European Network of
Transmission System Operators
for Electricity

**ENTSO-E SG PROTECTION EQUIPMENT**

# System protection behavior and settings during system disturbances
# REVIEW REPORT

Sylvain AUPETIT (RTE-FR), Martin POKLUDA (CEPS-CZ), Rev. 03-05-2018

ENTSO-E • Avenue de Cortenbergh, 100 • 1000 Brussels • Belgium • Tel +32 2 741 09 50 • Fax + 32 2 741 09 51• info@entsoe.eu • www.entsoe.eu

## TABLE OF CONTENTS

# 1 INTRODUCTION

The synchronously interconnected power systems of ENTSOE ensure a high level of security of supply in the most efficient way. The physical characteristics of the ENTSOE system form a “Backbone of Security”, which implies significant mutual help among the interconnected TSOs in a natural way. However, the favourable overall physical coupling of the system implies at the same time the risk of adverse effects on adjacent areas or even on the whole system, especially in case of extreme contingencies.

The consequences of partial or total blackouts in the highly industrialised countries are enormous and minimizing the probability of such events as much as possible is of utmost importance. The ENTSOE power system has gone through fundamental changes during last decades. The implementation of market rules, the increasing generation by renewables and the geographical extension of the system by the connection of new countries created and is still creating new challenges. An inevitable consequence of this development is the operation of the system closer to its limits with reduced safety margins. This leads to more severe consequences for the security of the system in case of contingencies beyond the design criteria. These facts became evident during the recent incidents in the interconnected system[1].

Consequently, it is obvious that there is the need for implementation and harmonization of measures against extreme contingencies in order to mitigate the consequences for the operational condition of the power system itself and its grid users.

It should be noticed that the planning of transmission networks has been performed separately by each TSO in a decentralized manner. In this regard, binding rules exist in the frame of the security package of ENTSOE (Operational Handbook, System Operations Guideline, etc.). Moreover, planning and operating guidelines are being harmonized in respective ENTSOE working teams. Particularly, the most credible contingencies affecting generating units or transmission system elements must not lead to (severe) consequences (e.g. interruption of supply) for consumers. Thus, the planning and operating rules ensure that the power system will remain viable if one system element (generating unit, transmission line) is lost (so called n-1 rule).

However, beyond such credible contingencies, a power system may also experience more severe disturbances, resulting from multiple and simultaneous outages. Depending on the system conditions such disturbances can lead to emergency conditions with the risk of dramatic consequences. In such a situation, the power system has to be prevented from the loss of stability and cascading effects including partial or total system collapse (blackout) by specific defence plans.

Defence plans have been developed and updated continuously by individual countries or TSOs. These plans include a set of measures, mostly automatic, to ensure fast reaction to large disturbances in order to contain their spread within the smallest possible network.

But moreover, a safe operation of the protection of the transmission lines or transformers during a severe disturbance is essential to avoid an uncontrolled evolution of the power system.

The aim of this report is to provide a technical analysis of protection behaviour during severe disturbances and to propose recommendations regarding protection strategy. This will help to manage critical system conditions and will prevent the ENTSOE power system or parts of it from the loss of stability and cascading effects leading to major blackouts.

---

[1] For instance, 2003 Black-out in Italy, European System Disturbance on 4 November 2006



ENTSO-E • Avenue de Cortenbergh, 100 • 1000 Brussels • Belgium • Tel +32 2 741 09 50 • Fax + 32 2 741 09 51• info@entsoe.eu • www.entsoe.eu

These recommendations are based on questionnaire answers of TSOs involved in the ENTSOE "Protection Equipment" working group.



ENTSO-E • Avenue de Cortenbergh, 100 • 1000 Brussels • Belgium • Tel +32 2 741 09 50 • Fax + 32 2 741 09 51• info@entsoe.eu • www.entsoe.eu

# 2 CLASSIFICATION OF SYSTEM DISTURBANCES

## 2.1 CONTEXT

Power system stability has been recognized as an important problem for secure system operation since the 1920s and several major black-outs caused by power system instability have illustrated the importance of this phenomenon.

The purpose of this chapter is to define and classify the instability phenomena and to illustrate the classification based on examples of black-outs or large disturbances on large scale transmission systems.

## 2.2 CLASSIFICATION OF STABILITY PROBLEMS ACCORDING TO CIGRE

According to CIGRE definition the, "power system stability can be defined as the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact" [1].
Based on proper planning criteria, most modern power systems are able to operate safely and in a stable fashion for single or multiple common mode contingencies.

However, power systems are subjected to a wide range of disturbances, small or large. Small load, generation or topology changes, without any faults, occur continually and the system must be able to adjust to these changing conditions and operate satisfactorily.

It must also be able to survive numerous disturbances of severe nature, such as short-circuit on a transmission line or loss of a large amount of generators, even if the large disturbance may lead to structural changes due to cascading events and the isolation of the faulted elements.

Due to the speed of instability phenomena engaged, the necessity exists for proper automatic control actions or operator interventions. In this context, the analysis of such situations and the design of effective countermeasures can be highly assisted by an appropriate classification of power system stability problems, based on the following considerations [2]:

- The physical nature of the resulting instability;
- The size of the disturbance considered;
- The devices, processes, and time span that must be taken into consideration, in order to judge stability, and
- The most appropriate method of calculation and prediction of stability.

Such a classification scheme is depicted in the following Figure 2-1 and, in the following paragraphs, a short description of each stability problem is provided in accordance with CIGRE definition.

It must be noticed that such a classification is important for understanding the underlying causes of the problem in order to design appropriate protection schemes and reliable settings, during large disturbances or black-out, all these instability phenomena can appear simultaneously or successively in a very complex manner. This is particularly true in highly stressed systems and for cascading events; as systems fail, one form of instability may ultimately lead to another form.


ENTSO-E • Avenue de Cortenbergh, 100 • 1000 Brussels • Belgium • Tel +32 2 741 09 50 • Fax + 32 2 741 09 51• info@entsoe.eu • www.entsoe.eu

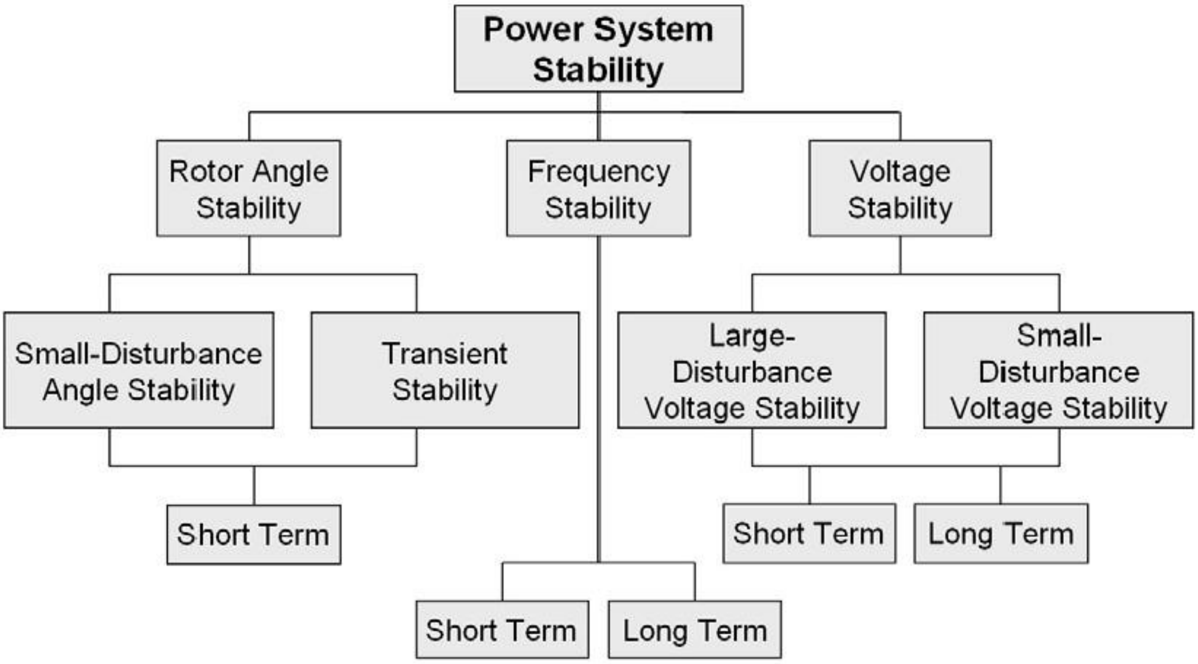



**Figure 2-1: Classification of power system stability**

## 2.2.1 ROTOR ANGLE STABILITY

Rotor angle stability refers to the ability of synchronous generators of an interconnected power system to remain in synchronism after a disturbance. It depends on the ability to maintain/restore equilibrium between electromagnetic torque and mechanical torque of each synchronous machine in the system and depends on the initial operating state of the system. Instability that may result occurs in the form of increasing angular swings of some generators leading to their loss of synchronism with other generators or aperiodical divergence of the angle between the machine (or the cluster) and the rest of the system.

The change in electromagnetic torque of a synchronous generator following a perturbation can be analysed in two components, a synchronising torque component, in phase with rotor angle deviation, and a damping torque component, in phase with the speed deviation. System rotor angle stability necessitates the existence of both components.

Lack of sufficient synchronising torque results in aperiodic or non-oscillatory instability, while lack of sufficient damping torque results in oscillatory instability.

**Rotor angle stability problems can be divided in small-disturbance and transient stability sub-categories**.

- **Small-disturbance (or small-signal) rotor angle stability**

For this sub-category of instability, a power system is considered stable if it is capable to maintain synchronism under small disturbances. The size of the disturbances (typically, white noise) allows the linearization of system equations for purposes of analysis. The stability problem is usually associated with insufficient damping of electromechanical oscillations.

Damping decreases if:

- Gain of exciter increases;
- The impedance seen from the plan increases;
- The inertia of the unit is low;
- Produced active power increases;
- The machine is under-excitated.

Small disturbance rotor angle stability problems may be either local or global.

- Local problems concern a small part of the power system and are usually associated with rotor oscillations of a single power plant against the rest of the power system [0.8 → 2 Hz]. Such oscillations are called local plant mode oscillations.

- Global problems are caused by the interaction among large groups of generators and have widespread effects. They involve oscillations of a group of generators in one area against a group of generators in another area. These oscillations are called inter-area mode oscillations [0.2→ 0.8 Hz]. The time frame of interest, for small signal rotor angle stability, is on the order of 10 to 20 seconds following a disturbance.

- **Large-disturbance rotor angle stability or transient stability**

Transient rotor angle stability refers to the ability of the generators to maintain in synchronism after a severe disturbance (such as a short circuit on a transmission line or bus). Instability is usually in the form of aperiodic angular separation due to insufficient synchronising torque, manifesting as first swing instability. The time frame of interest in transient stability studies is usually 3 to 5 seconds following the disturbance and the resulting system response involves large excursions of generator angles being influenced by the non-linear power-angle relationship. It may extend to 10 to20 seconds for very large systems. Normally, in large production pole, it is possible to recognize a cluster of generators driven by a dominant machine. This kind of phenomena can be contrasted by:

- Fast valving protection adoption;
- As extreme solution, tripping the “dominant cluster generator” in such a way so to decrease the local acceleration

As shown in figure 2-1, both types of rotor angle stability are classified as short–term phenomena.

### 2.2.2 FREQUENCY STABILITY

Frequency stability is related to the ability of a power system to reach and maintain a stable operating point (sustainable from generators) following a severe disturbance (resulting in a significant imbalance between production and consumption). Instability that may result occurs in the form of sustained frequency swings leading to tripping of generating units and/or loads, or in an aperiodic transient.

In large interconnected power systems, this type of situation is most commonly associated with situations following splitting of systems into islands. Stability in this case is a question of whether each island will reach a state of stable operating equilibrium with minimum unintentional loss of load. It is determined by the overall response of the island as evidenced by its mean frequency, rather than relative motion of machines.

Frequency stability problems are associated with:

- inadequacies in regulation/control of power plants;
- poor coordination of control and protection equipment;
- intempestive protection trips leading to islands or high load-generation;
- imbalance;
- out of step of power plants;
- voltage instability;
- Insufficient generation reserve, respectively excessive load imbalance.

During frequency excursions, the time constants of the processes and devices participating will range from fraction of seconds (corresponding to the response of devices such as under-frequency relays and generator controls and protections) to several minutes (corresponding to the response of devices such as prime mover energy supply systems and load voltage regulators). In this sense, frequency stability may be a short-term or long-term phenomenon.

### 2.2.3 VOLTAGE STABILITY

Voltage stability refers to the ability of a power system to maintain acceptable voltages at all buses in the system under normal conditions and after a disturbance, and depends on the ability of the system to supply the active and reactive load through the operating grid.

Instability that may result occurs in the form of a progressive fall or rise of voltages at some buses. A possible result of voltage instability is the loss of load in an area, or tripping of transmission lines and other elements by their protection systems, leading to cascading outages. Another cause of instability can be reaching of the limit in over or under-excitation; the first case is associated to voltage collapse phenomena. The second case typically arises when the impedance seen from the power plant is approximatively capacitive (i.e. during low load of the grid or after a large area load shedding); the reaching of under-excitation limit in the exciter drives the system to operate in an unstable point.

Loss of synchronism of some generators may result from these outages or from operating conditions leading to violation of field current limit.

Moreover, progressive drop in bus voltages is a phenomenon appearing due to rotor angle instability. As an example, the gradual loss of synchronism as rotor angles, between two groups of machines approach or exceed 180°, would result in very low voltages at intermediate points in the network, close to the electrical centre. The voltages near the electrical centre rapidly oscillate between high and low values.

A slow voltage collapse caused by load increasing, lack of reactive power and tap changer movements occurred during the incident on winter 1987 in France. A fast voltage collapse caused by loss of angle stability occurred during the separation phase of Italy from ENTSOE (2003). The above issues show that a distinction between voltage and rotor angle instability is not always clear. However, such a distinction is important for the understanding of the underlying causes of the problem and the development of appropriate design and operating procedures.

The driving force for voltage instability is usually the load. In response to a disturbance, the power consumed by the loads tends to be restored by the action of motor slip adjustment, distribution voltage regulators, tap-changing transformers, and thermostats. Restored loads increase the stress on the high voltage network by increasing the reactive power consumption and causing further voltage reduction. Voltage instability occurs when load dynamics attempt to restore power consumption beyond the capability of the transmission network and the connected generation.

