Disturbance Analysis for Power Systems

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Agenda

- **Power System Disturbance Analysis Function**
- Determination of Power System Equipment Health through System Disturbance Analysis
- Phenomena Related to System Faults and the Process of Clearing Faults From a Power System
- Classification of Shunt Faults
- Power System Phenomena and their Impact on Relay System Performance
- Generator System Disturbances
- Transformer System Disturbances
- Breaker Failure Protection System Disturbances

Power System Disturbance Analysis Function

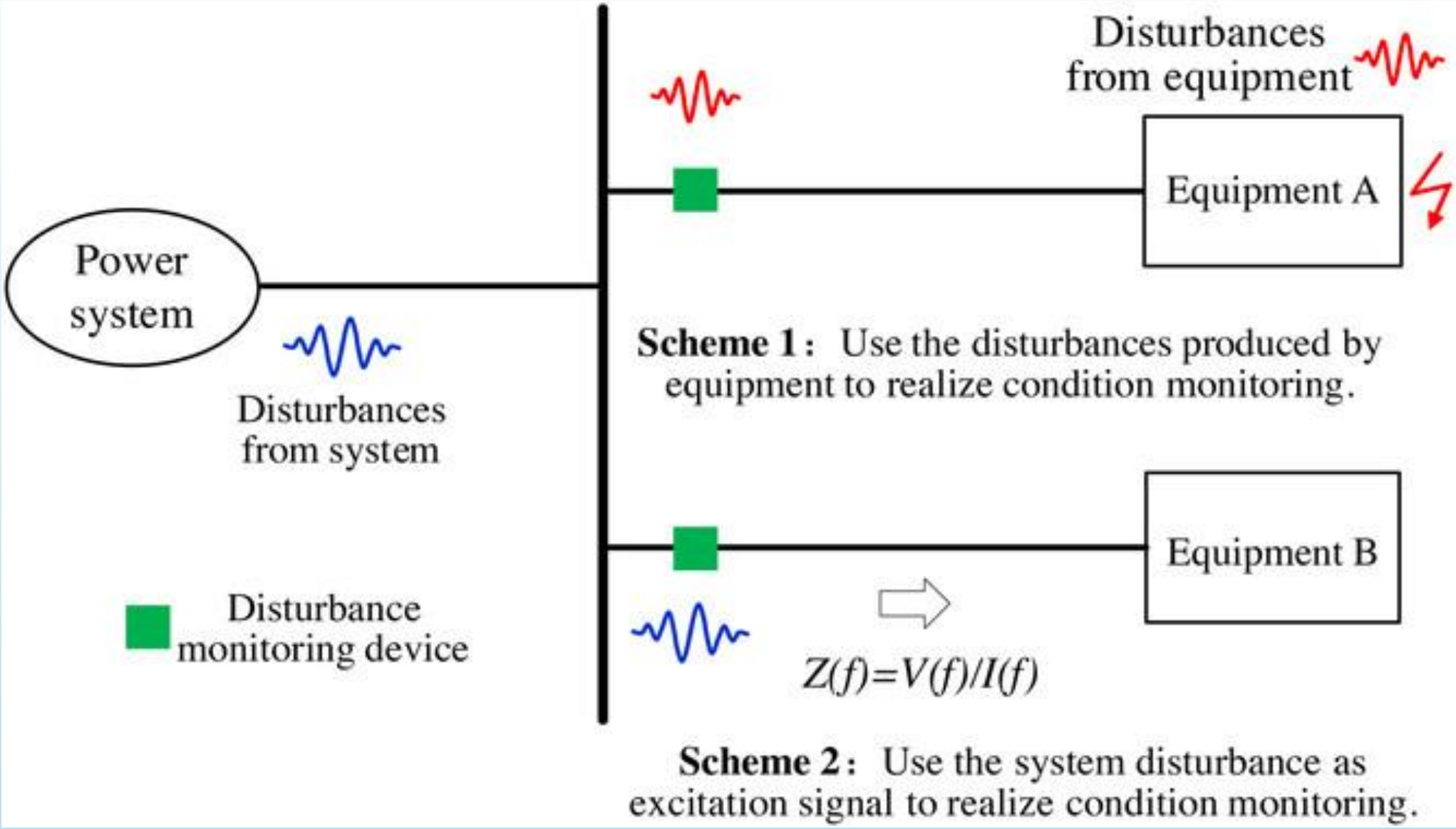
- Power system disturbance analysis is a critical function in the operation and maintenance of electrical grids.
- Its primary purpose is to

➢ identify,

➢ classify, and

➢ understand the causes and effects of abnormal events or "disturbances" that disrupt the normal flow of electricity.

- This analysis is vital for ensuring the reliability, security, and stability of the power system.
- The **function of power system disturbance analysis** can be broken down into several key components:



Power disturbance waveform analysis and proactive application in power systems

1. Data Collection and Monitoring

The foundation of disturbance analysis is the ability to accurately **monitor and record power system behavior.**

- **Intelligent Electronic Devices (IEDs)**
- **Data Acquisition**
- **Power Quality Monitoring**

2. Event Identification and Classification

This involves:

- **Trigger Detection**
- **Fault Analysis**
- **Disturbance Type Classification**

Common classifications include:

- **Faults:** Caused by short circuits or insulation failures.
- **Switching Operations:** Planned or unplanned changes in the network topology (e.g., line tripping, breaker opening).
- **Abnormal Operations:** Conditions like generator trips, load shedding, or equipment malfunctions.
- **Power Quality Events:** Sags, swells, transients, and harmonics caused by non-linear loads or other system issues.

3. Root Cause Analysis and System Behavior Assessment

This is the core of the analysis function.

This involves:

- **Sequence of Events:** Establishing a millisecond-level timeline of events, from the initiating event (e.g., a lightning strike) to the subsequent tripping of relays and circuit breakers.
- **Protection System Performance:** Evaluating whether protective relays and circuit breakers operated correctly and in coordination with one another.

- **Modeling and Simulation:** Using the recorded data as inputs for power system analysis software to replicate the event and verify the sequence of events and system behavior.
- **Equipment Health Determination:** Disturbances can reveal the health of power system equipment.

By analyzing the data, engineers can detect signs of **deteriorating performance,** such as **slow breaker operations** or **relay setting issues**, which can be used for **predictive maintenance.**

4. Application and Improvement

The ultimate goal of disturbance analysis is to use the findings to improve the power system. This includes:

- **Corrective Actions:** Implementing necessary repairs or adjustments to equipment and protection.
- **Operational Procedures:** Modifying operating procedures to better handle specific types of disturbances.
- **System Planning:** Providing valuable feedback to system planners for future expansion and upgrades.
- **Knowledge Base:** Building a historical database of disturbances and their analysis results, which can be used for **training, research, and for anticipating future events.**

Tools and Methods

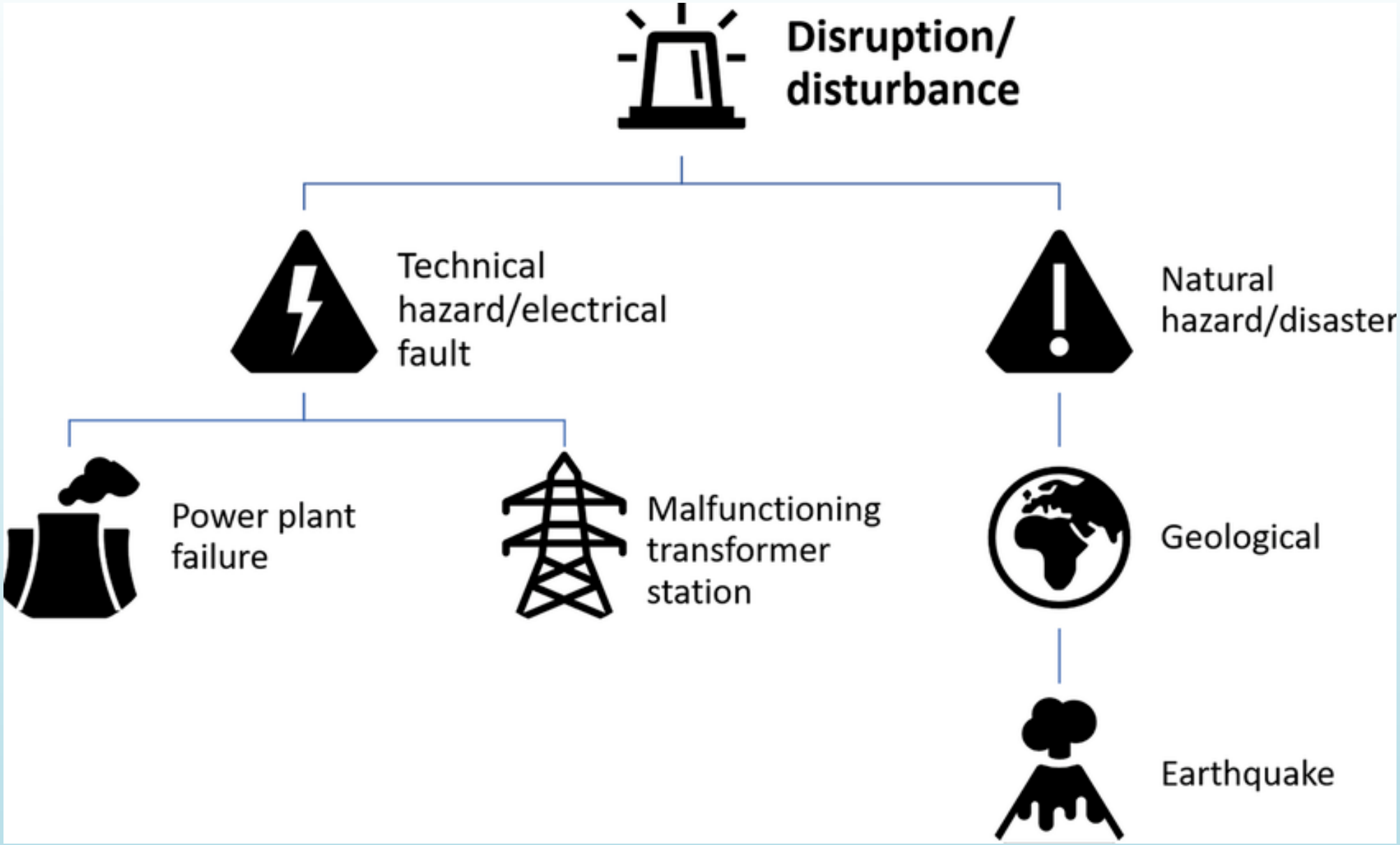
- **Signal Processing:** Techniques like Wavelet Transform and S-Transform are used to analyze the non-stationary signals of voltage and current waveforms during a disturbance.
- **Data Analysis and Visualization:** Software platforms are used to manage, process, and visualize the large volume of data collected from IEDs.
- **Mathematical Models:** Symmetrical components, per-unit systems, and phasor analysis are fundamental mathematical tools used to simplify and analyze fault conditions.
- **Advanced Analytics:** Machine learning and AI-based methods are increasingly being used to automate the **classification of disturbances, predict potential issues, and identify subtle anomalies.**

