Integrated Monitor Facilities for the Eastern Interconnection:

Management & Analysis of WAMS Data Following a Major System Event

Working Note of the

Eastern Interconnection Phasor Project (EIPP)

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1. Preface

This document deals with a Wide Area Measurement System (**WAMS**) for the eastern interconnection. WAMS is considered both as a distributed measurement system, and as an infrastructure that provides dynamic information for grid management. People, in the form of staff, procedures, and practices, are the most essential aspect of that infrastructure.

A major WAMS does not emerge overnight -- it evolves over time, building upon existing resources to address additional needs. This implies a mixture of technologies, data sources, functionalities, operators, and data consumers. Some governing realities are the following:

- **System configuration** is strongly influenced by geography, ownership, selected technology, and the technology already in service (legacy systems).
- **Required functionalities** are determined by who must (or must not) see what, when, and in what form.

Overall, the forces at work strongly favor wide area measurement systems that evolve as "networks of networks" through collaborative agreements among many parties.

There are a lot of advantages to this situation. Interleaving networks that have different topologies and different base technologies can make the overall network much more reliable, while broadening the alternatives for value engineering. It also permits utility level networks to be operated and maintained on the basis of ownership. The ability of a utility to retain data until it is no longer sensitive is an important aspect of information sharing in the new power system.

Salient disadvantages to this situation include protracted reliance upon obsolescent or incompatible equipment types, plus various institutional impediments to sharing of costs and information. These are major factors in the deployment, operation, and value of the WAMS infrastructure.

2. Summary

This document provides basic guidelines concerning the management and use of WAMS data following a major system event. The core objectives to be served are just two:

- ***Obtain good data, and keep them safe.***
- ***Translate the data to useful information, and promptly deliver that information to those who need it.***

Properly integrated into a PDC data system, the DSI Toolbox[1] can deliver an initial disturbance report about one minute after disturbance files are received. Such performance requires a mature data system, however, and it is just part of a much broader picture.

The overall paradigm shown in Table 1, in which some of the indicated activities overlap. Precisely who will perform these activities is a matter to be worked out among the owners, managers, and users of WAMS data. For present purposes it is assumed that the data owners have at least basic capabilities for analysis of the data they record, and that some higher level entity has been established to manage and analyze data collected on the overall WAMS. The overall process will, inevitably, be a distributed one that accommodates the resources at hand to the particular event which has occurred on the power system.

Noteworthy system events vary widely in their nature and degree. WAMS information probably attains its highest value during the period when a system collapse is pending but still avoidable. Comparably high information values can occur during the restoration of electrical services and facilities, and during the revision of facility ratings and operating practices.

Under such circumstances it is critical that the WAMS operate reliably. It is also critical that the extracted information be timely, correct, and sufficiently comprehensive. Such performance can only be assured for major events if the WAMS infrastructure is exercised on a regular basis, through direct observation and analysis of power system behavior in its many forms [1]. The associated roles for WAMS data are listed in Table 2.

[1] The **Dynamic System Identification Toolbox**, available from BPA and PNNL.

Table 1. Management and use of WAMS data following a major system event

- **Emergency Response Plan for WAMS Operation**
  - Determine dynamic information needs and WAMS facilities to meet them
  - Develop necessary agreements for sharing of costs, data, and staff for WAMS deployment and operation
  - Develop procedures for safe retention and timely integration of WAMS data
  - Develop procedures and resources for integrated analysis of WAMS data together with relevant information from all other sources (to include model studies)
- **Preparations for WAMS Emergency Response**
  - Identify and train key staff
  - Develop, maintain, and document technologies that convert WAMS data into useful information
  - Regularly test, maintain, and document all aspects of WAMS performance
  - Regularly analyze WAMS data, to determine the normal range of power system behavior and to facilitate recognition of abnormal behavior
  - Regularly compare WAMS data against model studies, to facilitate the interpretation of measured data and to determine model fidelity
- **WAMS Emergency Response: On Line**
  - (not covered in this document; see [1,2])
  - Develop, maintain, and document technologies that convert WAMS data into useful information
- **WAMS Emergency Response: Data Management**
  - Determine the nature and severity of the event
  - Issue ”Secure Event Data" Requests (**SEDR**s) to appropriate data owners. Must indicate recorders from which data may be requested later; data owners should examine data to verify that the secured records are the correct ones and that the data have been stored correctly.
  - Issue ”Provide Event Data" Requests (**PEDR**s) to appropriate data owners. Must indicate specific signals and time frames. May be constrained by timed release agreements, may be repeated if files initially obtained are incomplete or defective.
  - Obtain and integrate records from primary ("backbone") data sources. Assess all records in context of operator logs, event recorders, and model studies.
  - Obtain and integrate records from secondary data sources according to above assessment. Repeat as needed.
  - Share data and findings among appropriate staff. Must rigorously observe security issues, and log all requests for or transfers of information materials.

- **WAMS Emergency Response: Analysis and Reporting**
  - Integrate WAMS data into one or more portraits of system behavior. Document all data sources, and all repairs or changes made to the data.
  - Validate the data for record alignment and signal quality. Document all repairs or changes made to the data.
  - Prepare initial report materials concerning measured dynamic performance. Include powerflow data before the event and following system recovery, transient waveforms for the event, and frequency domain results for oscillatory dynamics if appropriate.
  - Integrate and extend initial report materials in collaboration with overall event analysis team. This may include development and analysis of computer simulations, comparisons against other events from the WAMS archive, and follow-up tests of the power system itself.

