POWER PLANT DYNAMICS MONITORING
A REVIEW OF THE NEEDS, DIFFICULTIES, AND POSSIBILITIES

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1. INTRODUCTION

This paper presents considerations relating to the monitoring of power plants to meet the requirements of transmission grids for information on their dynamic behavior.

Nearly all power plants today are supervised by Digital Control Systems (DCS) and most, though not all, of these DCS provide some form of trend recording. Nearly all plants now have a Plant Information (PI) system, either as an integrated part of their DCS or as a free standing unit. These trend recorders and PI systems can usually provide a fair picture of how a plant has behaved in normal slowly varying operation and through normal load change maneuvers. However it is still difficult to find good data on the dynamic behavior of plants when they are disturbed by events on the grid. This suggests that the present standard monitoring elements in a power plant, the DCS and PI systems, are oriented to in-plant interests and are not well suited to the needs of the grid through which the plant delivers its product to market. The consideration presented here, then, describes a monitoring system that is in addition to standard DSC and PI system functions.

2. POWER PLANT OPERATION AND MONITORING

2.1 Plant Control

The primary focus of plant operations is the condition of the boiler and turbine. Power production is controlled by changing fuel flow but the operator is as concerned with the effect of changes of fueling on temperatures and pressures in the boiler / turbine as with the effect on the transmission grid. The grid is regarded as maintaining steady conditions as it receives the power produced in the plant. The thermodynamic processes of the boiler and turbine take place on a time scale of tens of seconds to many minutes.

2.2 Grid Control

The fundamental principles of grid control have changed little in the hundred and twenty years and can be stated simply in terms of four variables:

- each turbine generator must be controlled second-by-second so that its real power output and shaft speed are held in the droop relationship shown in figure 1.
- each generator must be controlled second-by-second so that its reactive power output and terminal voltage are held in the droop relationship shown in figure 2.

These two relationships are enforced by the turbine governor and the generator voltage regulator, respectively. The responses of these controls are much quicker than the variations of temperature and pressure seen on the boiler / turbine side of the plant; key time constants range between 0.1 and 10 seconds.

The interest of the transmission grid is focused on the way the plant behaves in brief transient disturbances of the four key variables. These transients:

- in many cases may not even be noticed by the plant operators
- in nearly all cases run their course so quickly that the plant operator could not do anything about them, even if he should see them
- cannot be 'captured' accurately, and can even be missed completely, by recording systems using sampling rates appropriate for the boiler-turbine side of the plant

2.3 Arrangement of Power Plant Controls

The control and monitoring systems in a typical plant reflect the differences in interest and time scale noted above. A typical arrangement of plant and control elements is shown in figure 3. The main elements of the plant, the generator, turbine, and boiler are shown in black. The generator primary control, the voltage regulator, is shown in light blue. The turbine primary control, the governor, is shown in red. The plant DCS, PI system, and associated supervisory data paths are shown in green. The paths of control setpoints sent from the DCS to primary controls, and from the grid control office to the DCS, are shown in brown.

The most direct influence on the grid is the voltage regulator, shown in light blue. The control inputs are voltage and current at the generator terminals; the output is the voltage applied to the generator field. The bandwidth required of the voltage regulator dictates that the input signals be hard wired and that the digital regulator cycles 15-50 times per second. The voltage setpoint is forwarded (brown) from the DCS at its cycle rate of one repeat per second or slower. Voltage regulator status signals are forwarded to the DCS for display on control desks.

The primary turbine control, the governor, is shown in red. Its cycle rate is 10-30 per second; it can act very quickly in response to small variations of grid frequency. The speed signal is taken directly from the turbine-generator speed pickups. As with the voltage regulator, the governor setpoint is forwarded from the DCS at the DCS cycle rate (brown) and governor signals are sent back to the DCS for display and use in boiler control functions.

