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Blackout Prevention by Power Swing Detection and Out-of-Step Protection

J. Blumschein, Y. Yelgin, M. Kereit

Infrastructure & Cities Sector, Siemens AG, Munich, Germany
Email: joerg.blumschein@siemens.com

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Abstract

Power swing evoked by sudden changes like faults or switching operations will become more and more important for protective relaying, due to the growing load flow in electrical power networks. Unwanted trips of the distance protection function must be avoided to prevent cascading effects and blackouts in the network. Selective out-of-step-tripping is required to stop unstable power swing and to prevent damage to affected generators. Therefore a reliable method for detection of power swing is presented, which requires no settings for operation. Power swing can be detected from 0.1 Hz up to 10 Hz swing frequency, also during open pole condition and during asymmetrical operation. A blocking logic prevents unselective trips by the distance protection. However, faults that occur during a power swing must be detected and cleared with a high degree of selectivity and dependability. For unstable power swing a flexible out of step tripping function will be proposed. The coordination of power swing detection, distance protection and out of step protection provides a reliable system protection.

Keywords

Power Swing Detection; Distance Protection; Out of Step Protection

1. Power-Swing-Detection Algorithm Based on Continous Impedance Calculation

Classical power swing detection methods based on concentric characteristic or blinders need a sophisticated grid study to determine the correct settings. The settings are fixed and will not adapt to any changed system condition. If the grid study does not consider the worst case, then the appearance of a power swing or out of step condition could lead to a maloperation.

Also the assumption that a power swing is always a symmetrical phenomenon and any asymmetrical current (or voltage) can be used for releasing the distance protection function is not fulfilled in a complex application. A proper power swing detection function has to perform also during these conditions.

The following method described below solves these problems. It is based on a continuous impedance calculation [4]. This method has the following features:

- No settings are required, thus no complex calculation is needed.
- Detection of power swing with frequencies from 0.1 Hz up to 10 Hz.
- Detection of power swing that occur during single-pole open condition and during faults.

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- Unblocking of distance protection on all kind of faults occurring during power swing.
- Out-of-step tripping in case of unstable power swing.

The power swing detection function is based on continuous impedance calculations. The impedances are monitored continuously four times per cycle of the power system frequency for each phase separately. During power swing condition these vectors move on an elliptical path. When the impedance vector of at least one phase enters the power swing area, as shown in **Figure 1**, the power swing algorithm starts to analyze each impedance trajectory separately. The power swing area will be calculated automatically so that no settings are needed.

If a power swing is detected, the power swing detection will stay active, even if the impedance vector leaves the power swing area. It will drop off in case of a power system fault of if the system turns back to normal load condition.

The algorithm calculates new R and X values for each phase and compares them with the history (memorized values). The main criteria, which are used to detect a power swing, are monotony, continuity and smoothness.

The applied thresholds are calculated dynamically. This automatic adaptation to the change of the trajectory speed enables the function to detect low frequency power swing as well as high frequency power swing.

Monotony: The directions of the derivates of R and X will be evaluated. To guarantee a directional move at least one of them should not change the direction (**Figure 2**).

Continuity: The distance between two R or X values has to exceed a threshold. This ensures that the impedance vector is not stationary (**Figure 3**).

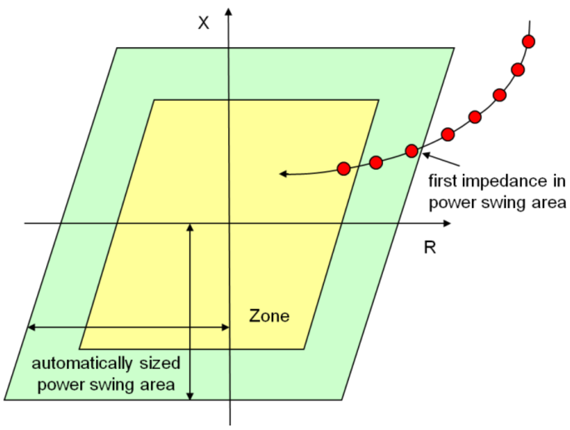

Figure 1. Automatically sized power swing area.