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Determination Of Power System Equipment Health Through System Disturbance Analysis

- Power disturbances are any change in the power system's waveform under normal or abnormal conditions.
- Analyzing power system disturbances is a critical method for assessing the health of power system equipment.
- Disturbances, which are deviations from the normal operating state of the system, contain valuable information about the condition of the grid and its components.
- By analyzing the characteristics of these disturbances, engineers can identify issues, predict potential failures, and implement condition-based maintenance strategies.



Categorization of disruptions/disturbances that can paralyze the electricity system. Figure is modified from a table in Organization for Security and Co-operation in Europe

How Disturbance Analysis Reveals Equipment Health

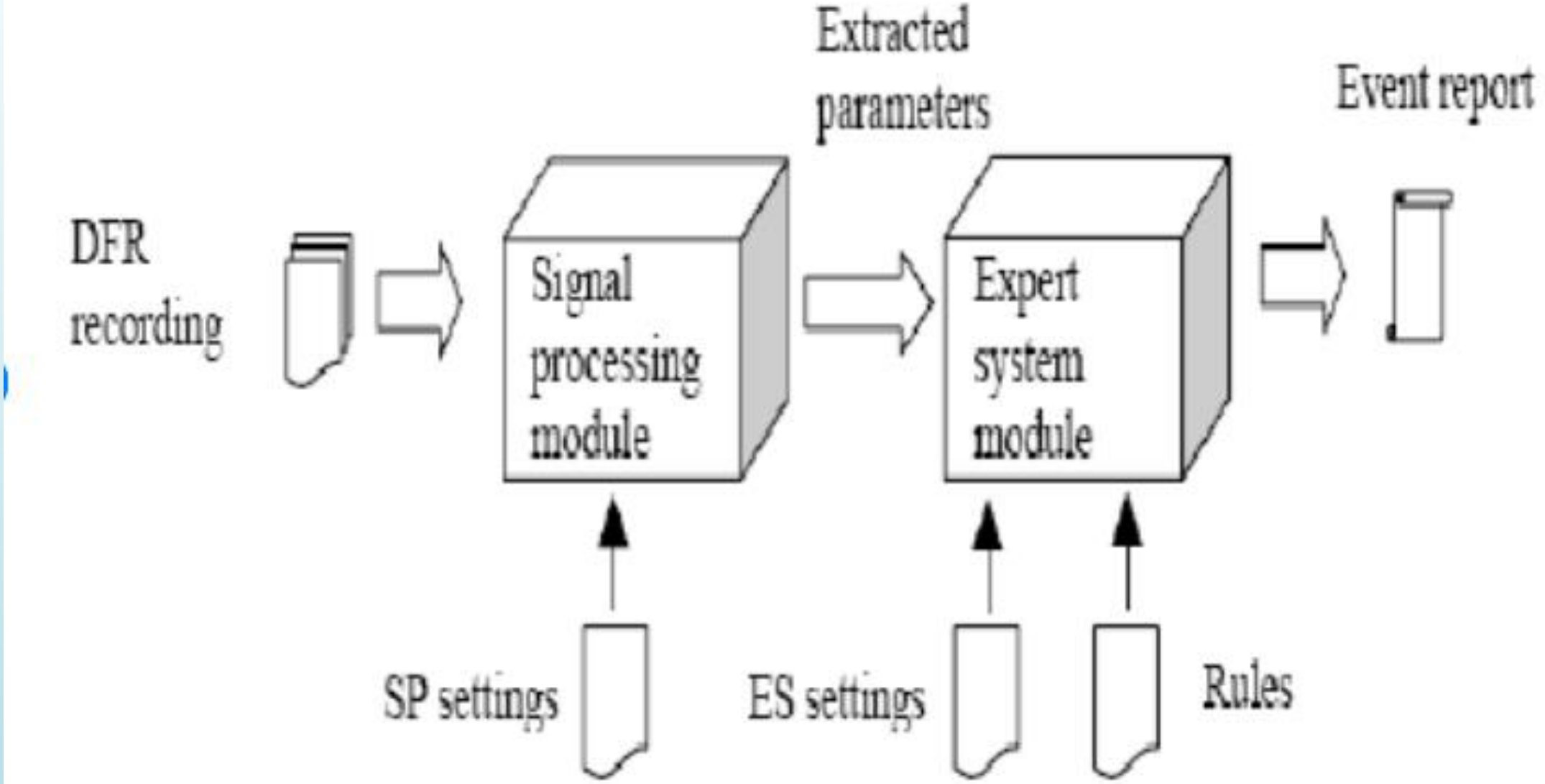
1. Analysis of Fault Records

Fault recorders (also known as digital fault recorders or DFRs) capture high-speed waveform data (voltage and current) before, during, and after a fault. Analyzing this data can provide a wealth of information:

- **Relay and Circuit Breaker Performance**:

➢ By examining the timing of the fault, the trip signal from the relay, and the circuit breaker's operation, engineers can assess if the protection system is operating correctly.

➢ Deviations from expected timing can indicate a sluggish circuit breaker or a relay with incorrect settings.



Digital Fault Recorder Analysis Software Modules

- **Insulation Health:**

➢ The specific characteristics of a fault, such as the magnitude of fault current and voltage, can be used to diagnose issues with equipment insulation.

➢ A high-impedance fault might be a sign of deteriorating insulation.

➢ Partial discharge (PD) is another indicator of insulation health, and the high-frequency electromagnetic waves produced by PD can be detected and analyzed to locate the source of the defect.

- **Transformer Condition:**

➢ Analysis of dissolved gas in transformer oil, combined with fault data, can provide a comprehensive view of a transformer's health.

➢ Gases produced during a fault can indicate specific types of internal damage.

2. Waveform Analysis

The detailed waveform data from disturbances can be analyzed using various signal processing techniques to extract crucial information:

- **Fourier Analysis:** This technique helps in identifying harmonic components in the voltage and current waveforms.
- **Wavelet Transform:** This is a powerful tool for analyzing transient events and identifying abrupt changes in the signal, which can be linked to specific events like switching operations or faults.

  It helps in locating the exact time and frequency of a disturbance.

- **Polarization Ellipse Method:**

➢ This method is used to extract unique fault signatures.

➢ During healthy conditions, a polarization plot of voltage and current might be circular, but during a fault, it becomes an ellipse, and the parameters of this ellipse (major/minor axis, angle) can be used to classify the fault and determine its location.

3. Data-Driven and AI-based Methods

The increasing availability of data from modern power systems, including from **Phasor Measurement Units (PMUs),** has led to the development of more advanced, data-driven methods:

- **Health Index (HI) Calculation**:

➢ A health index is a composite score that evaluates the overall condition of a piece of equipment.

➢ It can be calculated by combining various data points, including disturbance analysis results, maintenance history, and other sensor data (e.g., temperature, dissolved gas analysis).

➢ This provides a single, easily understandable value for decision-makers.

- **Machine Learning and Deep Learning:**

➢ These techniques are used to analyze large datasets of disturbance waveforms to automatically detect and classify faults.

➢ They can be trained to recognize patterns that correlate with specific equipment issues, making the diagnostic process more efficient and accurate.

- **Predictive Maintenance:**

➢ By analyzing trends in disturbance data over time, machine learning models can predict the remaining useful life of equipment.

