European Network of
Transmission System Operators
for Electricity

ENTSO-E CE Subgroup System Protection and Dynamics[1]
ENTSO-E StO Protection Equipment Subgroup[2]

Best Protection Practices for HV and EHV AC-Transmission Systems of ENTSO-E Electrical Grids

Version 2

June 2018

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[1] For initial Version of 12.04.2012
[2] For Version 2

Contents

1 DOCUMENT HISTORY AND PERSPECTIVE

The present version is an update of the initial document, version 1.

Version 1 was published on the 12th of April 2012 and was previously produced under the care and the responsibility of the System Protection and Dynamics Subgroup of the regional area Continental Europe of the System Operations Committee.
According to the current ENTSO-E organizational set-up, the responsibility for protection equipment in context with the devices and the field components is assigned to the ENTSO-E / SOC / StO / Protection Equipment (PE) Subgroup. The PE Subgroup was requested to update the initial version of the *Best Protection Practices for HV and EHV AC-Transmission Systems of ENTSO-E Electrical Grids* study.

Significant changes/edits were performed to the document in terms of structure and content, as well as terminologies and English writing. Certain parts of the document were withdrawn in order to strengthen the focus of the document (e.g. fault location, device's acceptance, disturbance recording, analysis and fault statistics, and maintenance issues were withdrawn).

It is planned that (a) future/s edition/s will be produced to further include / clarify issues such as:

- A definition / terminology list
- Redundancy criterion (likely to be based on the dependability requirements rather than Fault Critical Clearance time), differences between redundancy and backup; the best practice for the solution of the backup protections with modern digital relays, integrated or standalone. Availability of the backup function in case of main protection failure - the key criterion
- Achievable fast fault clearance time – 100ms: Analysis for its guarantee
- Duplicated busbar protections; the dependability vs. the security of the protection
- Protections for Series Reactors, Series Capacitors (Series Compensation)
- Protection of Phase Shifter Transformers
- The use of reactors for fault limiting purpose with series connections
- Advanced methods to define the maximum current that can flow through a tie-line and is allowed by a distance relay installed on the line, based on the state-of-art of TSO (Transmission System Operator) practice
- WAP issues
- Protections of dispersed generation
- New principles of protection
- Should ANSI code or Logic Nodes for protection engineering be used?
- More references to updated ENTSO-E network connection codes and guidelines, regarding protection issues

2 INTRODUCTION

The combination of increased renewable energy sources, the simultaneous operation of different type of generations (conventional, non-conventional, renewables etc.), power transmission over long distances under extreme loading conditions and the influence of electricity markets have introduced new challenges in maintaining and improving the quality and security of network operations. It cannot be assumed that the transmission systems will develop and expand at the rate necessary to meet these challenges, therefore there is a need to reliably and safely maximise the capacity of existing apparatus, within the operational limits and conditions.

Increased power flow requires advanced and secure methods to protect transmission systems. In addition, the changes in system dynamics due to the introduction of Power Electronics, such as DC converters in new generation technology, can lead to a more stressed system. These new technologies and devices may cause difficulties or even incorrect operations under some complex conditions. The main specifications for the protection schemes are described in the national grid codes or in approved technical documents and standards.

This document describes the best practices for protection schemes with considerations of security of supply and safety of personnel and equipment. The focus is on the protection application of equipment, at mainly extra high voltage (EHV) AC, i.e. 400 kV, or high voltage (HV) AC, i.e. less than or equal to 220 kV, and in some special cases other voltage levels as well.

The objective of this document, as initially described in the “Terms of Reference” statement of the System Protection and Dynamics Sub Group dated 19-03-2010, is to recommend common procedures and principles and to define common methods concerning protection engineering, as a supplement to the Operational Handbook Policy 3 *Operational Security*, or to the System Operation Guideline.

The scope of this document matches the overall mission of the PE Subgroup; that is, the improved system operation and the provision of necessary background for new operational procedures. Technical solutions mentioned in this document are not considered as mandatory, but they are described as illustrations for complying with a set of protection principles.

Alternative technical solutions can also be adopted following a thorough study. These solutions are technically and financially justifiable with the same or better overall performance and comply with the national grid codes, the ENTSO-e Operational Handbook or other ENTSO-e Technical Standards or Guidelines, as well as the International Standards.

Therefore, the recommendations presented in this document may be specified and supported by specific solutions based on local analyses from various TSOs.

Note 1: The protection systems described herein are designed for 110 kV to 400 kV. Unless specified separately, the technical guidelines refer to all voltage levels.
Note 2: In this document, protection systems are considered as integrated solutions and include one or more protection equipment/functions, instrument transformer(s), wiring, tripping circuit(s), auxiliary supply(s) and,

where applicable, communication system(s). Depending upon the principle(s) of the protection systems, it may include one end or all ends of the protected circuits, possibly with automatic reclosing equipment. The circuit-breaker(s) [CB] are normally excluded, unless specifically mentioned otherwise.

3 PROTECTION PRINCIPLES

3.1 General aspects

There are three main requirements to which any protection system has to conform: reliability, dependability and security [1]:

Operational reliability - For this purpose, two independent auxiliary direct current (DC) power supplies are recommended for a protection system, with two separate trip coils at any case and – if the company's policy or legacy mandates- two separate closing coils[3] (autoreclosing [A/R]) for each Circuit Breaker (CB). No connection between DC1 and DC2 is acceptable – not even via auxiliary relays when tripping or autoreclosing. The main and backup protection functions (tripping and A/R) should be separated between at least two independent devices from two different manufacturers or should operate with different protection principles. The relays may be connected at two different correctly rated current transformer cores, according to reliability assessment or imposed by operating conditions of the protection systems. Each CB should have two independent trip coils and two independent trip circuits and – upon the selection of the company, i.e. not necessarily - two separate closing coils with two separate closing circuits for AR. Each protection device should trip, at least one of them powered by an independent auxiliary DC-supply. To allow for maintenance while the EHV-circuit is in service, the protection devices should be equipped with appropriate testing facilities such as slide clamps, test plugs, etc.

For lower transmission voltages (i.e. less or equal than 150 kV) it is the duty of each TSO and/or Transmission Owner (TO) to comply with certain principles that aim to guarantee the operational reliability. For example, two separate protection devices (one distance and one overcurrent) or self-supervision functions with immediate trouble-shooting of any defected device faults or defects, to achieve the maximum possible reliability and availability of the protection systems for the transmission Systems.