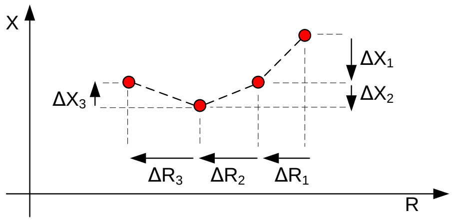

Figure 2. Monotony criterion.

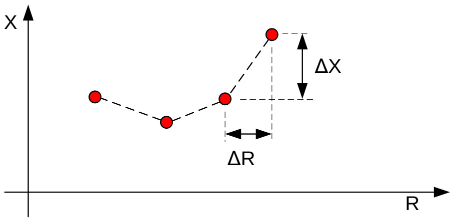

Figure 3. Continuity criterion.

Smoothness: The ratio of two successive differences of R or X has to be below a limit. This ensures that the impedance locus has a uniform movement with no abrupt changes (**Figure 4**).

These criteria are fulfilled only during power swing condition. Neither during load condition nor during faults, the impedance vector moves smoothly along an orderly path. During faults, the impedance vectors jump immediately to a fault impedance. During load condition, the impedance vectors usually do not move.

The logic in **Figure 5** is used to ensure stable and secure operation of the power swing detection without risking unwanted power swing blocking during faults.

In reality the impedance trajectories will not follow a perfect elliptical path. **Figure 6** shows an idealized impedance trajectory for a power swing with three machines oscillating against each other.

It is obvious that such impedance trajectories will be difficult to manage if static thresholds like blinders are used. The above mentioned criteria are able to detect power swing for this kind of impedance trajectory.

Another challenge is to detect stable power swing with low frequency. **Figure 7** describes how the velocity of the impedance vector changes during a stable power swing.

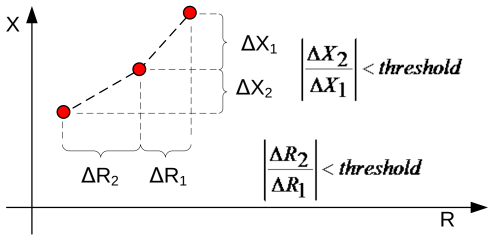

Figure 4. Smoothness criterion.

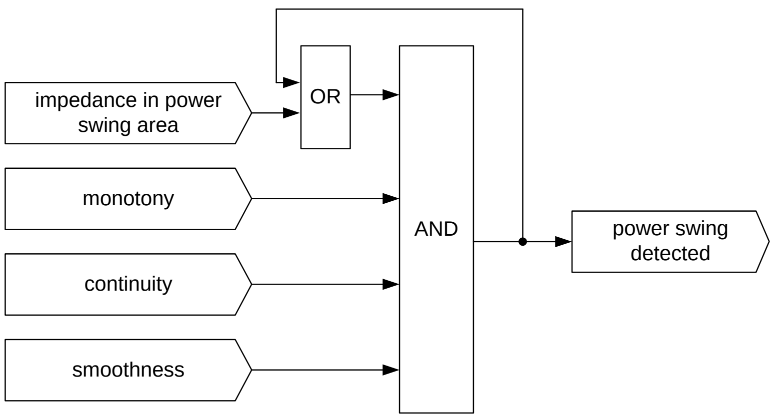

Figure 5. Logic for power swing detection.

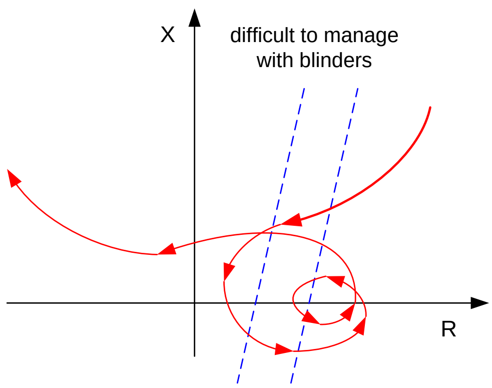

Figure 6. Impedance trajectory for 3-machine power swing.