➢ This allows for a shift from reactive or time-based maintenance to a more efficient condition-based maintenance approach.

Key Equipment Monitored

Disturbance analysis is particularly effective for monitoring the health of critical power system equipment, including:

- **Transformers:** Fault data and dissolved gas analysis (DGA).
- **Circuit Breakers**: Analysis of trip times and contact wear.
- **Generators:** Monitoring for disturbances like voltage fluctuations and frequency anomalies.
- **Transmission Lines and Cables**: Detecting high-impedance faults and other subtle insulation issues.
- **Protective Relays**: Verifying their correct operation and timing.

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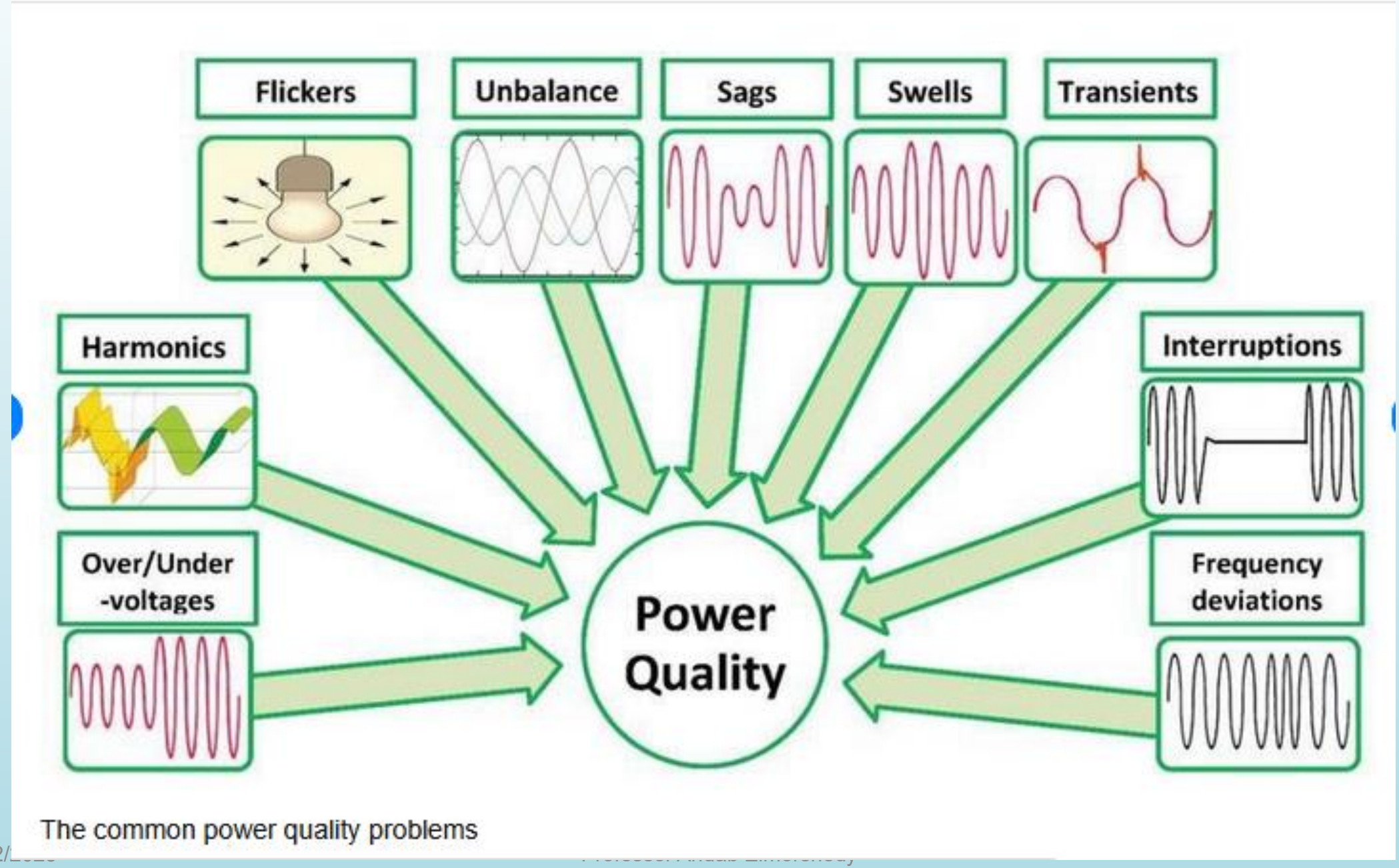
Phenomena Related to System Faults and the Process of Clearing Faults From a Power System

- Power system disturbances, such as **faults, switching events, and power quality issues,** contain a wealth of information about the condition of the system and its components.
- By **analyzing the data recorded during these events**, engineers can proactively identify deteriorating equipment, prevent cascading failures, and improve the overall reliability and safety of the power grid.

Key Concepts

Power System Disturbances: These are abnormal events that disrupt the normal operation of a power system. They can be classified by their cause and characteristics:

- **Faults**: Short circuits (phase-to-ground, phase-to-phase), open circuits, and high-impedance faults.
- **Switching Events**: Normal operations like switching on/off transformers, capacitors, or loads, which can still cause transients.
- **Power Quality Issues:** Abnormalities in voltage and current waveforms, including voltage sags, swells, transients, harmonics, and flicker.



The common power quality problems

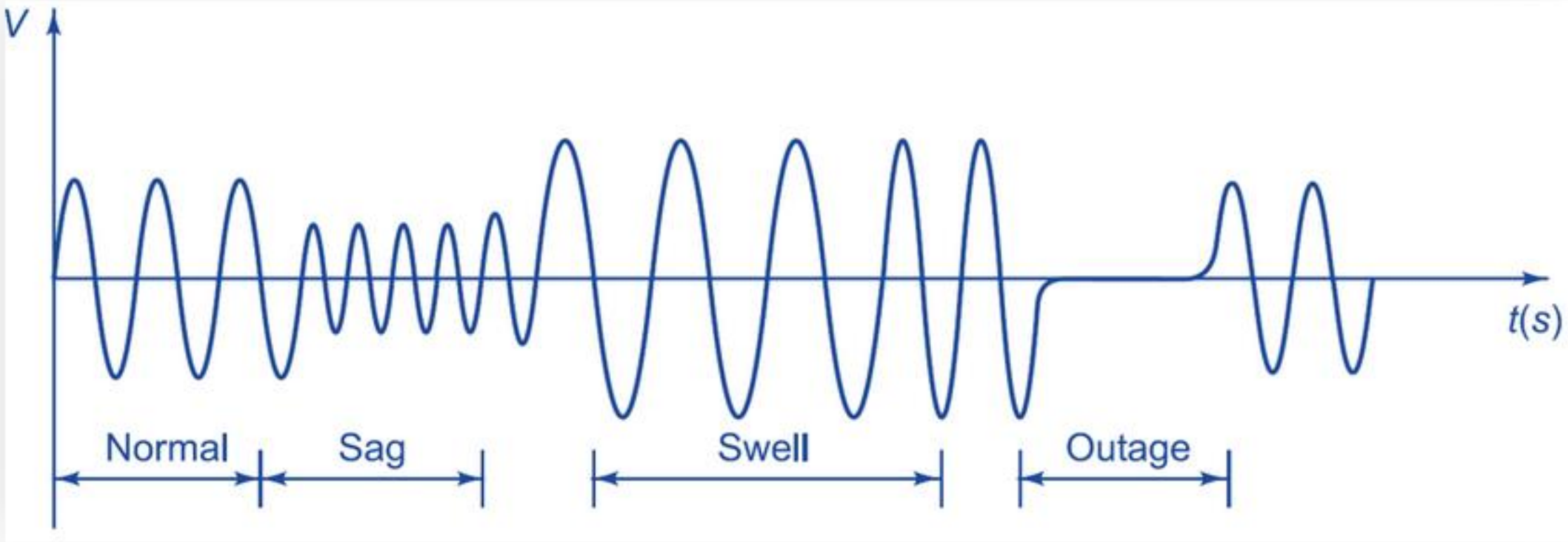


Fig.1: Voltage sag, voltage swell, and outage.