Dependability - A system fault could generate a very high fault current and has great destructive power. Power plants close to short circuits may lose synchronism. Therefore, it is important to clear any faults within transmission networks as fast as possible. For this reason, at least two different main protections with instantaneous tripping are recommended for an EHV circuit, which can be either double distance protections or one differential protection and one distance protection, with teleprotection schemes to enhance the performance where appropriate and necessary. Different types of protection systems may have different qualities and features. The differential protection is faster and has a higher sensitivity, but – e.g. for transmission lines - it needs an effective telecommunication system. In addition, for this latter case, it does not cover busbar faults, or small zone faults (the "dead zone" between the current transformer and CB when line side CTs are used). The distance protection is flexible to use and may cover the busbar faults. Moreover, a distance function should also act as back up protection, therefore it is necessary to coordinate with

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[3] For example, distance and differential protections of same equipment should trip and autoreclose the CB separately

other protections in the meshed grids. Appropriate protection schemes or suitable protection functions shall at least ensure there are no unprotected zones along the whole path of a circuit including busbars, CTs, Voltage Transformers (VTs), CBs, line trap, transmission line etc.

In addition, appropriate CBs with rapid tripping and arc quenching are recommended. Any faults should be cleared within the Critical Fault Clearance Time (CFCT) (usually less than 150 ms, i.e. including CB arc quenching, in EHV transmission systems especially) as specified in the national grid codes.

Additional functions, such as automatic reclosing (A/R), residual voltage / current protection and logical controls are also common practice. In solidly earthed EHV networks, single phase A/R should be generally implemented. After execution or update of necessary stability studies, three phase fault A/R may also be allowed, but not in a way that endangers the system stability and security.

Security - Any protection systems should not limit the maximum transmission capacity of a power grid. Distance protections in particular could cause spurious tripping due to specific grid conditions such as high load operations. Therefore, any special network operating arrangements or topologies must be known and considered for protection parameterization. For parallel circuits, it is necessary to consider the rapid increase of load current including dynamic overshoot in the healthy line when a faulty line trips and the protection operation must allow for re-dispatching (load transfer etc.). In some cases, it may be necessary to apply Power Swing Blocking (PSB) functions as well as Out-Of-Step (OOS) operations, if necessary. Nevertheless, for dependable fault detections, the distance protection settings need some minimum impedance reserves to cater for the maximum loads. The load encroachment function should be used whenever possible and it is strongly recommended for the cases when the longest zone-reach conflicts with the maximum transmitted load on the protected circuit. More details concerning the issues of maximum load are discussed in the respective chapters below.

3.2 Protection fundamentals for transmission lines, power transformers and substation busbars

EHV-overhead lines are generally protected [2], [3] by line differential relays and/or distance relays with teleprotection schemes such as Permissive Underreach Protection (PUP), Permissive Overreach Protection (POP), Accelerated Underreach Protection (AUP) and Blocking Overreach Protection (BOP).

EHV/HV power transformers are protected by instantaneous and selective protections, typically current differential relays (preferably with an overall and some restricted earth fault (REF) differential protections) and back-up overcurrent relays with multiple stages. Additionally, distance relays may be provided on (or both) side(s) of the transformer if the overcurrent (O/C) relays prove to be inadequate. The integral O/C-backup function in the differential relays may also be used. Buchholz alarms and tripping (tank and tap-changer) are normally used as standard mechanical protections. Other equivalent principles may also be adopted (e.g. for power transformer > 150MVA using two differential protection devices by different vendors). Special attention should be paid in the proper setting of instant elements in order to avoid unwanted tripping due to inrush currents during energization. CTs in the transformer bushings may be used for a second differential protection, added to the standard differential protection connected to the CTs in the bays, in the event that the ("equivalent") policy of the individual TSO allows it.

EHV busbars (BB) are normally protected by a "two out of two" BB current differential protection scheme. The "two out of two" scheme means that two "criteria" or conditions are checked or applied - one of them is the differential current - in order for the differential protection to trip. That means, for example, either two separate relays or two independent algorithms inside the device that will simultaneously be satisfied and met in order for the trip command to be issued; alternatively, a check- and discriminative "zone" of the differential protection or a directional check (against CT-saturation) may be used. Some TSOs apply an overall check zone for a whole substation and a discrimination zone per each busbar section. These principles aim to increase the security of the busbar protection (BBP) in order to avoid a possible maloperation that has severe consequences for the System.
The disconnectors/CBs status (auxiliary contacts) is required to provide a selective tripping of the faulty BB-section. The measurement has to be phase segregated; summation current transformers are not recommended. A Circuit-Breaker Failure protection (CBFP) may be integrated in the BB-protection if appropriate. The CBFP should be initiated from the protections in the bays (overhead lines [OHLs], transformers). The total tripping time for a CB failure should not exceed 250 ms for HV and EHV levels or as it is specified in the grid codes.

BBP and CBFP in transmission substations (220 kV – 400 kV at least) should be supplied with independent CT cores from each substation (s/s) bay if the CBFP is not integrated into the BBP. The core used only for BBP and CBFP is suggested to be independent from other protections of the bay. It is also possible use the same CT core to connect BBP/CBFP and other protections (i.e. distance relay, etc.) depending on how many CT cores there are in the substation bay, following the applied design principle of the company; and taking into consideration the fact that the reliability and the security of the systems is guaranteed and it is the responsibility of the company.

For lower voltage levels such as 110 kV or below, less onerous practices adopted by the individual companies are also accepted, such as a substation with only one DC supply system and transformers protected by one overall differential protection and O/C back-up, as well as shared teleprotection channels (where they are foreseen) for OHLs.

Protections of generators are not within the scope of this document. Although they are mainly aimed to protect the equipment within the power plants, they also play an important role in the transmission protection systems. As generation protections are normally energized during transmission faults, they must perform selectively with the line protections and should have a properly graded back up for external faults in the network they connect to.

3.3 Protection studies and settings

High quality protection studies (e.g. power flow studies, short-circuit studies, relay simulation and coordination studies and any other related to protection function study according to the TSO's methodology), should be performed to guarantee the reliable operation and security of the system. Procedures and validation requirements are very important and should be observed according to the practices of each TSO [4].

The reasons for initiating and/or undertaking a network protection study are varied, such as, but not limited to:

- Replacement or addition of new protection related equipment
- Changes in the primary topology of the supervised network area or of the neighbouring interconnected areas, such as: new power links, integration of new generation, shut down of existing classical generation, maintenance works, refurbishment works, etc.
- Changes in the settings and/or tripping logic philosophy of certain protection relays (e.g. to set off any lack of telecommunication, or temporary lack of BBP etc.) or a decision to implement new protection functions that could interfere with the selectivity plan already applied in the supervised network area
- Protection mal-operations and/or post fault analysis after an area disturbance
- Periodical, recurrent verification of the protection settings and coordination in a wide area network, a practice adopted as a general rule by the TSO
- For filing purposes (e.g. for integration of validated settings, their calculations and calculation rules in a centralised corporate database).

