SECURE AND DEPENDABLE PROTECTION RELAY BEHAVIOUR IN EXTREMELY HIGH LOADED TRANSMISSION SYSTEMS

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Abstract

Current developments in the electricity grids demand for an optimal utilization of existing grids. To make this possible, more measurement, communication, computing, active control equipment and automation needs to be implemented into the grids. As a consequence, this entails extremely high loaded transmission corridors. While such operation is on the one hand a big challenge from a grid control perspective, the protection systems too need to behave securely and dependably under such circumstances. This work discusses the various ways in which conventional protection systems are influenced by extreme loading using the example of distance protection. After that, numerous existing solution approaches to these challenges are presented. The described methods can be categorized in those that directly improve the behaviour of the relays and those that concern the protection congestion consideration in the control centres. They range from small adjustments like changed safety factors to adaptive techniques to avoid constant worst-case assumptions to modified measurement algorithms and completely new designed fault detection and localization approaches. It is highly probable that the field of secure and dependable protection systems in extremely high loaded grids will be of increasing importance in the future.

1 Introduction

The need for transmission capacity is growing due to increased renewable generation far from load centres and increased energy trading. [1] At the same time, building new corridors is often very difficult in densely populated areas because of regulatory challenges and resident protests. That is why existing grids must be fully utilized without compromising operation safety. There are three major aspects to this: 1. Improved load distribution, 2. Better utilization of actual thermal reserves through monitoring, 3. Curative grid operation.

Aspect 1 means the balanced utilization of parallel transmission facilities through load flow control. Aspect 2 means considering the current weather conditions when assessing loadability limits. Aspect 3 means that contingencies are not handled preventively (i.e. not using existing transmission capacities as reserve), but curatively (i.e. reduced reserves, instead having fast acting interventions at hand). In case of a contingency, the permanently permissible loading limits are deliberately exceeded by making use of the thermal reserve (heating duration) of transmission assets. For that, extended measurements, communication, computing power and active control equipment (HVDC, FACTS, PST, large storage systems), as well as new system control processes (measure assessment and selection, automation) are needed. [2]

With regard to the maximum load in the transmission grid (to be handled by protection systems), aspect 1 has no impact, whereas aspect 2 can lead to significantly higher loading in certain situations. Load increase of aspect 3 is dependent on the time scale of available curative actions and the pre-loading. In theory, it can be extremely high. The major questions of this work are: 1. In which way are protection systems impacted by extreme load flows? 2. Which solution approaches exist for these challenges? The investigation is done for the distance protection principle, as it is the most important non-unit primary protection.

These questions are highly relevant, as can be seen from several blackouts in the last decades that usually started from highly stressed load conditions and often involved protection system malfunctioning [3]. The outline of this work is as follows: chapter 2 discusses different protection system problems resulting from high load. Chapter 3 covers existing solution approaches. At the end, a brief summary is given.

2. Influence of extreme loading on distance protection systems

Distance protection is a protection for shunt faults. It should recognize and resolve short-circuits while it should not pick up in any other condition, especially high loading situations. Fig 1 shows a mind map regarding different aspects of impacts of high loading on distance protection.