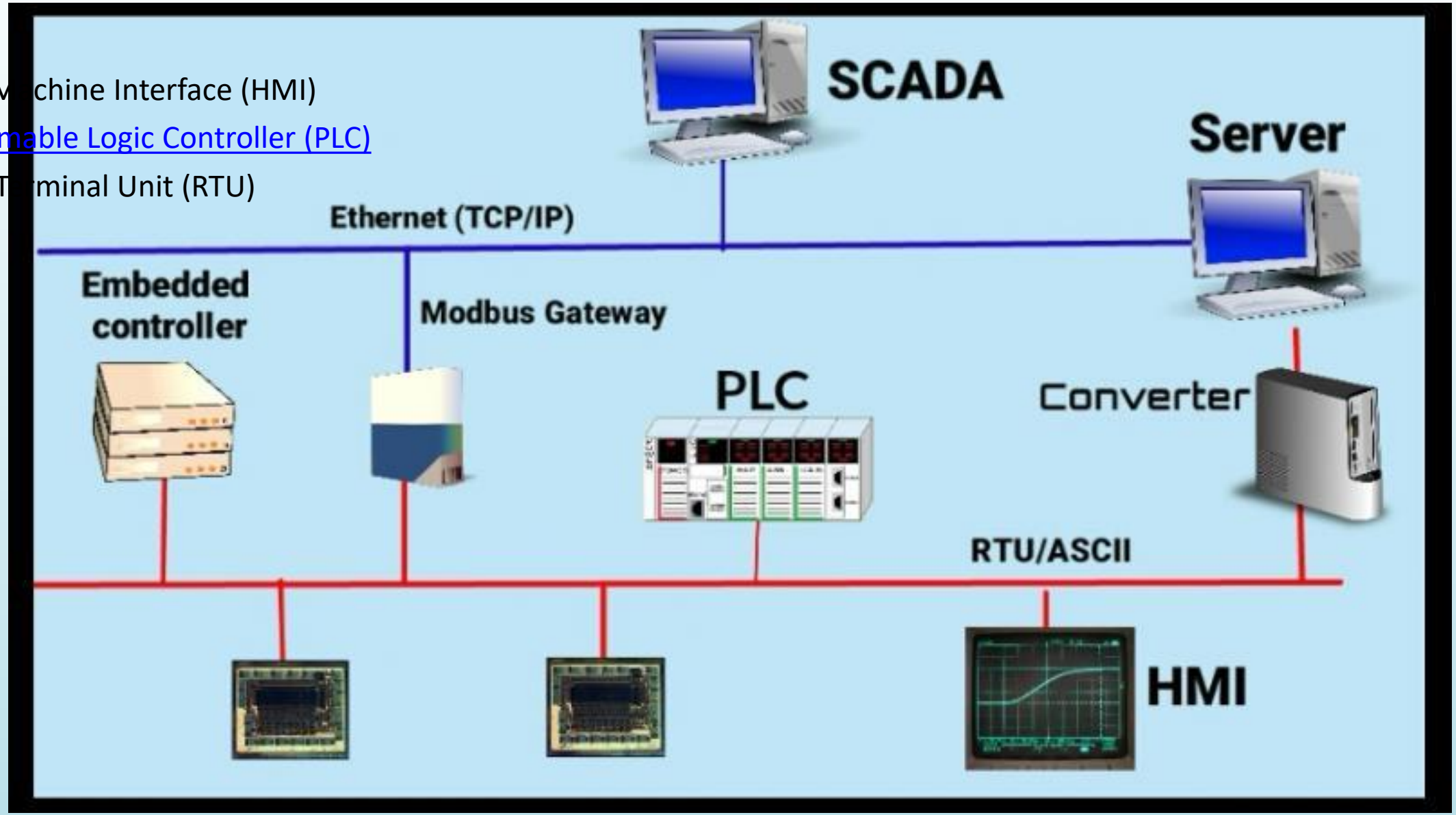
Data Recording and Monitoring:

- **Digital Fault Recorders (DFRs):** These devices are specifically designed to capture high-speed, high-resolution waveform data (voltage and current) before, during, and after a fault.
- **Intelligent Electronic Devices (IEDs):** Modern protective relays and other smart devices that can record fault data, operational statistics, and diagnostic information.
- **Supervisory Control and Data Acquisition (SCADA) Systems:** These systems provide real-time monitoring of system parameters (voltage, current, power flow) and can record sequence-of-events (SOE) data.

Human-Machine Interface (HMI)

Programmable Logic Controller (PLC)

Remote Terminal Unit (RTU)



Supervisory Control and Data Acquisition (SCADA) Systems

Analysis Methods and Techniques:

- **Waveform Analysis:** Engineers analyze the raw voltage and current waveforms from DFRs and IEDs to identify specific patterns related to different types of disturbances and equipment behavior.
- **Time-Domain Simulation (TDS):** This involves simulating the system's response to a disturbance to assess its stability and to compute critical parameters like the Critical Clearing Time (CCT) for transient stability.
- **Prony Analysis**: This technique is used to estimate modal parameters (damping and frequency) from the system's time response to a small disturbance.

A low damping ratio can indicate a system nearing instability.

- **Machine Learning and Artificial Intelligence (AI):** Artificial Neural Networks (ANN) are being used as a fast and accurate tool for dynamic stability assessment.
- **Statistical and Historical Analysis:** By analyzing a large number of disturbance records, statistical trends can be identified.

For example, a recurring fault at a specific location or a consistent pattern of circuit breaker operation times can point to a deteriorating component.

Practical Applications

The information gained from disturbance analysis is used to determine **equipment health** in several ways:

- **Relay and Circuit Breaker Performance:** Analysis of DFR data can verify the timing and accuracy of protective relay and circuit breaker operations.

A slow circuit breaker operation time or a failure to trip could indicate a mechanical or electrical issue with the device.

- **Transformer and Generator Health:** The analysis of disturbances involving these components can reveal issues like internal faults, winding degradation, or insulation breakdown.

For example, specific harmonic patterns or inrush currents can be correlated with a transformer's condition.

- **Transmission Line and Cable Integrity:** Disturbance analysis can help pinpoint the location of faults on transmission lines and cables.

A change in the fault signature over time could suggest a weakening of the line's insulation or a chronic problem area.

- **Power Quality Monitoring:** Continuous monitoring of power quality disturbances like voltage sags and harmonics can indicate problems with specific loads or sources.

High harmonic distortion, can lead to overheating in transformers and motors, causing premature failure.

- **Preventive and Predictive Maintenance:** By correlating disturbance data with equipment performance, utilities can transition from time-based maintenance to a more efficient and effective predictive maintenance strategy.

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Classification Of Shunt Faults

- Shunt faults are a type of short-circuit fault that occur in a power system when an abnormal connection of very low impedance forms between two points of different potential.
- These faults are characterized by an increase in current and a decrease in voltage and frequency in the affected phases.
- Shunt faults are broadly classified into two main categories: **symmetrical and unsymmetrical faults.**

1. Symmetrical Faults (Balanced Faults)

- A symmetrical fault is one in which the fault currents in all three phases are equal in magnitude and displaced by 120° from each other.
- The system remains balanced even after the fault occurs.
- **These faults are rare,** accounting for only 2-5% of system faults, but they are the most severe, leading to the highest fault currents.

The two main types of symmetrical shunt faults are:

- Three-phase fault (L-L-L): A short circuit between all three phases.
- Three-phase-to-ground fault (L-L-L-G): A short circuit involving all three phases and the ground.

2. Unsymmetrical Faults (Unbalanced Faults)

- Unsymmetrical faults are far more common than symmetrical faults, making up the majority of faults in a power system.
- In these faults, the currents and voltages in the phases are not equal in magnitude or are not displaced by 120°.
- The system becomes unbalanced after the fault.

The three main types of unsymmetrical shunt faults are:

- **Single line-to-ground fault (L-G):** A short circuit between one phase and the ground. This is the most frequent type of fault, accounting for 65-70% of all faults.
- **Line-to-line fault (L-L):** A short circuit between two phases. These are less common than single line-to-ground faults.
- **Double line-to-ground fault (L-L-G):** A short circuit involving two phases and the ground.

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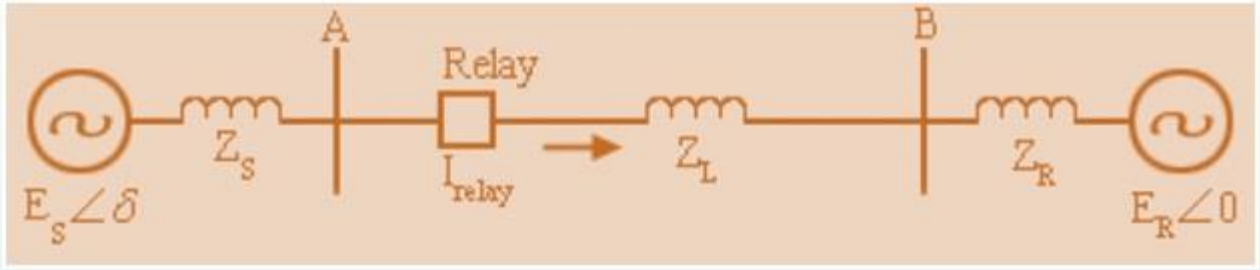
Power System Phenomena and their Impact on Relay System Performance