The boiler and secondary turbine controls are implemented in the plant DCS. The DCS receives hundreds of data points from transducers around the boiler, feedpumps, fuel control system, and other plant elements at rates of 0.25 to 1.0 samples per second, as indicated by broad green data paths in figure 3. Control loops managing these elements run in the DCS at varying cycle rates, typically from 0.5 to 1.0 cycles per second. Operator displays are updated every 1-4 seconds.

3. RELATIONSHIP OF PLANT AND GRID OPERATION

The operation of a modern power system is based on a hierarchy of pre-filed plans, authorized deviations from plans, prearranged provisions for uncertainty, and planned provision for emergencies.

The principal steps in a days operations proceed roughly as follows:

- A profile of total grid load for the day is prepared in advance; estimates are made as long as one week ahead and each day's scheduling is based on a profile prepared the preceding day.
- Individual plants prepare operation plans for the day indicating the output that they would prefer to, or be able to, produce in each hour. These plans range from very simple in the case of base loaded plants to complex where a plant must accommodate varying ambient conditions like temperature (gas turbines) or river flow (hydro).
- The grid operator assigns a plan of output for each hour to each plant under its control

- The individual plants set their output each hour in accordance with the assignment; changes in output are executed as a ramp beginning a few minutes before and ending a few minutes after each hour

- The grid operator assigns selected plants to Load-Frequency-Control duty. These plants vary their output continuously in accordance with command signals from the grid control center; the command signals are updated every few seconds and plants typically follow command with time lags ranging from 10 to 30 seconds.

The grid operator would instruct individual plants not assigned to LFC duty to deviate from the preassigned output when necessary to accommodate unanticipated or emergency conditions on the grid.

In a normal day where the error in the grid's load forecast is small most plants can expect to maneuver very much according to the preassigned program. Output levels are anticipated in advance and maneuvering is gentle in relation to the rate-of-change capabilities of the plant equipment.

4. REGULATION OF GRID FREQUENCY AND VOLTAGE

Grid frequency and voltage are not constant, though most plant owners wish they would be and often act as if they are. In fact the frequency and voltage of even the best operated grid *vary* continuously and rapidly in response to both:

- constant small random variations (sizzle) of the electric load on the grid

- discrete events on the grid such as the sudden disconnection of a large generator or block of load

The satisfactory operation of the grid requires that the output of generating plants be adjusted continually to maintain a very close balance of load and generation. Adjustments to maintain this balance must be made on a time scale that is much quicker than can be achieved by the grid operation mechanism described above; the required speed of action can only be achieved by autonomous regulating action within the individual power plants. Thus, in addition to providing real and reactive power output in accordance with the operational schedules that they establish and agree upon with the grid operator, most power plants are required to operate their machinery such that it responds immediately to small changes of grid frequency and grid voltage.

The ability to provide this response is inherent in all turbine-generators (except some wind machines) and is provided naturally, as distinct from in response to commands. In practical fact, however, while most turbine generators have the ability to provide this natural response many are operated in modes that either suppress it completely or countermand it quite quickly after it has taken place.

In well operated grids the natural response is seen in a power plants as a small "sizzle" component superimposed on the scheduled hourly profile of output. It is the prompt provision of this "sizzling" variation of output that holds grid frequency and voltage close to their scheduled values. When an adequate fraction of the total plant on the grid is operated so as to provide this natural response the 'sizzle' of frequency and voltage is small and balanced above and below nominal values. In well operated grids the natural variation in the output of a plant is less than 1 percent of rating.

The natural frequency and voltage sensitivity of plants serves a second critical function in addition to accommodating the normal "sizzle" of the load. It is the first line of defense and corrective action when the grid experiences a major discrete event such as the sudden loss of a large generating unit. There are many units in the Western USA system, for example, whose loss causes frequency to fall as fast as 60mHz per second. A dip in frequency of 200mHz is considered to be large and, accordingly, the total power delivered to the grid must be restored into balance with the load within a very few seconds; this can only be achieved by having a large fraction of the plants on the grid respond in their natural manner to the frequency dip.

