Benefits of Power Swing Recording

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INTRODUCTION

Power system dynamics such as short circuits, auto-reclosures, line switching, or fluctuations due to significant variations in load cause the system's generators to adjust to the new conditions in the network. These large disturbances may cause generators in one part of the system to accelerate, while generators in another part of the system decelerate, thereby creating a condition where the two parts of the system are likely to separate due to loss of synchronism.

Abnormal voltages, high currents, and abnormal phase angles usually accompany these adjustments. Consequently high equalizing currents and reduced voltages appear as small impedances to distance relays, which can lead to tripping. In extensive networks, which carry high loads, the stability of the energy transfer can be endangered by such power swings.

This paper addresses power swing theory, and explains how to monitor and analyze swing with advanced monitoring / recording devices and benefits it can yield for the utility. It further describes, through analysis of records, a use of today's digital recorders, which are capable of monitoring and recording power system data at multiple timeframes – from high-speed transients to long-term trends. Of these recording modes, dynamic swing recording is often least understood, although it is potentially most critical to understanding system stability and optimizing wide area system performance.

RELIABILITY AND SECURITY OF POWER SYSTEM

Recent major blackouts in North America, London, Sweden and Italy have demonstrated tremendous impact they have on national economies and people's lives. It is very obvious that the security and reliability of power system networks, and more broadly of the total delivery system, is of paramount importance.
Security of a power system [1] refers to the degree of risk in its ability to survive imminent disturbances without interruption of customer service. It is a time-varying attribute, which can be studied by reviewing the performance of the power system under a particular set of conditions.

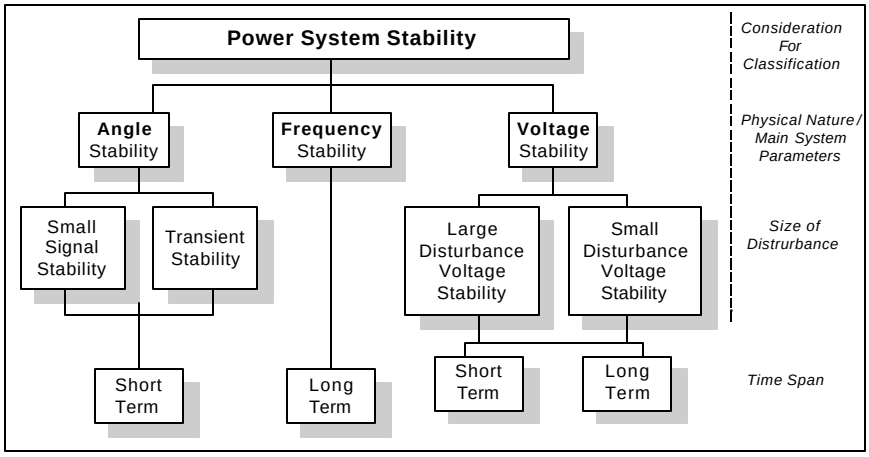


Figure 1. Classification of Power System Stability

Reliability of a power system refers to the probability of its satisfactory operation over the long run. Reliability is a function of the time-average performance of the power system; it can only be judged by consideration of the system's behavior over an appreciable period of time.

Power system stability is usually described by three fundamental parameters: line angle, frequency and voltage. Watts and Vars transferred are consequential measures of stability. Figure 1 describes the classification of power system stability looking at those three fundamental parameters: angle, frequency, and voltage.

CHALLENGES

Today's bulk electricity system is the critical energy infrastructure that supports digital society, and appears to be left behind as an industrial relic of the 20th century.
The power system we are dealing with today:

- Was predominantly built with 1950's technology
- Was designed for the power needs of that time
- Have shown 35% load growth versus 18% capacity growth in the last decade
- Requires substantial upgrading to meet current digital society demand

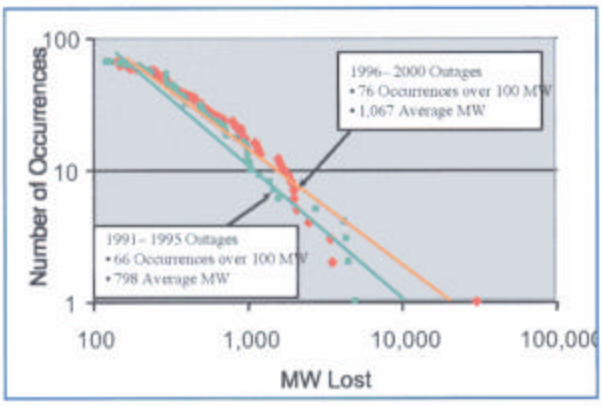


Figure 2. Historical analysis of US outages in terms of the amount of electrical load lost (1991-2000) [1]