Table 2. General applications for WAMS data

- Real time observation of system performance
- Early detection of system problems
- Real time determination of transmission capacities
- Analysis of system behavior, especially major disturbances
- Special tests and measurements, for purposes such as
  - special investigations of system dynamic performance
  - validation & refinement of planning models
  - commissioning or re-certification of major control systems
  - calibration & refinement of measurement facilities
- Refinement of planning, operation, and control processes for best use of transmission assets

3. Initial Management of WAMS Data for System Events

The first step in data management for system events is to recognize that a significant event has occurred. Subsequent actions depend upon the nature and severity of the event, the topology of WAMS facilities, and agreed procedures among data owners and data users. Establishing the overall procedure can be a substantial undertaking, and it should commence well in advance of major emergencies on the system.

Significant system events can be roughly categorized as major disturbances, staged tests, and benchmark events that are rich in formation about system performance. This last category includes but is not limited to events that involve the following:

- Critical system dynamics or facilities
- Major changes in system topology
- Sustained or protracted oscillations
- Unusual behavior in system frequency
- Unusual control actions
- Issues that are known to be of special interest to staff in system operations or planning

Rule sets that define the events of interest should be coordinated among all established users of WAMS data.

Once a significant event has been recognized, authorized WAMS operation staff should issue ”Secure Event Data" Requests (**SEDR**s) to appropriate data owners. This requests that data for a specific time frame be stored in a secure manner for later delivery, but it does not request that data be provided as yet.

The first "call in" of WAMS data for a recognized event will usually go to operators of PDC units. Phasor data collected on PDC units are a primary and preferred means for obtaining a first overall view of system dynamic performance. It is highly desirable that a necessary minimum of PDC data be obtained and secured for every major event.

The need for additional "call ins" of supplemental WAMS data may be emerge during the course of event analysis. In such case additional data may be requested from the same PDC facilities, or from secondary monitors for local behavior.

Requested data may arrive along a variety of paths, and in a number of forms. The more common situations are these:

1. **Raw data files acquired on a local PDC unit**.
2. **Raw data files acquired on remote recording device**, accompanied by data extraction software if needed. Delivered by FTP or on physical media such as compact disk.
3. **Processed data files acquired on remote recording device**, consisting of selected signals only. Delivered by FTP or on physical media such as compact disk.

The DSI Toolbox [3,4,5,6,7] has been developed in the WECC to deal with most though not all of the more likely situations and data types.

WAMS data managers should plan for all of the situations listed above. Reasons for this include the following:

- **Communication failures** may cause data to be lost en route to the local PDC, or to the data archiving units downstream from it. Retrieval of backup data produces situations 2 or 3.
- **Limited networking** may preclude that all data are sent to the local PDC in real time—e.g., a communication link of sufficient capacity may not be available, the source data may not be PDC compatible, or the data may be subject to a delayed release agreement. This produces situations 2 or 3.
- **Data formats** may not be PDC compatible—e.g., PDC data may have been processed into some other format, or recorded on some other type of device. This produces situation 3.

Other common problems are failure to issue, receive, or properly act upon a SEDR. Timestamp discrepancies, in particular, may well lead a WAMS operator to secure the wrong records while the records of interest are lost from storage. All of these problems are highly likely in the wake of massive disturbances such as the US-Canada Blackout of August 14, 2003, in part because data are requested a very wide range of data sources [8,9,10].

4. Preparation of WAMS Data for Analysis

The range of installed WAMS equipment types is fairly broad, and many were not initially designed for use in a system wide information system. Integration of data obtained from these sources will generally involve the following technical operations:

- Copying the provided data to a central location for integration and analysis
- Detection & repair of data that are defective, missing, or improperly scaled
- Correcting erroneous time stamps, or applying time stamps when none are provided
- Resampling data that were not collected at a multiple of 30 samples per second
- Translation of phasor data to basic RMS quantities (e.g., voltage magnitude and line MW)
- Translation of point-on-wave data into phasors and basic RMS quantities
- Standardized naming of signals for multi-source integration, sorting, display, and export for additional processing
- Compensation for excessive filtering or other instrument effects (special cases only)
- Integration of selected data into one or more files for detailed analysis
- Development of relational quantities such as relative bus angle, relative frequency, total interchange

Using high quality data that were collected according to a uniform standard simplifies these tasks considerably. Some tasks can be made unnecessary, and it is possible to automate most of the others.

Vendors are becoming more attentive to these problems, and the future may see progressive use of the IEEE synchrophasors standard as a basis for developing a fully integrated synchronized system measurements (**SSM**) network [11,12].

5. Efficient Use of the DSI Toolbox

Analysis in depth of a large dynamic system is never a routine matter. The analysis always commences with an initial review of the data, however, and the basic mechanics of this review can be automated in large part. It is also possible to incorporate "expert system" logic that would point the user toward aspects of system behavior that merit closer attention in a particular case, and then guide the user through the process. These are just some of the value engineering issues for design of the overall WAMS information process, however. *Automated analysis is an expensive, limited, and dangerous substitute for staff expertise*.