In the meshed transmission networks, the protection coordination is especially difficult due to the variability of short-circuit fault levels and the intermediate of the infeeds, which often leads to problems with the coordination and reliability protection systems.

A wide area coordination study should include thousands of faults simulations in the system using computer aided protection simulation software. The correct and coordinated response of the relays should be checked, especially in the event of protections' maloperations.

Two basic network study cases should be considered: PEAK CASE with all available generation connected, and OFF-PEAK CASE that considers the same network topology with certain generation disconnected for power balancing and transmission equipment outages ("N-1" criterion), according to the common dispatching practices or realistic scenarios. The study case(s) should include the functions of real time substation switching such as the double busbar configuration, where available, in order to check the relay's response to the operation of the bus coupler/section. The cases should also include the whole generation and transmission electrical system models down to transformer low voltage distribution and generation levels. Models must be sufficient to the scope of each study (e.g. transient or subtransient, saturated or non-saturated, where applicable). It is especially recommended to consider the proper simulation of the non-conventional generating sources.

For checking coordination, only "non-unit" protections (i.e. all protections except differential) should be included in the study network models. As busbars, lines and transformer differential protections are all absolutely selective and non-time-delayed protections, they are not concerned with the coordination. The communication failure for transfer trip distance protections should also be modelled as this is equivalent to an N-1 situation for a protection system where only overcurrent and distance relays are considered for clearing the faults.

In the study, both three phase and single phase to ground faults should be simulated. The transient line faults and faults with reasonable impedance should also be examined. These faults are applicable to all elements included in the coordination area. It is also good practice to consider different (more crucial) network topologies for the fault simulations, as well as the situations with minimum infeed.

Day by day, society has become increasingly dependent on the reliability of the power systems. This makes the coordination of the protection within a region and with the surrounding areas even more mandatory and critical.

3.4 Coordination of tie-lines, generations, transmissions & distributions

Although the generation, transmission and distribution within a power network may belong to different companies, the complete path must be considered as an interlinked entity and faults passing through different voltage levels must be cleared co-ordinately with selectivity. A safe margin between the main and next stage or back-up protections should be considered between 0.2 – 0.5 s for digital relays and 0.3 to 0.5 s for the older generation relays. A short margin (but not less than 0.15 s) may be acceptable for the protection schemes, such as tie-line circuit breakers (bus-couplers), where selectivity is required. It is advisable that the standardization of the grading times for the coordination should be made over a regional and for the same voltage level with a network. Standardization of the zone delays is not necessary for the tie-lines between neighbouring TSOs because, in those cases, the selectivity is based on the trip time discrimination strategy of the interconnected systems. Nevertheless, the safe margin must be respected in these cases as well.

4 FAULT CLEARANCE TIMES

4.1 Introduction

The maximum fault clearing time should be less than the CFCT[4]. By using modern protection relays and circuit breakers (two-cycle-CBs), the fault clearing times less than 100ms are generally possible [5]. Shorter fault clearing times will provide better system stability in the event of faults, but this should not jeopardize the overall security of the protection system. Furthermore, the maximum protection time delay for zero impedance faults and for the whole protection of the system should be considered. This longest time delay can be either the delay time of the highest distance relay zone or of the highest overcurrent stage. It is suggested to keep this time delay as low as possible and coordinated with grid automations and special protections schemes. A value between 0.6 and 5 s, depending on the available zones, has been recorded currently for some regional grids and, hence, deemed to be acceptable.

4.2 Busbar faults

A busbar fault may endanger the whole system stability due to the loss of many transmission lines and generation units. Busbar faults should be cleared within the CFCT. All busbars at voltage level greater or equal to 250 kV should principally have the differential BBPs. For busbars at less than 250 kV, the decision to use the busbar differential protection for each TSO depends on issues of stability, reliability, availability and security. If, for some reason, a BBP fails to operate, the protections of the connected feeders (either distance protection Zone 2 or 3 at remote ends or reverse zones at local ends) should be

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[4] ENTSO-E report: "Determining generator fault clearing time for the synchronous zone of Continental Europe - Version 1.0 -RG-CE System Protection & Dynamics Sub Group/RG CE/StO/SOC

implemented as backup for the BBP and the fault clearance time should be kept as short as possible.

The depletion time (the duration of non-availability of the busbar protection) has to be kept as short as possible because of the potential endangering of the system stability.

According to the strategy of certain TSOs, for EHV-substations with high transfer loads or other high importance (connected special customers, power stations or other TSOs) they have decided to install a second BBP system to avoid any non-availability of the BBP in the event of works on site or faults in the protection system.

On the contrary, some substations may not be equipped with a differential BBP. This is only acceptable if stability studies are performed to confirm that the arrangement is sufficient or if this is argued and foreseen by official national technical standards (e.g. at locations remote from generation or in cases of special substation configurations such as ring type buses etc.). For these cases, it must be ensured that instant tripping takes place where there is a busbar fault.

5 REDUNDANCY OF PROTECTION SYSTEMS

For a reliable and safe electrical power supply, the protection relays have to operate ***fast***, ***selectively*** and ***reliably***.

5.1 Redundancy

The level of redundancy may depend on the company's policy / specifications [6]; it could also depend on the CFCT of the protected element for a three-phase fault, as this is the most severe system fault for the stability studies. The most onerous conditions for critical time calculation are the three phase faults followed by failures of a three pole or single pole CB, especially for 220 kV and 400 kV voltage level.

According to the strategy of some TSO(s), the level of redundancy is defined in the following table, considering all lines and bays with the typical remote backup tripping time:

Tc_{L} (ms)	Tc_{R} (ms)	Tc_{LZI} (ms)	Redundancy
< 350	< 350	------	2SP/2C
	> 350	< 350	2SP/2C
		> 350 (**)	2SP/1C
> 350	> 350	-----	2SP/1C

(**) In this case it is required to comply with the critical clearing time for 3phase faults in the 20% from the local end in less than 350 ms and Z2 typical clearing times for the remote end (sequential clearing of the fault is assumed)

Tc_{L} Critical clearing time at local end
Tc_{R} Critical clearing time at remote end
Tc_{LZI} Critical clearing time at Z1 distance protection reach

Degree of redundancy:
2SP/2C double system protection with double communications channels
2SP/1C double system protection without communication redundancy (one communication channel)

If there is no teleprotection redundancy, a BOP scheme should be used to ensure the guaranteed performance of the tripping time. Other teleprotection modes, such as usage of accelerated Z1b for AR, which operates delays in the event of communication failure for faults at the remote end of the OHL, should be also accepted. Alternatively, the Permissive Under Reach communication scheme can be used, which is faster than the BOP scheme and less expensive than two independent communication channels. In the event of communication failure, the distance protection relays on both sides of the protected line work as if they would receive a teleprotection signal known as “auto-teleprotection”.