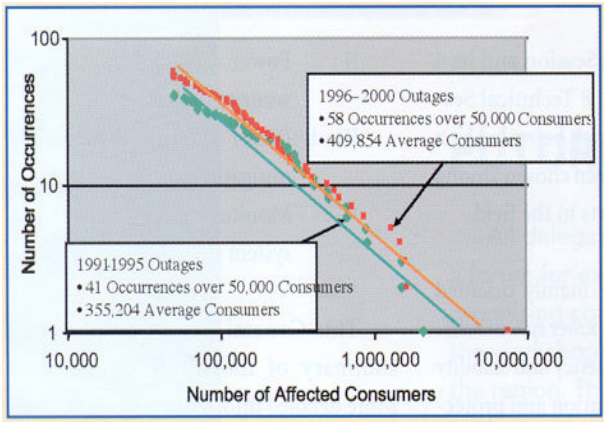


Figure 3. Historical analysis of US outages in terms of affected customers (1991-2000)[1]

The nature of electricity demand is undergoing a profound shift in industrialized nations across the globe. Figures 2 and 3 show that outages in the US are increasing in terms of lost energy supplied and in terms of customers affected.

Economic losses from power disturbances and power outages include production downtime, loss of raw material, damaged product and equipment, disrupted supply chains, even bankruptcy. The large scale outages rose to the rank of the major disasters. Societies have become dependant upon electricity, considering it a given and not really questioning its presence. Human behavior in industrialized nations changes instantly with the occurrence of a power outage. Reactions range from tolerance through discomfort to very high intolerance. Figure 4 depicts a degree of societal reaction to blackouts.

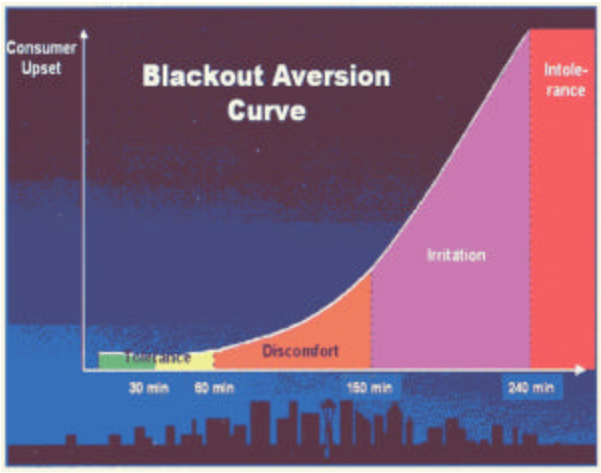


Figure 4. Societal reaction to blackouts [1]

In the recent blackout of August 14th in the Northeastern US, the system collapsed in 9 seconds, 50 million people were affected, and 22 nuclear power plants shut down. The size of power swing was ~5000MW, as compared with the recorded power swing of 800MW during the US Northeast Blackout of 1965.

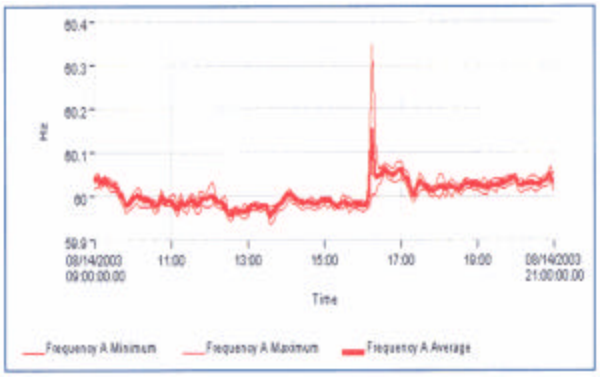


Figure 5. Frequency data, New Jersey, August 14, 2003 [1]

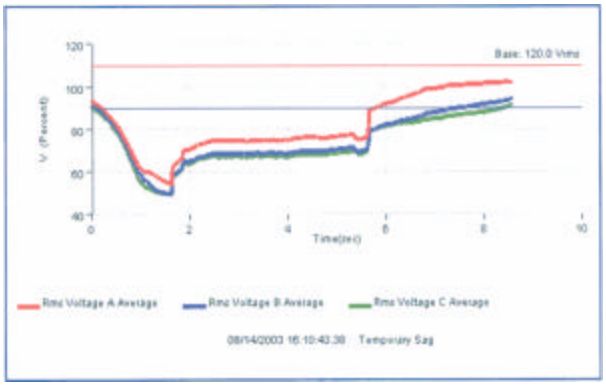


Figure 6. RMS variation, New Jersey, August 14, 2003 [1]

Due to the interconnected nature of large power systems, variations in the grid's voltage and frequency quantities can be measured hundreds of miles away. Figures 5 and 6 are examples of recordings taken some distance away from the source of the problem, where deviations were shown in the system's frequency and voltage quantities in the New Jersey area during the event on August 14th, 2003.