5.INTERESTS OF THE PARTIES

The first concern of all parties responsible for the grid is that frequency and voltage must be held stable and within statutory limits. This must be handled on a time scale of seconds. Then, given stable frequency and voltage, the operation of the grid in accordance with loading schedules is carried out on the time scale of minutes to hours, that is, on the time scale of commerce.

The interests of the parties are largely aligned with these time scales.

Plant owners are interested in the heat rate and economics of their equipment in relation to the scheduling of output and trading of energy. They need monitoring of a very large number of signals from the plant, recorded at a rate of samples per minute.

Plant operators are concerned with the maneuvering required by grid operations. They need trend records of signals over periods ranging from minutes to an hour, typically sampled at intervals of 1 to 4 seconds.

Grid operators share the interest of the plant operators. Current grid control systems receive data from the plants at sampling intervals ranging from 2 to 10 seconds.

The majority of PI and data historian systems in power plants are oriented to the requirements of owners, plant, and grid operators.

Interest in the quick natural response of the power plant controls to the sizzle and sudden events on the grid is increasing rapidly among entities concerned with predicting the behavior of the grid and among regulatory entities. This increasing interest stems from the role of regulatory entities in ensuring the reliability of the grid and from the evidence provided by recent major grid incidents that accurate simulation of grid behavior is essential in the assessment of reliability.

6.MONITORING RELATED TO FREQUENCY/VOLTAGE DYNAMICS

The entities involved in grid analysis and regulatory entities exercising independent supervision of grid reliability now pay close attention to effective control of frequency and voltage. Grid codes, which originally addressed grid operations on the time scale of minutes, increasingly cover issues related to the second-by-second control of frequency and voltage. Because this control necessarily takes place autonomously within power plants, the analytical and regulatory communities now take a strong interest in the second-by-second dynamic behavior of individual plants, going well beyond what can be observed from the operational monitoring available in grid SCADA systems:

- The analytical community is required to construct calibrated dynamic models to represent the plants in comprehensive grid simulations, and to revalidate these models at regular intervals.

- The regulatory community sets standards for dynamic performance of plants and, increasingly, monitors the compliance of plants with these standards,

These two factors are the driving force in the present movement towards permanently installed dynamic monitoring systems in power plants. The driving influences are outside the plants, but the signals ofinterest are inside. The outside communities need similar levels of monitoring but make different use of the monitored data:

- The regulatory community wants to know what the plant did
- The analytical community needs to deduce how it did it

We now review what is needed to meet these emerging monitoring needs; looking at the following aspects:

- access to monitored data
- signals and transducers
- sampling rates and signal latency
- storage and retention of monitored data

7. MONITORING OR DYNAMIC BEHAVIOR

7.1 Access to Monitored Data

Plant owners see the uses of dynamic monitoring data obtained within their plants as not directly in their commercial interest and, quite reasonably, have concerns about providing unrestricted access to it. Grid codes are presently inconsistent in the extent to which they require that monitored plant data be available to the outside communities. There is a strong argument, though, that it is beneficial to both plant owners and the outside communities to have all parties work with accurate data whose bandwidth is appropriate for their various tasks.

Surely, the plant owner should share the interest of the regulating entity at the technical level. If the plant does not respond as called for in grid code standards he should be aware of this as soon as possible.

Good dynamic monitoring can be a key element in resolving contention between the plant owner, the grid operator and the regulating entity. The data most readily available to the grid operator and regulating entity when a question of plant behavior arises is that from the grid SCADA system. Because of its low bandwidth and poor time synchronization, this data can give misleading impressions of how a plant has behaved on the second-by-second time scale. Discussions on the basis of such data have an unfortunate tendency to substitute speculation for absent fact regarding behavior not revealed by low-bandwidth records. The bandwidth of plant DCS and PI systems, while often somewhat better that that of grid SCADA systems, is not sufficient to replace this speculation with fact. Data from a high quality dynamic monitor is the authoritative information needed to simplify and clarify relations between the plant and the grid in such situations.