The DSI Toolbox is engineered under very specific guidelines. These guidelines require that the code be open source, they place a high premium upon flexibility of application, and they establish a basic framework for customized automation by expert users. *At minimum*, the user is expected to perform the following steps:

- **launch the application** (pushbutton or text command)
- **indicate the files to process** (first and last in a series, most recent event, etc.)
- **confirm any strategic operations** (posting of data for public access, extensive processing tasks)

These particular requirements derive from considerations of operational security, not technical necessity.

The DSI Toolbox consists of two primary modules, PSM Tools [3] and the Ringdown GUI [4]. Within PSM Tools, PSMbrowser is the overall driver for the DSI Toolbox and the primary link to the Ringdown GUI.

It is intended that the DSI Toolbox be customized to its specific application environment during installation, and that it be further customized as data facilities expand. Options for doing this are summarized in Table 3, and demonstrated in various examples that accompany the Toolbox. Any nonstandard version of PSMbrowser should be assigned a different name, so that it can be launched and maintained separately.

Table 3. Customizing the DSI Toolbox to a Specific Application Environment

- **Basic options** (all users)
  - accept the standard options to speed processing
  - customize PDCmenu to recognize the specific data source and present menus of preferred signals
  - attach "add-on" codes for special calculations or displays
- **Modifications to PSMbrowser** (experienced users)
  - revise the standard options (starting directory, data type, files to process)
  - customize the processing controls (processing steps, signals and parameters at each step)
- **Major extensions to PSMbrowser** (advanced users)
  - insert "button bar" GUIs to condense the user dialog (but maintain entries to processing log)
  - complete "Repeat Case" logic so that PSMbrowser will automatically repeat earlier processing
  - complete event scanning logic, with links for real time application

6. Preparing for Analysis of PDC Data

Properly integrated into a PDC data system, the DSI Toolbox can deliver an initial disturbance report about one minute after disturbance files are received. Such performance requires a mature data system, and a tightly meshed infrastructure for WAMS operation. Development of these resources is very much a work in progress.

Local results can none the less be obtained very quickly. The key, as always, is planning and preparation of the resources.

6.1 Preparing for Event Analysis – Refining the .ini File(s)

PDC technology that is consistent with BPA practices [12] provide data in .dst files. The key to using the data is a configuration file (**CF**) of type .ini, which provides the following primary information:

- the data source to which the CF applies (name of the archiving device, allowable time range of the records)
- structure of the data source records (number of PMUs, PMU names, number of phasors for each PMU)
- signal parameters
  - scale factors and type (voltage phasor, current phasor; other)
  - associations between voltages and currents
  - text data for signal naming

The .ini file initially received may not be entirely suitable for general processing with the DSI Toolbox, or with other software packages for that matter. Likely problems include the following:

- a simplistic CF name that does not indicate the CF version and the intended data source
- CF contents that depart from with the established format
- Text data that produces poorly organized or uninformative signal names
- A poorly organized data layout that encourages data entry errors as the .ini file evolves

Any change made to the CF should be documented within the file comments, and the CF name should be revised. E.g., a CF file called BPA1_040704.ini might become BPA1_040704M1.ini. The CF name is automatically included within processing summaries issued by the DSI Toolbox.

Some data owners are willing to share some or all of their PDC data, provided that the data is made anonymous. Text data indicating data sources is contained within the .dst files themselves, and the text data there must match certain entries in the CF. Options within the DSI Toolbox permit automatic translation between generic and specific data source names, under control of a Master CF [13]. Data released with generic names is accompanied by a Generic CF.

6.2 Preparing for Event Analysis – Matching Custom Menus to the .ini File

Table 4 shows a DSI Toolbox dialog for selection of a PDC signal extraction menu. The utility called PDCmenu has recognized the configuration file in use (_BPA2_040610.ini**)**, and has presented the user with custom menu options 6 through 17. Options 1 through 5 are standard ones that appear in many other dialogs with the DSI Toolbox.

The final line in Table 4 is **Select submenu - enter 1 to 17 [2]:** and the user entry is **17**. The square brackets **[ ]** enclose the designated default entry, which would be used if the user pressed the **enter** key or if the **Accept Defaults** flag were on.

Table 5 provides the signal list for menu 17. The user can continue on to add further menus, and to edit the overall signal list.

Table 4. Dialog for selection of PDC signal extraction menu

```
In PDCmenu: CFname = _BPA2_040610.ini
In PDCmenu: Match found to _BPA2_040610.ini
In SigSelect: Automatic defaults suspended
  Select signals for PDC signal extraction

In SigSelect: Number of stored signals=451
   Includes time axis inserted at column 1

Building signal extraction list: Submenu options are
      001  Initial user selections
      002  All channels
      003  No channels--exit
      004  Interactive selection of channels
      005  Sort by signal type
      006  Ringdown Summary
      007  Interactions Summary
      008  Coulee Overall
      009  Malin/CJack Overall
      010  Celilo Overall
      011  Sylmar Overall
      012  Colstrip Overall
      013  Celilo Probe
      014  Celilo Probe (ModeMeter)
      015  Model Validation #1
      016  RobustSigs
      017  BPA Datapost

   Select submenu - enter 1 to  17  [2]:  17
```