As for the case of rotor angle stability a categorization to large and small disturbance voltage stability can be applied. The time frame of interest for voltage stability problems may vary from a few seconds up to tens of minutes due to the fact that the dynamic of instability depends on high dynamic elements (such as induction motors, electronically controlled loads, SVC, HVDC converters, voltage controller and limitations of generators) and on slower acting equipment ( such as On Load Tap Changers, generator current limiters, thermostatically controlled loads or secondary voltage control). Thus, this phenomenon may be considered as a short-term or a long-term, according to figure 2-1.

## 2.3 DEMONSTRATION OF CLASSIFICATION BY MAJOR INCIDENTS

Taking into consideration the definitions and classification of different instability phenomena, the purpose of this chapter is to illustrate each one with recent large disturbances or black-outs which occurred on large-scale transmission systems.


ENTSO-E • Avenue de Cortenbergh, 100 • 1000 Brussels • Belgium • Tel +32 2 741 09 50 • Fax + 32 2 741 09 51• info@entsoe.eu • www.entsoe.eu

The following figure presents the chosen incidents with their main corresponding instability phenomena:

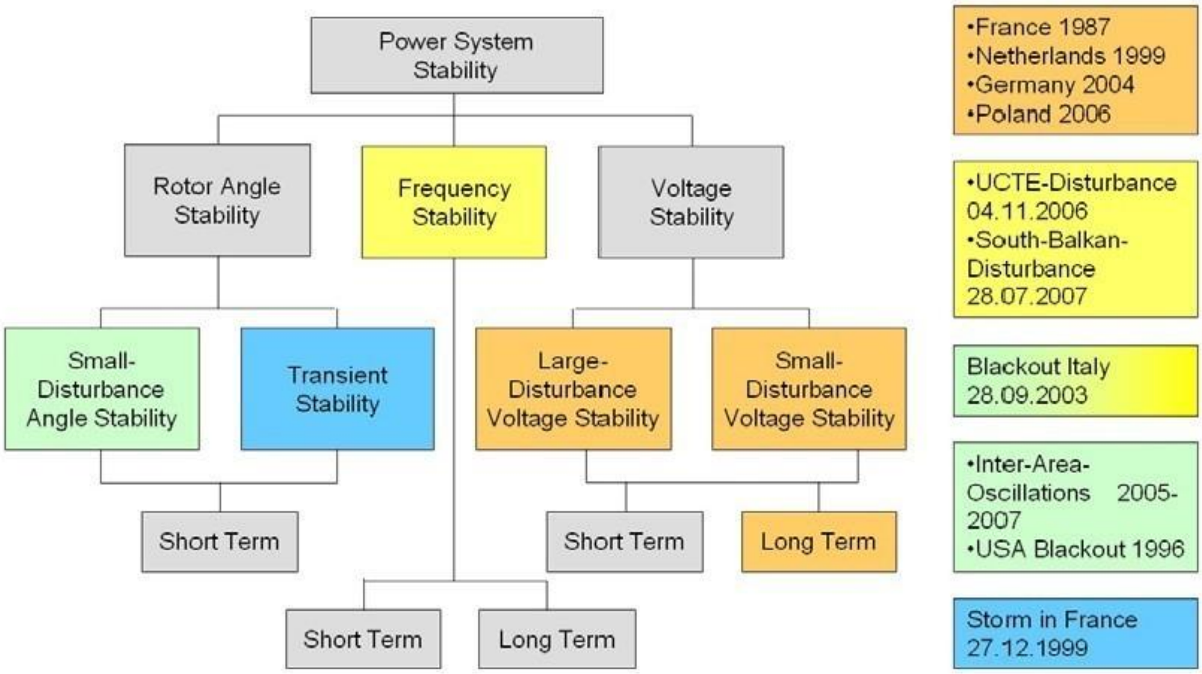



**Figure 2-2: Illustration of instability phenomena**

Note: Sub-synchronous resonance (SSR) is not in the scope of this document.

SSR is a dynamic phenomenon of interest in power systems that have certain special characteristics.

SSR is an electric power system condition where the electric network exchanges energy with a turbine generator at one or more of the natural frequencies of the combined system below the synchronous frequency of the system (with possible torsional fatigue that can cause damage to the turbine-generator shaft).

# 3 ANALYSIS OF LINE PROTECTION SYSTEM IN ABNORMAL SYSTEM CONDITIONS – RELAY PERFORMANCE DURING SYSTEM DISTURBANCES

## 3.1 SUMMARY

The recent wide-area electrical disturbances have clearly demonstrated the vulnerability of the interconnected power systems when operated outside its intended design limits.

Recent disturbances have shown that protective relay systems are very often involved in major wide area perturbations, sometimes preventing further propagation or sometimes triggering the disturbances by their maloperation and contributing to the spread of the disturbance.

Protective relay elements are designed to respond to overcurrents, over- or undervoltages, over- or underfrequency, and underimpedance. These abnormal system conditions will cause the relay systems to operate during major system disturbances. The relays most likely to operate during disturbances are:

- Distance relay elements (first or higher zones)
- Backup distance relay elements (first and higher zones)
- Instantaneous directional and nondirectional overcurrent relays
- Differential line relay
- Under- and overvoltage relays
- Underfrequency relays
- Loss-of-field relays
- Volts/Hz overexcitation relays
- Generator backup relays
- Voltage restraint overcurrent relays
- Voltage controlled overcurrent relays

Some of these relays are generator protection or load shedding relays. This document will focus on the relays functions usually found on transmission systems. We analyse the root causes why transmission network relay systems are most prone to operate during stressed system conditions. The stressed conditions for which the behaviour of the relays have been analysed are those that, typically, could potentially jeopardize the system security: undervoltage situations, heavy dynamic line loadings, power swings, and abnormal frequency conditions.

As for the different relay technology found on transmission systems (e.g. electromechanical, static & numerical) the conclusions of this document apply to all of them. However, the actual trend is to install numerical relays, and the performance of these technology relays during abnormal frequency is of special interest and it is covered in the last sections of this document.

Finally, as a sort summary, the following table shows, for each of the system stressed condition analysed, which elements are prone to maloperate. The check mark means that the relay element is prone to maloperate.



ENTSO-E • Avenue de Cortenbergh, 100 • 1000 Brussels • Belgium • Tel +32 2 741 09 50 • Fax + 32 2 741 09 51• info@entsoe.eu • www.entsoe.eu

| | Distance Protection | Overcurrent Protection | Differential Protection |
|---|---|---|---|
| Undervoltage | ✓ | ✓ | ✗ |
| Line Loading | ✓ | ✓ | ✗ |
| Power Swing | ✓ | ✓ | ✗ |
| Frequency aberration | ✓ | ✓ | ✓ |

## 3.2 RELAY PERFORMANCE DURING UNDERVOLTAGE

This section analyses the behaviour of transmission system relays during situations of undervoltages caused typically by voltage stability problems.

The immediate impact of a voltage stability problem on a network will be a reduction of the phase voltage magnitudes at the local substation buses. This reduction of magnitude is a three-phase phenomenon (all three phases should be equally affected) and the rate of change of the voltage should normally be a slow value (corresponding to voltage reduction occurring in time frames of a few seconds to a few hours). Sudden changes in voltage magnitudes occurring in a few cycles are to be considered as exceptional, but should not be discounted.

Voltage instability can occur in heavily loaded systems when the available reactive power from capacitors, generators, synchronous condensers, line charging, and static VAR compensators falls below or does not greatly exceed the system reactive losses and load.

Typically, voltage instability can occur following the loss of several equipment outages, or when the system is heavily loaded following a lesser system disturbance. Reactive reserves are quickly exhausted when the system lacks the required reactive power and system voltages start to decline.

Distinguishing features of voltage instability and voltage collapse are:

- ✓ Low system voltage profile
- ✓ Heavy reactive power flows
- ✓ No substantial frequency change
- ✓ Inadequate reactive support
- ✓ Heavily loaded power systems

In these situations, unwanted tripping of relays could lead to a wide area disturbance.

### 3.2.1 DISTANCE PROTECTION

A distance element basically computes the ratio of a voltage over a current to measure impedance. When the ratio gets low enough, due to the reduction in the voltage magnitude, to enter the applied impedance characteristic, the relay issues a tripping signal, so low voltage contributes to line tripping by distance protection.

When a voltage stability problem occurs on a network with the expected reduction of the voltage magnitudes and increase of the load current at the same time, the possibility exists that the impedance measured by the distance relays could infringe into the element characteristic and the voltage instability could then be the cause for the tripping of the line.
This situation is the same as the one occurring during an out-of-step condition when the distance element will trip not because of a phase fault but because the computed impedance infringing into the element characteristic. In general terms, the apparent impedance $Z_r$ seen by a distance relay corresponds to:


ENTSO-E • Avenue de Cortenbergh, 100 • 1000 Brussels • Belgium • Tel +32 2 741 09 50 • Fax + 32 2 741 09 51• info@entsoe.eu • www.entsoe.eu

$$\overline{Z}_r = \frac{U^2 \cdot (P + jQ)}{P^2 + Q^2}$$

where $U$ is the line to line voltage and P and Q are the injected active and reactive power at the location of the relay.

In case $Z_r$ remains within the area of one of the predefined zones of operation during a time exceeding the setting of the timer associated with the zone, the relay will operate. It follows from the equation that these events may cause distance relays to mal-trip as a depressed voltage, and generally high values of P and Q make the value of $Z_r$ low enough to be in the tripping characteristic of the distance relay. This behaviour is undesirable since it will aggravate the status of the power system in an already severe situation.

Undesirable relay operations due to voltage instability will mainly be initiated by the zone with the longest reach. Normally this is the zone used for remote back-up protection which usually is zone 3.

### 3.2.2 Overcurrent Protection

In some transient scenarios, low voltage levels can result in high load currents above the pick-up of the overcurrent relays. If the time exceeds the time setting delay, it can cause an undesirable trip.

### 3.2.3 Differential Protection

Line current differential and phase comparison relaying systems, applied for transmission line protection, are immune to voltage instability. Because of their principle of operation, current going into an apparatus must be equal to the current leaving the device when there is no fault.

## 3.3 Relay Performance with dynamic line loading

### 3.3.1 Distance protection

The effect of load on the operation of distance relays is well known and studied. It may lead to under or over-reaching of the distance characteristic.

This is especially true in the case of long transmission lines, multiterminal lines and the Zone 3 elements that have to provide backup protection for lines outgoing from substations where those lines are connected This system topology leads to a very high zone 3 reach to provide back-up to the primary protection of the lines that could then encroach on the line load, leading to line tripping

Tripping heavy loaded lines is quite dangerous during wide area disturbances and will result in quick deterioration of the system and a possible blackout.

As an example, during the 14 August 2003 event in Ohio (USA) the Sammis-Start 345 kV line tripped as a consequence of zone 3 tripping. Figure 3-1 shows the apparent impedance inside Zone 3 seen by the distance relay of that line that was clearly inside the tripping area of zone 3.



ENTSO-E • Avenue de Cortenbergh, 100 • 1000 Brussels • Belgium • Tel +32 2 741 09 50 • Fax + 32 2 741 09 51• info@entsoe.eu • www.entsoe.eu

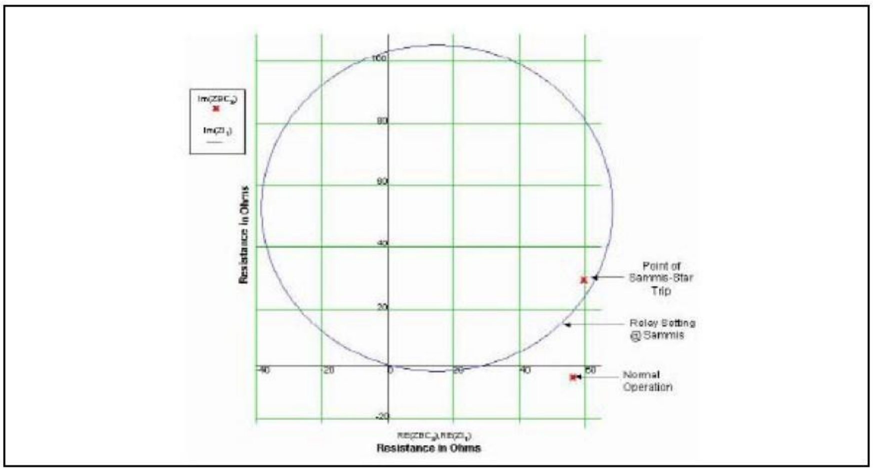



**Figure 3-1: Zone 3 distance relay operation on the 345 kV Sammis-Star transmission line**

Low voltage levels combined with high load currents and, in some cases, very high reactive flows result in the tripping of time delayed distance elements. The relay operates as designed and set.

### 3.3.2 OVERCURRENT PROTECTION

Since phase overcurrent protection has limited use at the transmission or bulk level of the power system, high balanced current should not result in protection operation. However, in real life the system is quite often not balanced. Un-transposed transmission lines may have a difference in the impedance of the individual phases in the range of up to 10 %.

As a result, the high current during dynamic loading or system oscillations may create sufficient zero sequence current that will lead to the operation of a backup ground overcurrent element of a multifunctional protection relay. A ground pilot element could also operate to trip, for example, in a DCB (Directional Comparison Blocking) scheme, if the blocking signal is interrupted and sufficient unbalance current exists.

Over-current protection is sometimes installed on transformers to provide back-up protection to transformer differential relay. Over-current relays also provide some degree of thermal protection to the transformer and back up protection to the relays protecting equipment connected to the transformer. Over-current relays are set to pick up around 130% to 200% of the rating of the transformer. System contingencies leading up to the overloading of the transformers beyond the over-current relay pick up setting will result in tripping the transformer. Some users have chosen to provide redundant differential protection instead of providing over-current back up to avoid tripping due to overloads.

### 3.3.3 DIFFERENTIAL PROTECTION

Differential protection is exchanging current information from the both ends of the protected elements. The operating current and restrain current are expressed as:

Operating Current = | I1 + I2|; Restrain Current = (|I1| + |I2|)/2

During an overload, the current load is high but equal at both ends, so the line current differential relaying systems are immune to high load currents.

## 3.4 Relay performance during power swings

### 3.4.1 Distance Protection

Power swings can, for example, cause the load impedance, which under steady state conditions is not within the relay's operating characteristic, to enter into the distance relay-operating characteristic.