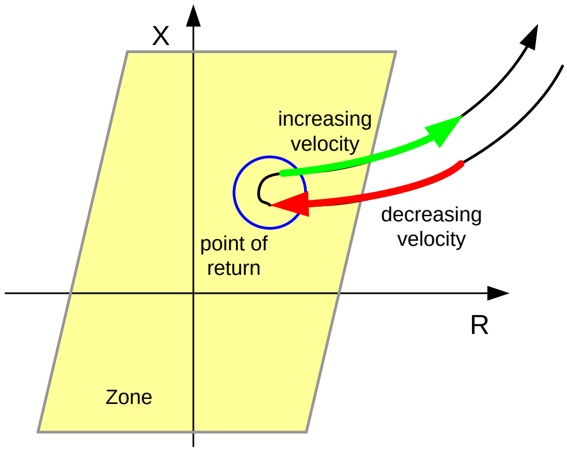

Figure 7. Impedance trajectory during stable power swing.

At the beginning of the power swing, the impedance vectors move quite quickly. The velocity of the impedance vectors decreases, until they reach the point of return. At the point of return the velocity of the impedance vectors is very low, nearly zero. After passing the point of return, the impedance vectors move with increasing velocity.

At the point of return it looks like a three-phase fault, because all impedance vectors are in the zone with nearly no change. To distinguish between three-phase faults and stable power swing with low frequencies a time delay is used. The delay is calculated dynamically and depends on the velocity of the impedance vectors.

2. Selectivity of Distance Protection during Power Swing

To maintain the stability of the power system and to prevent cascading effects a selective tripping of a fault is very important, more than ever under power swing conditions.

The selectivity of a distance protection device is dependent on the following characteristics:

- Determination of the faulted loops (loop selection)
- Determination of the direction to the fault
- Measurement of the distance to the fault

Loop selection and directional measurement must work in different ways under steady state or power swing condition to get the best results.

Normally a distance protection device with a polygonal tripping characteristic detects the faulted loops by checking which of the six loop impedances $\underline{Z}_{AG}$, $\underline{Z}_{BG}$, $\underline{Z}_{CG}$, $\underline{Z}_{AB}$, $\underline{Z}_{BC}$, and $\underline{Z}_{CA}$ are within one of the tripping zones. An additional logic guarantees the correct loop selection even in difficult situations, when not only faulted loop impedances are within the tripping zones (see also [1]-[4]).

Under power swing condition these measures are not sufficient to prevent unselective trips, because the impedance vectors of the unfaulted loops will also move into the tripping zones and even the phase angles between the impedances will give no information about the type of fault. A phase selective and reliable power swing detection is necessary to find out the correct type of fault.

3. Determination of the Faulted Loops under Power Swing Condition

A correct determination of the faulted loops is obligatory for a distance protection relay. A selection of a non-faulted loop for the distance measurement could result either in an unwanted trip in case of an external fault or the absence of a necessary trip. Under steady state conditions the loop selection is no problem for modern distance protection relays. The location of the impedance vectors in the impedance plane and the voltage and current phasors give enough information about the type of fault. Under power swing conditions the loop selection is much more difficult: The impedance vectors of the unfaulted loops may be located within the tripping zone and the voltage and current phasors don't indicate the faulted loops. A reliable and phase selective power swing detection is necessary to get the faulted loops under power swing conditions. **Figure 8** shows a network with an internal fault in B-G. **Figure 9** shows the related fault recording from the distance protection relay D1.

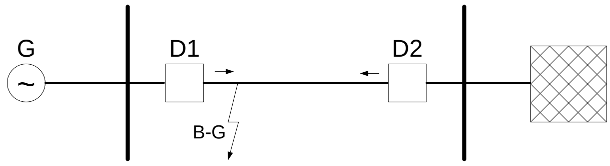

Figure 8. Internal fault B-G during a power swing.