Table 5. Signal list for PDC extraction menu 17 (configuration _BPA2_040610.ini)

```
Submenu  017: BPA Datapost
     %   1  Time
     %   4  GC50 Grand Coulee Hanford Voltage              FreqL
     %  80  MALN Malin N.Bus Voltage                       FreqL
     % 300  SCE1 Vincent Voltage                           FreqL
                    •
                    •
     %   2  GC50 Grand Coulee Hanford Voltage              VMag
     %  78  MALN Malin N.Bus Voltage                       VMag
     % 298  SCE1 Vincent Voltage                           VMag
                    •
                    •
     %   3  GC50 Grand Coulee Hanford Voltage              VAngL
     %  79  MALN Malin N.Bus Voltage                       VAngL
     % 299  SCE1 Vincent Voltage                           VAngL
                    •
                    •
     %  81  MALN   MALN-Round Mountain 1 Current           MW
     % 301  SCE1   SCE Vincent-Midway 1                   MW
     % 308  SCE1   SCE Devers-Palo_Verde                   MW
     % 100  COLS   COLS-Broadview 1 & 2 Current            MW
                    •
                    •
Add this submenu to extraction list?  Enter y or n [ ]:  y
```

6.3 Preparing for Event Analysis – Customizing Defaults to the Application Environment

A general list of options for customizing the DSI Toolbox is presented in Table 3. The simplest of these involve customizing various defaults within PSMbrowser and PDCmenu. Suggestions and examples are shown below.

- **Within PSMbrowser,** modify CDpath so that signal extraction starts in the folder where the data is located

  Example: **`CDpath='c:\Monitor Analysis (WSCC)'  %[CUSTOM]`**

- **Within PSMbrowser and other codes,** modify and use the standard processing defaults

  Example: **`Select submenu - enter 1 to  17  [17]:`**

  Example: **`In PSMplot2: 53 Signals to Plot`**
  `How many traces per page?`
  `Select a value between 1 and  30: [8]:`

- **Within PSMbrowser only,** predefine the signals to process

  Example: **`chansP0=[2:6 2 7:10 23 25 29]; %Signals to plot`**

  Example: **`chansA0=[2:6 2 7:10 23 25 29]; %Signals for Fourier analysis`**
  `refchan=0;  %Fourier reference signal (none)`

As always, any special version of PSMbrowser should be uniquely named and the changes should be indicated by comments within the code [3].

7. Basic Analysis of PDC Data with the DSI Toolbox

This Section outlines the basic procedure for analysis of PDC data with the DSI Toolbox. It is assumed that

- the data are acquired on a single PDC of BPA type, and that the data require no special repairs or compensation.
- **the event is a fairly ordinary transient disturbance, with the general shape indicated in**

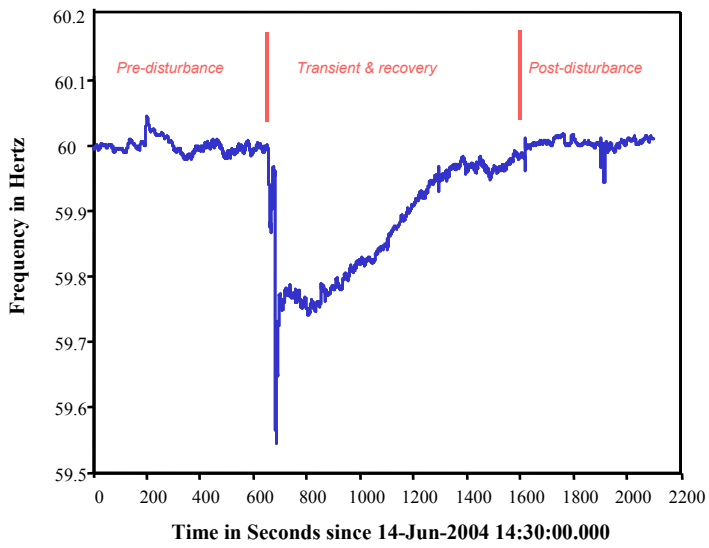
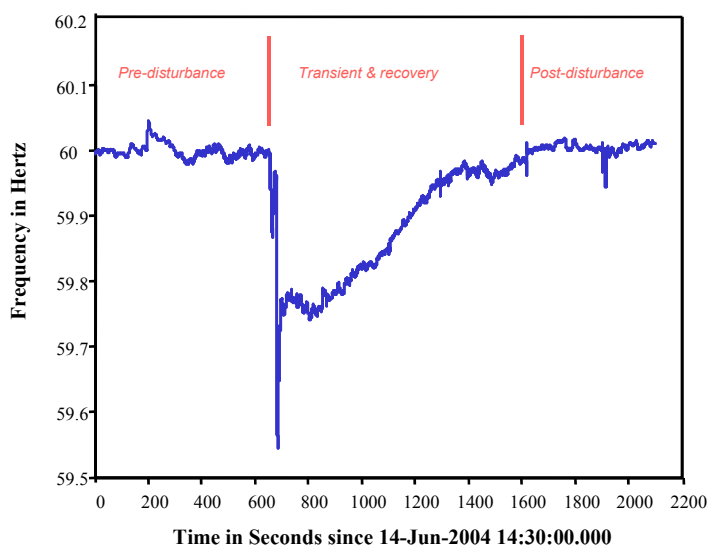


Fig. 1.



The nomenclature shown in Fig. 1 is used throughout the discussion. The primary menu of processing options presented by the DSI Toolbox is shown in Table 6 for late reference.

