figure 9 : Probability distribution of total time delay

Since PMU data is used as feedback for real time control system, it is important for the time delay to be bounded. In networked control systems, it is not possible to achieve zero jitter (variance of time delay). However, results show that jitter is limited to less than one sample (16.7 ms).

The sampling rate of PMUs (60 samples/s) is sufficient for the control of inter-area oscillations in power systems in the frequency range of 0.4 to 0.8 Hz with 75-150 samples per cycle. A jitter of less than a sample will be filtered by the low pass characteristic of the PSS filters. Moreover, with less than one sample jitter, it is not possible to have packet disordering, simplifying the packet reception management by the control system.

VI – Conclusion

Phasor data concentrators can be used for wide-area control systems with a strict constraint on processing time. A PDC built for Wide-Area Measurement Systems (WAMS) may not be able to meet this requirement. Hydro-Quebec decided to use custom PDC and SPDC to get the maximum performances using the specific implementation presented in this paper. The PDC and SPDC are able to translate data from various sources to IEEE C37.118 phasor format in real time and to calculate the phasors differences from two main generation areas in less than 14 ms. This processing time is fast enough to allow the control of dynamic shunt compensation equipment for oscillation damping and load voltage support in extreme contingencies.

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