DEFINITION OF STABILITY

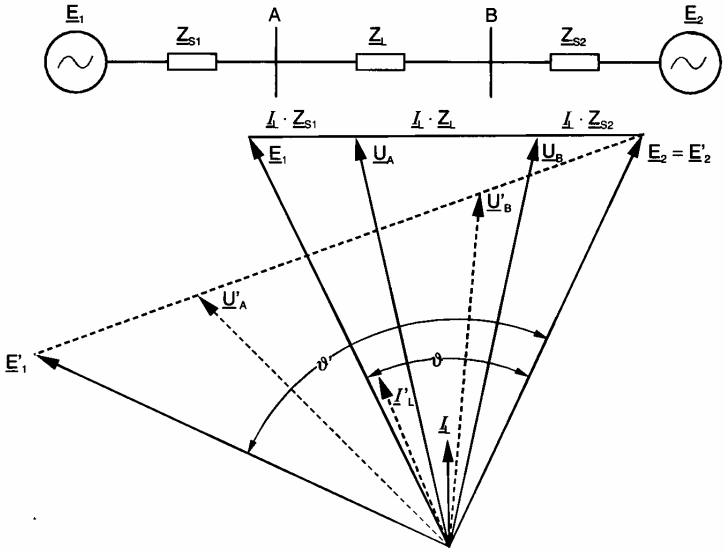
The concept of stability is central to several disciplines in electrical engineering, physics, and mathematics. Control systems that do not exhibit stable performance would be almost worthless and stability theory is central to control system design and analysis.
Power systems have a number of control, monitoring, recording and protective devices to ensure that the response to any change in system conditions is controlled. All these components work together so that the customers fed from the power system can rely upon fairly constant and dependable operating characteristics.

Stability is the ability of power system to remain in synchronous equilibrium under steady state operating conditions and to regain a state of equilibrium after disturbance has occurred [3].

The disturbance can be of any type, but short circuits are of particular interest, since these events result in conditions that are relatively severe to the surrounding power system. In addition, short circuits have the potential of causing instability if not removed promptly. Extremely large disturbances are possible and may result in cascading outages due to large power surges that result in system separations. The power system is not normally designed to withstand these rare and unusually large disturbances, but the anticipation of such events may lead to the design of appropriate controlled response schemes. The major role, in defining system response to minor and major disturbances using properly designed controlled response schemes, plays the monitoring equipment such as digital fault recorders that have swing recording capabilities and relays with out-of-step control.

STATIC STABILITY

Figure 7 illustrates the voltage diagram of an overhead line under load. The connected networks are represented by the two equivalent sources E_1 and E_2. The source impedances Z_{S1} and Z_{S2} correspond to the respective short-circuit power of the two sources. The angle "***v***" is referred to as the transmission angle. As the transferred real power increases, this angle becomes larger. The transferred power is defined by the equation below:



$$P_{TP} = \frac{E_1 \cdot E_2}{Z_T} \cdot \sin\vartheta$$

with $\underline{Z}_T = \underline{Z}_{S1} + \underline{Z}_L + \underline{Z}_{S2}$

Figure 7. Power swing condition in a transmission system - voltage diagram. Static Stability [2].

The maximum power transfer is therefore achieved with the angle ***v*** = 90° between vector E_1 and E_2. At the same time this corresponds to the static stability limit.

Transmission voltage is needed to transfer electric power from the generation station to the load centers. Reactive power is a component that assists in maintaining proper voltages across the power system. As transmission lines become more heavily loaded, they consume more reactive power needed to maintain proper transmission voltage.

When heavily loaded transmission lines become faulted and their relay systems remove them from service, the lines that remain in service automatically pick up portions of flow formerly carried by the faulted line. This act of picking up load serves to increase the reactive power consumed by these lines. If reactive supply is limited, the increased loading will cause a voltage drop along the line. If reactive supply

is not provided at the end of the line, the voltage could fall precipitously. At that point, the transmission system can no longer transfer electric power from distant generation to load centers.

Various conditions can occur on the grid, such as excessive or inadequate voltage, resulting in changes in the system's apparent impedance. The power system is designed to ensure that if conditions occur that would threaten the safe operation of the transmission lines or power plants that the threatened equipment must be automatically separated from the network in order to minimize possibilities of damage to electrical equipment.

DYNAMIC STABILITY

Dynamic angle changes between E_1 and E_2 above 90^o are permissible without resulting in network instability. This is based on the "equal area" criterion, which is referred to in Figure 8. The transfer power is defined by the given equation and follows a sinusoidal curve depending on the load angle "***v***". The rated operating point corresponds to the connected turbine power P_T.

The pre-fault condition shows that the system is in equilibrium when the torque angle is $\boldsymbol{v}_0$. For this condition, there is no generator acceleration and the system is at rest - Curve 1. When the fault occurs, the operating angle is still $\boldsymbol{v}_0$ since the angle cannot change instantaneously, but the electric power is now given by the Curve 2, representing the power characteristics during the fault. The generator shaft begins to accelerate along the **P- *v*** characteristic until the fault is cleared at angle $\boldsymbol{v}_1$ - the clearing angle. Now, the electrical power suddenly jumps to the post-fault Curve 3 and the angle continuous to accelerate to its maximum value $\boldsymbol{v}_2$, at which point it reverses direction. The angle continues to oscillate about the mechanical power until it finally settles at a new equilibrium point at a new values $\boldsymbol{v}_e$, which is given by the intersection of the post-fault electrical power Curve 3 and mechanical power line P_T. Since the total susceptance of the network is lower due to the line outage, it requires a larger torque angle to maintain this value of generated power.