WECC experience suggests that, in the absence of contrary knowledge, data call-in for a disturbance should generally include about ten minutes of data for the transient plus system recovery, plus an additional ten minutes of data before and after. Advantages of such long records include the following:

- Increased likelihood of capturing the entire event, despite timestamp errors or imprecise information as to when the disturbance occurred.
- Increased likelihood of capturing secondary transients before or after the main disturbance.
- Sufficient "before and after" data for ambient analysis to determine changes in system dynamics produced by the event.

Further experience with events in the eastern interconnection may well lead to different guidelines.

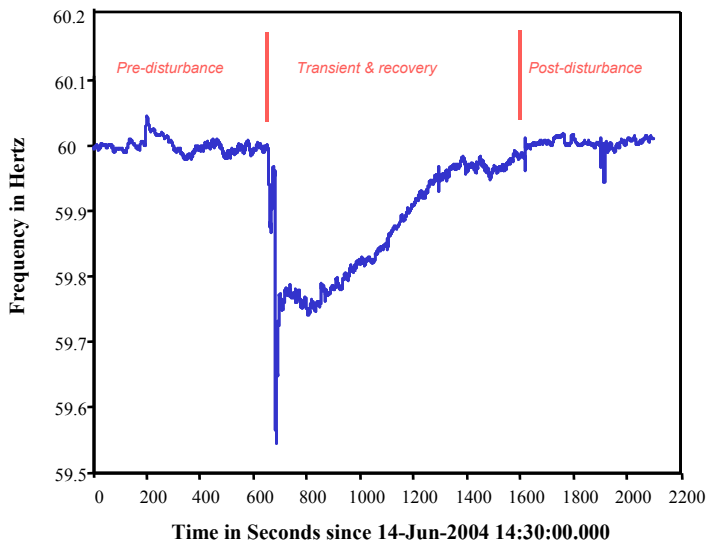


Fig. 1. Nomenclature for a disturbance record

Table 6. Primary menu of processing options presented by the DSI Toolbox

```
Select processing type: Options are
    1  Batch Plots
    2  Angle/Freq Refs
    3  Filter/Decimate
    4  Backload Filtered
    5  Fourier
    6  Histograms
    7  Ringdown GUI
    8  Ringdown Utilities
    9  AutoCorrelations
   21  ModeMeter
   22  EventScan
   41  Phasor Utilities
   42  Backload Phasor Results
   51  Special Displays
   94  DownSelect Signals
   95  Load new data
   96  save results
   97  keyboard
   98  Defaults on/off
   99  end case

   Indicate processing type - enter number from list above [1]:
```

7.1 Reviewing the Data

Disturbances on the power system produce immediate questions as to what happened, and what actions should be taken. Some initial screening can be performed automatically, by event detection logic that examines system activity according to magnitude, persistence, frequency content, and perhaps context [1].

More general screening must deal with broader questions such as

1. What is the general nature and importance of the event?
2. What is the quality and coverage of the acquired data set?
3. If the acquired data set does not contain sufficient information about the event, what additional records are needed?

Prompt review of the data can be very important to timely generation of needed information.

Data review usually begins with a straightforward display and assessment of time domain plots. Assuming an event as shown in Fig. 1, the display should show

- major excursions in system angles and frequency, plus recovery from those excursions
- profiles of key signals from pre-disturbance through to post-disturbance conditions
- details of major transients in key signals
- signatures and/or effects of control actions, especially major protective control
- any apparently anomalous behavior

These displays may well show that some signals were degraded or lost through problems in the hardware, or in WAMS operation. The displays, and overage of the overall WAMS, should provide sufficient redundancy to accommodate this without significant loss of total information.

Control action signatures, such as steps in voltage or line MW, can be very important in event analysis. Some reasons for this include the following:

- they provide supplemental timing information concerning the sequence of events
- they can be a useful means to verify record alignment
- they define points in time where some kinds of signal analysis must be started, terminated, or interpreted in a different context

This last consideration is an important one in Prony analysis, or in any other kind of analysis that assumes a "free" ringdown of the system without extraneous inputs.

7.2 Saving Results for Future Use – Archive Management

Noteworthy behavior in a large power system generally consists of occasional large disturbances, interspersed with a much larger number of small disturbances and other indicators of system performance. Some or all of these may provide benchmark information that is valuable for many years into the future.

Extracting and conserving benchmark information are both essential to the value of WAMS investments. Written reports and the data that underlie them must both be available for later use. Anonymous data can be worse than useless—"*Nothing is more expensive that cheap data*." Embedded within every data set should be the information needed for its efficient and correct use at future times.

Documenting the origins of raw data is comparatively straightforward. Large scale analysis is rarely performed upon raw data from one source, however. The definitive data base for a major event may incorporate data from many sources, and even the same signal may have been processed in several different ways. Preserving the context of particular signals within various data sets requires a well structured approach to the management, processing, and archiving of analysis results.

The DSI Toolbox provides a number of features to facilitate these operations. They include

- *Case tags*, consisting of a name (**caseID**) and an execution time (**casetime**) that are appended to all results produced by a particular case.
- An optional *diary file* containing all text that has appeared on the Matlab Command Window (**MCW**)
- **A** *summary processing log* (**CaseCom**) that is generated automatically as the DSI Toolbox executes. A copy (**CaseComR**) is exported to archive files when data is saved.
- *Automatic name generation* for modified signals and for archive files.