In this way, all faults on the protected line are switched off immediately. It is a standard function within some distance relays.

For short circuit protection of a system element with a 2SP requirement, the principle of dependability should be valid, as discussed in Section 2.1. In terms of protection requirements for EHV levels, the following is recommended:

- **Main protection,** which is the scheme that detects the faults in the power system and trips the protected element. The relay associated with the system is considered the main or primary relay.
- **Backup protection,** which is the protection system redundant to the main protection system in case the main protection fails to detect and clear a fault. This protection is called secondary or backup protection.
- **Double main protection,** if we consider full redundancy (2 SP with instantaneous tripping, DC supply, telecommunication, CT cores, VT windings, CB trip coils, etc.). For EHV systems, there are normally two main protections, which can include complementary principles
- For EHV, there is usually no defined hierarchy between the two schemes. They act independently and simultaneously. Nevertheless, we can have two main protections, which can include complementary principles. In case the backup protection primarily protects something other than the Main protection, the hierarchy should be valid between the Main and the Backup protection. There must be coordination between the main and the backup protection. This is described in chapter 5.2 in detail.

The maximum possible reliability, redundancy and availability of the measurement transformers and the DC supplies are required for the protection schemes. A standby power supply should be available with the capability to last a minimum of 4 (maximum 24) hours, which can be provided by either a battery system or auxiliary AC supply (diesel generators).

The two duplicated protection schemes may not be fully redundant, as some elements such as the VTs or circuit breakers do not need to be duplicated. However, both systems should use independent CT cores and the DC power supplies, and the tripping circuits should have redundancy (two trip coils and possibly, dependent on TSOs’ choice, two closing coils). In order to cover the failure of not redundant elements, remote or local back up protections should be used. The communication system should also be fully redundant where it is needed. The figure below shows the ideal redundancy case for demonstration purposes only. The tripping coils and communication paths should be redundant as much as possible; however, these can be applied according to each TSO’s own standards and practices (e.g. some TSOs, to achieve better dependability, send trip command of PP and PR to the both trip coils, meaning that PP and PR trips coils by Bat 1 and Bat 2. Separate BO should be provided).

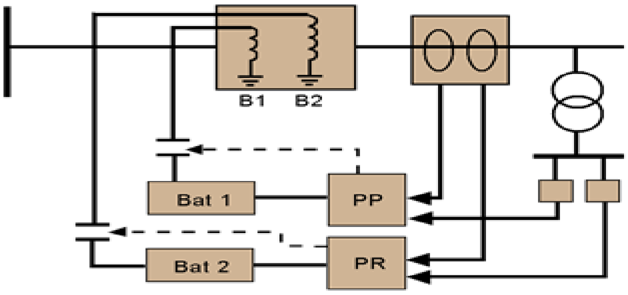


Figure 1 A typical example of the protection redundancy scheme

Key note: Bat: Battery, PP: main Protection PR: Secondary protection

The protection redundancy scheme should use two separate measurement transformers and two different operation principles or devices made by different manufacturers. In the case of short lines (mixed or not), multi-ended circuits and transformer feeders, line differential is preferable (see section hereafter). For short lines, a POP or BOP principle is also acceptable.

Current transformers should have appropriate accuracy by following standardized specifications and classes. They must be adequate for the maximum rated current capable of dealing with anticipated maximum permanent and temporarily load. They should not be saturated by maximum fault current. They should fulfil relay requirements for proper protection function, with the caveat that this is not necessarily the case for "high impedance" schemes.

5.2 Backup Protection

Main protection relays will trip for all faults on the protected transmission circuits or equipment without delay. By proper grading, the faults should be cleared by the backup protections in case the main protection fails to operate [7]. The backup protection could be the distance protection on the adjacent circuit with a time delay.

The backup function of the distance zones should cover all busbar faults in adjacent substation(s). To cover the failure of BBP, the reverse zones of the distance relays may be used either as a remedial action, when a failure of main BBP is being realized, or following the company's practice, and it is set with a delay time between Z1 zone delay time and Z2 zone or CBFP delay time.

A three-phase fault in the transmission system combined with a breaker failure will endanger the system stability in many places of the grid. The fault clearing time for a three-phase fault with breaker failure has to be kept as short as possible even if the probability of such a situation is very small.

Single-phase faults are the most frequent type of faults in the transmission grids. Even though these single-phase faults are less critical regarding the system stability than the three-phase faults, they should be cleared in a short time and, in the event of any breaker failure, the faults have to be cleared by a breaker failure protection as fast as possible.

The fault clearing time by the CBFP should be within 300ms for all types of faults and under all N-1 conditions at levels 250 kV and above, while in lower voltages the limit figure is 500ms.

5.3 Loss of Potential

The loss of potential (or “VT Failure” or “VT circuit failure” condition or “voltage measurement” function) should be considered by the design of the protection schemes. Though one VT is used, Main1 and Main2 distance protections are connected to the VT over separate Micro Circuit Breaker. When the MCB operate, or the auxiliary DC supply fails, the connected distance relay will be blocked. In the event the distance protections are blocked, the emergency non-directional overcurrent (O/C) should be automatically enabled. If this is not favourable due to a loss of selectivity, the O/C protection could be blocked as well, and let other protections trip the circuit breakers on the surrounding lines. Other countermeasures against the loss of voltage measurements or the auxiliary voltage could be :

- providing two protection relays with separate VT windings
- separate batteries
- switching to directional earth fault protection (taking voltage from open delta connection of the voltage transformer)
- switching the line on to the bypass busbar
- using differential and distance protection relays as Main1 and Main2 respectively (differential schemes are not affected by the loss of measuring voltage).

5.4 Open transmission conductor

The open transmission conductor situation is very important because firstly it can worsen the quality of supply and secondly it can rapidly evolve into a short circuit fault. This condition should be constantly monitored [8] and generate an alarm where necessary either with the Energy Management Systems (EMS)/SCADA systems or with the built-in functions within the intelligent electronic devices (IEDs). It is also possible to trip the circuits with this condition, which can be adopted by a utility based on the experience of each grid operator and consideration of the construction of the OHL, etc.