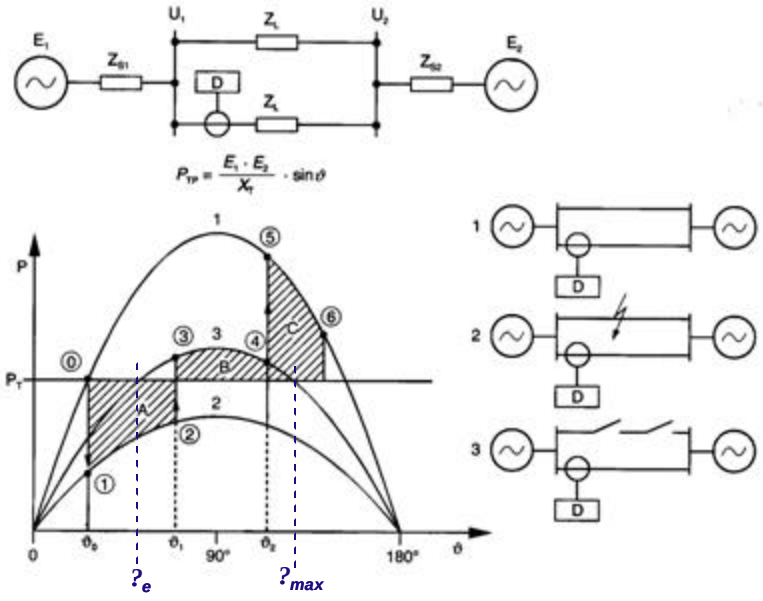


Figure 8. Dynamic stability. Equal Area Criterion [2].

Curve 1 – Electrical Power before the Fault
Curve 2 – Electrical Power during the Fault
Curve 3 – Electrical Power after the Fault
P_T Line – Mechanical Power Input

The generators return to their stable initial operating point as long as the decelerating area "**B+C**" remains larger that the accelerating area "**A**". Clearly, this will only be the case if the fault in a power system is rapidly cleared.

POWER SWING – WHAT IS IT

The equation that determines the behavior of a Generator for a network disturbance, such as a fault, is called the *swing equation* [3]. This equation is nothing more than Newton's second law, expressed in terms of power system quantities. The basic system to be considered is the generator and its prime mover, which can be described by the second order differential equation

$$J \frac{d^2 \nu}{dt^2} = T_a \, (Nm)$$

where, J = moment of inertia (kg-m^2)
ν = physical angle of shaft (rad)
t = time (s)
T_a = accelerating torque (Nm)

The major force that causes generating unit to respond to the disturbance is the rapid change in accelerating power, which is approximately the difference between the nearly constant mechanical power and the rapidly changing electrical power [3].

This simple concept has some important implications for protection systems, including the following:

1. It is important to clear the fault as quickly as possible, thereby limiting the area "A" to as small as possible.
2. It would be beneficial if the faulted line could be reclosed, perhaps after a brief delay needed to allow the arc to be deionized. This would permit area "B" to extend all the way to the upper curve 1, thereby giving a larger margin for stability.

The power swing process described above is usually represented as an impedance curve to illustrate how the relay or digital fault recorder measures the power swing vector in the impedance plane.

POWER SWING CHARACTERISTICS

Power swings are three-phase symmetrical phenomena. A precondition for their detection is the absence of any ground faults and the symmetry of measured loop impedances. In order to detect a power swing, the rate of change of the impedance vector is measured. They are distinguished by the following characteristics:

- stable swings have slow oscillations where the angles between two voltage sources vary, usually < 1Hz, 0.5-0.8Hz being common (greater than 1sec period of oscillation)
- large disturbances typically result in minimal oscillations, rather a monotonic increase in the angle until the voltage collapses at some point and relay operates
- Many power swings are caused by short circuits, auto-reclosures, line switching, and large changes in load

A swing causes voltage phase shift between sources E_1 and E_2 - angle ν in Figure 9.

Consequences of the swing include variation in system frequency & voltage and power flow. Heavy load transfers in a power network can result in portions of the system losing stability. Because faults represent the greatest threat to system stability, power swing detection remains in service during a single-pole auto-reclose cycle.

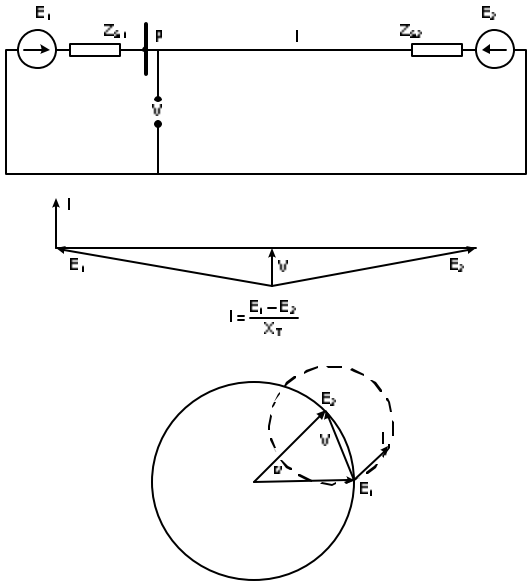


Figure 9. Current measured by relay (or DFR) at point "P", and voltage difference & phase shift between sources.