To be effective, these features must be used in tandem with an orderly archive structure.

Fig. 2 shows the archive conventions for WAMS data at PNNL. Salient features are these:

- The expanded view of directory structure is for an event called **040614PaloVerde.**
- Record folders are organized according to data owners, and data sources for each data owner**.**
- All date strings are in the format **yymmdd.**
- All event names start with a date string**.**
- The names of some folders or files begin with an underbar, either to place them at the top of a list or to indicate that analysis is still active**.**
- The name of the report folder always starts with an underbar**.**
- The names of archive files generated by the DSI Toolbox (e.g., file **040614PaloVerdeBPA2A.mat**) start with the event name (040614PaloVerde)**.**
- Though not apparent from the directory, the caseID (a text string assigned by the user) also starts with the event name**.**

These conventions uniquely associate data and results with a specific event on a specific date, and they assure that name-based directory displays will show the events in the order of their occurrence.

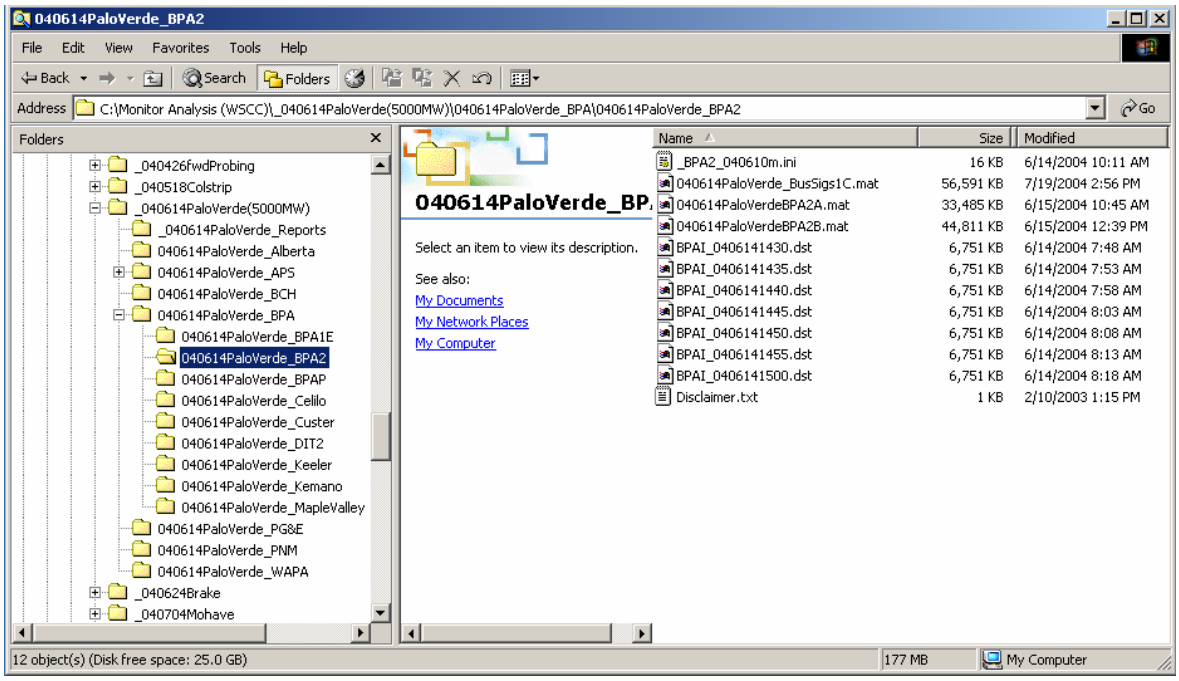


Fig. 2. An archive structure for major system events

7.3 Saving Results for Future Use – Report Generation

Report generation, like archive management, calls for suitable tools in combination with a well structured approach. As now practiced by the author, report generation for system events is based upon Microsoft PowerPoint and Microsoft Word (MS Word). It proceeds according to the following steps:

1. All graphics are pasted from Matlab into a PowerPoint file as they are developed.
2. To achieve consistency of scaling and overall presentation, some figures are revised in Matlab and re-pasted into the PowerPoint file. It is desirable that this be done while the original Matlab figures are "open" – otherwise the processing that produced them may have to be repeated.
3. All editing of the graphics is done in PowerPoint.
4. Initial PowerPoint reports are produced by adding text slides to the PowerPoint file, and then downsizing the file according to the interests of the audience.
5. A progression of MS Word reports are generated by downloading PowerPoint graphics into an MS Word environment and adding such text or other materials as may be appropriate. A SUITABLE TEMPLATE FOR SUCH REPORTS IS ESSENTIAL TO COLLABORATIVE DEVELOPMENT OF THE OVERALL DOCUMENT(S).

A suggested template for report generation in MS Word is provided with the DSI Toolbox. The present document was developed from that template, and can be used in lieu of it.

Those who use PowerPoint and MS Word to develop large technical documents should be very watchful for anomalous behavior of these tools. Typical problems are the following:

- Graphics that were developed outside the Microsoft environment may become impossible to edit, or totally unusable.
- Drawing tools within the Microsoft environment may sometimes work improperly.
- Graphics that are edited within the Microsoft environment may expand enormously when converted to a different format.

Problems within the Microsoft environment are usually temporary ones following the release of a new software edition. Prudent users will maintain an ample reserve of backup graphics for rebuilding figures that may become contaminated, or lost through other means.