6 SETTING OF DISTANCE PROTECTION WITH NORMAL OPERATION CONDITIONS

6.1 General

All TSOs within ENTSO-E should set the protection system in such way that short circuit faults in the grid will be detected and cleared selectively. Therefore, the settings depend directly on the technical conditions in the grid. Overload protection is not the rule for the OHL, but is a topic for the load dispatcher. Nevertheless, according to the practice of certain TSOs, the special (dedicated) overload monitoring could be installed so that the grid control centre can identify and remedy overload conditions. Other cases could include managing crucial cable circuits or heavy loaded circuits, or for operational purposes, or combined with other applications, such as dynamic line rating depending on weather, temperature, wind speed etc.

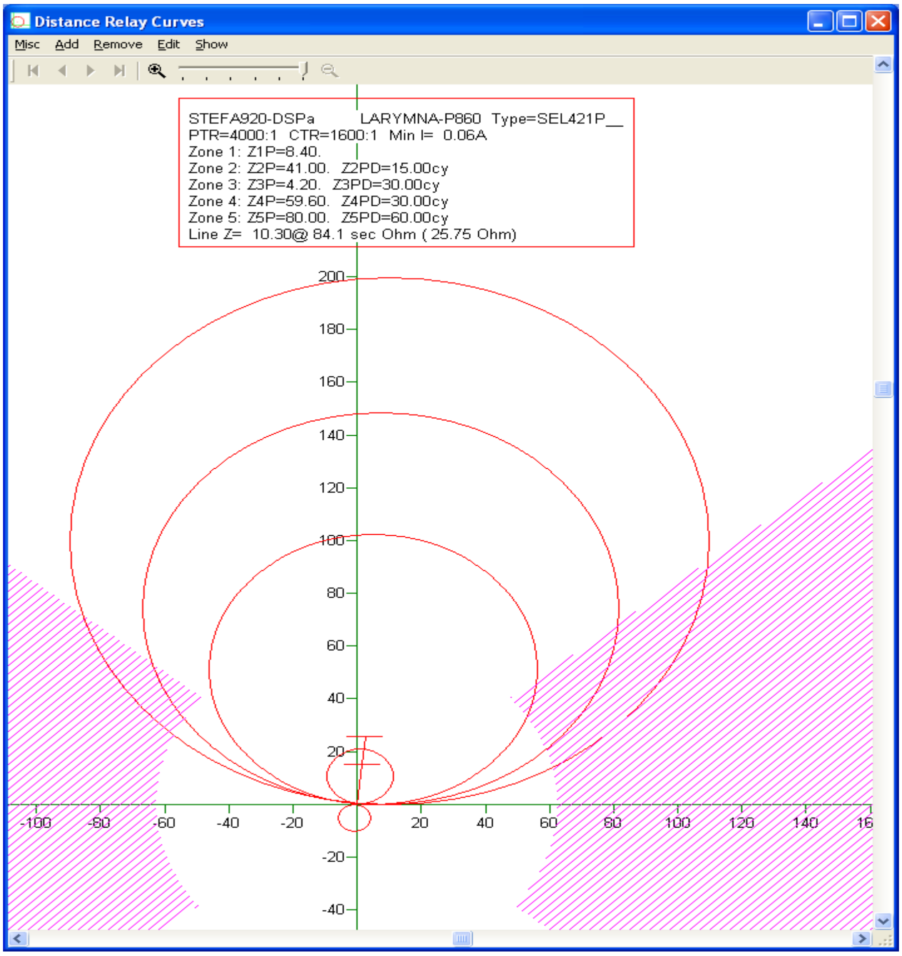
The Protection Limiting Current is defined as the value of the current which can be transferred safely, i.e. without picking-up by the starter elements and/or without generating a trip by the protection system. Thereby, the settings of starter elements, reset ratios, measuring tolerances and additional safety factors have to be considered by protection engineers.

The indication of the protection limiting current has to be done under pre-defined conditions (minimum operating voltage, load area etc.). A list of all Relevant CBs should be issued, updated and available to the dispatching personnel, indicating the normal and emergency operating limits of the transmission circuits and to be included in the EMS as line operating data.

The protection should be set not to trip under system transient conditions where there are no short circuits. Conversely, if there are short circuit faults, the fault current may be low due to local grid conditions (weak network) or due to high resistance of the arc. This must be taken into consideration and the relay must be tripped by using the most appropriate criterion. However, this should not cause the unwanted tripping during heavy load conditions, which could be achieved by lengthening the resistive blinder setting trip angle (as a ± angle area on both sides of torque vector of overcurrent setting), combined with load encroachment using ”relay trip logic” etc. (see also next).

6.2 Load encroachment

Protection relays must allow the maximum possible loadability of the protected equipment, without compromising the clearance of anticipated faults according to the simulation studies[9]. Special care must be taken to avoid the unwanted tripping of certain distance relays or decreasing the loadability due to the transient enlargement of the dynamic mho characteristic (if this type of characteristic is applied). This must be checked by the protection engineers based on the relay application manual and the algorithm of operation. The load encroachment feature of distance relays and, where appropriate, the setting of torque angle and trip angle of directional overcurrent relays, should be applied.



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STEFA920-DSPa        LARYMNA-P860  Type=SEL421P__
PTR=4000:1  CTR=1600:1  Min I=  0.06A
Zone 1: Z1P=8.40.
Zone 2: Z2P=41.00.  Z2PD=15.00cy
Zone 3: Z3P=4.20.  Z3PD=30.00cy
Zone 4: Z4P=59.60.  Z4PD=30.00cy
Zone 5: Z5P=80.00.  Z5PD=60.00cy
Line Z=  10.30@ 84.1 sec Ohm ( 25.75 Ohm)
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Figure 2: Load encroachment characteristic

6.3 *Interconnectors (Tie lines)*

There is no common rule to define the maximum current which is allowed to flow through a tie line, allowed by a distance relay installed on the line. Certain TSOs have agreed to common rules, especially after the known “disturbance of 2006”.

The following conditions could be considered for the protection limiting current on the interconnectors between TSOs, for standardization purposes and for enabling the cross reference / comparison:

- voltage > 90% * U_n (U_n = 400kV) and
- current in load area, i.e. cos(φ) > 0.8

Neighbouring TSOs may mutually agree on other conditions in special cases (e.g. lower voltage). Normally, the settings related to the maximum possible loadability of the protected equipment are specified after a dedicated load flow study and contingency analysis.