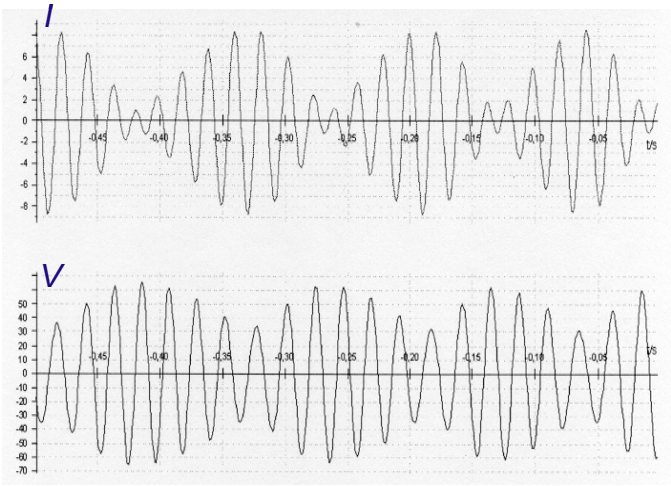


Figure 10. Current and voltage waveforms during power

OUT-OF-STEP CONDITION

If the load impedance vector enters and remains within a distance element's protection zone, tripping may occur. Tripping during the power swing may be inhibited by the so-called power swing blocking function. During a power swing, the impedance vector exhibits a steady progression rather than rapid change that might indicate a fault. By measurement of rate of change of impedance and comparison with thresholds it is possible to distinguish between short-circuits and power swings.

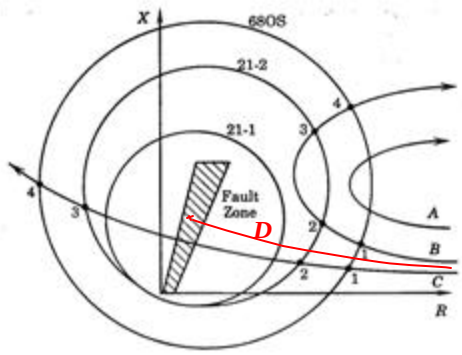


Figure 11. "Mho" type out-of-step detector [3].

A: Z moves into OS zone and leaves slowly
B: Z moves into OS & Trip zones and leaves slowly
C: Z moves slowly across = network becomes asynchronous
D: Fault = Z moves rapidly into Trip zone

When the criteria for power swing detection are not met and when out-of-step tripping is selected, all zones of the relay are blocked temporarily, in order to prevent premature tripping. When impedance vector "Z" leaves the power swing area, the vector is checked by its "R" component. If the "R" component still has the same sign as at the point of entry, the power swing is in the process of stabilizing. Otherwise, the vector has passed through the Mho characteristic (trace "C" in Figure 11) indicating loss of synchronism.

POWER SWING RECORDING

Dynamic swing disturbances may last over a period of several minutes, therefore they need to be recorded using different techniques than transient (short-duration) faults. Dynamic swing recordings must show

system performance for a longer time-frame due to the balanced nature of these events. Swing recordings typically monitor the changes in a power system's positive sequence voltage phasors, as well as system frequency, with a typical sampling/calculated rate of 1 phasor per cycle. Experimentation in monitoring power swings has shown that to obtain meaningful information about the event the recording should continue for 2 to 3 minutes in order to get a complete picture of the system swing.

Most often, swing recordings monitor the values of voltage phasor magnitude and angle, current phasor magnitude and angle, system frequency, and power flow (active and reactive) .

Records can be initiated on activation of any trip or alarm through the use of an external contact input, through impedance circle function independent of protection, or manually through the interface to Digital Fault Recorder equipped with a swing detection algorithm.
It is critical that when recording power swing events that each record be time stamped to an accuracy of 1ms. This could be achieved with wide area synchronization using IRIG-B time synch input. This method would enable comparison of times between event records seen by recording equipment at different points of the network. Sampling of data by recording equipment preferably should have higher rate than 64 samples per cycle, in order to get better resolution of the waveform for more accurate analysis.

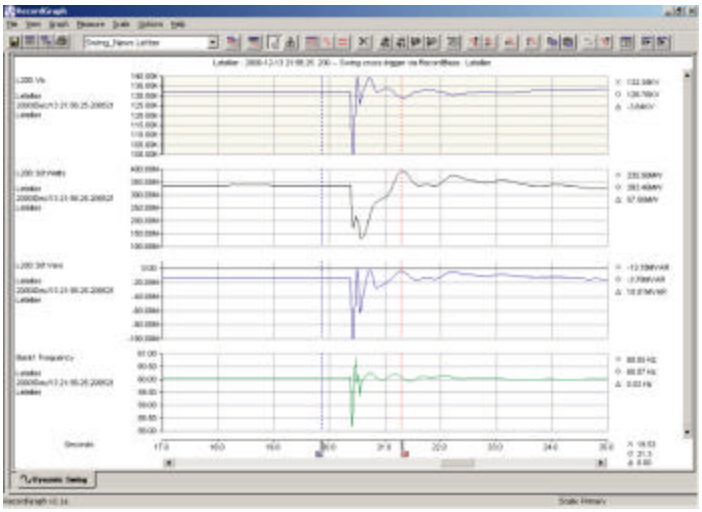


Figure 12. Typical Power System Swing Record (voltage, power flow in watts & vars, and system frequency) [5].