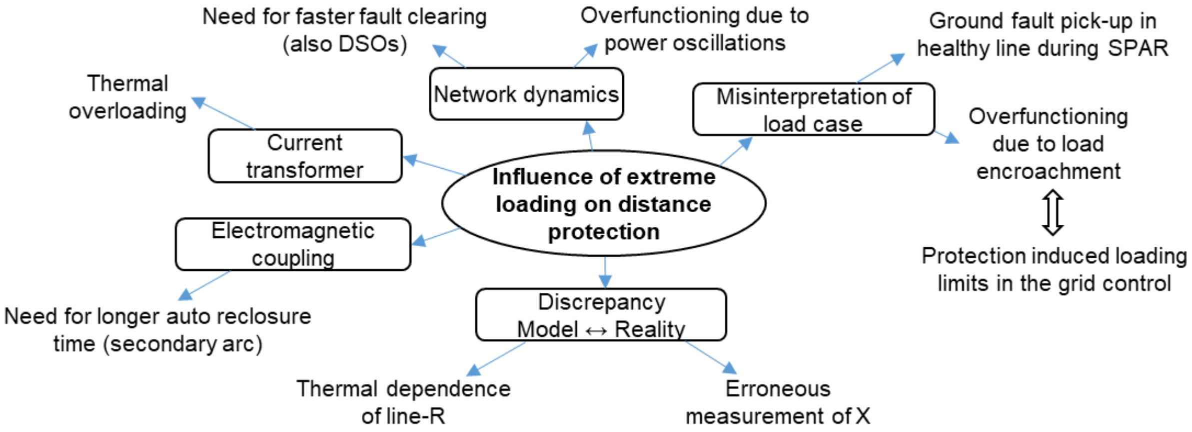

Figure 1 Influences of extreme loading on distance protection

In general, the causes of protection malfunctioning can be grouped as follows: measurement, protection algorithm, electromagnetic coupling. All but the two leftmost aspects in Fig 1 are dedicated to problems regarding the distance protection algorithm, which represents the largest group. Furthermore, it is to be noted that different aspects affect different protection system requirements: speed, security (no unwanted operation), sensitivity, selectivity and failure safety.

2.1 Thermal overloading of current transformers

For transmission circuits to be operated with higher load currents, the current transformers (CTs) used have to be reviewed regarding their thermal capacity. Technical specifications and properties of CTs have to comply with the European norms EN 61869-1 and EN 61869-2. From a thermal standpoint, all parts of a CT have permissible excess temperatures, which are not exceeded in normal operation as long as primary current $I_p \leq I_{cth}$ (thermally allowable continuous current, rating plate value). If not otherwise stated, I_{cth} is identical to the rated current I_{pr}. However, an extended value of I_{cth} can be defined by the manufacturer, such as 150% or 200% of I_{pr}. As the accuracy levels in the norm refer to certain temperature ranges as well, a critical review and an adequate replacement if necessary of CTs is required with regard to thermal capacity and measurement accuracy. [4]

2.2 Prolonged auto reclosure time due to secondary arc

In transmission grids, auto reclosures are the usual measure for clearing temporary faults (single-phase auto reclosure, SPAR in the case of phase-to-earth faults). According to field tests, the burning time of the secondary arc and thus the necessary dead time is proportional to the secondary arc current amplitude [5]. This current is determined mainly by the electromagnetic coupling of all live conductors in the vicinity of the opened conductor(s). While the capacitive coupling dependent from the operating voltage is dominant in short lines, the inductive part caused by the load current in the sound conductors can become significant when the coupling section becomes longer. For SPAR situations, the most severe coupling often comes from the remaining two conductors of the same system, but in special situations, also the coupling from complete neighbouring systems play a role [6]. In general, extreme loadings can make an extension of the dead time of auto reclosures necessary.

2.3 Need for faster fault clearing, also in distribution

During a short circuit, synchronous generators undergo an acceleration due to load imbalance on the shaft. To maintain synchrony with other generators in the grid, there is a speed requirement with regard to the maximum duration of fault clearing. The respective value is usually 150 ms in the transmission grid. Extreme load flows lead to increased angular displacements of generators in different parts of the grid. This intensifies the problem of transient stability further, potentially leading to even higher speed requirements for protection systems. In addition, with increased loadings this problem becomes also more relevant in distribution grids, where it has only seldom been considered until now. [7]

2.4 Thermal dependence of line-R

The resistance per unit length of transmission lines is temperature dependent. However, the effect is too small to expect any significant influence on distance protection.

2.5 Erroneous measurement of X

In reality, short-circuits represent a certain impedance, usually with ohmic characteristic. This impedance is not considered in the fault loop used to derive the measurement algorithm of the classical distance protection. Nonetheless, the fault resistance results in an additive part of the measured impedance. In the case of two-sided fault feeding (always in meshed transmission grids), this part is also influenced by the fault current from the opposite source, which is not being measured by the relay. In the case of a non-zero load flow and for inhomogeneous networks this results in an additional measured reactance added to the additional resistance. The corresponding reactance measurement error can lead to an over- or underreach of protection zones and therefore to a loss of selectivity. As the amplitude of the additional impedance is strongly dependent of the load flow, the problem worsens in the case of extreme loadings. [8]