7 PERFORMANCE OF LINE PROTECTION DURING STRESSED SYSTEM CONDITIONS

7.1 Definitions

Power Swing Detection	- function inside the distance protection which detects power swings by monitoring the impedance vector and issuing some specific actions (alarms, tripping of the tie-lines, etc.);
Power Swing Blocking	- (PSB) blocking of one or several zones of the distance protection during stable power swings;
Out of Step Protection	- (OOS) Tripping during unstable power swings if specific conditions are fulfilled, such as Out of step exceeding a specified number of power swings, etc.
Frequency excursion	- under frequency, over frequency

The System protection schemes must support the detection of abnormal system conditions, like large load / generation imbalance, voltage instability, rotor angle instability. They should lead to the predetermined, corrective actions (other than the isolation of faulted elements), with a quick time response. They must preserve system integrity and provide acceptable system performance. They should be able to assist with the split of system in order to mitigate against the instability and they must keep the system running in the event of stable oscillations or disturbances. These functions could be achieved by the out-of-step (or pole slip) feature and the PSB feature of the multifunctional distance relays.

7.2 Requirements for automatic protection schemes during power swings

The following section describes the performance requirements for the line protection schemes during power swings [10], [11]. They are related to power swings that triggered the starting and/or tripping of the distance protection functions.

1. All types of faults or short circuits, low impendence or high impedance, single phase - ground or multiple phases, temporary or permanent must trip the CBs instantaneously at both ends of a circuit
2. Stable i.e. damped (decreasing) power swings shouldn’t cause any trip of transmission lines
3. Increasing power swings shall cause a trip at the nearest electrical nodes of the power oscillations based on specific criteria (e.g. minimum impedance), and restore the operation only after an attentive stability study
4. Slowly drifting grids (phase angles) may trigger the operation of grid split based on specific criteria to avoid the loss of power stations, but only if this is proved by an attentive stability study
5. Asynchronous operation (out-of-step or pole slip) shall cause a trip at the nearest appropriate electrical nodes
6. Any faults occurring during a power swing have to be cleared selectively by the respective zone of the distance protection

7. Voltage collapse should be addressed by using under voltage relays, taking account of related loads as e.g. large induction motors etc. Special attention should be paid to the automatic restarting schemes after voltage recovery in order to avoid a subsequent voltage collapse due to too high reactive power demands during parallel restarting of too many machines simultaneously. In radial connected feeders equipped with transformers with automatic tap changer controls, a blocking scheme for the tap changer should be made available and accessible to the system operator, so that during high voltage decrease gradients in direction of a collapse, the transformer tapping can be blocked either automatically or by the system operator.

The impedance measurement criterion is a crucial condition for the items above, to specify a trip in tie lines or nearby to the electrical nodes at the beginning of grid collapse. This criterion must be duly followed in all distance protection schemes. Protection schemes not using such a criterion are therefore not acceptable at the tie lines.

Some companies may prefer to implement the power swing detection and protection functions using separate dedicated devices, which is also acceptable. Other relevant automation schemes (e.g. angle automations etc.) are also acceptable if they are based on the results of stability studies.

The above functions do not have to be implemented if the stability studies for all realistic operational scenarios prove that they are not necessary.

As a general requirement, a minimum safety-margin of 30% to the maximum operating current should be considered for the setting of distance protection relays for load flow conditions (see other relevant chapters in this document). The safety margin must take into account all the relevant factors, including the current transformers, asymmetry of lines, transients, measurement tolerances, etc. This shall prevent potential mal-operations caused by transients in the grid including a pick–up of starter elements within the distance relays. If there are any doubts that this margin might not be sufficient, a dynamic analysis of the grid should be performed. With the study results, it is possible to choose a required method against incorrect operations in case of transients (power swings) in the grid. As a basic principle, the smallest influence on the distance protection schemes shall be used for the process.

7.3 General protection measures for the dynamic transients

The system dynamic transients may lead to the start or operation of protection schemes (with consideration of settings above), therefore it has to be properly analysed. PSB functions or OOS tripping shall only be used if this is proved to be necessary by a detailed stability study.

The following can be used as protection measures for the dynamic transients [12]:

7.3.1 Appropriate settings of tripping zones

Unwanted starting and tripping of protection schemes may occur during damped synchronous power swings , where the impedance vector exceeds the limits set for starting and tripping for the distance protection zones.

A short pick-up of the starter elements of the protection scheme is not critical, as long as no tripping zone is reached and the starter elements reset clearly before the time setting of the final zone is reached. A less sensitive setting may be chosen if these requirements can't be fulfilled. However, the certain limits of fault resistance have to be considered to ensure the distance protections detecting short circuits in all cases. Regarding minimum reserve for fault resistance, any specific value could not be recommended; fault resistance depends on many factors. Generally speaking, the values for fault resistance are the subject of calculations depending on tripping time, magnitude of short circuit current, wind speed, isolators dimensions and manufacturers' recommendations related to X and R settings (R1/X1 ≤ 3 for example is proposed by certain manufacturers) etc. TSOs use different methods to calculate fault resistance (e.g. the known A.R. Van C. Warrington equation; manufacturers' recommendations; other equation depending on time with arc, etc.).

Concerning the minimum resistive reserve for arc depending on the inductive reach of the distance protection zones, a method that provides the rules for setting the fault resistance is presented in Table 1 to 4 in Annex 1

In addition, a table containing heuristic values (rule of thumb) of fault resistance is inserted in Annex 1 (Table No 5).

It is assumed that distance protection schemes without power swing detections fulfil the following, regarding the requirements as previously listed:

1. All types of faults, short circuits, low impendence or high impendence, single phase or multiple phases, temporary or permanent etc. must instantaneously trip the CBs at both ends of the faulted equipment
2. Not fulfilled, see below [5]
3. Increasing power swings shall cause a trip at the nearest appropriate electrical nodes (minimum impedance)
4. Slowly drifting grids (phase angles) may trigger the operation of grid split
5. Asynchronous operations (out-of-step or pole slip) shall cause a trip at the nearest nodes
6. Any faults have to be cleared selectively by the respective zones of the distance protection
7. Voltage collapse should be addressed by under voltage relays, taking into account related loads as e.g. large induction motors etc. Special attention should be paid to the relevant automatic restarting schemes after voltage recovery to avoid a subsequent voltage collapse due to too high reactive power demands during parallel restarting of too many machines simultaneously. In radial connected feeders equipped with transformers with automatic tap changer controls, a blocking scheme for the tap changers should be made available to the system operator, so that during high gradients of voltage decrease in direction of a collapse, the transformer tapping should be blocked either automatically or manually.

7.3.2 Application of PSB for the distance protection functions

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[5] Requirement 2 (Stable i.e. damped (decreasing) power swings shouldn't cause any automatic trip of transmission line) shall be tested by grid dynamic studies and simulations.

The PSB should be used after a detailed analysis of the grid's dynamics and if the other measures cannot be used to effectively avoid incorrect operations of the distance protection schemes [13], [14], [15]. This could happen, for instance, if the impedance vector exceeds the pre-set value and remains too long in the starting and/or tripping zones. The application of PSB should ensure the tripping is generated, where necessary, for the unstable power swings[6] (for more detail see also the OOS chapter).