The features of recording equipment that offer engineers additional flexibility and better analysis tool include an ability to trigger a swing record up to 20 minutes after a swing event occurred. This could be accomplished in part by rolling buffer or forced cross-trigger. Such feature permits a wide area dynamic swing recording to capture effects of the swing across the transmission network.

USE OF POWER SWING RECORDS

One unfortunate result of power swings is their tendency to cause the misoperation of impedance relays on a transmission system. Heavy load conditions on a transmission line result in the impedance measured by the relay to fall within the reach of the distance (or impedance) relay (s). Distance relays respond to the high equalizing currents and reduced voltages – particularly in the electrical center (as illustrated in Figure 9). Small voltages accompanied by high currents appear as small impedances to distance relays which can lead to tripping. In order to prevent uncontrolled tripping, distance relays must be provided with power swing blocking capabilities. In some cases, out-of-step tripping relays are applied so that once a system network is split into parts (sometimes referred to as "islands"), these "islands" can continue to serve their respective load.

As previously indicated, one of the consequences of dynamic swings are the misoperation of impedance (or distance) relays. Impedance relays are intended to protect against short circuits that occur on the transmission line. In such case the impedance changes essentially instantly. However, large system

swings can appear as impedance slowly moving into the impedance relay's tripping zone, initiating a trip of the respective transmission line. In some cases, tripping lines during power swings increases the severity of the problem, consequently increasing the likelihood of a system collapse.

Transient records (sampling rates typically greater than 5000 samples per second) cannot verify the correct or incorrect operation of impedance relays due to power swings. This is due to the fact that these high-speed recordings are designed to show the system's parameters (typically voltage and current) at the time of the relay's operation. These high-speed recordings are not capable of showing the slow speed changes in the quantities of a power system. For this reason, some impedance relays offer also dynamic swing recording algorithms, and more powerful Digital Fault Recorders have swing recording features with a variety of triggers designed for the purpose.

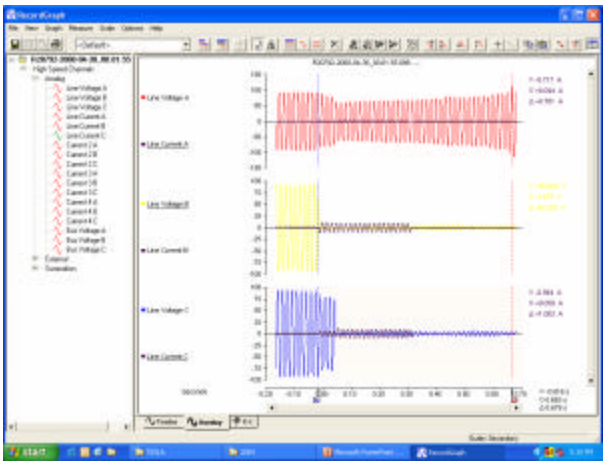


Figure 13. Transient record - Fault in phase B&C.

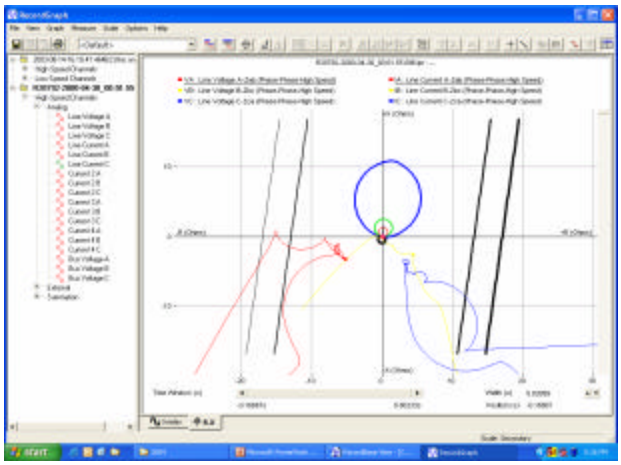


Figure 14. Impedance trajectories and fault clearing.

One of the benefits of power swing recording is to document the operation of the protection system during wide area disturbances. Dynamic swing records can prove that an impedance relay has performed correctly (did not operate) during a stable swing near its characteristic reach. They can also document when power swings cause the measured impedance to move into a relay's tripping zones.

Dynamic swing records can be used to provide root-cause analysis information for the misoperation of impedance relays due to power swings. In fact, dynamic swing records have already been used to verify impedance relay operation. Figure 15 and figure 16 show an actual power swing recorded by a newer-style Digital Fault Recorder (DFR), which was equipped with capabilities of recording dynamic swings on a power system. This plot was taken from the Northeastern U.S. event occurring on August 14th, 2003. At the location of this recorder, the swing was a stable power swing, outside the tripping zones of the local distance relay. In this instance, the dynamic swing record of the DFR proves the protection system was *correct by not operating* for this event on out-of-step condition.