2.6 Overfunctioning due to load encroachment
Many consider load encroachment the biggest problem with regard to protection in extremely loaded grids. Every condition, and therefore also the load condition is transferred to an impedance in the impedance plane as commanded by the impedance algorithm. As extreme loadings are characterized by high currents and often decreased operating voltages, they lead to a low measured impedance. Depending on the resistance reach of the relay, an extreme loading condition can therefore lie inside the outer protection zone (e.g. zone 3) and trigger a trip. False tripping of extremely loaded lines is particularly critical for the grid stability, as the loss of transmission capacity worsens a spatial load imbalance and can bring the system across its stability limits. The load shifting to parallel lines can then lead to false trippings there; cascaded tripping is the consequence. This leads to grid partitioning and widespread blackout.

Load encroachment is worsened by the fact that the measured resistance and therefore the resistance reach setting is very afflicted with uncertainty. Several factors contribute to this. On the one hand, the value of the physical fault impedance in the form of arc and contact resistance is very hard to estimate. Furthermore, the intermediate infeed from the opposite source explained in 2.5 leads to a strongly increased measured resistance depending on the ratio of currents from the opposite side to current from the local side. Thirdly, in line-to-earth loops, earth impedance adjustment factors that are often incorrectly set influence the resistance measurement. [8]

2.7 Protection induced loading limits in the grid control
In order not to endanger network security because of load encroachment (see 5.6), the contingency analysis processes in the grid control centre ensure that not only thermal current limits but also the protection congestion current is not exceeded. Below this value, there should be no risk of distance protection pick up. However, in its computation, several safety factors are applied, so that the distance protection function severely limits the maximum loadings in the grid [9].

2.8 Overfunctioning due to power oscillations
Large-scale power swings, which occur typically in case of outage of large generating stations, lead to pendular trajectories of the measured impedance of distance relays. Just like static load encroachment, this can lead to unwanted operation of distance relays. As this problem adds up to static load encroachment, it is also worsened by extreme grid loadings.

2.9 Ground fault pick-up in healthy line during SPAR
When a line-to-ground fault is cleared using SPAR in a double circuit line, the loss of one conductor leads to increased load flow in the corresponding conductor of the parallel system. This current transfer diminishes the measured impedance of affected measurement loops for the distance relay of the parallel system. Especially in earth-fault loops, the resulting current imbalance leads to an increased zero sequence current, which – together with the earth impedance adjustment factor – can provoke an earth fault pick up. Until now, this phenomenon probably hardly becomes visible because of sufficient safety margins. However, considering the extreme loadings in future grids, it should be examined in detail.

3 Solution approaches to protection challenges from extreme loading

The following sections describe different approaches that could be used to meet the challenges of extremely high loadings with regard to distance protection systems as discussed in chapter 2.

3.1 Dynamic protection security assessment and power swing blocking
There is a strong trend in the power industry to leverage sophisticated computer analyses in network planning and operation. On the one hand, increasingly Protection Security Analysis (PSA) Tools are used to assess protection settings using (quasi-)stationary short circuit calculations. On the other hand dynamic security analysis (DSA) tools are used to monitor the dynamic stability of the grid. The next step is an integration of these approaches in a “dynamic protection security analysis” (DPSA) tool. With it, weak spots in the protection system with regard to dynamic phenomena like fast fault clearing times (see 2.3) and unwanted operation due to power oscillations (see 2.8) could be detected. Where necessary, specific Solutions like particular protection functions, activation of power swing blocking or maybe even implementation of Special Protection Schemes (SPS) can be found.

In the future, an online-assessment of protection systems could also be incorporated into the contingency analysis, replacing the protection congestion current used nowadays (see 3.5.5).