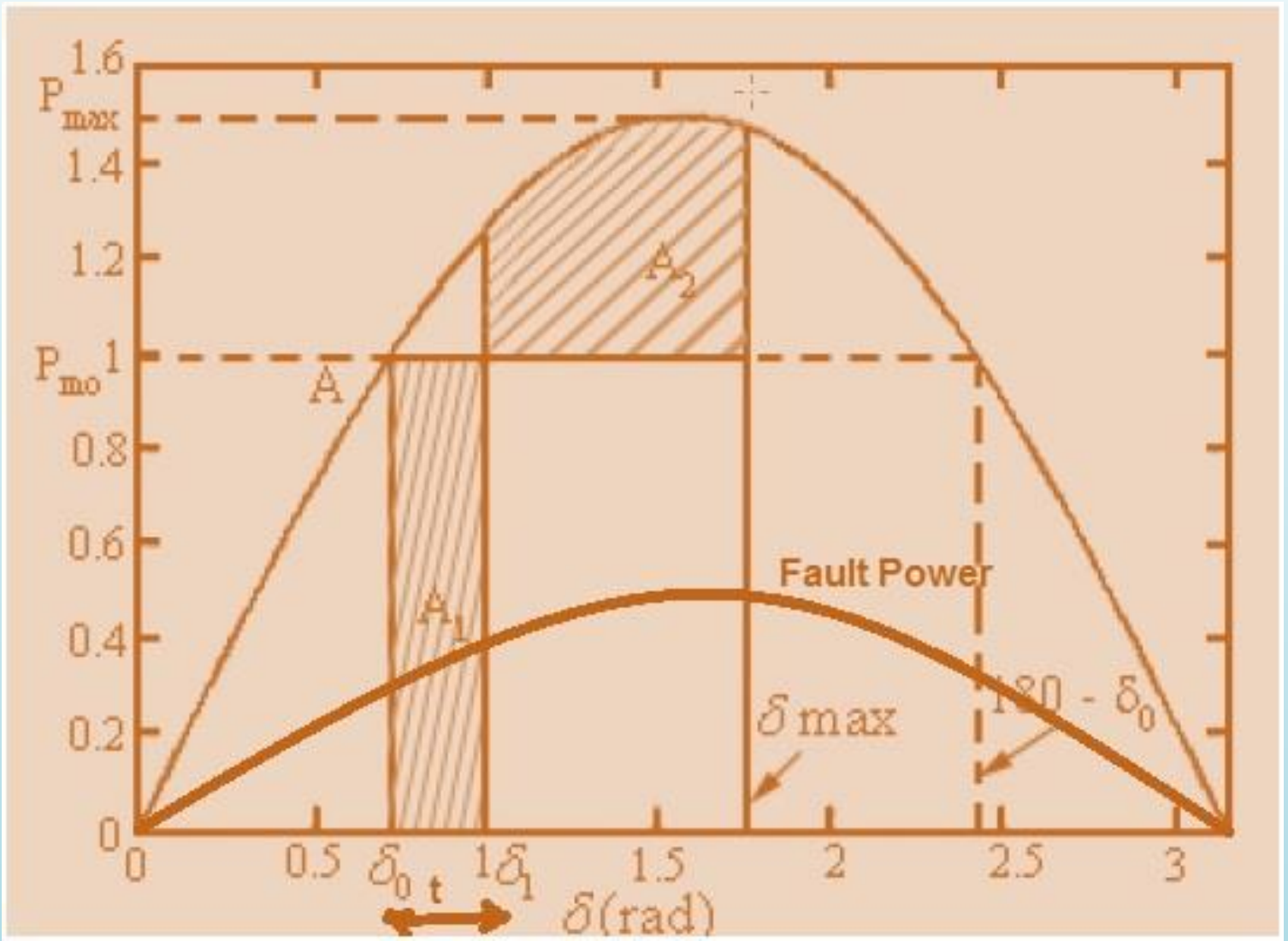
- Power system phenomena can significantly impact the performance of protective relay systems, leading to both **desired and, in some cases, undesired operations.**
- Protective relays are designed to **operate during abnormal conditions**, such as faults, to **isolate the faulted section and prevent damage to equipment and widespread outages.**
- The transient nature of many power system events can challenge a relay's ability to accurately distinguish between a true fault and a normal system disturbance.

Here's a breakdown of common power system phenomena and their impact on relay system performance:

1. Power Swings and Loss of Synchronism

- **Phenomenon:** Power swings are oscillations in power flow, voltage, and current that occur when generators and other synchronous equipment in a power system swing relative to each other.
- They are typically triggered by large disturbances like a sudden change in load, a generator tripping, or a fault that is cleared.
- If the swings are too large, the system can **lose synchronism, leading to an "out-of-step" condition.**





Power Swings

- Power swings are oscillations in power flow that occur after a major disturbance, like a fault, in an electrical system.
- If these oscillations are damped, they are stable, and the system returns to its stable operating point.
- If the swings are too severe and the machines' speeds become too desynchronized, the system can experience loss of synchronism or an unstable power swing, which requires intervention to prevent damage and widespread blackouts.

What is a power swing?

- **Oscillations:**

Power swings involve the **rotor angles of synchronous generators** varying in relation to each other, leading to slow fluctuations in power flow, voltages, and currents.

- **Cause:**

They are typically caused by significant events such as **faults, sudden changes in load, or the loss of generation.**

- **Response:**

In a stable swing, the system gradually damps these oscillations and returns to a new, stable operating point.

Why is it important to prevent loss of synchronism?

- Damage and Blackouts
- System Separation
- Load Shedding
- Protection Relays

- Power swings is defined as **oscillation in active and reactive power flows on a transmission line consequent to a large disturbance like a fault**.
- The oscillation in the apparent power and bus voltages are seen by the Relay as an **impedance swing on the R-X plane**.
- If the impedance trajectory enters the Relay zone and if stays there for sufficiently long time, then the relay will issue a trip decision on Power Swing.
- **Tripping on Power Swings is not desirable.**

Impact on Relays:

- **Distance Relays:** Power swings can cause the impedance "seen" by a distance relay to enter its operating characteristic, even though there is no fault on the line. This can lead to an incorrect and unwanted tripping of a healthy line.
- **Solutions:** To prevent this, protective relay systems often include a "**power swing blocking" (PSB) function**.
- The PSB logic can detect the **unique impedance trajectory** of a power swing and block the distance relay from tripping.
- If an unstable power swing is detected, a separate "**out-of-step tripping**" (OOT) function can be used to purposefully trip specific breakers at predetermined locations to separate the system into stable islands and prevent a total collapse.

2. Saturated Current Transformers (CTs)

Phenomenon: Current transformers (CTs) are essential components of relay systems, used to **step down high currents for measurement and protection.**

During a severe fault, the high current flowing through the CT can cause its magnetic core to saturate.

When this happens, the CT can no longer accurately reproduce the primary current waveform, leading to a **distorted secondary current.**

Impact on Relays:

Waveform Distortion: The distorted current from a saturated CT can cause a relay to misinterpret the fault condition.

This can lead to a **delayed trip** or, in some cases, **a relay not tripping at all**, even though a severe fault exists.

Relay Mal-operation: Relays that rely on the magnitude and phase angle of the current for their operation (e.g., overcurrent and differential relays) can be particularly affected.

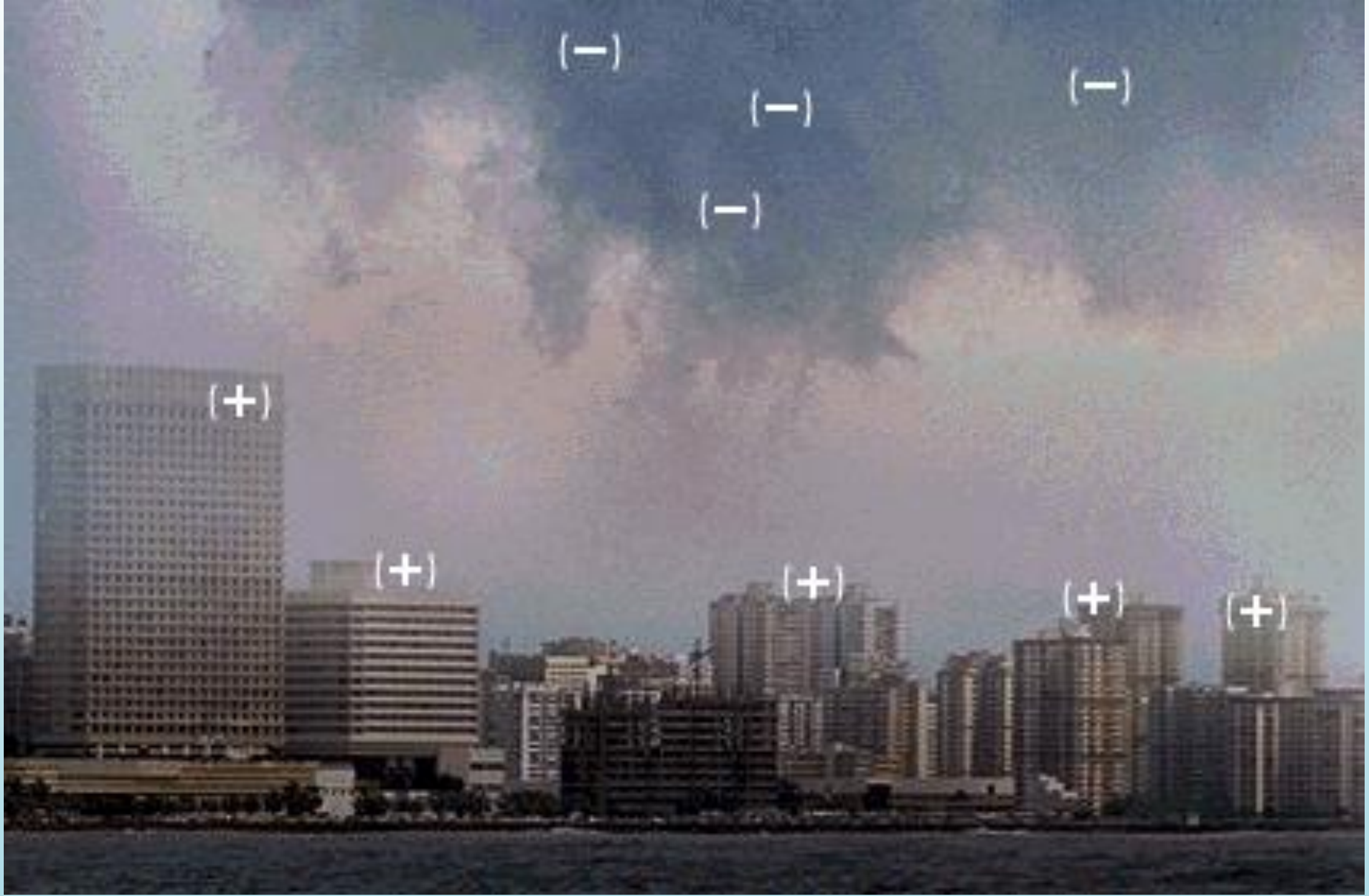
The misrepresentation of the current can lead to incorrect relay operation and **poor coordination between protection devices.**