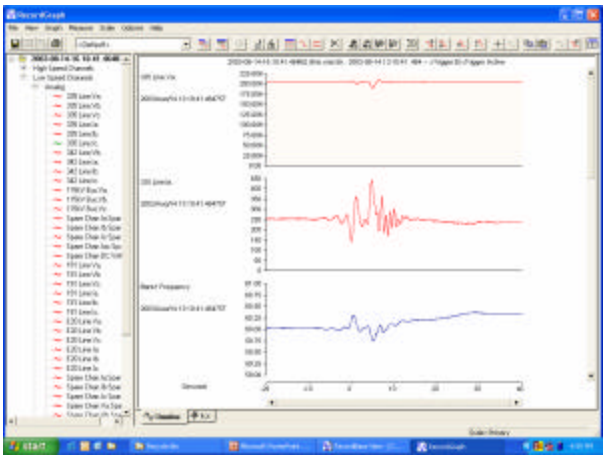


Figure 15. Swing - voltage, current and frequency.

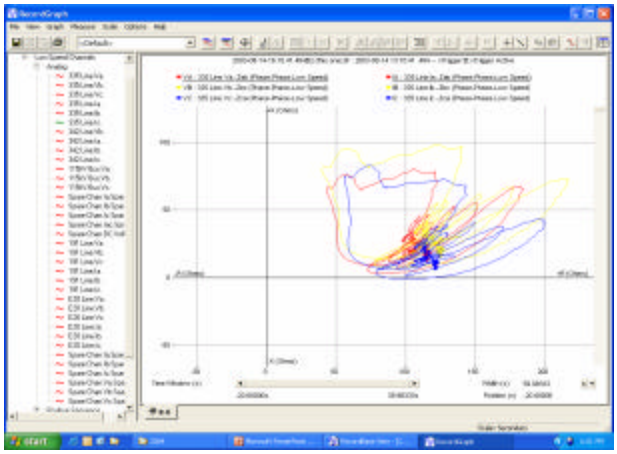


Figure 16. Swing impedance trajectories of phase A,B,C

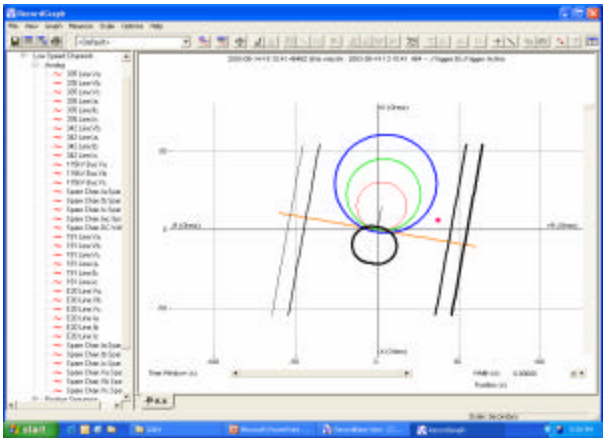


Figure 17. Line relay R-X characteristics.

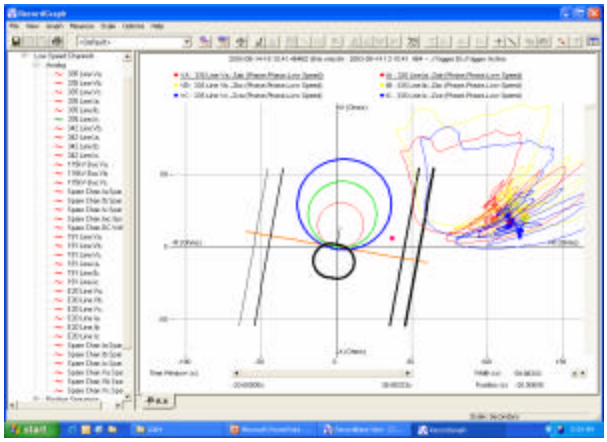


Figure 18. Power swing impedance vs. relay tripping zones [5].

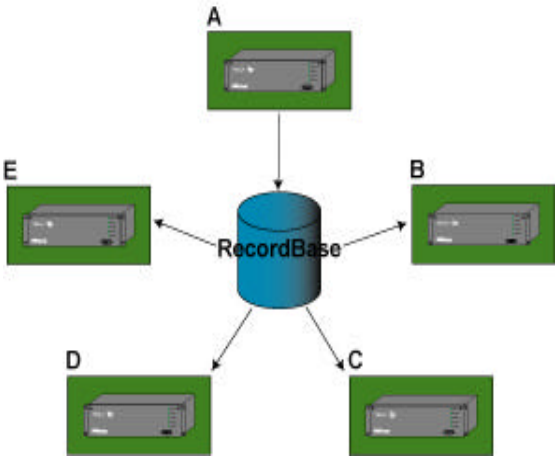
This power swing record illustrates the positive sequence impedance as seen by DFR and the relay. The impedance due to the power swing is outside of Zone 3, the largest relay tripping zone, documenting the correct *non-operation* of the relay for this event. It further verified the reliability of relay operation on out-of-step conditions, confirming that the settings were correct, and relay responded as intended.