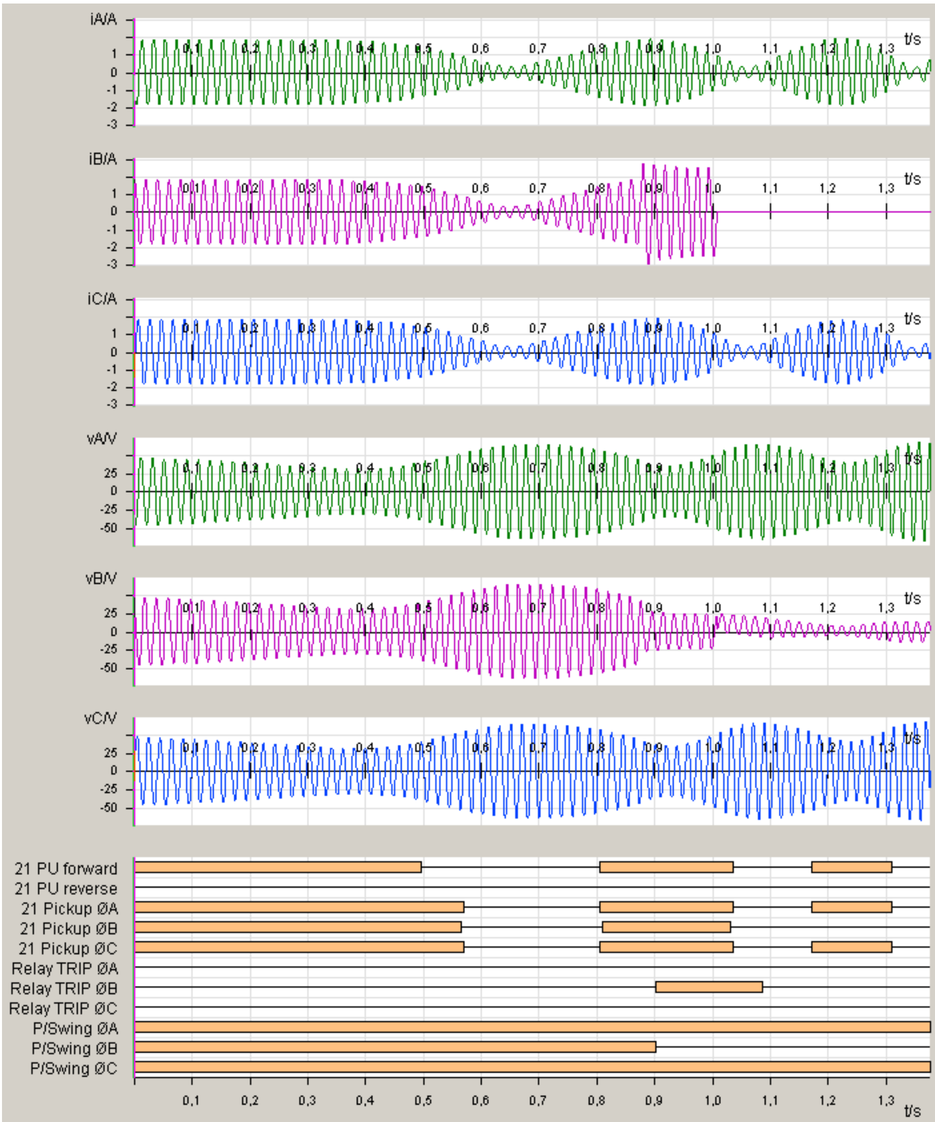

Figure 9. Internal fault B-G with single pole trip during a power swing.

Before the fault begins a power swing is detected in all phases. After the fault inception, only the power swing detection for the faulted phase B is dropped off. As can be seen in the binary output signals from the relay, a pickup-signal is also generated for the non faulted loops. The fault occurs nearly at this time, when the phase currents reached their maximum value due to the power swing. The phase currents of the unfaulted phases have nearly the same magnitude than the current of the faulted phase. Standard phase selection methods will not work under these conditions. The power swing detection for the phases A and C will block a trip-signal signal for all loops except the faulted loop B-G. With this additional information a single pole trip including an auto reclosing cycle is possible instead of a definite three pole trip command.