3.2 Accelerated zone 2 tripping
Increasing requirements with regard to the clearing time conflict with the time delayed tripping of distance relays in zone 2 for faults near the line end (and if communication is not present). However, there is a range of proposed methods for non-communication accelerated sequential tripping. This means that the remote circuit breaker opening (RCBO) is detected from local measurements in order to then initiate immediate opening of the local circuit breaker. What differs is the detection method: some evaluate the fundamental frequency currents of the sound phases, others assess the symmetrical components of currents and voltages, others use high frequency signal properties, changes in impedances or power flows. [10]

3.3 Optimization of auto reclosure dead time
As explained in section 2.2, extremely high load flows can lead to prolonged burning of secondary arcs, which makes longer dead times for auto reclosures (especially SPAR) necessary. A simple extension of the constant dead time setting based on worst-case considerations is not sensible from a stability standpoint. There exist however several approaches to implement a real time adaption of the dead time, so that it always only is as long as needed. Most of these techniques analyse specific signal properties of the recovery voltage of the affected conductor, aiming at recognizing the extinction of the secondary arc: DC component, fundamental component,

harmonics and transients are being used [11-14]. A different approach is employed in [15], where the necessary dead time is derived from the RMS value of the secondary arc current, which is being estimated from the fault location and the measured load flow in the sound conductors.

3.4 Blocking of earth fault detection during SPAR on double line

A simple yet effective possibility to avoid incorrect earth-fault detection during SPAR on a parallel circuit (see 2.9) could be a temporary blocking of the function during the dead time.

3.5 Load encroachment and limitation of line loading due to protection congestion

With respect to this most important problem of protection in extremely highly loaded grids, there are a number of very different approaches. Some tackle the actual load encroachment (unwanted operation) of the relay; others alleviate the corresponding problem of limitation of loading on the level of the grid control.

3.5.1 Reduce resistive reach setting: The most straightforward approach to allow increased load flows without higher risk of unwanted operation is to move the trade-off between security and sensitivity more towards security. Specifically, this means reducing the resistive reach setting. Losses in sensitivity can possibly be compensated for by using other protection functions (e.g. sensitive earth-fault protection).

3.5.2 Optimization of load blinder shape: The effective resistive reach of distance protection relays is often determined by the parameterization of a load blinder. This is a region of assumed load conditions in the impedance plane, inside of which tripping is blocked to prevent unwanted operation. Its conventional shape is a circle segment bounded towards the origin at a certain resistance value. Its position is derived in a simplified manner from assumed limiting parameters of the load: maximum current, minimum voltage and maximum leading and lagging phase angle. Hereby, physical interdependencies of these quantities as well as grid effects are not considered. That is why not all impedances covered by the conventional blinder represent meaningful load conditions, while at other points potential for higher loadings might be wasted.

Taking into account operational limitations for the reactive power due to maximum voltage drop, the conventional load blinder can be trimmed at certain locations. This shape modification allows to increase the maximum load without reduced security [16]. Furthermore, it can be shown that a correct mapping of maximum load current and minimum operating voltage in the impedance plane leads to circular location curves, whose position is dependent on the Thevenin source impedance. A realistic blinder shape in this way can also be used for increased security or loadability [17].

3.5.3 Adaptive resistive reach according to grid situation: Depending on the protection philosophy of system operators, the resistive reach of distance relays can be set in consideration of backup overcurrent protection systems. In such cases, the local short circuit power has a decisive influence. As the minimum (worst-case) short circuit power has to be taken into account when a static setting is used, this approach can significantly limit the maximum loading. In such cases, an adaptive adjustment can therefore lead to big loadability gains. Periodically and/or event-triggered, the optimal resistive reach for every relay is calculated in the control centre and communicated to the protection devices. However, a reduction in resistive reach setting must never fall below the necessary minimum resistive reach for all relevant faults. [18]

3.5.4 Modification of protection congestion current determination: In section 2.7 it was explained, that several safety factors are employed when deriving the protection congestion current, leading to decreased maximum loadings. Some of these quite conservative safety factors can be reduced based on technical justifications. As an example, the safety factor for dependability can be reduced from 25% to 15% considering the digitization of the protection systems [9]. The factor for reduced operating voltage can possibly be oriented towards stricter operational requirements and the factor for transient events can be eliminated if power swing blocking schemes are employed [16].