WIDE AREA MONITORING AND POWER SWING DATA MANAGEMENT

As seen by previous example, dynamic swing recording is useful at local terminals to verify the correct operation of local equipment, or to provide root-cause-analysis of incorrect operation of local equipment. However, dynamic swing recording is most useful when showing the effects of power swing across the entire network. By collecting and coordinating dynamic swing records from multiple locations on the network, an engineer can evaluate response of the system to disturbances and the degree of power grid stability during an event.

Central server Data Management Software that communicates with Digital Fault Recorders located in various substations enables:

- Automatic retrieval: scheduled, or by recorder when triggered
- Cross-trigger dynamic swing recording over entire population of DFR's connected to the server
- System wide synchronized snapshot of grid's response to swing
- Display and analysis of data from multiple records simultaneously
- Exporting swing records in COMTRADE, ASCII or PTI formats for comparison of system model.



The RecordBase central station offers: (a) Integrated record database with search, sort and filter functions by date/time, IED, fault class data, swing class data and record sets, (b) Graphical, interactive record display with timebase, phasor, harmonics and symmetrical component analysis tools, (c) Record summaries with classification, priority assignment, event lists and shared analysis comment field.

Figure 19. Cross triggering of newer-style DFR's over wide area network [5].

RecordBase, shown in Figure 19, manages system wide dynamic swing recording, accepts a dynamic swing recording trigger from a DFR (A), and issues time-synchronized cross triggering commands to other DFRs (B–E). RecordBase ensures a system wide synchronized snapshot of the grid's response to a dynamic disturbance using the DFR's 20 minute record buffer and IRIG-B time synchronization inputs.

This feature and records so collected are particularly useful to validate the system stability models and how they may respond to disturbances that cause power swings. Unfortunately, in most of the utilities in North America, a wide area automated and time synchronized information gathering from DFR's is rarely available today. The events of August 14th, 2003 have shown a renewed interest in the recording of dynamic swings.

BENEFITS OF SWING RECORDING DURING AUGUST 14TH BLACKOUT

Us Department of Energy have initiated a process to data gathering right after the blackout of August 14th occurred [4]. The objective of this task was to seek all available information that would aid to understand the event. The North American Electric Reliability Council (NERC) was commissioned to investigation it and came up with the report, which among other findings, determined that:

- Some prolonged out-of-step conditions were evident
- Time stamping is critical to be able to evaluate thousands of discrete events
- Some Utilities did not have effective monitoring capabilities
- System planning, facilities ratings and modeling data accuracy were ineffective preparations for 8/14 event
- Power system was being operated with insufficient reactive margins to meet NERC criteria
- Improvements need to be made with respect to the control of reactive power and voltage
- Measurements of power system quantities should be time synchronized

Importance of retaining data for analysis was strongly emphasized. In conjunction with type of data required, it confirmed a need of having synchronized time stamped log of frequency, voltage and power flow to understand the system swing and how it lead to the cascaded collapse of the grid.

It has further become evident that DFR's with swing recording and analysis capabilities, time synchronized over a wide area network, would have significantly contributed to a better understanding of the system's behavior during the event. Other benefits of this data would be improved understanding of a power system's stability limits, and a more thorough post-mortem analysis of an event, leading to an improved security of the power system, in general.

CONCLUSIONS

The sequence of events for the August 14, 2003 blackout summarizes some of the many significant events that occurred before and during this widespread and complex system failure. It reflects events that have been identified and verified in the fall of 2003.

Evidently, no sufficient data and swing records had been available to precisely conclude how the system behaved prior and during its eventual collapse. It has been cited that the availability of time synchronized records at different points in the networks would have been invaluable to better model the behavior of the power system with all of its interconnections, thus enhancing the stability of the system.

It is also evident that the use of swing recording equipment on major busses within interconnected system would enable better understanding of system swings and their impact upon the performance of impedance (or distance) relays during power swing events.

Dynamic swing recordings are a powerful tool in improving the operation of the transmission network, and can be used to identify the key system conditions that may result in relay misoperations and/or loss of system stability.

REFERENCES

1. Robert A., “Quality and Security of Electric Power Delivery System – General Report”, Electra (CIGRE), issue No 210, October 2003, pp 37-45.

2. Ziegler G., “Numerical Distance Protection, Principles and Application”, Publicis-MCD-Verl., ISBN 3-89578-142-8, 1999, pp. 48-51.

3. Anderson P.M., “Power System Protection”, IEEE Press, Piscataway, NJ, 1999, pp. 858-862 and 897-901.

4. Glotfelty J., “Authorization for Donald Lekang to collect data records and other information on behalf of the Department of Energy pertinent to events contributing to the August 14 blackout”, Letter dated August 22, 2003.

5. Klimek A., Hunt R., “Dynamic Power Swing Recording”, Application Note, 2003.

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