3. Transient Phenomena

Phenomenon: Transients are **short-duration electrical disturbances** that can occur for a variety of reasons, including:

- **Lightning Strikes:** Can induce very high voltage surges that travel through the system.
- **Switching Operations:** The opening and closing of circuit breakers, especially for **long transmission lines or capacitor banks**, can create transient over-voltages and oscillations.
- **Ferroresonance: A nonlinear phenomenon involving transformers and system capacitance that can lead to high over-voltages.**

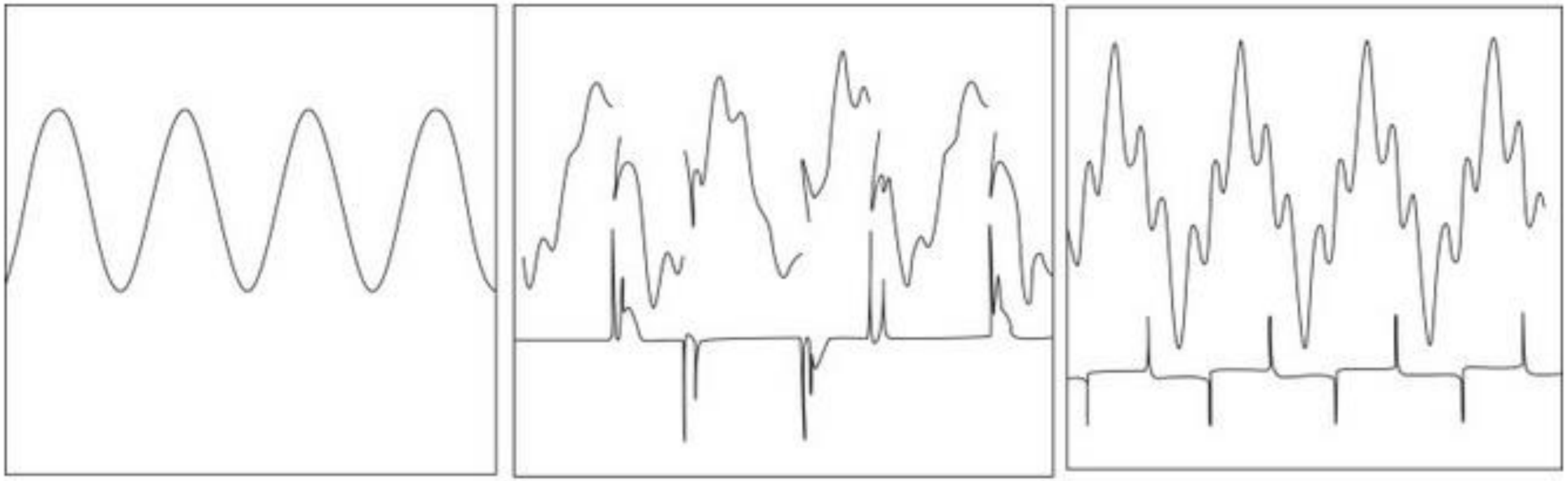

Lightning



- Ferroresonance is a dangerous, nonlinear resonance phenomenon in power systems caused by the interaction of a **nonlinear inductance** (like a transformer's core) with **a series capacitance** (often from underground cables) under specific disturbance conditions, such as switching.
- This leads to severe overvoltages and overcurrents that can **damage equipment, distort waveforms, and cause operational malfunctions.**
- Mitigation often involves using **damping resistors** connected to voltage transformers to dissipate the excess energy




ABB
ECP BUS B METERING
& EARTHING
90BBB06
WARNING
ECP SUPPLY INCOMER B
FROM 19BBB11
90BBB07
WARNIN



Normal transformer voltage
scale 1.9 p.u./cm

Transformer voltage and current
during subharmonic oscillation
showing 43% overvoltage

Transformer voltage and current
during ferroresonance showing
70% overvoltage

Ferroresonance - an overview

Impact on Relays:

- **Over-voltage and Over-current**: The high-magnitude, high-frequency nature of transients can cause over-voltage and over-current relays to operate incorrectly.
- **Relay Sensitivity**: While relays must be fast to clear faults, they must also be immune to these normal system transients.

Relay design and settings must be carefully chosen to avoid tripping for these non-fault events.

4. Power Quality Issues (Harmonics, Sags, and Swells)

- **Phenomenon:** The increasing use of non-linear loads and inverter-based resources introduces harmonics into the power system. Harmonics are currents or voltages at frequencies that are **integer multiples** of the fundamental frequency. Other power quality issues include voltage sags and swells.
- **Impact on Relays**:

Harmonic Interference: Traditional relays that assume a pure sinusoidal waveform for their operation can be negatively affected by harmonics.

The presence of harmonic components can cause relays to miscalculate impedance or operate with incorrect timing.

Incorrect Operation: While a relay should respond to a voltage sag caused by a fault, a sag caused by a large motor starting might also be detected, and without proper settings, could lead to an unwanted trip.

5. System Inertia and Impedance Changes

- **Phenomenon**: The integration of **inverter-based resources** (IBR) like wind and solar farms changes the dynamic characteristics of the grid. Unlike traditional synchronous generators, which provide a large amount of system inertia, IBRs have very little or no inertia. This can lead to faster frequency changes following a disturbance.
- **Impact on Relays**:

Frequency Relays: Relays designed to detect under-frequency conditions might operate too quickly or incorrectly due to the faster rate of frequency decay.

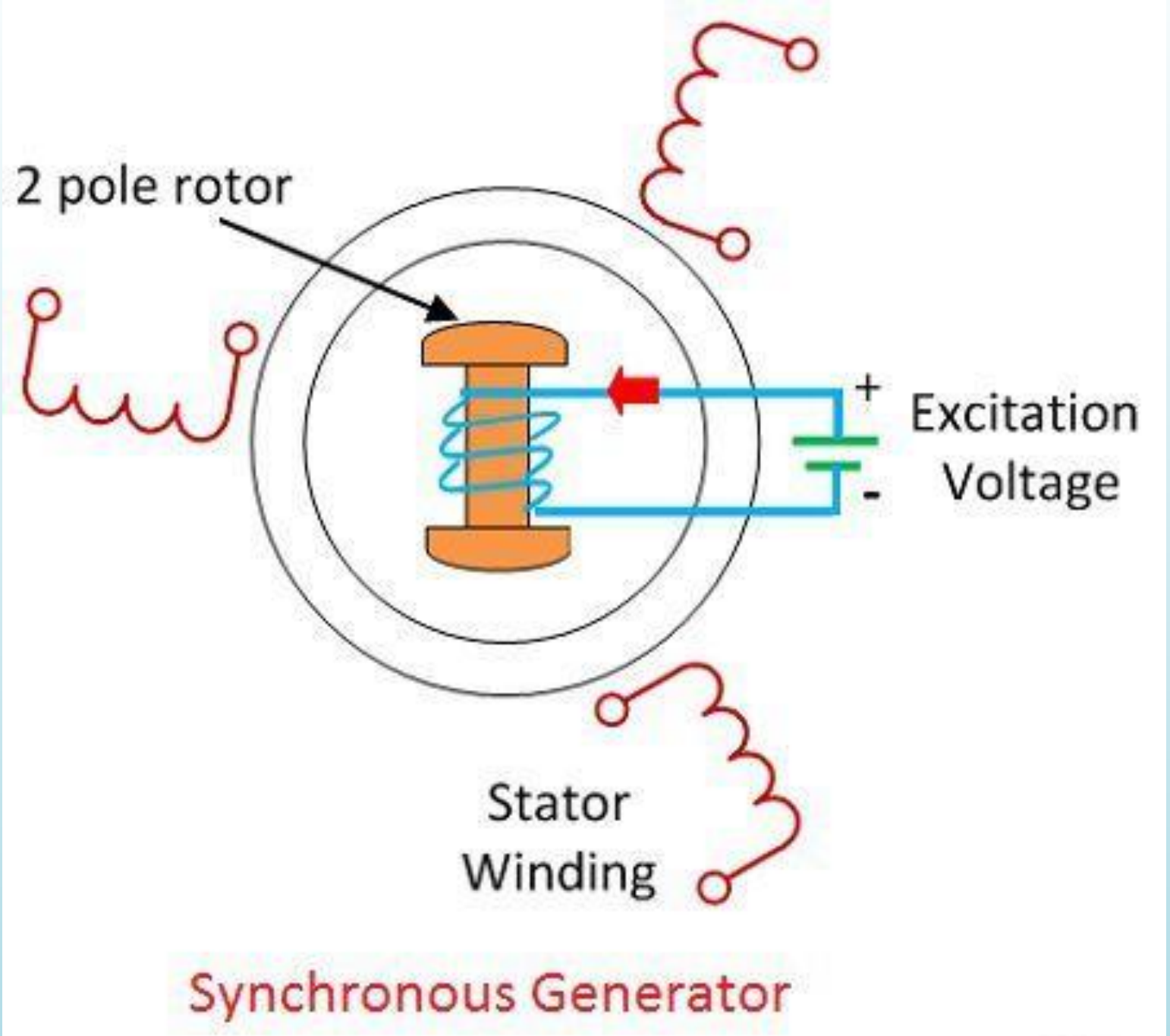
Fault Current Contribution: IBRs have different fault current characteristics than synchronous generators, which can affect the magnitude and phase of fault currents. This can make it difficult to set distance and overcurrent relays accurately.