Owners are acutely aware of the costs of staged testing done to develop, calibrate, and revalidate analytical models; effective dynamic monitoring can significantly reduce the associated costs.

It is hardly surprising that the plant owners will prefer the monitoring of signals within their plants to be under their control. Grid codes are presently inconsistent in the extent to which they insist that monitored plant data be available to the outside communities.

7.2 Signals and Transducers

A typical list of signals for a dynamics monitor would be as follows, roughly in order of importance and priority:

Signal	Sampling Rate s/sec		
	Min	Optimum	Test
a . generator stator voltage (RMS)	10	30	60
b . generator stator current (RMS)	10	30	60
c . generator real power (RMS)	10	30	60
d . generator reactive power (RMS)	10	30	60
e . generator field voltage (DC)	10	30	60
f . generator field current (DC)	10	30	60
g . power system stabilizer output	10	30	60
h . turbine shaft speed	10	30	60
i . turbine valve reference/ command	10	30	60
j . turbine speed/load reference	10	10	60
k . ST main steam pressure	2	5	5
1 . ST hot reheat steam pressure m. GT fuel gas pressure	2	5	5
n . Auxiliary bus voltage (RMS)	2	5	5
o . Auxiliary transformer real power	10	30	60
p . Auxiliary transformer reactive pwr	10	30	60
q . Condenser bypass valve position	10	30	60
r . Generator main circuit break status	2	5	5
s . Turbine run/trip status	10	30++	60

The sampling rates given above are:

- the minimum rate for useable monitoring of grid-related dynamic behavior
- a near-optimum rate for monitoring of grid-related dynamic behavior
- a sampling rate suitable for special use in test work of limited duration

It is important that the signals are provided by transducers of appropriate bandwidth and with appropriate transmitters. At best, a transducer and the signal transmission associated with the DCS or PI system has sufficient bandwidth for our new purpose and a dynamic monitor can 'pick up' its signal at a convenient point in the relay or computer room. At worst, a new transducer and new signal wiring are required. For example, the power transducers often used in association with DCS / PI systems are frequently found to have response times measured in seconds, where effective dynamic monitoring requires power to be measured with a time constant on the order of 50 msec.

7.3 Sampling Rate, Synchronization, and Latency

Many digital turbine controllers and most plant DCS computers already monitor most of the required signals but sample them at such a slow rate that they are of little value in relation to grid dynamics. The table above indicates the minimum acceptable and optimum sampling rates for monitoring dynamic behavior of interest to the grid. These rates are much faster than those available in most present DCS / PI systems.

Electrical signals such as generator power and terminal voltage are sometimes available at suitable bandwidth and sampling rate from the voltage regulator but, again, their presence does not ensure that they are is suitable for dynamic monitoring.

A sufficiently fast sampling rate is far from a sufficient condition for satisfactory dynamic monitoring. It is equally important that the complete set of signals be sampled as nearly simultaneously as possible, that is with minimal difference in latency among signals arriving at the monitor. Because the signals are used for monitoring but not for control uniform latency is acceptable but variability of latency is not. Where all signals are delivered from transducers by direct analog wiring and scanned by a single high speed digitizer it is normally possible to ensure that the time 'skew' between the actual instants of sampling of a set of nominally simultaneous values is known and acceptably small.