7.4 Time Domain Plots

Time domain plots are essential to an initial review of the data, and they are usually a major element in the final report. The general guidelines in Section 7.1 apply in both situations.

Graphics in a final report will often condense several figures into one, and benefit from special annotation by the user. The user should expect to copy traces from one figure to another, change the colors and weights of the traces, and refine the text in plot legends. PowerPoint has proven to be a good tool for this, and preferable to MS Word in this respect.

7.5 Producing Relative Angles & Frequencies

An initial set of time domain plots is often followed by one or more cycles through processing option 2, **Angle/Freq Refs**. This provides the following calculations:

- all voltage frequencies from voltage angles
- all voltage angles relative to some indicated voltage angle
- all bus frequencies relative to some indicated bus frequency

The calculated signals are automatically assigned special names, and the standard default appends the calculated signals to those being processed within the workspace. Once this is done, the user can invoke the **DownSelect Signals** option (processing option 94) to discard unwanted signals, or just to resort the signals into some more convenient ordering.

The following should be considered when using **Angle/Freq Refs**:

- calculated voltage frequencies are an alternative to the measured PMU frequencies. Frequency signals produced by some PMUs have been deficient with regard to timing, filtering, or resolution.
- displays of relative voltage angles benefit from a good choice of reference bus. Sometimes they can be improved if some signals are changed by 360 degrees, perhaps under keyboard control.
- system dynamics that are strongly observable in local frequencies may be less so in relative frequencies, and vice versa.

Specific preferences in these matters are easily coded into a custom version of PSMbrowser.

7.6 Data Filtering

Signal filtering within the DSI Toolbox may be required for a number of reasons. The more common of these are to:

- remove excess measurement noise
- enhance the visibility of the signal components within a particular frequency range
- remove offsets or slow trends
- limit the signal spectrum prior to decimation (i.e., to avoid aliasing when the sample rate is reduced)

Some or all of these may be steps in preparing the signals for frequency domain analysis.

General guidelines for signal filtering in the DSI Toolbox are the following:

- Review relevant materials contained in the PSM Tools User Guide [3].
- Use established user options to extend the signal names to indicate which filtering has been applied.

  E.g., signal **MALN MALN-Round Mountain 1 Current MW**

  might become **MALN MALN-Round Mountain 1 Current MW_BP1**

  after application of a filter designated (by th3 user) as **BP1**.
- After filtering is done invoke the **Backload the filtered signals into the working signals** option (processing option 4). Then select backload option **Append filtered signals to working signals**. This preserves the original signals, and it allows the filtered signals to be compared against them directly.
- If necessary, invoke the **DownSelect Signals** option (processing option 94) to discard unwanted signals, or just to resort the signals into some more convenient ordering.

- As a precaution, periodically invoke the **save results** option (processing option 96) to archive processed data. One can revert to that data by invoking the **Load new data** option (processing option 95), or by launching another DSI Toolbox case.

The backload option **Append filtered signals to working signals** can only be used if the filter signals have the same sample rate as the unfiltered signals—i.e., if the filtering is not accompanied by decimation.

If decimation is desired it can be performed as a separate processing step. One can also use the option **Replace working signals by filtered signals**, but then it is no longer possible for the filtered and the unfiltered signals to be compared directly. Also, since this operation overstores the unfiltered signals, they should be safely archived before it is performed.

7.7 Prony Analysis of Oscillatory Transients

In the broadest sense, a Prony model is a linear sum of damped sinusoids and Prony Analysis is any process that fits a Prony model to a collection of signals. The DSI Toolbox offers two primary resources for Prony analysis. These are

- The Ringdown GUI (processing option 7)
- The Ringdown Utilities (processing option 8)

User documentation for Prony analysis is found in [4,5,**Error! Bookmark not defined.**] plus a large number of application notes. All of these are distributed with the DSI Toolbox.

Prony analysis involves the following tasks:

- selecting signals and time ranges for processing
- detecting hidden inputs that may have occurred during the ringdown
- selecting modes to include in the Prony model
- displays of response data, model fit, mode tables, and modeshapes
- export of the fitted model for simulation and/or controller design

The Ringdown GUI assists the user in this by various time domain and frequency domain displays that compare model response against that of the dynamic system. To do this, and to condition the signals for analysis, the Ringdown GUI provides a subset of the more general plotting, filtering, and Fourier analysis functionalities that are supported by PSM Tools.

The Ringdown Utilities are used in tandem with the Ringdown GUI, but after a Prony model has been constructed. Their primary use is to display the modeling results for report generation, and to export the fitted model for use in simulation and/or controller design.

Model export generally involves specialized design tradeoffs that are not easy to automate. Model export codes within the Ringdown Utilities are executed under keyboard control, using the editor to select/revise the appropriate instructions and then past them into the Matlab Command Window (MCW). Some of these instructions assume that the Matlab Control System Toolbox has been installed.

There are several places where the Ringdown GUI can be launched as a secondary option within the primary processing menu. This generally involves the analysis of "synthetic" ringdown signals that are derived as inverse Fourier transforms (**IFFT**s) or as time domain correlation functions. Once the Ringdown GUI is open and a Prony model has been constructed, the user can launch the Ringdown Utilities when next offered this option. It is not unusual to have several copies of the GUI open at the same time, but it is always necessary to provide the Utilities with the figure number of the correct GUI window.