3.5.5 Considering the protection congestion in terms of impedance rather than as current: The protection congestion concept can be developed more consequently than as in section 3.5.4. In converting the zone characteristic of the distance protection to a congestion current, a lot of information is lost due to assumptions and simplifications. If the impedance calculation as well as the comparison with tripping zones would be replicated in the control centre, a much more accurate representation of the protection congestion could be achieved. This in turn could lay open more possibilities for higher loadings. The challenge is to reach a reliable accordance of the real protection system behaviour and the replication in the control centre. In light of the fact that relay manufacturers start to provide accurate software versions (digital twins) of their protection equipment, such attempts seem viable in the future. [9][19]

3.5.6 Reactance Method for R: In distance relays, the resistance measurement serves the purpose to discriminate between load and fault conditions. It is however not a matter of measuring some exact value of a physical resistance. The idea of the reactance method for R is therefore a distorted resistance measurement, leading to extremely high values in any load situation, while fault conditions still result in rather small values. This way, the discrimination becomes easier and the setting of the resistive reach becomes less error prone. The methods used come from fault locator algorithms (see 3.6.3) and entail in particular the clever use of negative and/or zero sequence currents. Some manufacturers start to offer the method in their devices. [20] [21]

3.5.7 Alternative fault detection methods: While distance protection uses (solely) the R-measurement to provide fault detection, a fundamental forward-thinking approach is to combine various established and new criterions in order to obtain a secure and dependable protection system. Modern digital protection devices are capable enough to perform multiple signal processing methods in parallel to extract all relevant features from the measurement inputs. Aside from classical fundamental frequency properties (Fourier transform), other frequency techniques like S-transform and wavelet transform, but also time-domain methods using individual samples, delta quantities (prefault – postfault) and change rates can be used. Furthermore, different deduced quantities like symmetrical components, space phasors, impedances, power, difference and scaled quantities can be used. Also with regard to decision-making methods, new ways can be taken. Apart from classical binary threshold logics, other classification algorithms like fuzzy inference systems or methods from machine learning like decision trees, nearest neighbour classifier, support vector machine, and artificial neural networks are possible. In all of these fields, investigations have already been made with noteworthy success. [22-24]

3.6 Measures against loss of selectivity by erroneous reactance measurement

The risk of loss of selectivity by erroneous X-measurement (section 2.5) is well known, but is had been of little practical relevance in the heavily meshed European grid for example. However, due to future extreme loadings, appropriate solution approaches become much more important.

3.6.1 Static zone inclination: This is a classic measure for special applications, where load flow magnitude and –direction are known and constant (e.g. remote large power plants). The reactance measurement error can be compensated by a static parametrized inclination of the upper zone boundary. [8]

3.6.2 Dynamic zone inclination: A distortion of the zone characteristic in order to compensate the load flow induced reactance measurement error can also be done adaptively based on pre-fault currents and voltages. This way, it is also suitable for fluctuating load currents. [25]

3.6.3 Reactance method for X: In the context of fault locators, algorithms for exact reactance measurement in the case of high load flow and inhomogeneous networks exist under the name of reactance methods already for a long time. The approach first multiplies the voltage equation with the complex conjugate of an approximation of the fault current to make the error producing term real. After that, it takes the imaginary part, eliminating the error term. For the fault current approximation, either stored pre-fault values or symmetrical component values are used. Additionally, aside from the influence of the load flow, also the influence of an inhomogeneous network can be compensated to a certain degree. This requires the fault feeding Thevenin sources to be known however [20]. Like the reactance method for R, the method has meanwhile been introduced into some manufacturer’s devices [21].

3.6.4 Alternative fault localization methods: As with the fault detection, it holds that the fault localization method of conventional distance protection may be the most common, but still only one possible method. Another already established method uses travelling wave signals, but also completely new approaches like comparison of negative sequence currents and again machine learning methods are active research areas. [26][27] As to how well individual of these methods are influenced by extreme load flows has to be assessed separately.

4 Conclusion

Current developments in electricity grids demand optimal utilization of existing transmission capacities. This poses on the one hand new requirements to the grid control in handling contingencies, on the other hand the protection systems need to continue to work secure and dependable. In the first part of this work, different problem areas of extremely high network loadings have been discussed from a protection perspective, specifically with regard to distance protection. In the second part, many different solution approaches were presented, that can contribute to a secure protection in extreme loading conditions. The described methods can be categorized in those that directly improve the behaviour of the relays and those that concern the protection congestion consideration in the control centres. They range from small adjustments like changed safety factors to adaptive techniques to avoid constant worst-case assumptions to modified measurement algorithms and completely new designed fault detection and localization approaches. It is highly probable that the field of secure and dependable protection systems in extremely high loaded grids will be of increasing importance in the future.

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