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Generator System Disturbances

- Generator system disturbances are events that affect the normal operation of a power generator, which can range from minor issues to catastrophic failures.
- These disturbances can originate from internal generator problems, external grid events, or issues with the prime mover.
- The impact of these disturbances can be localized to the generator itself or can propagate throughout the entire power system, leading to widespread outages.
- Here is a **classification of common generator system disturbances and their effects:**


2 pole rotor
+
Excitation
Voltage
-
Stator
Winding
Synchronous Generator
Circuit Globe

1. Internal Generator Faults

These are faults that occur within the generator's windings or core. They are typically the most severe type of generator disturbance.

- **Stator Winding Faults:** A short circuit within the stator windings, which can be **phase-to-phase, phase-to-ground, or turn-to-turn faults.**

o Cause: Insulation failure due to aging, thermal stress, or mechanical damage.

o Effect: High fault currents that can cause significant damage to the stator core and windings. It can lead to a complete failure of the generator.

- **Rotor Winding Faults**: Faults in the field winding of the rotor.

o Cause: **Mechanical stress, overheating, or insulation degradation**.

o Effect: Can cause vibrations, unbalance, and overheating of the rotor. A shorted field winding can reduce the generator's ability to maintain voltage and can lead to a loss of field.

2. Abnormal Operating Conditions

These are not necessarily faults but are deviations from the normal operating parameters that can lead to damage if not addressed.

- **Loss of Field (Loss of Excitation):** The generator's excitation system fails, causing it to lose its magnetic field.
  - **Cause:** Tripping of the field breaker, open circuit in the field winding, or failure of the excitation system.
  - **Effect:** The synchronous generator can lose synchronism with the grid and act as an induction generator, **drawing reactive power from the system.**

This can lead to overheating of the rotor, and significant voltage drops on the power system.

- **Overexcitation and Overvoltage**: The generator's field excitation is too high for the operating conditions.
  - **Cause:** Malfunctioning voltage regulators or incorrect manual settings.
  - **Effect:** Can cause the generator and connected transformers to be over-excited, leading to core saturation and high flux levels (over-fluxing). **This can damage insulation and cause severe overheating.**
- **Underfrequency and Overfrequency**: The generator's rotational speed deviates from its synchronous speed.
  - **Cause:** A sudden imbalance between generation and load.

An underfrequency condition results from a generation deficit, while an overfrequency condition results from excess generation.

- **Effect:** Prolonged operation at off-nominal frequency can damage both the generator and other connected equipment.

Underfrequency can lead to a cascading failure as other loads and generators trip off.

- **Negative Sequence Current (Unbalanced Current):** The currents in the three phases are not equal in magnitude or are not separated by 120°.
- **Cause:** An unsymmetrical fault (e.g., single-line-to-ground fault) on the power system, or an unbalanced load.
- **Effect:** The negative sequence current creates a **magnetic field that rotates at twice the synchronous speed in the opposite direction of the rotor**. This induces currents in the rotor that cause severe localized heating and can damage the rotor components.

- **Loss of Prime Mover (Motoring):** The mechanical power input from the prime mover (e.g., turbine) is lost.
  - **Cause:** A trip of the prime mover due to a mechanical issue (e.g., low steam pressure, loss of fuel).
  - **Effect:** The generator starts to draw active power from the grid to continue rotating, acting as a **synchronous motor**.

This "motoring" can damage the prime mover, especially steam turbines which can be severely damaged if a reverse steam flow is not prevented.

3. External System Disturbances

These are events on the power system that affect the generator but do not originate within it.

- **External Faults:** A fault on the transmission line or busbar connected to the generator.
  - **Cause:** Short circuits outside of the generator, often due to lightning strikes, equipment failure, or human error.
  - **Effect:** The generator will contribute fault current to the external fault. If the fault is not cleared quickly, the generator's terminal voltage will drop significantly, and the generator may lose synchronism with the grid.
- **Power Swings (Out-of-Step):** Large oscillations in power flow, voltage, and rotor angle.

- **Cause:** A severe disturbance or a fault that is not cleared quickly.
- **Effect:** If the rotor angle oscillations are too large, the generator can fall "out of step" and lose synchronism with the rest of the grid. This can cause severe voltage and current fluctuations, leading to a system collapse if not isolated correctly.

• **System Overload:** The generator is asked to supply more active or reactive power than its rating.

- **Cause:** Unexpected load increase or loss of other generation units.
- **Effect:** Can cause the generator to overheat and eventually trip. Modern generators have thermal protection to prevent this from happening.

Agenda

- Power System Disturbance Analysis Function
- Determination of Power System Equipment Health through System Disturbance Analysis
- Phenomena Related to System Faults and the Process of Clearing Faults From a Power System
- Classification of Shunt Faults
- Power System Phenomena and their Impact on Relay System Performance
- Generator System Disturbances
- **Transformer System Disturbances**
- Breaker Failure Protection System Disturbances

Transformer System Disturbances

- Transformer system disturbances can be categorized into two main types: those originating within the transformer itself (internal disturbances) and those caused by events external to the transformer (external disturbances).
- These events can lead to a range of issues, from minor alarms to catastrophic failures, and are a primary focus of power system protection.

Transmission Transformer



Distribution Transformer



1. Internal Transformer Disturbances (Internal Faults)

Internal faults are typically the most destructive and are often caused by insulation breakdown, which can be accelerated by electrical, thermal, and mechanical stresses.

- Winding Faults: These are the most common and severe internal faults.
- Phase-to-Phase Fault: A short circuit between two phases of the winding.
- Phase-to-Ground Fault: A short circuit between a phase winding and the grounded transformer tank or core.

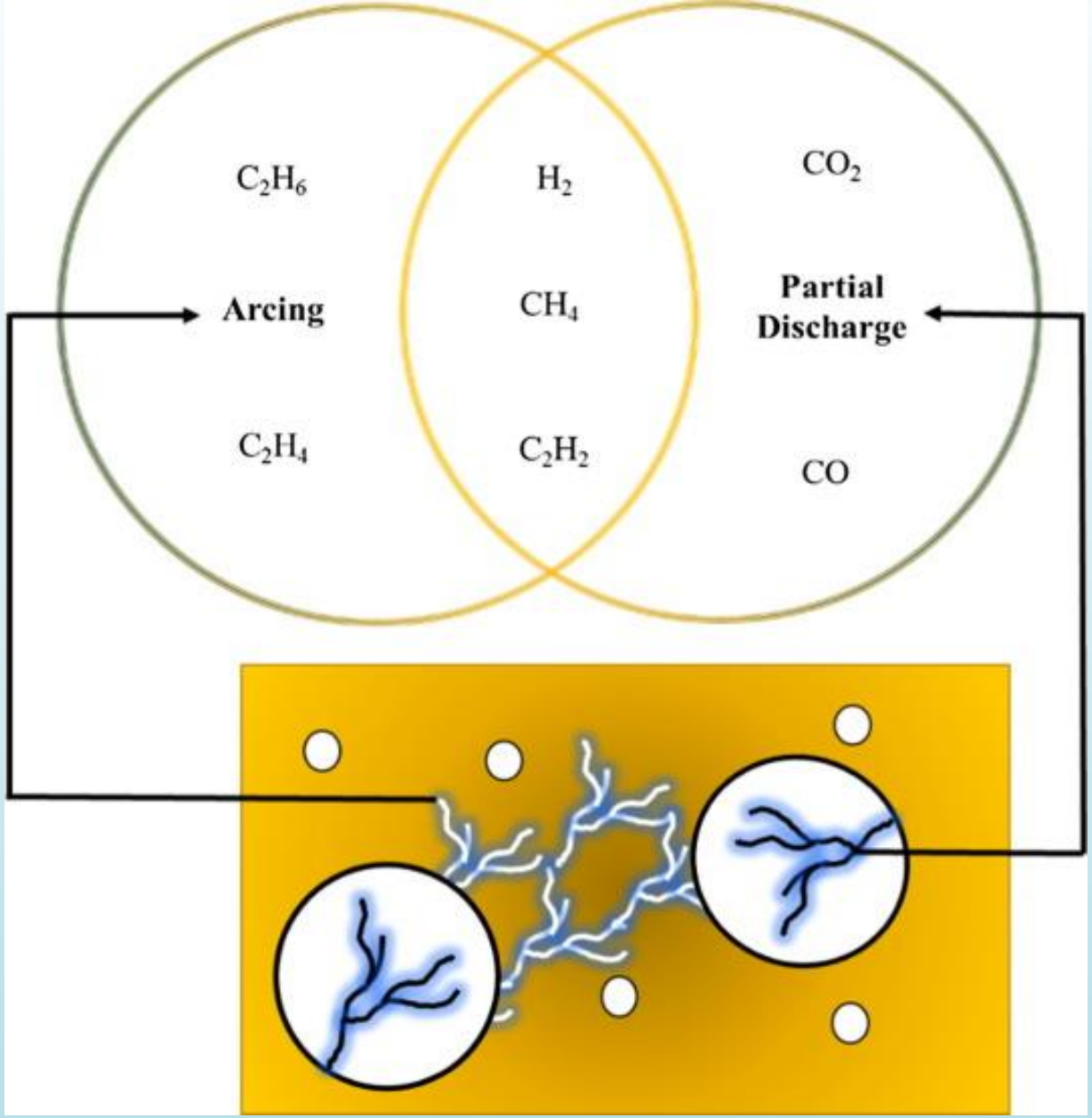
- Inter-Turn Fault: A short circuit between adjacent turns of a single winding coil.
- This is particularly dangerous because the fault current is confined to a small loop of the winding, resulting in very high heat generation that can quickly lead to a more severe phase or ground fault.
- The terminal currents may be very small, making them difficult to detect with traditional overcurrent protection.