The active blocking time of the PSB should be limited and set according to the expected cycle duration of the power swing, e.g. 5 seconds. In the event of a decreasing voltage caused by slowly drifting grids (phase angles), it is suggested that the PSB should be inactive and so the distance protection may trip the nearest appropriate electrical node.

Whereas stable power swings shall not cause any tripping, unstable power swings shall be detected and generate proper tripping in time. Each crossing of the PSB polygon may be counted with the PSB application; several crossings (starts) of the PSB polygon may indicate low damped or even increasing power swings. In this case, the PSB may be unblocked after a given number of power swings. (Figure 4 trajectory 3, proposing three times crossing before PSB unblocking). A detection of increasing power swings by tracking the reversal point is preferable. However, the selection of the power swing detecting method and action mode will be decided by each TSO. A more conservative solution for grid faults during stable power swings would be to not block the first zone by the PSB and to trip only after a given number of (unstable) power swings[7]. In the next two sections, the two options regarding the Z1 blocking are presented.

For the PSB features such as the OOS feature, this can also be achieved in a dedicated device outside the distance protection.

Short circuits have to unblock the PSB immediately (item 1 of the "requirements"), to permit tripping in such fault cases. The criteria for this may be based on zero sequence currents or negative sequence currents.

7.3.2.1 Application of the PSB without blocking the first zone (Z1) of the distance protection

One application is to set the arc reserve of the first zone to 10 ΩPhase $_{\text{prim}}$ and this will not be blocked by the PSB. All other zones (also starting element) will be blocked during power swings by the PSB. In this case, the non-blocked first zone ensures the tripping of the distance protection scheme at the nearest appropriate node during extreme power swings and splitting of the grid. The non-blocking of the first zone extension (Z1X) secures the protection for the whole line (100%) even during power swings and three phase faults. However, this may cause the POP to be mal-operated. By application of a POP scheme, the signal sent from zone 2 may have to be blocked by the PSB in any case. In addition, the historical scheme used on the 400 kV network (acceleration by Z2) should release PSB in the case of reception of the acceleration signal. All faults in the close-up range will be tripped by the non-blocked zone 1.

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[6] ENTSO-E document: "System protection behaviour and settings during system disturbances", TOPIC 2 technical report of SG PE/StO/SOC.

[7] It has to ensure that the PSB may block all zones including the final zone. The PSB shall preferably start with the starting of the protection scheme

7.3.2.2 Application of the PSB by blocking the first zone (Z1)

It may also be necessary to block zone 1 of the distance protections by the PSB. Precautionary measures have to be taken to ensure the grid split in the event of asynchronous operations (OOS) at the nearest appropriate electrical nodes. This may be realised by e.g. a non-sensitive OOS protection (Figure 4, trajectory 1). This non-sensitive OOS protection trips if the impedance vector enters the dark-blue area at one side and leaves this area at the opposite side (OOS).

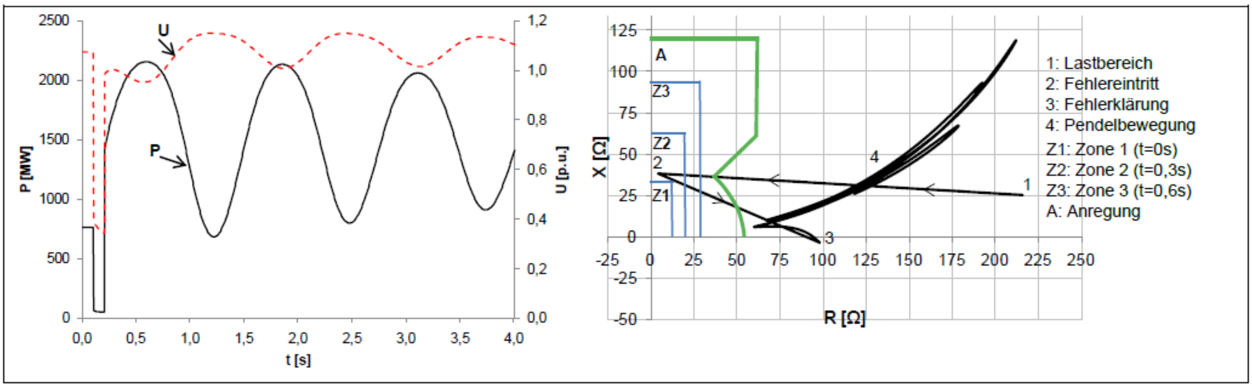

Figure 3. A Typical PSB characteristic in Z level
(Source: "The Power Swing Blocking – a Solution for all oscillatory problems?" Martin Lösing, Klaus Vennemann, Rainer Krebs, VDE Conference, March 2011, Munich)

The trip of symmetrical faults during power swings may be realised by detecting the fast change of the impedance ("leap") and subsequent unblocking of the PSB.

7.3.2.3 OOS protection

The OOS protection trips if the impedance vector enters the OOS area on one side and leaves this area on the opposite side. An example of the application is given in Figure 4. The non-sensitive OOS protection is represented by the blue area in Figure 4 (trajectory 1). The reactance of the OOS area is set according to the length of the protected line (e.g. 115% of line length).

For the sensitive OOS protection, the reactance is set to a higher value (e.g. up to the starting of the PSB-polygon) as shown by trajectory 2 in Figure 4. A sensitive OOS protection will only be used in exceptional cases at selected stations.