The impedance trajectory during a power swing will cross any relay characteristic that covers the line, causing the electrical centre to fall inside the line. Phase distance relays respond to positive-sequence quantities. The positive-sequence impedance measured at a line terminal during a power swing condition varies as a function of the phase angle separation, δ, between the two equivalent system source voltages.

Zone 1 distance-relay elements, with no intentional time delay, are the distance elements most prone to operate during a power swing, if the power swing blocking (PSB) relay function is not enabled.

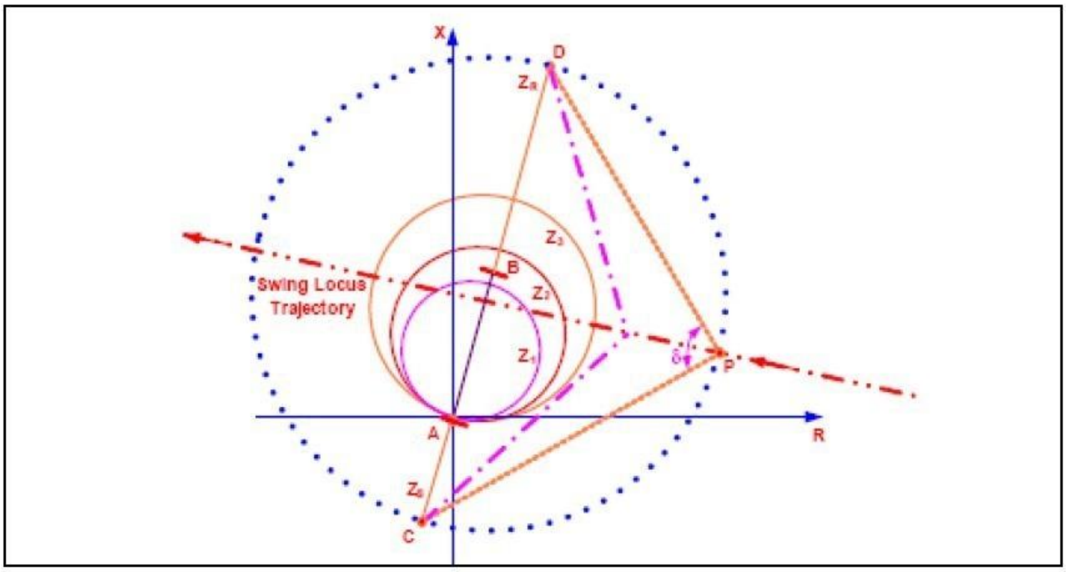



**Figure 3-2: Swing locus trajectory when the magnitude of ES/ER = 1.0**

As we can see in the Figure 3-2, the swing locus passes through the zone 1 tripping zone and, because usually it is no time delay, the protections will trip the protected element as if any real short-circuit happening.

Backup zone step-distance relay elements will not typically operate during a swing, depending on their time-delay setting and the time it takes for the swing impedance locus to traverse through the relay characteristic.

### 3.4.2 Overcurrent Protection

When power swings reach certain amplitudes (e.g. due to insufficient damping) they can generate high currents during part of the swing cycle that may impact the performance of phase directional or non-directional instantaneous overcurrent relays. Instantaneous phase overcurrent relays will operate during those power swings if the line current during the swing exceeds the pickup setting of the relay.

Likewise, directional instantaneous overcurrent relays operate if the swing current exceeds the pickup setting of the relay and the polarizing and operating signals have the proper phase relationship during the swing. Time-overcurrent relays will probably not operate but this will depend on the swing current magnitude and the time delay settings of the relay.

### 3.4.3 Differential Protection

Modern numerical line current differential and phase comparison relaying systems, applied for transmission line protection, are immune to stable and unstable power swings, because of their principle of operation.

However, differential protection performance can be challenged in the case of an unstable power swing associated to an important power flow.

Particularly, at extreme conditions, when power swing phenomenon occurs with an important current flow (around short circuit level, in order of magnitude), this current flow increases the restrain current to attempt the same level as a short circuit current: the more the power flow is important, the more the restrain current is important. A fault that occurs at this moment is seen by the differential protection, but the tripping does not occur, while operating current is lower than restrain current.

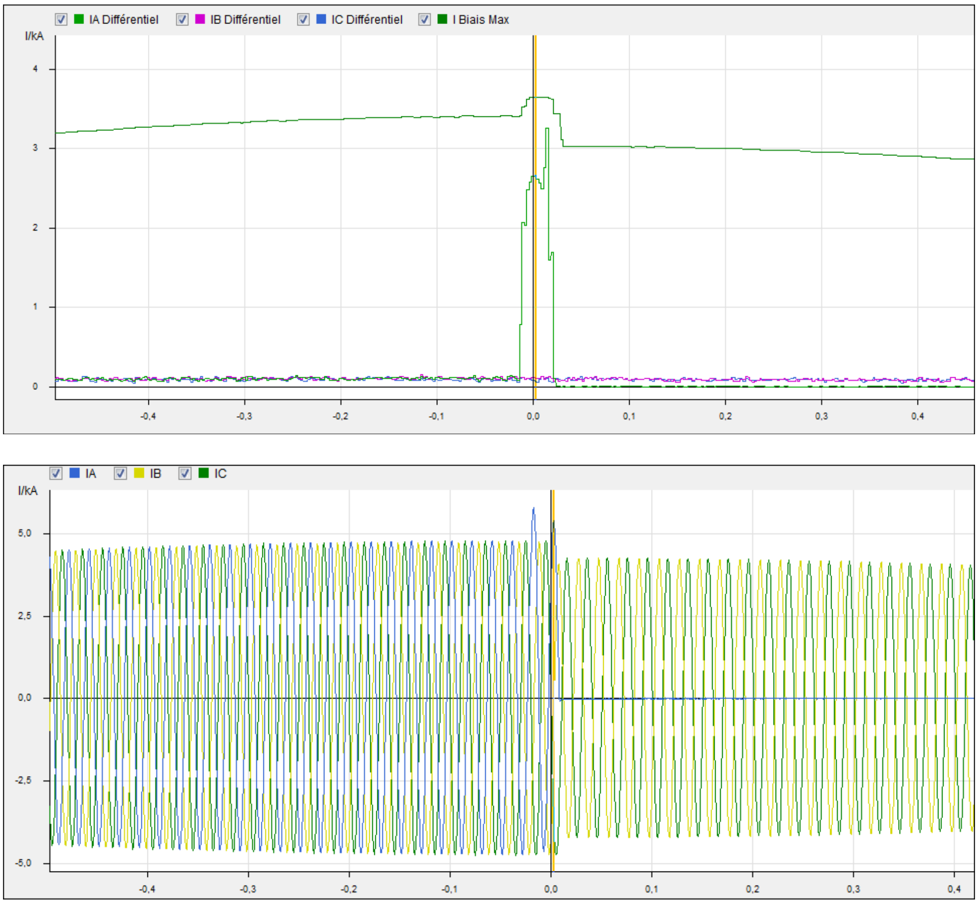



**Figure 3-3: Restraint current (IBiais) and differential current (IA Différentiel) for a phase to ground fault on an 225 kV underground cable during an unstable power swing (0.2 Hz)**

## 3.5 Relay Performance during Power System Abnormal Frequency Conditions

This is a critical issued for the numerical relays that are installed in most of the power systems. The numerical relays track the system frequency to calculate the current, voltage and impedance phasors. Under abnormal frequency situations, phasor errors calculations could lead to unwanted operation of the relays based on this technology.

Without getting into the detail, the performance of these relays, during a frequency excursions, depends on:

- ✓ The type of filtering
- ✓ If the relay has frequency tracking or not
- ✓ The measurement and tracking speed
- ✓ And the type of polarizing memory.

### 3.5.1 Distance Protection

Frequency variations in the power system, with respect to nominal frequency, produce errors in Fourier filter (DFT) calculations as the samples used no longer equal exactly an integer multiple of the system frequency.

However, the tendency of a distance relay to misoperate due to a frequency variation is not predominantly caused by phasor calculation errors, as they are relatively minor even for a comparatively large frequency deviation. The main cause for undesired tripping is due to the way memory polarization is utilized, as will be discussed below.

Distance relays algorithms generally employ a memorized voltage taken several cycles before the fault inception in order to ensure correct operation for the following conditions:

- ✓ Faults with low voltage at the relay terminal, where the polarizing voltage is below the signal threshold required for accurate voltage measurement.
- ✓ Faults with voltage inversion on series compensated lines.
- ✓ Faults in applications with capacitive voltage transformers (CCVT's) that may generate significant transients, especially for low voltage faults.

The memory time required for the polarizing voltage depend on the type of fault and the system characteristics:

1. Faults with low voltage at the relay terminal, where the polarizing voltage is below the signal threshold required for accurate voltage measurement.

In general, low- or zero-voltage faults occur for faults very close to the relay terminal where there is little line impedance between the relay and the fault location. Close-in faults are located within the relay Zone 1 reach. As Zone 1 trips instantaneously, the polarization memory time required is very short. Typically, 2 - 3 cycles' memory is sufficient.

However, in applications with high source-to-line impedance ratio (SIR), the voltage may drop to a very low value also for external faults, beyond the remote line terminal in Zone 2 or even Zone 3. The distance units should remain asserted until the corresponding timer has timed out and it may be necessary to increase polarization memory time up to Zone 2 or Zone 3 time delays.

2. Faults in applications with capacitive voltage transformers (CCVT's) that may generate significant transients, especially for low voltage faults.

For applications with CCVT's, the voltage polarization memory time should be long enough to last during the subsidence of any transient produced.

The use of longer polarization times presents a serious problem for distance protection in the presence of frequency excursions. A change in frequency will cause a phase angle shift between the frozen memory voltage phasor and the actual voltage phasor. This shift is especially detrimental for distance relay Mho characteristics.



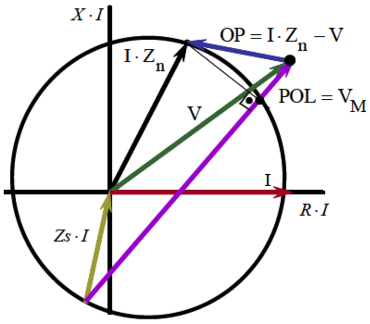
ENTSO-E • Avenue de Cortenbergh, 100 • 1000 Brussels • Belgium • Tel +32 2 741 09 50 • Fax + 32 2 741 09 51• info@entsoe.eu • www.entsoe.eu

The Mho characteristic is formed by comparison of the angle between an operating quantity and a polarizing quantity:

$$OP = I \cdot Z_n - V$$
$$POL = V_M \qquad (1)$$

where

I = the fault current for the impedance measuring unit
V = the fault voltage for the impedance measuring unit
$V_M$ = the polarizing memory voltage
$Z_n$ = Zone n reach setting




The mho characteristic operates when the angle between the operating quantity and the polarizing quantity is less than 90 degrees:

$$|\angle OP - \angle POL| \le 90° \qquad (2)$$

The mho elements tend to overreach for decreased frequency and underreach for increased frequency.

It is important to note that the tendency for a false operation by the mho characteristic does not only occur while the frequency varies with time, but also for any discrete change, because in both cases there is a shift between the polarizing and operating phasors, although the shift is constant in the latter case, instead of varying with time.

For distance relay quadrilateral characteristic, the use of memory voltage is not as prone to cause misoperations during frequency excursions as for the mho elements. The reason for this is that the memory voltage is used for directional measurement only, and not for reach. It is possible that a large frequency variation could cause loss-of-directionality of the quadrilateral characteristic, but undesired tripping would still not occur as the apparent impedance would be outside the set reactive and resistive reach. However, it could result in a missed trip for a forward fault or a trip for a reverse fault if the directional element makes an erroneous decision.

## 3.5.2 Overcurrent Protection

Overcurrent elements calculate the current phasor and compare it with a threshold to make a protection decision. In most of the applications, the overcurrent has a time delay to coordinate with other protections devices. The typical errors for phasor magnitudes are between 1% and 11%, depending on the magnitude of frequency excursions and the tracking algorithms. Therefore, if the frequency ramps quickly (10 Hz/s), the error could be around 7% and one should increase settings thresholds of overcurrent to prevent misoperations.

Overreaching of overcurrent elements is proportional to the difference between the input and the relay tracking frequencies.



ENTSO-E • Avenue de Cortenbergh, 100 • 1000 Brussels • Belgium • Tel +32 2 741 09 50 • Fax + 32 2 741 09 51• info@entsoe.eu • www.entsoe.eu

### 3.5.3 Differential Protection

Differential protection is a pilot protection and therefore is exchanging current information from the both ends of the protected elements. The operating current and restrain current are expressed as:

Operating Current = | I1 + I2|; restrain current = (|I1| + |I2|)/2

For external faults, the currents at both ends are equal. Both currents are the same phasor with opposite polarity. When the relay calculates the phasor sum, the phase shifts and magnitude oscillations cancel themselves, so the operating current is a perfect zero (disregarding the small charging current). Because the restraining current is an average of phasor magnitudes, the magnitude of oscillations of an individual phasor pass directly to the restraint current.

For zero fault resistance,  both the operating current and the restrain current oscillate with similar magnitudes errors. In general terms, the differential element is secure against external faults, regardless of system frequency, and it is dependable for internal faults without resistance and could reduce its sensitivity for high resistance faults.

Differential protections with frequency tracking capability may track frequency in symmetrical or asymmetrical manner. Differential protection devices must stay in synchronism with each other and should stay in synchronism with the power system for accurate phasor measurements. Devices track the system frequency in either a symmetrical or asymmetrical manner to adjust the sampling process or compensate the raw phasors. A symmetrical scheme uses an equivalent average frequency between all devices, and an asymmetrical scheme uses local frequency measurement at a given device. The symmetrical schemes are immune to off-nominal frequency problems, because all devices use the same tracking frequency. In case of asymmetrical schemes, the tracking frequencies may differ considerably between devices because each device uses frequency derived locally and may respond differently to their local input signals.

Differential protections measure currents in the phase-segregated or mixed-mode. Phase-segregated differential schemes are immune to errors caused by off-nominal frequencies, opposite to mixed-mode, because of occurrence of spurious negative sequence currents in response to off-nominal frequencies, which can jeopardize security of the line differential scheme. The mixed-mode system is not widely used on high voltage levels (except for short coupling lines without requirements of single-phase auto recloser).