Core Faults:

- Short Circuits in the Core: The core of a transformer is made of laminated silicon steel to reduce eddy currents. If the insulation between the laminations is damaged, it can lead to short circuits, causing localized overheating and burning of the core.
- Core Grounding Issues: If the core is improperly grounded (e.g., has two or more grounding points), a circulating current can flow, causing overheating.

Insulation Breakdown and Partial Discharge:

- Partial Discharge (PD): Small, localized electrical discharges within the transformer's insulation system. PD can be caused by **manufacturing defects, contamination, or aging insulation**. It slowly erodes the insulation, eventually leading to a complete breakdown and a major fault.
- Oil Degradation: Over time, the insulating oil can degrade due to **heat, moisture, or chemical reactions.** Degraded oil has a lower dielectric strength, increasing the risk of flashover and arcing.



Gases generated from arcing and partial discharge.

2. External Transformer Disturbances

These disturbances originate outside the transformer but can still cause significant damage if not addressed by the protective systems.

- Through Faults (External Short Circuits): A fault on a transmission line or busbar connected to the transformer.
- Effect: The transformer is subjected **to very high mechanical and thermal stresses** as it contributes a large fault current to the external fault. This can cause **winding deformation, damage to insulation, and overheating**. Protective relays are designed to detect and clear these external faults before they can damage the transformer.

- **Overexcitation:** This occurs when the ratio of voltage to frequency (V/Hz) applied to the transformer's terminals exceeds its design limits.
- **Cause:** A high voltage condition, a low frequency condition, or a combination of both. This can happen during load rejection, when a generator trips, or due to improper voltage regulator settings.
- **Effect:** The transformer's magnetic core can saturate, leading to a large, non-sinusoidal magnetizing current. This current causes severe overheating of the core and structural components, which can lead to rapid and permanent damage.

- **Overloading:** When the transformer is required to supply a load that exceeds its rated capacity.
- **Effect:** Overloading causes the transformer's windings and oil to overheat, which accelerates the **aging and degradation of the insulation materials**. While a short-term overload may not cause immediate failure, repeated or prolonged overloads significantly **reduce the transformer's life expectancy.**

External Surges (Overvoltages):

- **Cause:** Lightning strikes, switching operations, or other transient events on the power system.
- **Effect:** These high-magnitude, high-frequency voltage surges can travel into the transformer, placing severe stress on the winding insulation, particularly the end-turns. Without proper protection (e.g., surge arresters), these surges can cause insulation failure and winding faults.
- **Underfrequency:** Operation at a frequency below the transformer's nominal rating.
- **Effect:** An underfrequency condition, like an overvoltage, **increases the V/Hz ratio, leading to overexcitation and potential damage.**

Transformer Protection

Due to the variety of disturbances and the high value of transformers, multiple layers of protection are used to ensure their reliability.

These include:

- **Differential Relays:** The primary protection for internal winding faults. They compare the current entering and leaving the transformer. Any significant difference indicates an internal fault.
- **Overcurrent Relays:** Provide backup protection for both internal and external faults.
- **Sudden Pressure Relays**: Detect a rapid increase in pressure inside the transformer tank, which is a key indicator of a severe internal arcing fault. **They are often the fastest protection for these types of faults.**

Buchholz Relay: A gas-actuated relay that detects minor internal faults (e.g., arcing) by collecting gas bubbles in the oil. It can also detect a sudden surge of oil, indicating a more serious fault.

- **Volts per Hertz (V/Hz) Relays**: Specifically designed to detect and protect against overexcitation conditions.
- **Thermal Relays:** Monitor the transformer's winding and oil temperatures to provide alarms or trips in case of overheating due to overload.

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Breaker Failure Protection System Disturbances

- Breaker failure protection (BFP) is a backup protection scheme designed to address the potential failure of a circuit breaker to clear a fault.
- While the primary purpose of BFP is to operate during a breaker's failure, it can also be a source of disturbances itself if it operates incorrectly or is subject to its own set of issues.

How Breaker Failure Protection Works

- A BFP system is initiated when a primary protection relay (e.g., a distance or differential relay) sends a trip command to a circuit breaker.
- The BFP then **starts a timer and monitors the breaker's status** and the fault current.
- If the breaker fails to open within a set time delay, and a current is still flowing through it, the BFP system concludes that the breaker has failed.
- It then sends a "breaker failure trip" command to all adjacent circuit breakers to isolate the fault and the failed breaker.

Disturbances Related to Breaker Failure Protection

Breaker failure protection can be a source of disturbances due to:

- **Failure of the Breaker Itself:** The most significant disturbance that BFP is designed to handle is the failure of the circuit breaker to interrupt the fault current. This can be caused by:

❑ **Mechanical Failure:** The breaker's trip mechanism, springs, or linkages may fail, preventing the contacts from opening.

❑ **Electrical Failure:** A problem with the trip coil, DC control circuit, or wiring can prevent the trip signal from reaching the breaker.

❑ **Medium Issues:** Problems with the arc-quenching medium (e.g., low gas pressure in SF_6 breakers or low oil level in oil breakers) can prevent the fault from being cleared.

Consequence: A breaker failure leaves the fault energized, causing **prolonged high currents and low voltages**. This can lead to **equipment damage, system instability, and the risk of a widespread cascading outage if the fault is not cleared by BFP.**

- **Unwanted BFP Operation (False Tripping):** This is a serious disturbance because it can unnecessarily isolate healthy parts of the system, leading to a wider-than-necessary outage.

Cause: This can happen due to **human error during testing, wiring mistakes, or relay malfunction**. For example, a "stuck" breaker trip initiate signal to the BFP relay, combined with a misconfiguration, could cause the BFP to trip adjacent breakers even if the original fault was cleared.

- **Consequence:** A false BFP operation results in an outage of a large section of the power system, often including the entire bus, which is a significant reliability event.
- **Failure to Operate (Hidden Failures):** A BFP system itself can have a "hidden failure," a defect that only becomes apparent during a real system disturbance.
- **Cause:** A failure in the BFP relay's internal logic, a wiring issue that wasn't caught during testing, or a malfunctioning sensor can prevent the BFP from operating when a breaker fails.
- **Consequence:** The system relies on the BFP to clear the fault. If the BFP fails, the fault will remain, potentially leading to a widespread blackout. The system would then have to rely on remote backup protection, which is much slower and less selective, and may still not be sufficient to prevent a total system collapse.

- **Inadequate Current Detection:** Some BFP schemes rely on a current detection element to confirm that a current is still flowing after the trip command.

Cause: In some cases, a high-resistance fault or a fault on a very long line may not produce enough current to be detected by the BFP's current element, even if the breaker is still closed.

Consequence: The BFP may not operate, leaving the fault energized and risking system instability. To address this, some modern BFP schemes also use breaker auxiliary contacts to detect the breaker's position in parallel with the current detection.

Conclusion

- The Power System Disturbance Analysis Function is a critical element of modern grid operation and resilience.
- By systematically **detecting, recording, classifying, and analyzing abnormal events**, it provides operators with the insights needed to understand root causes, assess impacts, and implement corrective measures.
- Beyond troubleshooting, **it strengthens protection coordination, enhances power quality, and supports long-term planning for system reliability.**
- Ultimately, effective disturbance analysis **transforms unexpected events into opportunities for learning and continuous improvement, ensuring a more stable, reliable, and secure power system.**


THANK YOU