In practice it is necessary to examine each transducer and the path by which its signal reaches the dynamic monitor, and to be wary of several factors that can spoil the simultaneity of sampling:

- transducers may digitize their signals locally and forward them by ethernet, GPIB, RS232, or other transmission protocols, all of which can introduce delays that are significant in relation to the sampling rate

- transducers may retransmit their signals at a sufficiently rapid rate, but only update their measurement at a slower rate and, of course, it is the slower rate that defines the usefulness of the signal

- transducers may sample and update their transmitted signals only when polled and may have unknown or variable delays between receipt of poll and transmission of data

- signals may be sampled and transmitted at appropriate rates by their transducers but be routed to and through computers than introduce significant and, worse, unknown transmission delays

Experience with the fault recording and electrical monitoring industry is significant in relation to latency and simultaneity of sampling. Experience to date is bad and emphasizes that:

- time stamps applied to signals at the point of recording are useless if the time delay between signal acquisition at the transducer and application of the stamp is unknown

- a single time stamp applied to a 'row' of samples in a data record is meaningless if the latency between acquisition and stamp application is not uniform across the set of signals

A further issue with time stamping is that the time clocks of individual dynamic monitors should be synchronized to an accuracy consistent with the requirements on sampling rate and latency.

A dynamic monitor should be able to ensure that the time spread covering a set of nominally simultaneous samples is less than 50 msec. The time references of all dynamic monitors should be synchronized within 20 microseconds, worldwide.

7.4 Storage and Retention of Monitored Data

The purpose of the dynamic monitor is to capture the behavior of the plant in response to the continual and unpredictable variation of grid conditions. The monitor will see long periods of uninteresting normal operation punctuated by brief periods of intense activity and interest. The periods of interest will occur without warning and without the possibility of anticipating their character. Thus triggered recording, which was the only choice until recently, has been unsatisfactory for a number of reasons. Among these:

- the character of important events is unknown in advance and the importance of an event may become apparent only <u>after it is over</u>

- significant events cannot be assumed to have initial features conducive to triggering such as sudden jumps or rapid changes in monitored signals

- triggering arranged to reliably capture events of great interest to one party can miss events of primary interest to others

Further, in regard to triggering, the very normal appearing behavior of plants that are far from an initiating event are often as important in grid analysis as the strong responses of close-by plants. It is important to be able to retrieve the recorded behavior of many and widely dispersed plants as questions arising in grid analysis raise the need.

While these factors have often lead to difficulty and dissatisfaction with triggering, recent advances in computer storage capacity have rendered the issue moot. It is now practical to record signals in the numbers considered here continuously for the full 8760 hours of each year, 3600 seconds of each hour. At 30 samples per second such continuous recording of 20 signals would require approximately 151 Gigabytes if stored in ASCII files. This is entirely within the capability of current moderately priced computers. Using a scaled binary storage format would reduce this storage requirement to about 50 Gigabytes but would only be desirable if the storage format was open, published, and non-proprietary.

High speed or real time transmission of monitored data to outside users is a low priority at the present stage of dynamic monitoring. Nevertheless, the continuously monitored data must be stored in a modular manner in preparation for retrieval upon demand. Data files covering periods of the scale of 5 minutes are of a size that can conveniently be carried in portable media (USB memory sticks) or up/down-loaded via the internet. A degree of refinement is important. For example:

- time periods covered by data files should 'butt together' without loss of data or should overlap by a few seconds

- time stamps on files should be consistent with the timing of sampling and synchronized to "GPS" (ie microsecond) accuracy.

8.SUMMARY AND CONCLUSION

In summary of the main points:

Monitoring of power plants for grid-related purposes requires sampling rates in the range of 10-30 samples per second, but requires a relatively small number of signals in comparison to the hundreds of signals that are sampled and stored by PI systems for plant-related purposes.

Present PI systems are not designed for and cannot provide the kind of monitoring that is needed for grid related dynamic performance analysis.

To meet grid requirements fully monitoring must be continuous, but real time delivery of recorded data is not needed and rapid retrieval, even, is less important than continuity of the record.

Continuous monitoring of plant variables for use in grid-related engineering is now both practical and desirable.