# 4 Use of protection against grid instability

The following protection actions could be used regarding the different grid instability described in the previous parts of the document.

The aim is to identify the actions (**bold**) that are in relation with protection used for transmission lines (in particular, the distance protection).

**Small disturbance angle stability**

The following systems are used to manage this type of disturbance:

- Improved excitation controls (generators),
- Power System Stabilizers - PSS (generators),
- SVC voltage controls,
- HVDC special controls,

**Transient stability**

The following system can be used to manage this type of disturbance to avoid unstable power swing:

- Turbine fast valving (generators),
- Improved excitation controls (generators),
- HVDC fast active/reactive power change,

The following emergency action can be used after unstable power swing inception:

- **Unstable grid part separation,**
- Unstable generator disconnection,
- Generation rejection,
- Remote load shedding,

**Frequency stability**

The following systems are used to manage this type of disturbance:

- Underfrequency load shedding
- Generator fast start-up
- HVDC fast active power change
- Generation rejection (for over-frequency)

**Voltage stability**

The following systems are used to manage this type of disturbance:

- Tap changers blocking,
- Under voltage load shedding,
- HVDC special controls

The only action in relation to the transmission lines protections is the separation of unstable grid part in case of unstable power swing. Distance protections can be used to perform this function.

# 5 PROTECTION STRATEGY AGAINST UNSTABLE POWER SWING

Unstable power swing is a severe disturbance for a power system. It can lead to a loss of synchronism between generators, or between neighbouring grid systems. For the most severe cases, it can lead to the shutdown of major parts of the power system.

A protection strategy against unstable power swing must be defined to avoid an uncontrolled evolution of the power system. Most of the time, generators are the only power component able to generate this power swing.

Two different strategies may be defined in case of unstable power swing:

- Fast disconnection of unstable generators,
- Separation of the unstable part of the grid

Dynamic studies must be carried out to validate the applied strategy (which implies having dynamic models of the generator, load, HVDC links, FACTS connected to the grid).

The most important factors in the selection of the appropriate protection strategy against unstable power swing are:

- Scenarios of contingencies,
- Grid structure (meshed vs radial),
- Location of the generation and load,

- Type of interconnection with the neighbouring grid system.
- Grid code (What measures are being imposed for the generator in case of unstable operation?)

## 5.1 SCENARIOS OF EXTREME CONTINGENCIES

Grid systems are generally designed and operated to be stable for the most probable contingencies (design contingency).

An extreme contingency is an event which exceeds, in severity, a design contingency and has low probabilities of occurrence.

The objective of extreme contingency study is to determine the effects of extreme contingencies on grid system. This is done in order to obtain an indication of system strength, or to determine the possible extent of a system disturbance.

Scenarios of extreme contingencies are particular to each power system and must be based on knowledge of the characteristics of the power system and past experiences with major disturbances.

For instance, scenarios of extreme contingencies could be:

- Multiple loss of grid components (transmission line, transformers, interconnections),
- Loss of transmission lines with very heavy load or very heavy generation hypothesis for an area,
- Loss of synchronism of group of generators (for instance following a 3-phase fault with a long clearing time),

## 5.2 GRID SYSTEM CHARACTERISTICS

The structure of the system and its type of interconnection with its neighbours are the most important factors in the selection of the appropriate strategy to counter an extreme contingency.

Power system structure depends mainly on the respective localization of loads and generation:

- Densely meshed transmission systems with dispersed generation and demand;
- Lightly meshed transmission systems with localized centres of generation and demand.

The number and type of interconnections (AC, HVDC) is also important to define the system strength.

# 6 USE OF PSB FUNCTION

In normal operation, a power system is in a steady state operating condition. If a disturbance from its steady state operation occurs, the system can return to a new steady state or it can lose its synchronism, synchronism between groups of generators. It depends on how serious the disturbance was. The transition from one state to another is accompanied by periodical change of power flowing among generators. It is caused by oscillations in the relative positions of machine rotors that result in power flow swings. For protection relays, the power swing appears as periodical change of measured voltage and current phasors.

As mentioned before, some types of protection relays can operate unintentionally during a power swing. Especially during stable power swing, it is not desirable to switch off any lines which could worsen the situation in the network. On the other hand, during an unstable power swing, which leads to slip of poles of generators that means an enormous strain on them, it is desired to separate the power system into islands, to prevent wide area blackouts and equipment damage. The system can be divided either into predetermined islands or in a swing centre during an unstable power swing.

Ideally, the split should be made in a such way that the plant capacity and connected loads on either side of the split are matched.

To prevent unwanted operation, the power swing blocking (PSB) function is used. The function discriminates between faults and power swing and blocks relay elements, which are prone to operate during power swing.

Most power swing detection methods are based on impedance measurement.

## 6.1 IMPEDANCE BASED POWER SWING DETECTION

Power swing detection is based on the rate of change of the measured impedance. The measured impedance is compared with an element characteristic on the impedance plane. This characteristic may consist of circles, blinders or polygons.

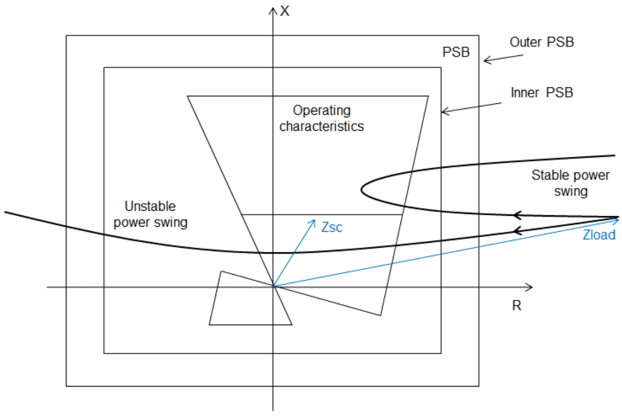



**Figure 6-1: Impedance diagram for impedance based PSB**

During normal operation, measured impedance is somewhere in the load area. When a short circuit occurs on the protected line, the measured impedance immediately changes to the value Zsc. On the other hand, the power swing is characterized in relatively slow change of measured impedance because of large generator rotors inertias. A power swing with sufficient accelerating power, once initiated, will traverse 360 degrees and, unless interrupted, will continue. The impedance seen by an impedance relay at either the sending or receiving ends of the transmission line will look like a three-phase short circuit as the impedance trajectory crosses near the electrical centre of the system. This apparent three-phase fault will be either in front of or behind the impedance relay applied to the protected line terminal. The power swing blocking function is accomplished by the measuring of elapsed time between the passing of measured impedance through the outer and the inner zone of PSB elements. If the elapsed time is greater than the defined value, the operation of the distance protection in distance zones is blocked. Usually, we can choose that either all zones are blocked or some zones remains unblocked. Sometimes we can have all elements unblocked.

The application when the Zone 1 is not blocked by PSB is a reasonable compromise. It comes from the philosophy to better safe than sorry. All possible faults on a line will be cleared quickly and reliably. There is no danger that the clearing of a fault during power swing detection will be delayed. On the other hand, there is a small probability that a line can be switched off even during stable power swing. Only the characteristic for 3-phase faults is affected by a power swing because the stability swing is a balanced phenomenon. Its reach in the resistance direction can be small because the probability of a three-phase high resistive fault in transmission systems is low. All stable swings come no closer than a



ENTSO-E • Avenue de Cortenbergh, 100 • 1000 Brussels • Belgium • Tel +32 2 741 09 50 • Fax + 32 2 741 09 51• info@entsoe.eu • www.entsoe.eu

certain minimum distance from the origin of the impedance plane [10]. If a power swing reaches the zone 1, it probably will be an unstable swing. This solution separates the network before the first pole slips, when the angle between the equivalent generators at both sides of the relay is less than 180 degrees. In this case, the circuit breaker is stressed by transient recovery voltage during interruption process. Circuit breakers must be properly rated for the application. As you can see in chapters 8.1., 8.2. and 8.3. this application can cope with an unstable power swing very well.

The setting of the impedance based PSB function is quite difficult. For an accurate setting an extensive stability study on the system should be done. The aim of the study is to determine the fastest power swing which can occur in the protection relay position. The impedance trajectory seen by the distance relay for each of the possible stable cases is examined.

There are some general rules which should be completed for a proper setting of PSB impedance characteristics.

- PSB characteristic is composed of either two concentric characteristics or blinders. Concentric characteristics usually have a shape either of polygon or circle. Sometimes, lenticular characteristics can be used.
- The inner characteristic should be set outside the largest distance element characteristic that is required to be blocked when a power swing occurs. Because the protection relay needs to have enough time to process all information and to block its function, there should be a margin between the inner PSB characteristic and the outer distance protection characteristic. Usually, 10% margin in both resistive and reactance direction should be enough.
- The outer characteristic should be set so that it does not operate for the maximum load conditions with some margin. The distance between the inner and the outer characteristic will determine a time for distinguishing between a short circuit and a power swing. Usually it is sufficient to set the outer characteristic about 25% bigger then the inner characteristic. After that it must be controlled that the outer characteristic does not reach into the maximum load.
  Sometimes, especially if longer reach in resistance direction on a highly loaded line is required, it can be impossible to comply with rules mentioned above. It can be impossible to place the PSB characteristic between the load and distance characteristics. Modern digital relays usually offer to use a load encroachment function.
- Based on the outer and inner blinders set in the previous steps, the PSB timer value, T1, can be calculated from the following equation with information of the local source impedance, Z1S, the line impedance, Z1L, and the remote source impedance, Z1R. Ang2R and Ang1R are machine angles at the outer and inner blinder reaches, respectively, as illustrated in Figure 6-2. The maximum slip frequency, Fslip, is also assumed in the calculation. Typical maximum slip frequency is chosen anywhere between 4 to 7Hz [6].

$$T1 = \frac{(Ang1R - Ang2R) \cdot F_{nom}}{360 \cdot F_{slip}} \qquad [cycle; Hz, Hz] \qquad (3)$$

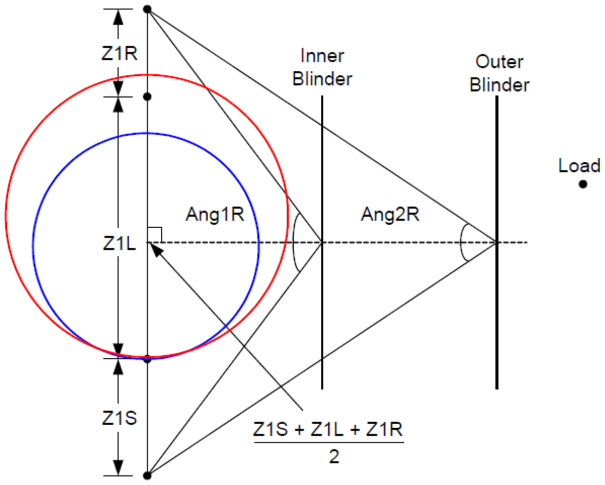



**Figure 6-2 Equivalent two-Source machine angles during unstable power swing**

It is very difficult in a complex power system to obtain the proper source impedance values, as shown in Figure 6-2, that are necessary to establish the blinder and PSB timer settings. The source impedances vary constantly according to network changes, such as, for example, additions of new generation and other system elements. The source impedances could also change drastically during a major disturbance and at a time when the PSB function is called upon to take the proper action.

If we assume a typical maximum oscillation frequency for swing between 4 to 7Hz, the excursion from the farthest to the nearest point on the impedance trajectory would take one half the period of the typical oscillation, or between about 120 to 70ms. For more cases, it is possible to set the minimum time for the first oscillation between 40 and 50ms. From recommendations mentioned above, we can see that the larger the reach of distance zones, the greater the distance between inner and outer zones of PSB. Because the speed of change of measured impedance goes down when rotor angle excursions approach to 180 degrees, the same settings of time is in order.

- If there is a pole slip allowed, we should take into consideration that the initial power swing usually is not as fast as the later swings are. In that case, it should be checked that the time set for power swing detection is short enough to be able to detect subsequent swings.

As far as possible, non-symmetrical faults have to unblock the PSB immediately to permit tripping in all cases. Criteria may be zero sequence currents or negative sequence currents.

Moreover, the interaction between PSB strategy and distance relay schemes (for instance POP schemes) must be studied.

## 6.2 RATE OF CHANGE OF SWING CENTRE - VOLTAGE DETECTION METHOD

Other Power Swing detection methods are possible, e.g. the rate of change of the swing centre voltage detection. The Swing Centre Voltage (SCV) is defined as the voltage at the location of a two source equivalent system where the voltage value is zero, when the angles between the two sources are 180 degrees apart. Figure 6-3 illustrates the voltage phasor diagram of a general two-source system, with the SCV drawn in it.

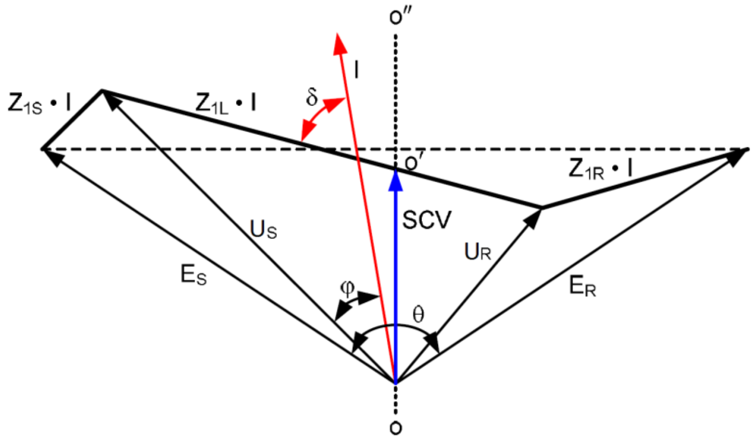



**FIGURE 6-3 VOLTAGE PHASOR DIAGRAM OF A TWO-SOURCE SYSTEM**

When a two-source system loses stability and enters in out of step condition, the angle difference of the two sources, θ(t), increases as a function of time. The magnitude of the SCV changes between 0 and 1 per unit of system nominal voltage. Under normal load conditions, the magnitude of the SCV stays constant.

One popular approximation of the SCV obtained by locally available quantities is as follows [14]:

$$SCV \approx |U_S| \cdot cos\varphi$$

where:

$|U_S|$ … the magnitude of locally measured voltage
φ … the angle difference between VS and the local current, as shown in Figure 6-3.