4. Determination of the Direction to the Fault

During a power swing the frequency of the voltage is permanently changing. Therefore the phase angle of the stored voltage phasors cannot be matched to the actual phasing. The un-faulted voltage (cross polarization) is also not valid for the direction measurement during power swing.

The actual faulted loop voltage provides a correct direction decision, but during close in forward faults and reverse busbar faults this voltage is zero or approximately zero. For this reason the voltage of the actual faulted loop cannot be used in all cases. In this case, the negative sequence direction measurement is applied.

Contrary to the standard measurement methods the negative sequence impedance is not affected by the power swing so that it indicates the correct direction. **Figure 10** shows a network with an external fault in BC-G. **Figure 11** shows the related fault recording from the distance protection relay D1.

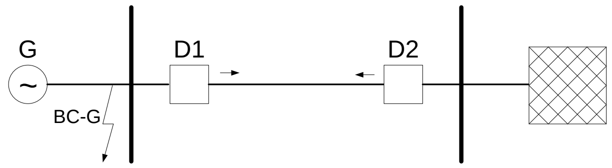

Figure 10. External fault in BC-G during a power swing.

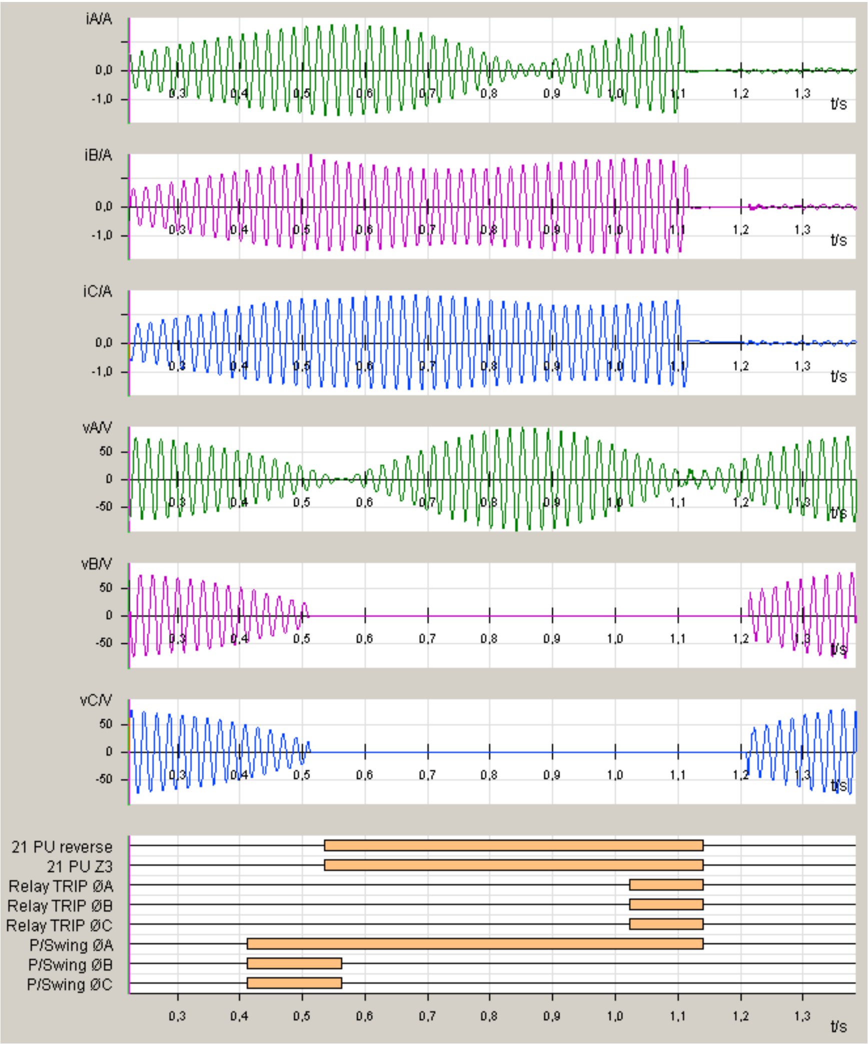

Figure 11. Example of a reverse busbar fault during power swing.