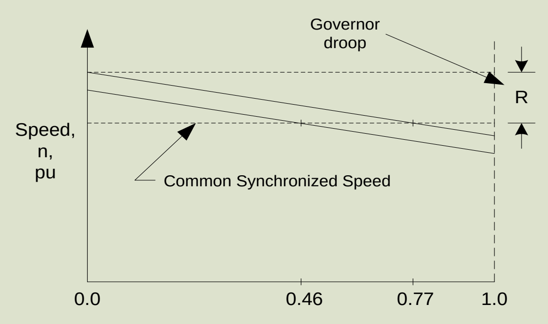

Figure 1 Governor Speed-Power Relationship

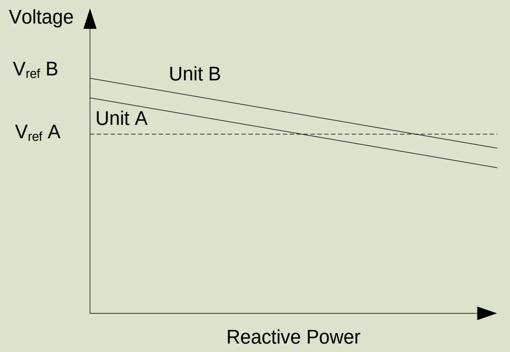

Figure 2 Voltage Regulator Voltage-Reactive Power Relationship

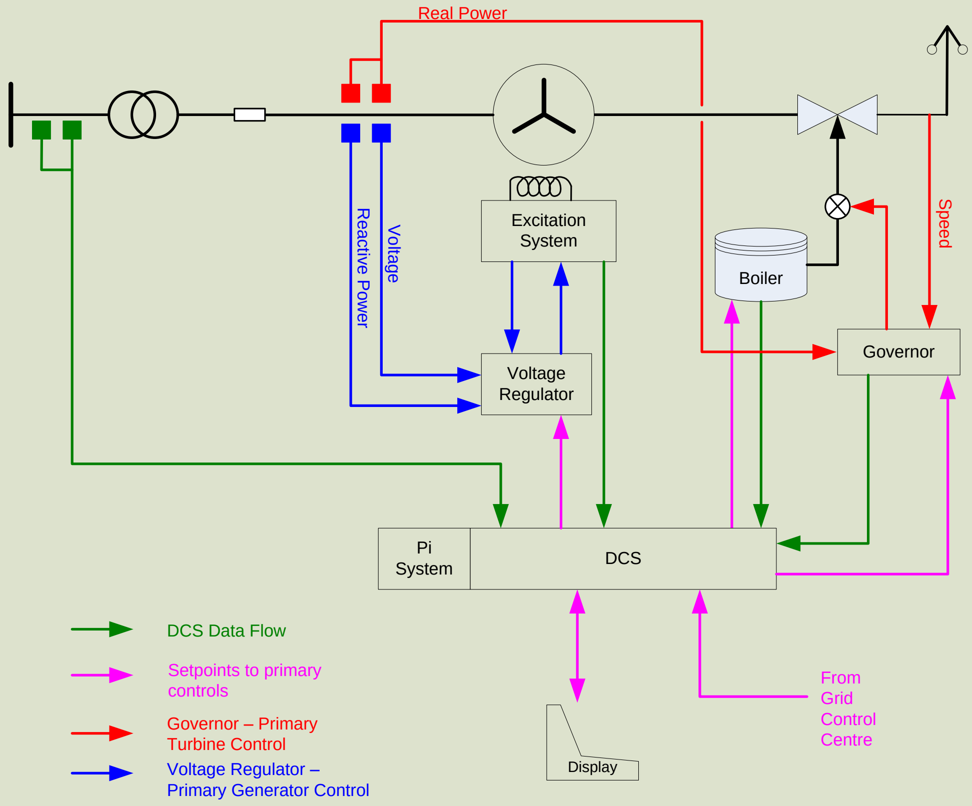

Figure 3 – Overview of Plant Control Elements