The quantity of U•cosφ does not completely match SCV in amplitude. For the purpose of power swing detection, it is the rate of change of the SCV that provides the main information of system swings. Therefore, some difference in magnitude between the system SCV and its local estimate has little impact in detecting power swings. The magnitude of the SCV is at its maximum when the angular difference between the two sources is zero. Conversely, it is at its minimum (or zero) when the angular difference between the two sources is 180 degrees. A power swing can be detected by calculating the rate of change of the SCV.

As for the previous method, the fastest power swing which can occur in the protection relay position should be determined to be able to distinguish between a short circuit and a power swing.

In some cases, there can be differences between the system SCV and its local estimate:

- When there is no load flowing on a transmission line, the current from a line terminal is basically the line charging current that leads the local terminal voltage by approximately 90 degrees. In this case, the local estimate of the SCV is close to zero and does not represent the true system SCV.
- The local estimate of the SCV has a sign change in its value when the difference angle, θ, of two equivalent sources goes through 0 degrees. This sign change results from the reversal of the line current (i.e., φ changes 180 degrees when θ goes through the 0-degree point). The system SCV does not have this discontinuity.

## 6.3 SYNCHROPHASORS MEASUREMENT DETECTION METHOD

Another power swing detection method uses synchrophasors. The power swing detection algorithm uses the positive-sequence voltage angles that relays with synchrophasors measurement capabilities acquire at two different power system buses to calculate the load angle $\delta$ between these buses. Once we are able to do this, we can calculate the slip frequency S and its acceleration $\alpha$ during the power swing [15].

## 6.4 OTHER PSB STRATEGIES

Other strategies can be applied regarding the PSB strategy of distance protection:

- **No power swing detection**
  This strategy does not use any PSB function in distance protection and accepts lines tripping in case of power swing. In case of stable power swing, the uncontrolled trip may bring grid constraint like line overload or voltage event. Obviously, a detection of unstable power swing is required in the power system: **Unstable generator power plants are the ones who have to trip after detecting an unstable power swing.**

- **Block all zones during power swing**
  This strategy consists in blocking all zones of the distance protection during a stable or unstable power swing. This strategy is not recommended if no OST function is used to achieve a separation of the unstable part of the grid in case of unstable power swing.

- **Block all zones during power swing and use of OST function**
  This strategy aims to achieve a controlled separation of the grid in case of unstable power swing.
  Preselected locations for the grid separation are determined by dynamic studies. This strategy may lead to a grid separation with a generation/load balance of the islands.

  In summary, the different PSB strategies are:

| **PSB Strategies for distance protection** | | |
|---|---|---|
| | *Advantages* | *Disadvantages* |
| **No power swing detection**<br><br>**(unstable power swing detection by generator power plants)** | Fault detection is all the time in operation during power swing.<br><br>With this PSB strategy, unstable generator power plants are the ones who have to trip after detecting an unstable power swing. | Risk of unwanted tripping in case of stable power swing. |

| | | |
|---|---|---|
| **Block all zones during power swing** | Protection immunity for stable and unstable power swing. | Protections are not in operation during stable or unstable power swing (however distance elements can be made operative in case of unbalanced faults).<br><br>Once an unstable swing starts, there are no relaying functions able to detect it and eliminate it. With this PSB strategy, generator power plants are the ones who have to trip after detecting an unstable power swing or OST functions are needed. |
| **Block all zones except zone 1** | Protection immunity for stable power swing (assuming that swings do not enter zone 1).<br><br>An unstable power swing detection function is in operation (assuming that unstable swings enter zone 1). | Risk of non-detection of unstable power swing if the swings do not enter zone 1.<br><br>Distance relay schemes operation during unstable power swing should be checked. |

# 7 Use of OST function

Uncontrolled tripping of transmission lines during unstable power swing could contribute to cascading outages and further to the shutdown of areas of the power system.

Therefore, controlled tripping of power system components is necessary to prevent outages and to minimize the effects of the disturbance.

Regarding out-of-step philosophy, the practice of each TSO can differ. The swing detection function and the separation function have to exist at the most appropriate place according to the results of the studies (at the generators interface for sure, at the connection feeders of generators to the grid or at specific points of the grid).

The Out of-Step Trip (OST) function of distance protection is designed to accomplish this detection and separation at specific locations of the grid. The main purpose of the OST function is to discriminate stable from unstable power swings and initiate system area separation at predetermined network locations in order to maintain grid system integrity and consumer supply.

The selection of network locations for placement of OST protections can best be obtained through dynamic studies, taking into account many operation conditions and contingencies.

The recommended method for OST function setting are (see [13]):

1. Perform dynamic studies to identify system stability constraints based on many operating conditions and contingencies scenarios. The studies will identify the parts of the power system that impose limits to angular stability, generators that are prone to be unstable during system disturbances and those that remain stable, and groups of generators that tend to behave similarly during a disturbance. The results of stability studies are also used to identify the optimal location of OST and PSB protection relay systems.



ENTSO-E • Avenue de Cortenbergh, 100 • 1000 Brussels • Belgium • Tel +32 2 741 09 50 • Fax + 32 2 741 09 51• info@entsoe.eu • www.entsoe.eu

2. Determine the locations of the swing trajectory during various system conditions and identify the optimal locations of the OST protection function. The optimal location for the detection of the power swing condition is near the electrical centre of the power system.

3. Evaluate the balance load/generation of the separate areas to check that the islands are viable,

4. Compute the settings for the OST protections.

Set the OST inner zone at a point along the unstable power swing trajectory.
Set the OST outer zone such that the minimum anticipated load impedance is outside the outer zone.
The OST time delay is set based on the settings of the inner and outer zone resistance blinders and the fastest unstable swing frequency expected or determined from dynamic studies.

When the swing trajectory enters the outer zone, a timer starts and detects out-of-step tripping conditions.
The OST function detects an unstable power swing if the positive-sequence swing trajectory enters the OST inner zone before the timer expires.
The OST function allows to trip on-the-way-in (TOWI) or trip-on-the-way-out (TOWO).

TOWI is selected if one desires to trip when the timer expires and the trajectory enters the OST inner zone.
TOWO is selected when one desires to trip when the timer expires and trajectory enters and then exits the OST inner zone.

TOWO is the most common way to apply out-of-step tripping since the breakers will be given a tripping command when the two equivalent voltage sources will be close to an in-phase condition. In rare occasions, system stability requirements are such that a TOWI is needed.

5. Include models of the PSB and OST functions and their operation behaviour in dynamic study tool to verify correct application of the power-swing protection strategy.

See [13] for more explanations about OST settings computation.

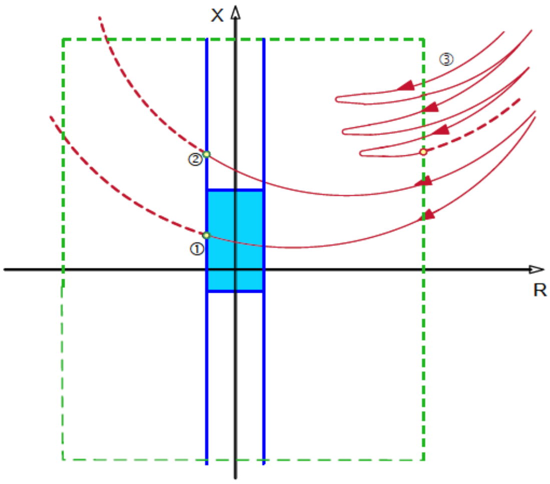



**Figure 7-1 Out-of-Step protection**
(source: “Requirements for Protection schemes in EHV Transmission Systems, PG Systems Stability, Amprion-EnBW-transpower-50HeRTZ; original title: Anforderungen an Netzschutzeinrichtungen im Übertragungsnetz- PG Systemstabilität, 20-05-2010”)

# 8 EXAMPLES

In the following chapters, there are some events described which occurred in last twenty years and which are connected with power swing detection and out of step issues.

## 8.1 DISTURBANCE ON 26TH NOVEMBER 2001 – THE CZECH REPUBLIC

On 26. 11. 2001 occurred a loss of stability of a part of 220kV network and an island was created in the Czech Republic transmission network.

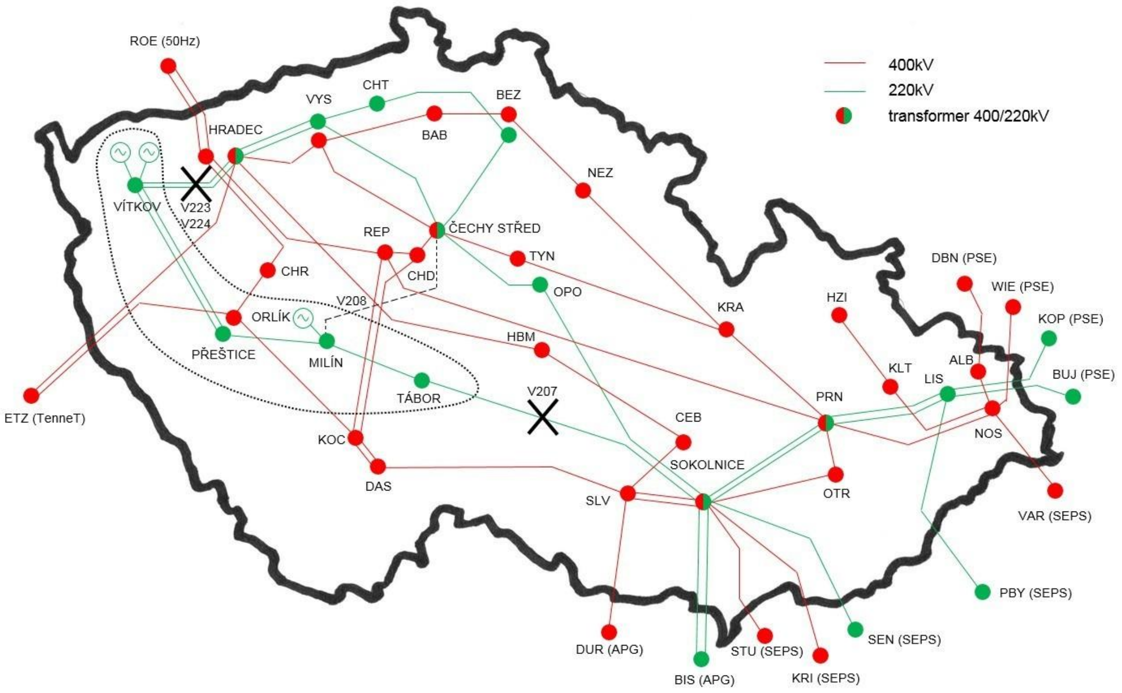



**FIGURE 8-1: EXTENT OF DISTURBANCE**

Due to maintenance, the line 220kV V208 between substations Milin and Cechy Stred was disconnected. Further, due to large generation of power into substation 220kV Vitkov, two lines V223 and V224 between substations Vitkov and Hradec were highly loaded. Close before the incident, the hydropower plant Orlik had been put into operation. The power plant is connected to the substation Milin. This led to the further increase of load of lines V223 and V224. In the substation Hradec, there were electromechanical protection relays D114 (ZPA Trutnov) installed on the lines V223 and V224. Afterwards, a defective initiating element was detected in both relays by measuring – they were more sensitive than would correspond to their setting. Transmitted power through lines V223 and V224 stepped into start protection characteristics of these relays of the two lines. Both lines were switched off by protections in the reverse direction, in the end time 6s in the substation Hradec. This resulted in long distance lines had to transfer the power of approximately 590MW, which until then had flowed through lines V223 and V224, to the substation Sokolnice. This change resulted in power swing of generators connected to substations Vítkov and Milin, and ultimately the loss of stability. The power swing centre laid on the line V207 between substations Tabor and Sokolnice.

Distance protection relays of the line V207 saw the swinging as a gradual change in the measured impedance. The measured impedance at the bay V207 Tabor gradually entered into impedance zones Z3, Z2 and finally Z1. Distance protection relays of the line V207 are equipped with a power swing detection function. The function blocks an operation of distance protection relays in zones Z3 and Z2. Zone Z1 is not affected by it. When the measured impedance entered into the zone Z1, the line V207 was switched off.

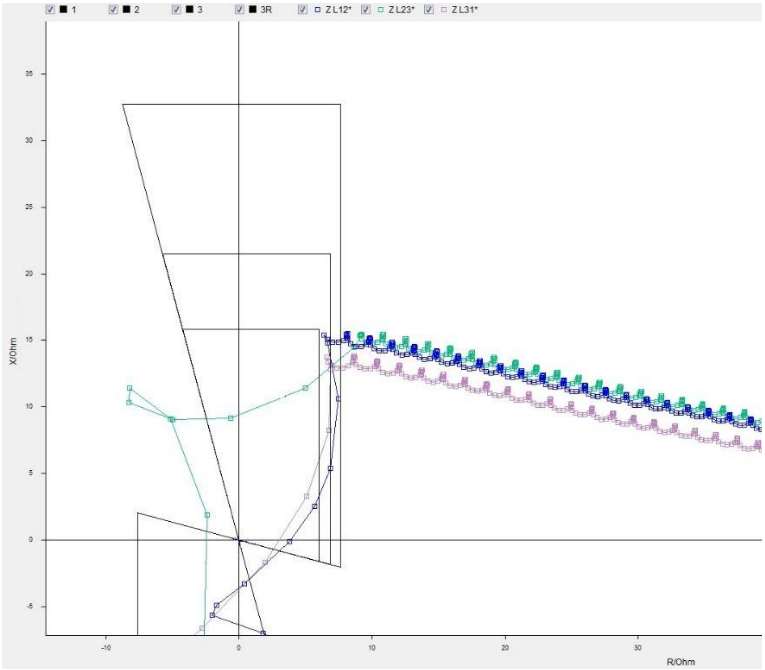



**FIGURE 8-2: IMPEDANCE PLANE V207 TABOR**

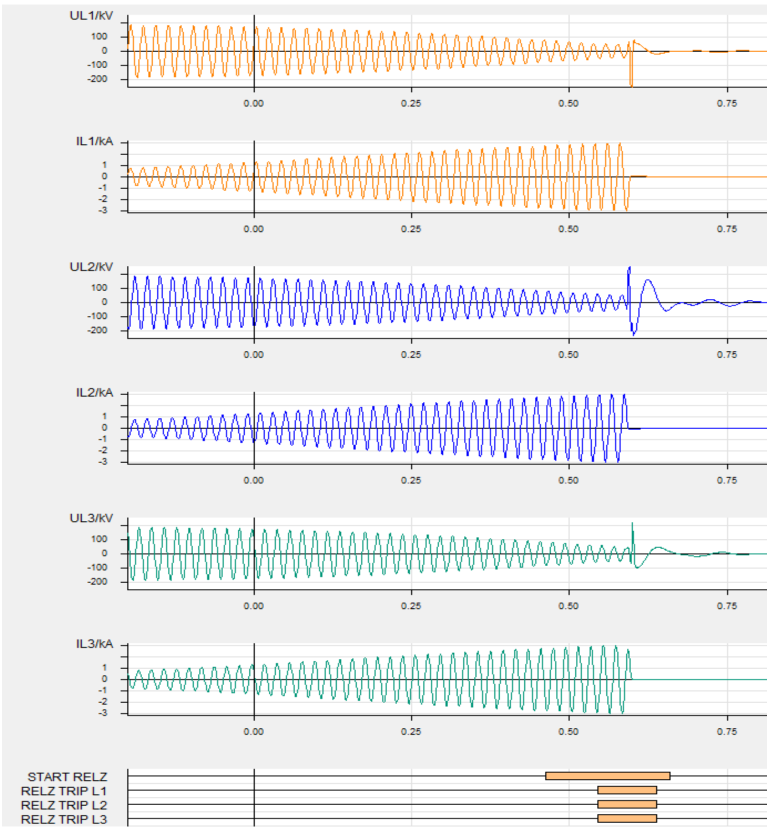



**FIGURE 8-3: DISTURBANCE RECORD V207 TABOR**

An island occurred which was formed by substations Vitkov, Prestice, Milin and Tabor. In the island, the generation was decreased by 190MW and about 120MW supply constraints caused by switching off several 110kV lines by frequency relays. The island remained stable.