The impedance vectors of the phases B and C stop moving after fault inception. This leads to a drop off of the power swing blocking in phases B and C because of the continuity criterion. Due to the fact that the fault is in reverse direction, the protection relay D1 doesn't trip immediately. The relay recognizes a fault in reserve direction and expects a trip signal from another relay that is primarily responsible for that area. If the fault is not cleared, the backup protection of the relay D1 will trip after the grading time for reverse faults expired, which is also displayed in **Figure 11**.

With the negative sequence direction determination it is not possible to determine the direction of each measured loop separately. For this reason, the negative sequence direction check should only be used under power swing condition.

The power swing detection is not only needed to generate blocking signals, it can be also used to adapt protection functions to the actual state of the network. One example for such an adaptive protection function is the directional check for the distance protection.

5. Backup-Protection for 3-Phase Faults during Power Swing

Another challenge is to ensure backup distance protection for 3-phase-faults during power swing. **Figure 12** describes a simplified network scheme from [3], where a 3-phase-fault on an external radial feeder occurred. A power swing is evoked as a result of the fact that the protection relay A did not trip on time.

Figure 13 illustrates the impedance trajectory of a phase to phase loop after fault inception by the distance protection relay D4. The impedance trajectories for the other distance protection relays are similar.

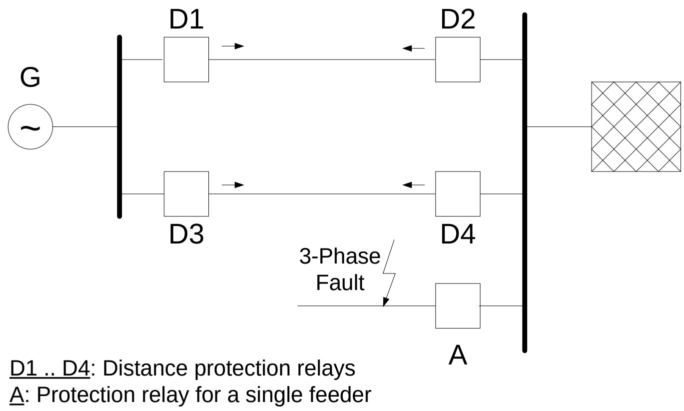

Figure 12. Power swing due to a 3-phase-fault. Simplified network scheme from [3].

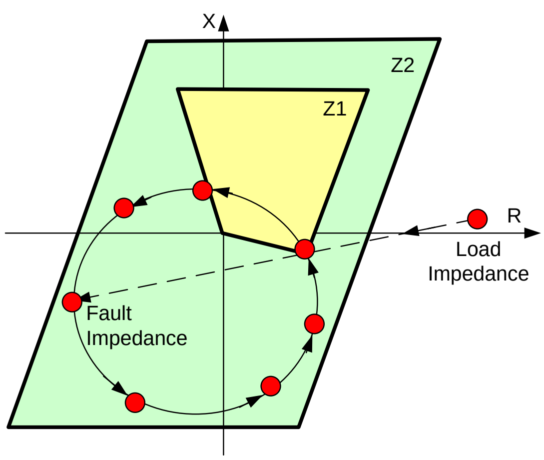

Figure 13. Impedance trajectory of a phase-phase-loop after fault inception.

After fault inception the impedance vector jumps from the load impedance to the fault impedance. The distance protection relay D4 measures a 3-phase-fault in Zone Z2 and does not trip immediately. Due to the fact that the protection relay A did not trip on time, a power swing is evoked. As a result of the continuing power swing, the impedance vector moves on an elliptical trajectory and crosses the Zone Z1. To avoid an unselective trip in Zone Z1, a special logic is applied. This logic releases only zones for which a pickup was recognized before the power swing is detected.