7.8 Fourier Analysis of Small Signal Activity

Broadly described, a Fourier model is a linear sum of undamped sinusoids that are harmonically related, and Fourier Analysis is any process that fits a Fourier model to a collection of signals.

The DSI Toolbox offers processing option 5 (Fourier) as the tool for Fourier analysis. User documentation for Fourier analysis is found in [3] plus a large number of application notes. General information about Fourier analysis is available in texts such as [14,15].

Fourier analysis is usually applied in one of two different frameworks:

- **Large signal analysis**, in which each the fast Fourier transform (**FFT**) is applied to each signal across just once. The signals are usually transient ringdowns.
- **Small signal analysis**, in which an FFT processing window "slides" along each signal and the results are accumulated as running averages called *periodograms*. The signals often represent small fluctuations in much larger signals that have been passed through a bandpass filter.

When the signals are processed individually the final result is an *autospectrum* that displays the frequency content of the signal. The *waterfall plot* is a useful way to display periodograms as a function of time [10].

It is also useful to process the signals in pairs, with one signal designated as the reference signal. The resulting *correlation analysis* produces the following quantities or other quantities equivalent to them:

- The autospectrum **A11** for the reference signal (**S1**)
- The autospectrum **A22** for the signal (**S2**) correlated against the reference
- The apparent transfer function **T12** from S1 to S2
- The coherency function **C12** from S1 to S2

The coherency function is especially useful as an indicator of small dynamic interactions that would not otherwise be visible [14,16]:

7.9 Assessing the Event through Integrated Analysis

A major event on the system produces three broad questions:

- What happened?
- Why did it happen?
- What does it mean?

The first topic in the Basic Analysis section expanded these questions within the context of an initial data review. These same questions underlie all later analyses, but with a context that shifts as results and insights accumulate. It is not unusual for one event to add information about another, even when they are separated by several years.

System events and their analysis may differ considerably from one to the next. Despite this, *strategic* issues in their technical assessment with the DSI Toolbox reduce to just two:

- Determining the signatures and/or effects of control actions, especially major protective control
- Comparing system behavior against past behavior and/or expected behavior

Addressing these issues requires insightful and well coordinated use of both time domain and frequency domain tools. This is exemplified by the basic waterfall plot, which is a limited case of what is sometimes called Joint Time/Frequency Analysis (**JTFA**) [17].

Discrete control actions, such as line tripping or capacitor insertion, usually define points in time where some kinds of signal analysis must be started, terminated, or interpreted in a different context. This is an important consideration in Prony analysis, or in any other kind of analysis that assumes a "free" ringdown of the system without extraneous inputs.

8. Concluding Remarks

The analysis of dynamic systems is a vast, complex, and rather mathematical subject. The overview undertaken in this document can, at best, merely provide guidelines as to what actions may be necessary within fairly limited situations. For deeper insights the reader should turn to the user guides and application notes that accompany the DSI Toolbox, and to the general literature of dynamic systems.

Experts in systems analysis will recognize that the DSI Toolbox provides a framework and core menu of processing options that are basic to such work. The DSI Toolbox also provides or links to more advanced processing options that have not been discussed here. These include

- Alternate Prony analysis algorithms within the Ringdown GUI
- Use of the Ringdown GUI to extract dynamic parameters from the results of Fourier or time domain correlation analysis [18]
- Links to ModeMeter and other custom codes developed outside PNNL [19]
- Links to optional Matlab© toolboxes for filter design, control system analysis, system identification, and so forth

Users will often develop sufficient knowledge and skills in these matters on an "as needed" basis, according to the requirements of specific projects or tasks.

Much of the DSI Toolbox has evolved on this same basis. All development of the DSI Toolbox since 1999 has been incidental to other work – i.e., without funding specifically for development. Funded development is needed and somewhat overdue in the following areas:

1. **EventScan** (processing option 22)
   A. *Event Detection Logic* (**EDL**) to detect and log the signatures of discrete events such as protective control action. Applies only to signals stored within the workspace.
   B. *Archive Scanning Logic* that allows EventScan to examine all files in a collection. For large collections, only a subset of the data reside within the workspace at any one time.
   C. *DataStream Scanning Logic* that allows EventScan to examine all data files as they are acquired in real time.

2. **Macro GUI**s, chiefly in the form of "button bars" to condense low level text-based menus
3. **Documentation updates,** plus integrated application notes.

All of these upgrades are easily done, and all of them enhance user productivity for data intensive environments.

Upgrade 1A, to automatically detect and log the signatures of discrete events, will also enhance the reliability of analysis procedures that should be confined to time intervals which are free of such events. The rapid growth of WAMS facilities across North America is producing far more signals than one can expect to review by direct visual inspection alone.

9. Glossary of Terms

DSM	Dynamic System Monitor
PDC	Phasor Data Concentrator
PMU	Phasor Measurement Unit
PPSM	Portable Power System Monitor
PSM	Power System Monitor (primary definition)
"	Power System Measurements (secondary definition)
WAMS	Wide Area Measurement System
DMWG	Disturbance Monitoring Work Group of the WECC
M&VWG	Monitoring & Validation Work Group of the WECC
WECC	Western Electricity Coordinating Council
EIPP	Eastern Interconnection Phasor Project
(others)	

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