If the first zone of a distance protection relay is not blocked during power swing, it has similar function like an out of step protection. During unstable power swing, the network is divided into islands in the power swing centre. These islands may remain stable. In the event of a fault during swinging, the fault is switched off immediately.

## 8.2 Disturbance on 25th July 2006 – The Czech Republic[16]

This chapter briefly summarizes events, which contributed to the declaration of an emergency state in the Czech power system.

The following factors were influencing the power system state before disturbance:

1 The consumption was greater than usually, especially due to using air conditioning.
2 Producers had operating problems, especially with cooling of steam power stations (export areas like France and Poland decreased or cancelled exports of electricity and theirs export's role was taken over by Switzerland and Austria with possibility of production in hydro stations).
3 Several lines were out of operation due to repairs and maintenance in the morning – see Figure 8-4
4 Transmission devices were stressed due to high temperature, sunshine and calm condition with mild wind (temperature reached for 33.5°C at 9:00 with mean value 27°C).
5 Small wind production, which was solved by imports of electricity and its transmission to large distance. Germany, with large portion of installed wind turbines (and usually high wind production), imported about 4 000 MW. Active trading with electricity during a day, caused large changes of control programs from hour to hour.
6 There were the unannounced outages of lines between Slovenia and Italy (due to fire under the lines) followed by switching off the 220 kV line between Austria and Italy (due to overloading).

The above mentioned factors influenced the transit and changed power flows through the Czech transmission system from the usual north – south direction to the east-west direction. Moreover, the overloaded line V415 Cechy Stred – Chodov was switched off at 11:10:49.

The line V415 Chodov – Cechy Stred tripped due to overloads. The event sequence is:

7 12:01 400 kV line V420 Hradec západ - Mírovka is switched off by distance protection due to line to ground short circuit caused by fall of rope (one of the ropes slipped from the coupling and fell dawn)
8 12:07 400 kV line V402 Krasikov – Prosenice is switched off manually due to fire on high frequency choke
9 12:07 220 kV line V203 Opocinek – Sokolnice was switched off by distance protection.

Part of the Czech transmission system (marked by blue colour in the Figure 8-4) stayed connected to the rest of the system only via one line V203, after switching off the line V402.



ENTSO-E • Avenue de Cortenbergh, 100 • 1000 Brussels • Belgium • Tel +32 2 741 09 50 • Fax + 32 2 741 09 51• info@entsoe.eu • www.entsoe.eu

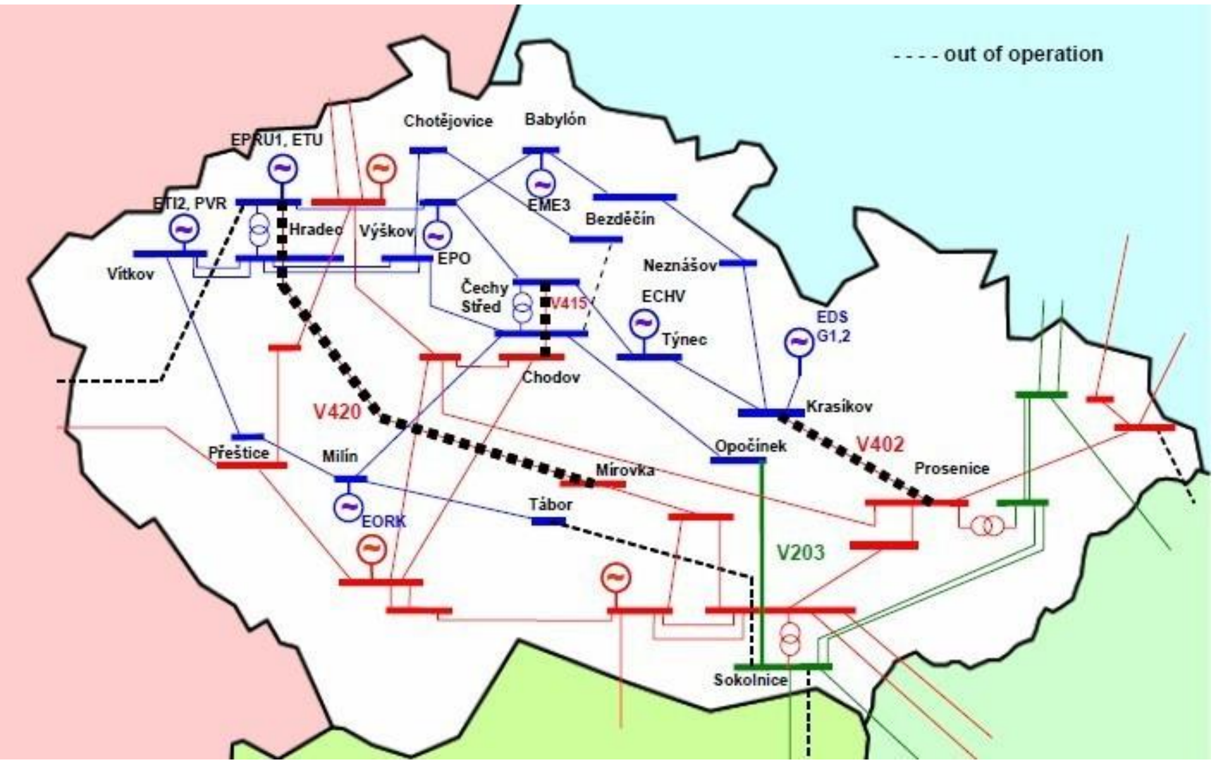



**FIGURE 8-4: TRANSMISSION SYSTEM SCHEME – STATE IN 12:07**

Since the generated power of nearly all large power plants was taken out via only one line, it was not physically possible to transmit this power excess. Electric power decreased and turbines started to accelerated rotors.

The affected part of the system might have become unstable and might have lost the synchronism without any corrective actions taken. In this case distance protection on V203 line operated and switched off the line. Distance protection measured the apparent impedance. Figure 8-5 shows a trajectory of apparent impedance measured in the Opocinek substation.

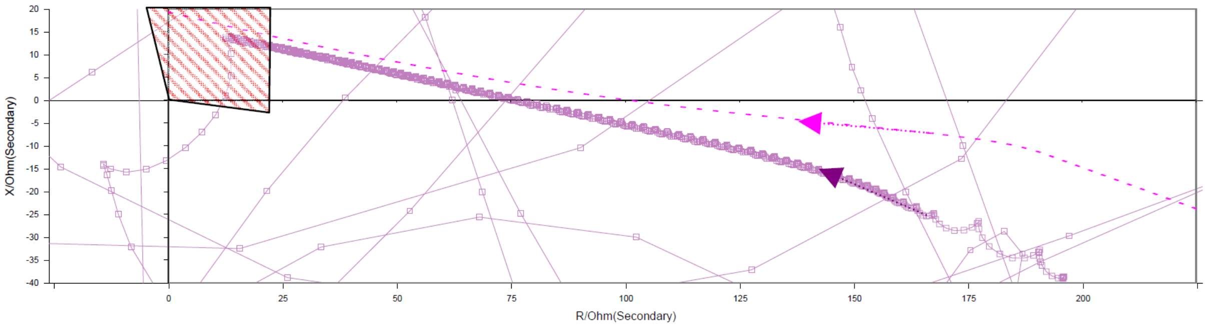



**FIGURE 8-5: COMPARING OF MEASURING AND SIMULATED TIME COURSES OF APPARENT IMPEDANCE**

The measuring trajectory is drawn in dark purple. Impedance is moving in the arrow direction from the right side (with large resistance R) to the imaginary axis X. It leaks in the first zone of distance protection (its characteristic is sketched in the upper part of the graph). Since the 1st zone has no blocking against swings, the protection switches off the line immediately. Sparsely marked trajectory shows swings after disconnection.



ENTSO-E • Avenue de Cortenbergh, 100 • 1000 Brussels • Belgium • Tel +32 2 741 09 50 • Fax + 32 2 741 09 51• info@entsoe.eu • www.entsoe.eu

The simulated (calculated by network simulator) trajectory is drawn by dotted line. It is seen as in a satisfactory agreement with the measured time course, especially in the vicinity of the zero-real part.

Switching off the line V203 resulted in a part of the transmission system passing into island operation. This action prevented the spreading of disturbances and preserved a stable operation. Transition into island operation was successful without frequency collapse. The time courses of speed deviations in the following figure prove it.

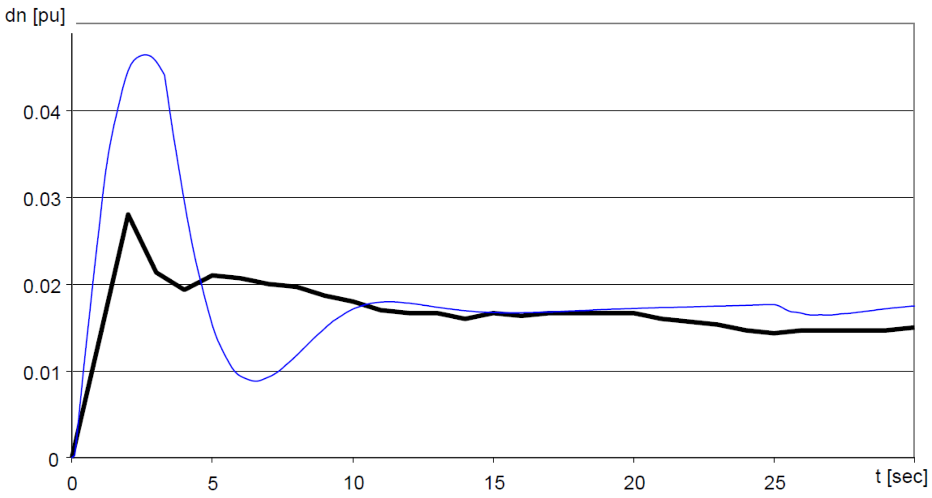



**FIGURE 8-6: MEASURED AND SIMULATED TIME COURSE OF SPEED DEVIATION**

The thick line represents the measured time course (with sampling 1s), the thin line is the calculation (with sampling 0.1 s). There is a satisfactory agreement of stationary deviations after the first swing subsiding.

The simulation calculation makes it possible to judge what happens if the distance protection does not operate. The following figure shows power swings caused by pole slips during loss of transient stability.

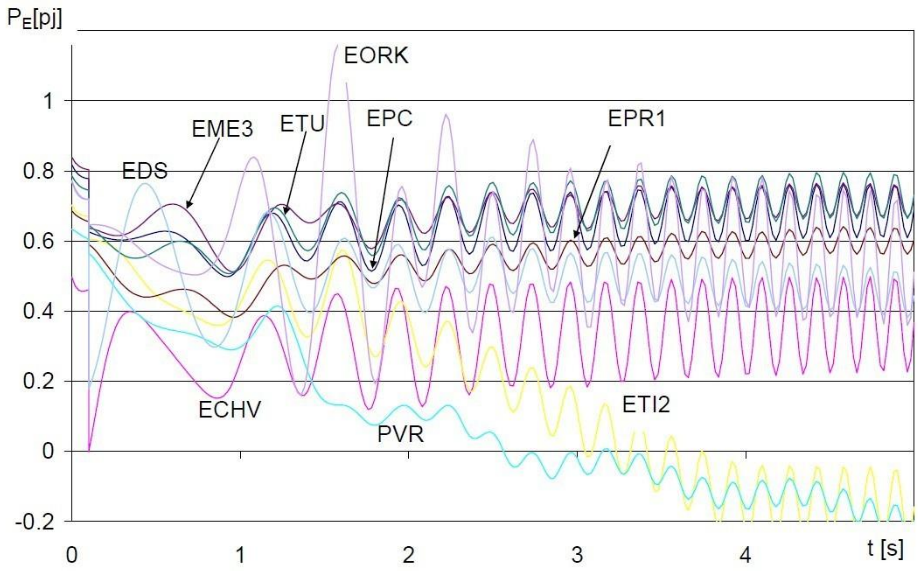



**FIGURE 8-7: CALCULATED OUTPUTS OF POWER STATIONS CONNECTED INTO AFFECTED PART OF NETWORK**



ENTSO-E • Avenue de Cortenbergh, 100 • 1000 Brussels • Belgium • Tel +32 2 741 09 50 • Fax + 32 2 741 09 51• info@entsoe.eu • www.entsoe.eu

## 8.3 DISTURBANCE ON 3RD AUGUST 2006 – THE CZECH REPUBLIC [16]

This chapter describes the dynamic behaviour of the power system during short circuit in the 400 kV substations Sokolnice. This situation is illustrated in Figure 8-8.