6. Out of Step Tripping

A sudden change of load in the power system caused by a fault, by disconnection of loaded lines or automatic reclosing forces the generators to adjust to this new load condition. The adjustment will not be instantaneous due to the mass of the generators, but rather in the form of oscillations, which is shown in **Figure 14**. Normally it will be a damped oscillation. The generators will be able to return to a normal steady state condition. In some cases the generators loose synchronism and run out of step. This situation can lead to a blackout of the whole grid.

During an out of step condition a trip of certain transmission lines can separate the unstable grid into sub grids with the goal to reach stability in these sub grids. The out of step protection has to distinguish between a stable power swing, where the system recovers and an unstable out of step condition. A trip is only required for the unstable out of step condition.

According to the network structure the out of step trip can be issued at different severity of the out of step condition.

In a strong network it can be advantageous to trip as fast as possible if the relay detects an out of step condition. In a weak network however a fast trip in case of out of step condition can lead to a blackout. Here it can be advantageous to keep the line in service as long as possible.

For that reason the out of step protection generates basic signals, which can be logically combined to generate the trip signal.

Figure 15 illustrates the following basic signals:

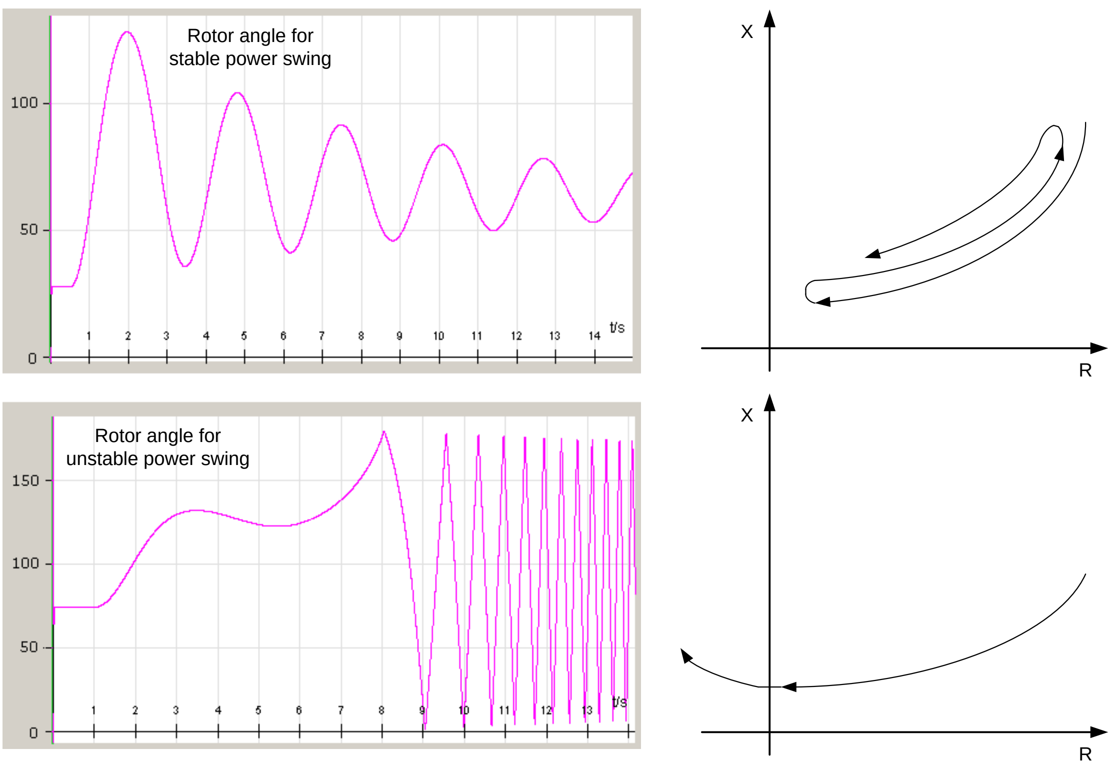

Figure 14. Rotor angle and impedance trajectories for stable and unstable power swing.