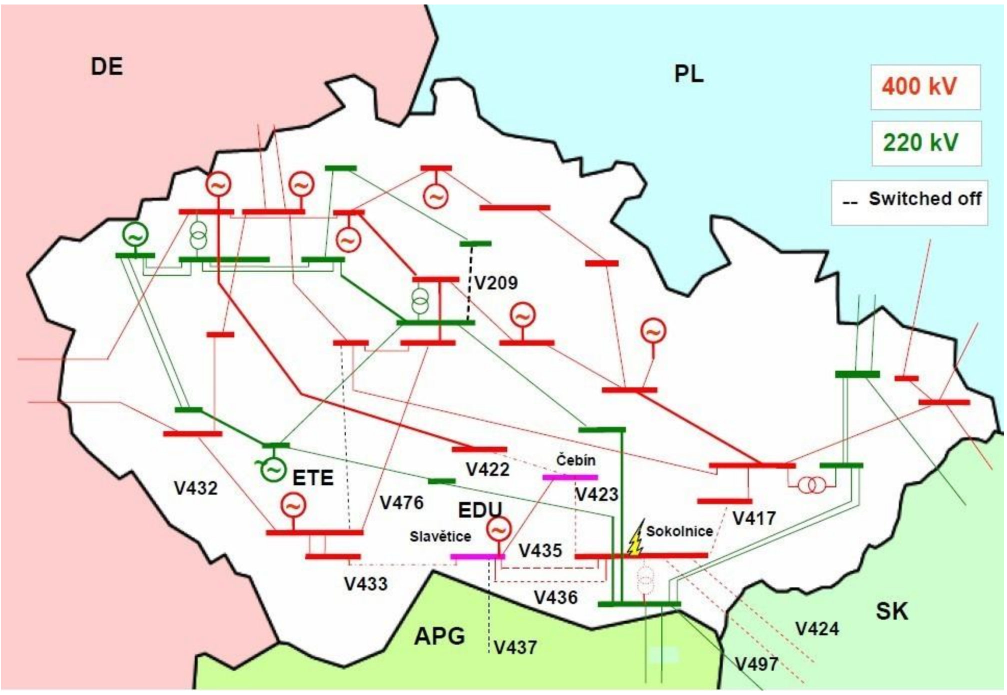



**FIGURE 8-8: ON LINE SCHEME OF TRANSMISSION SYSTEM IN 14:51**

Short circuit occurred on substation busbars during the ongoing long-term reconstruction (it was not possible to operate the busbar protection). Since it was busbar short circuit, it was cleared by the second stages of distance protections in longer times (line short circuit is usually cleared by the first stage of protection before 100 ms). All lines and transformers 400/220 kV were switched off (depicted by dashed red lines). The sequence of events is as follows (the initial time is considered 100 ms before short circuit for simplicity):

1 t=0.1 s: double line to ground short circuit in the Sokolnice substation
2 t=0.32 s: double line to ground short circuit changed into three-phase
3 t=0.58 s: lines V417, V435, V436 and transformer were switched off by distance protections
4 t=0.62 s: line V424 was switched off by distance protection
5 t=0.65 s: line V497 was switched off by distance protection
6 t=0.68 s: line V423 was switched off by distance protection
7 t=0.71 s: lines V433 a V422 were switched off by distance protections.

The short circuit was cleared in time t=0.68 s by switching off the line V423 (it means that the short circuit lasted 580 ms). The output of EDU power station was delivered to the rest of the system only through two 400 kV lines, which in combination with preceding short circuit, did not make possible a stable operation. This state was correctly evaluated by distance protections and they switched off the lines V433 a V422 in time.

The mechanism of this switching off by distance protections was similar to that one in the previous case of disturbance, on 25th July. The following figure shows the case of the line V433.

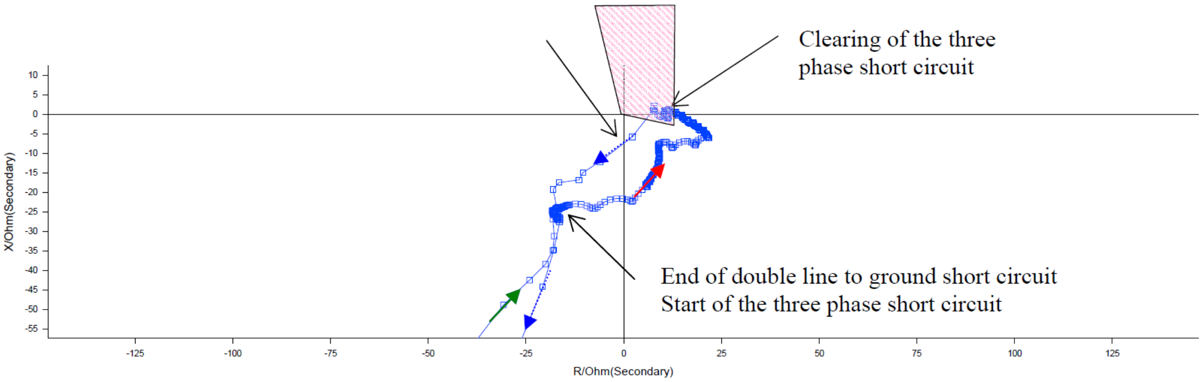



**FIGURE 8-9: TRAJECTORY OF APPARENT IMPEDANCE MEASURED IN THE SLAVĚTICE SUBSTATION**

The impedance started to move in the green arrow direction after double line to ground short circuit and it continued in the red arrow direction after change into three phase short circuit. The line is switched off with delay of circuit breaker operation immediately after crossing the first zone depicted by a polygon.

The Slavetice and Cebin substations fell into island operation, which is outlined in the Figure 8-8 by purple colour. The following figure presents a stable time course of frequency – comparing measured (black thick line) and calculated (blue thin line) time courses.

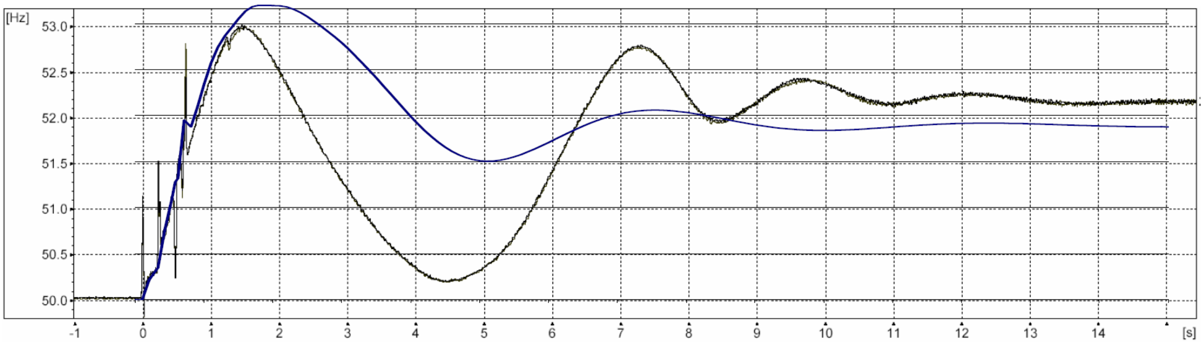



**FIGURE 8-10: MEASURED AND CALCULATED FREQUENCY TIME COURSE DURING PASSING INTO ISLAND**

The steady state frequency deviation corresponds approximately to the governor speed drop, which was about 5% and power surplus in the island, which was approximately 1360 MW.

Timely evaluation of asynchronous operation and distance protection actions prevented spreading of disturbance farther to the system and ensured stability of whole network and near power stations as well.

Similarly like in the previous chapter we can show the ability of the network simulator to answer questions „What happen, if ....? “. If, hypothetically, switching off these lines had not taken place, stability of near power station would have been threatened by pole slipping due short term asynchronous operation. These pole slips are depicted on time courses of current, powers and voltage (IGEN, PG, QG and UGEN) in Figure 8-11.

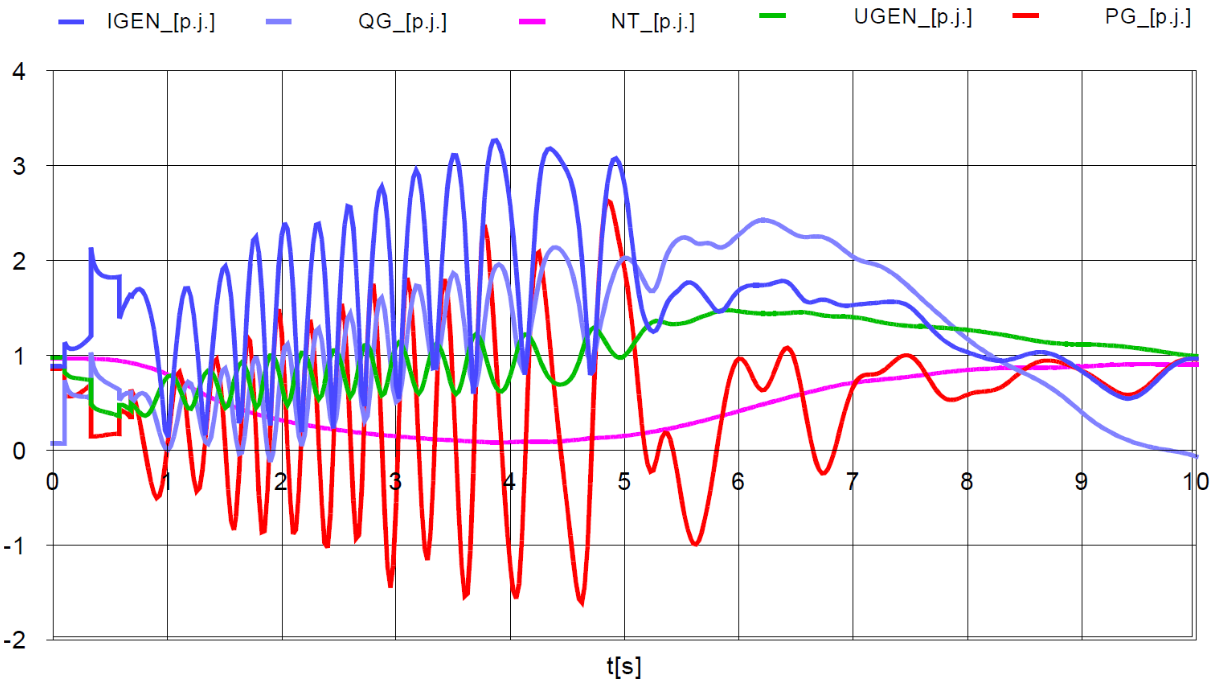



**FIGURE 8-11: SIMULATION OF HYPOTHETIC LOSS OF STABILITY**

The asynchronous operation lasted several slips and generator re-established synchronism again after turbine output NT decreasing. This decreasing was caused by fast valving, which closed the control valves temporary and stopped steam flow to the turbine.

## 8.4 SOUTH-WEST OF FRANCE DISTURBANCE-1999 STORM

This example is an illustration of the notion of maximum transfer capacity (from electrotechnical point of view) of a weak grid leading to the loss of synchronism of an area. It presents also the French issue to avoid a spreading of instability phenomena.

**Initial situation**

At time of event (27-12-1999), the situation of the French national grid was heavily impacted by a strong storm, which destroyed some lines and towers. Then, the system was not sufficiently meshed to ensure a normal synchronisation between the different areas.

The south-west of France and Spain was weakly linked to the rest of France only through:

- One 400 kV transmission line from Bordeaux (Braud) to West part of French grid;
- Three 400 kV transmission lines from Carcassone (Gaudière) to the Centre and the South-East of France,
- One 400 kV transmission line from Perpignan (Baixas) to Spain,

Moreover, the South-West of France was in an export situation to the rest of ENTSOE grid and the nuclear power plants of Blayais (connected at BRAUD substation near Bordeaux) and Golfech (connected at DONZAC substation near Toulouse) were at full power.

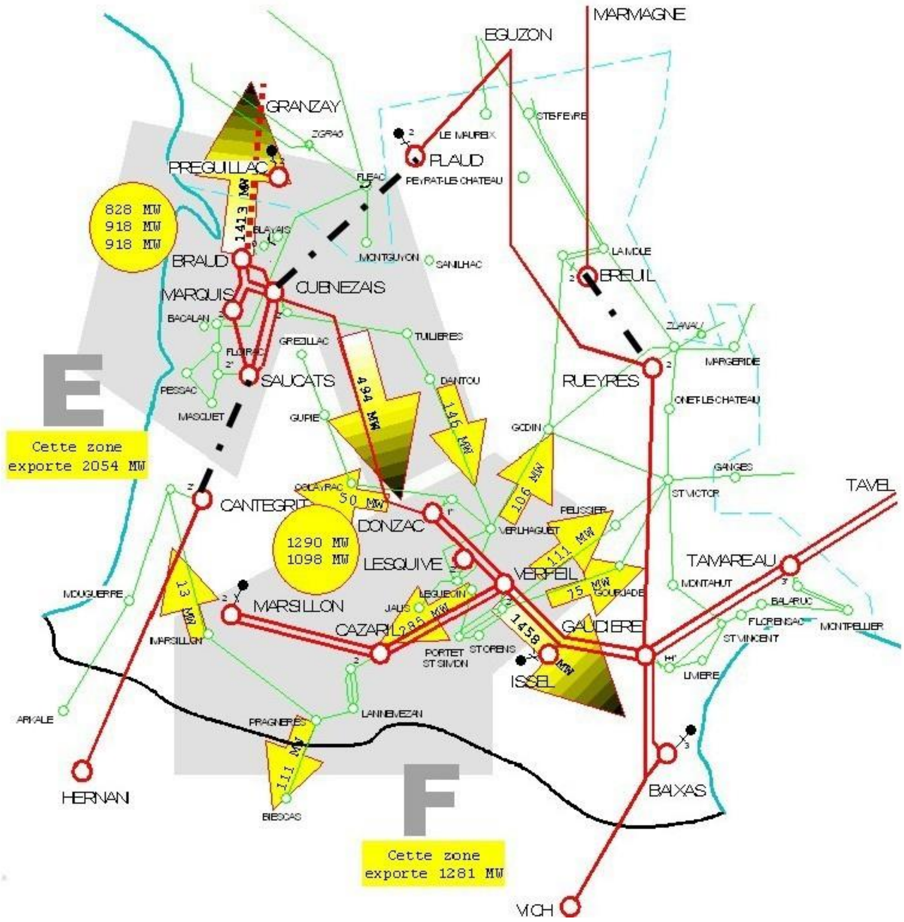



**Figure 8-12 : Initial situation before fault**

*The “E” and “F” grey areas are RTE defense plan synchronous areas at the border of which out-of-step relays are installed to avoid the spread of loss of synchronism. Dotted lines represent transmission lines destroyed by the storm.*

**Sequence of events**

1. Fault on the most loaded and synchronising transmission line of the Blayais nuclear power plant

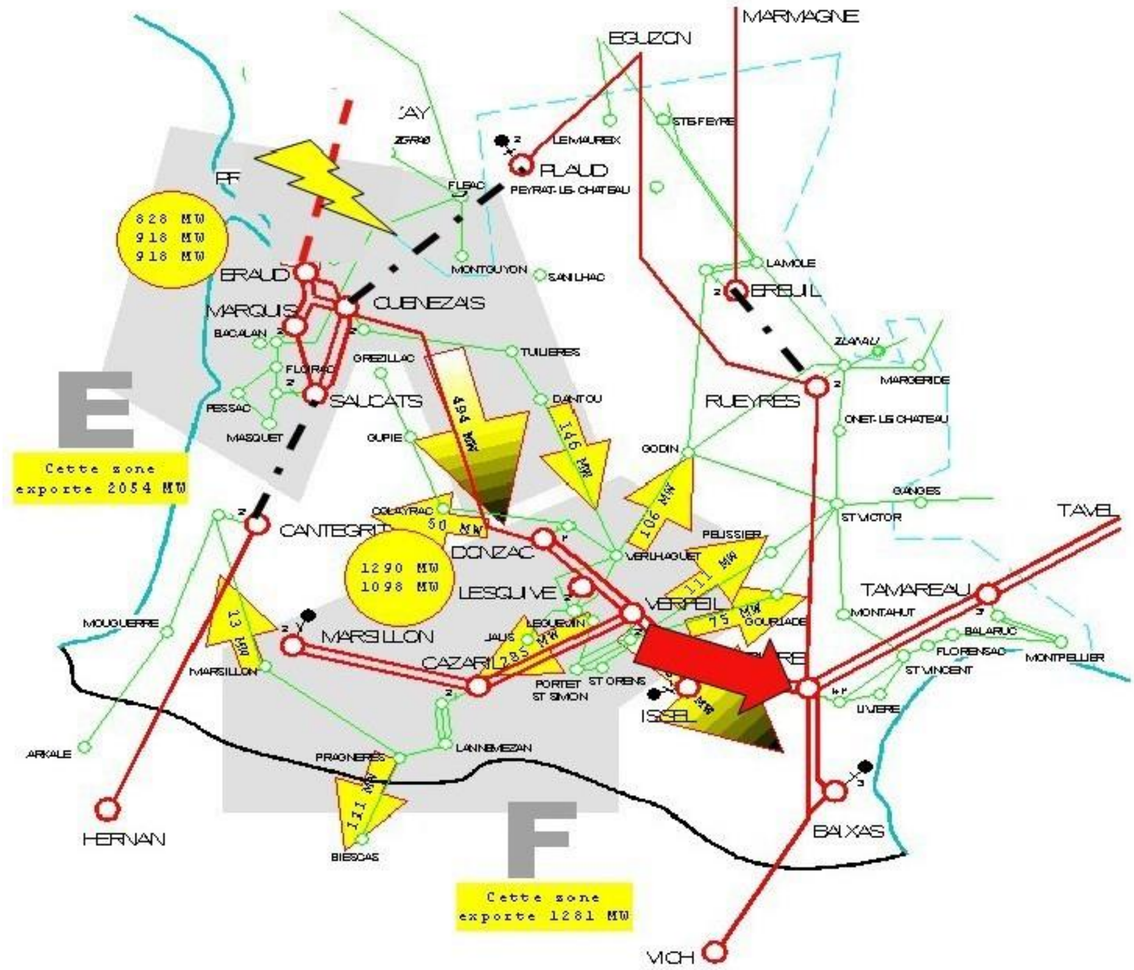



**Figure 8-13: Initial Fault leading to the exceeding of the maximum transfer capacity**

2. Maximum Transfer Capacity reached the remaining transmission lines following the fault and fast voltage collapse started within 2 seconds, due to the fact that the power could not be evacuated from this area.

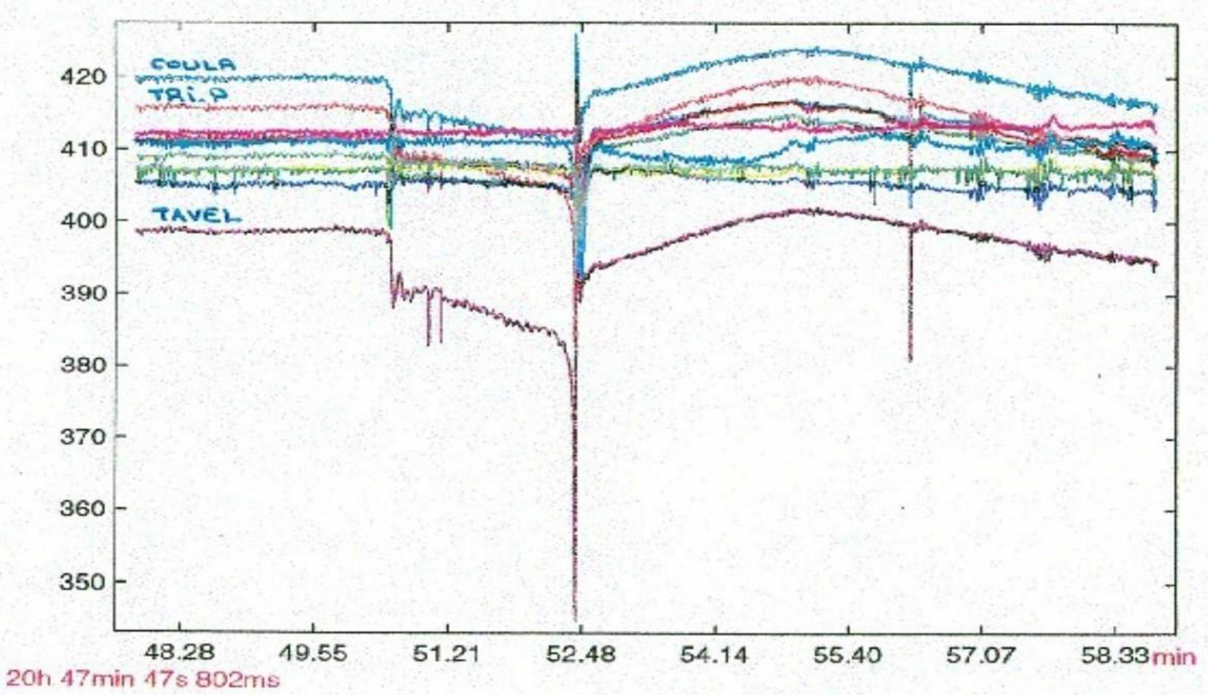



**Figure 8-14 : Voltage at several busses during the transient after fault**

3. Large power oscillations and adverse tripping of 2 nuclear power plants of the area;
4. Correct activation of out-of-step relays (French Defence Plan) separating the system in 3 areas within 2 minutes (South-West of France, Spain and UCTE) and avoiding the spreading of the loss of synchronism;
5. The situation is stabilized.

**Analysis of the incident**

Compared to frequency instability or long-term voltage collapse, the transient instability phenomena can be extremely fast with dramatic consequences, and, the solutions to face such incident are not obvious and depend on the philosophy of the protection system used to ensure a good coordination with the defence plan.

Thanks to the implementation of the French Defence Plan, which is dedicated to disconnect from the rest of the grid the area losing their synchronism, the spread of the loss of synchronism was avoided.

# 9 CONCLUSIONS AND RECOMMENDATIONS

The synchronously interconnected power systems ensure a high level of security of electricity supply. However, the physical coupling of the system implies a risk of adverse effects on adjacent areas or even on the whole system, especially during severe disturbances. The demands for protection relays during such big failures are high. Protection must ensure fast, selective and reliable disconnection of the faulted part of the system, but at the same time it must remain inert to the following power swings that accompany these disturbances in case that they are dumped.

The report presents the critical issues during severe system disturbances, resulting to undervoltages, overloading, power swing, frequency aberration, when certain protection functions are prone to maloperate. It describes protective actions which can be done during different grid instability.

Differential protection relays are the least susceptible to system instability. Although, they must be supplemented with other types of protection (like distance relays) to provide backup protection functions and this latter protections can be affected by system instability. Ideally, it is recommended that protection relays of transmission lines are able to recognize stable and unstable power swings in the network.

Unstable power swing is a severe disturbance for a power system. It can lead to a loss of synchronism between generators or between neighbouring grid system. For the most severe cases, it can lead to the shutdown of major parts of the power system.

Two different strategies may be defined in case of unstable power swing:

- Fast disconnection of unstable generators,
- Separation of the unstable part of the grid

The most important factors/tools for the selection of the most appropriate protection strategy against unstable power swings are:

- Scenarios of contingencies,
- Grid structure (meshed vs. radial),
- Location of the generation and load,
- Type of interconnection with the neighbouring grid system,
- Grid code (What measures are being imposed for the generator in case of unstable operation?)

Some types of protection relays can operate unintentionally during a power swing. Especially during stable power swing it is not desirable to switch off any lines which could worsen the situation in the network. On the other hand during an unstable power swing, which leads to slip of poles of generators which means an enormous strain on them, it is desired to separate the power system into “self-living” islands, to prevent wide area blackouts and equipment damage. The system can be divided either into predetermined islands or at the location of swing centers during an unstable power swing. Ideally, the split should be made in a such way that the plant capacity and connected loads on either side of the split are matched.

To prevent unwanted operation of distance relay the power swing blocking (PSB) function is recommended to be used. The function discriminates between faults and power swing and blocks relay elements which are prone to operate during power swing. Usually we can choose that either all zones are blocked or some zones remain unblocked. Sometimes we can have all elements unblocked. The application when the Zone 1 is not blocked by PSB is a reasonable compromise.

Most power swing detection methods are based on impedance measurement.



ENTSO-E • Avenue de Cortenbergh, 100 • 1000 Brussels • Belgium • Tel +32 2 741 09 50 • Fax + 32 2 741 09 51• info@entsoe.eu • www.entsoe.eu

The setting of the impedance based PSB function is quite difficult. For an accurate setting an extensive stability study on the system should be done. The aim of this study is to determine the fastest power swing which can occur in the protection relay position. The impedance trajectory seen by the distance relay for each of the possible stable cases is examined.

There are some general rules which should be completed for a proper setting of PSB impedance characteristics mentioned in the document.

Uncontrolled tripping of transmission lines during unstable power swing could contribute to cascading outages and further to the shutdown of areas of the power system. Therefore, controlled tripping of power system components is necessary to prevent outages and to minimize the effects of the disturbance.

If necessary, the Out of-Step Trip (OST) function of distance protection is designed to accomplish the detection of unstable power swing and separation at specific locations of the grid. The main purpose of the OST function is to discriminate stable from unstable power swings and initiate system area separation at predetermined network locations in order to maintain grid system integrity and consumer supply.

The recommended method for OST function setting is mentioned in the document as well.

Finally certain cases of big disturbances at the ENTSO-E system are mentioned and the main conclusions of the investigation contacted are summarized, concerning mainly the behaviour of the protection and automation systems. The behaviour of protection systems during these disturbances can prove that, while complying with the above mentioned recommendations, the system can cope with serious fault well.

This technical brochure aims to help to manage critical system conditions and to prevent the ENTSO-E power system or parts of it from the loss of stability and cascading effects leading to major disturbances even to blackouts.



ENTSO-E • Avenue de Cortenbergh, 100 • 1000 Brussels • Belgium • Tel +32 2 741 09 50 • Fax + 32 2 741 09 51• info@entsoe.eu • www.entsoe.eu

# 10 REFERENCES

[1] Relay Performance During Major System Disturbances. Demetrios Tziouvaras, Schweitzer Engineering Laboratories, Inc.

[2] Performance of Relaying during Wide-Area Stressed Conditions. IEEE PSRC, WG C12

[3] Application Guidelines for Power Swing Detection on Transmission Systems. Joe Mooney, P.E. and Normann Fischer, Schweitzer Engineering Laboratories, Inc

[4] Realy Element Performance During Power System Frequency Excursions. Daquing Hou. Schweitzer Engineering Laboratories Inc.

[5] Voltage Collapse Mitigation. Report to IEEE Power System Relaying Committee

[6] Power swing and out-of-step considerations on transmission lines - A report to the System Relaying Committee of the IEEE Power Engineering Society

[7] An Adaptive Scheme to Prevent Undesirable Distance Protection Operation During Voltage Instability. Mattias Jonsson, Student Member, IEEE, and Jaap E. Daalder

[8] Out-of-Step Protection Fundamentals and Advancements. Demetrios A. Tziouvaras, Schweitzer Engineering Laboratories, Inc., Vacaville, CA USA and Daqing Hou, Schweitzer Engineering Laboratories, Inc., Boise, ID USA, 2003

[9] Adapting Protection to Frequency Changes. R. Cimadevilla, R.Quintanilla and S. Ward 32nd Annual Western Protective Relay Conference

[10] Power System Relaying. Stanley H. Horowitz, Arun G. Phadke, ISBN 0-86380-185-4

[11] Transmission Network Protection, Theory and Practice. Y. G. Paithankar, ISBN 0-8247-9911-9

[12] Defense Plan against Extreme Contingencies, Task force C2.02.24, April 2007

[13] Power Swing and Out-of-Step Considerations on Transmission Lines, IEEE PSRC WG D6, July 2005

[14] Tutorial on Power Swing Blocking and Out-of-Step Tripping. Fischer, Benmouyal, Hou, Tziouvaras, Byrne-Finley, Smyth, Schweitzer Engineering Laboratories, Inc., Presented at the 39th Annual Western Protective Relay Conference, Spokane, Washington, October 2012

[15] Backup Transmission Line Protection for Ground Faults and Power Swing Detection Using Synchrophasors. Guzmán, Mynam, Zweigle. Presented at the 34th Annual Western Protective Relay Conference, October 2007

[16] K. Máslo: “Power system disturbances – technical point of view” in Proc. of the 7th int. conf. Electric Power Engineering, Dlouhe Strane Czech Republic