1) impedance in out of step area detected
2) power swing detected
3) impedance crosses the line angle from the right side
4) impedance leaves power swing area at opposite side after complete crossing
5) impedance crosses the line angle from the left side

For standard applications the out of step protection will trip if the impedance leaves the power swing area at opposite side after complete crossing (4). A fast trip for out of step protection is possible if the impedance crosses the line angle at (3) or (5).

With a flexible combination of these basic signals it is possible to generate an individual out of step trip. **Figure 16** shows special out of step logic which trips only if the power swing impedance crosses the line angle inside a predefined out of step area 3 times from the right side.

For the protection of the transmission systems of the future we recommend a strong coordination of power swing detection, distance protection and out of step protection.

This method, successfully used in Kazakhstan and Romania has the following advantages:
1) distance protection for selective clearing of faults in the protected zone.
2) block distance protection in case of power swing.
3) flexible out of step protection to split the grid selectively according grid study.

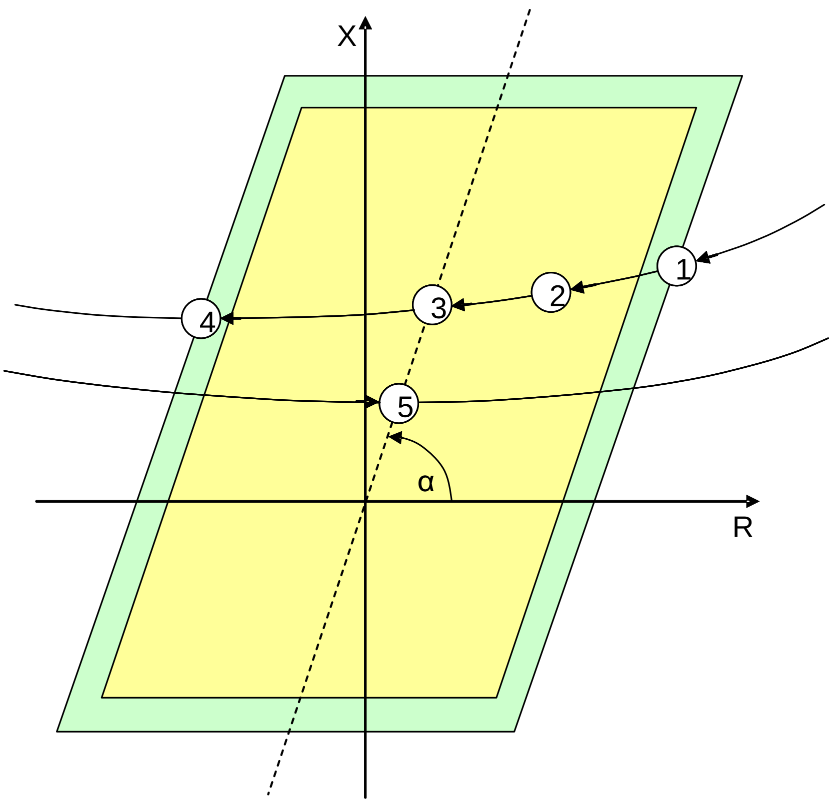

Figure 15. Basic signals for out of step detection.

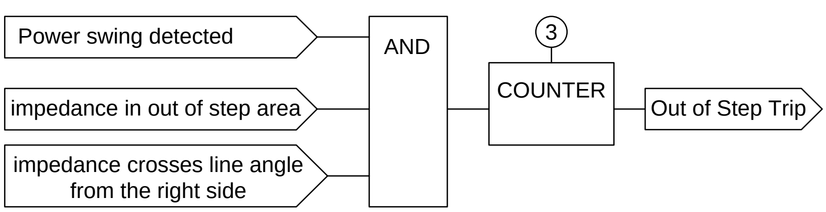

Figure 16. Logic for special out of step tripping.

4) optimal coordination of distance protection and out of step protection by using the same algorithm for power swing detection.

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[3] Jurisch, A. and Schwenke, M. (2000) Method of Deriving a Signal Indicating an Oscillation in an Electric Power Supply System. US-Patent 6104182.

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