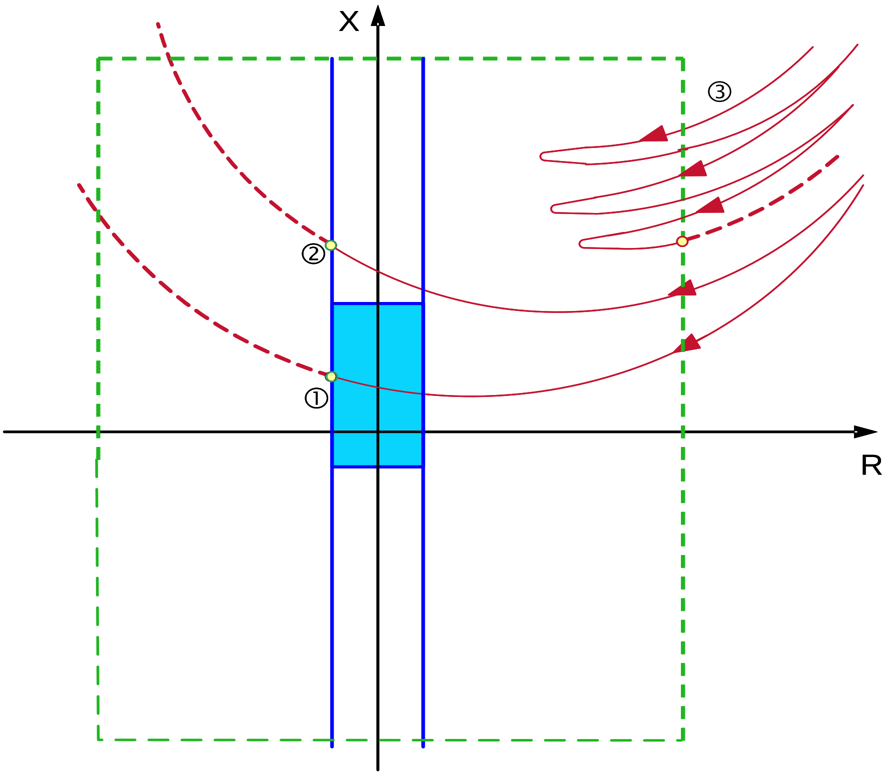

Figure 4 – An application example for the OOS protection (source: "Requirements for Protection schemes in EHV Transmission Systems, PG Systems Stability, Amprion-EnBW-transpower-50HeRTZ"; original title: "Anforderungen an Netzschutzeinrichtungen im Übertragungsnetz- PG Systemstabilität, 20-05-2010")

8 TELEPROTECTION

Telecommunication aided protection should be used to ensure the safe, reliable and fast clearance of faults in any points of a line [16], [17]. For 2SP/2C and 2SP/1C schemes, the following teleprotection schemes could be alternatively used:

- Distance protection with over- or underreaching schemes Directional Comparison Protection (blocking or permissive schemes or hybrid)
- Phase Comparison
- Load Comparison
- Line Differential
- Distance protection / Line Differential protection

For the aided communication distance schemes, the preferred scheme is the accelerated or PUP scheme. In case this preferred scheme is not possible, then the alternative should be the POP scheme, with zone 2 as the pilot zone. For this alternative option, special care should be taken (e.g. the current inversion logic could be included in the distance protection) for the case of multiple circuit lines to avoid unwanted tripping due to current reversal phenomenon.

Blocking schemes should not be used except when it is not possible to use permissive schemes or for other reasonable technical reasons.

In addition, the decision of selection may also depend on the quality of telecommunication.

For the weak infeed end cases, a week infeed logic should be used for the teleprotection aided distance schemes (e.g. the "echo" function with the weak infeed end). The weak infeed end will be that whose short circuit current (or impedance equivalent) is less than the minimum setting value for the distance protection used to protect the line. The week infeed end logic will alternatively operate if the following two conditions happen: the existence of an under-voltage or the absence of the distance protection start. This logic should be activated if there are less than three active feeders connected in a substation or in T-offs on an OHL with weak infeed. SIR (source impedance ratio) should also be considered when deciding a week infeed end. Additionally, in order to qualify a line end as a weak infeed, it should satisfy the above criteria for at least 10% of the yearly hours or as a permanent setting due to the grid topology.

8.1 Requirements of the communication system for teleprotection schemes

The communication system should be designed to work when there is a short circuit in the protected line, in compliance with the IEC 60834. The availability of the communication system should be in the order of 99.9% as high as possible.

From the protection point of view, the pick-up time should be the adequate for the correct operation of the relays and the schemes. In general, this time should be less than 20 ms.

For the different protection schemes, the following typical times are recommended:

- Distance protection with zone acceleration
    - Command pick-up time 20 ms
    - Command drop-out time 500 ms
- Directional comparison with permissive over-reaching scheme:
    - Pick-up and drop-out time 10 ms
- Directional comparison blocking scheme:
    - Pick-up and drop-out time less than 5 ms

In the case of using a direct transfer trip, when there is no local condition supervision for the reception, the security should be more important than other factors, therefore the pick-up time should be at least 40 ms.

8.2 Redundancy requirements for teleprotection systems

For 2SP/2C protection systems, the teleprotection system should be fully redundant. That means:

- double physical communication channels, either copper cables or fibres, with low probability of common mode failures;
- redundancy of the teleprotection equipment, one associated to each of the main protections;

- Power supply from redundant sources is preferred.

When requirements are the 2SP/1C type protection schemes, both protection systems may use the same communication and teleprotection devices without complete redundancy.

It is possible in lower voltages (e.g. less than or equal to 150 kV), radial feeding OHLs, substations far away from generations or for any other reasons (e.g. due to company's practice or in accordance with national grid code) that the teleprotection system may not be mandatory. In any case, the fault clearance time must be kept as low as possible for the protections at all ends.

Teleprotection may also be absent in the event of maintenance or other works on the transmission line and this must be considered for temporary measures about protection settings.

9 AUTOMATIC RECLOSING

Automatic reclosing (A/R) should be applied for all overhead lines [18], [19] as it is usually also foreseen by the national grid codes.

Automatic reclosing is normally suspended for cable faults, transformer faults, busbar faults and generator faults. In the mixed circuits (combination of overhead lines and underground or undersea cables) controlled auto-reclosing may be allowed if the faults are not on the cable and re-energization will take place after the cable's discharging. The location of the fault is detected with special devoted zones (the so called "control zones"). Those depend on the length of the cable, considering in addition a safety margin upon it.
There are some applications for which the combined circuits (OHL+ cable) are treated as overhead lines according to the successful practice of certain TSOs and where automatic reclosing is permitted all over the combined circuit. This may occur for cases such as the following:

- The length of the cable is short (i.e. less than 1 km) or it is less than a certain percentage of the total mixed-circuit length - defined by each TSO - (for all possible configurations: transformer feeders, interconnection transformers, tapped transformers or a cable as part of a mixed circuit –siphon link);
- Client Transformers in radial feeders: if the cable belongs to the client, it is the client's responsibility to choose if the automatic reclosing is permitted on the circuit or not (the client has to consider if this circuit should be treated as a cable or as an OHL);
- TSO´s transformers in radial feeders with underground cable where the length of the cable is less than a certain percentage of the total length of the circuit defined by each TSO (e.g. less than 40%); this circuit is considered as an OHL.

In the lower voltages (e.g. 150 kV and below), the A/R could not always be applied due to the safety concerns, this will depend on the construction of the line and the tradition / practice of the electricity companies. The lines that are in a more crowded environment where the chance of touching the line with a machine is high - lines running through urban areas or transmission circuits connecting to manned substations with fast restoration - can be excluded from the application of the A/R.

All possible A/R modes (fast, delayed, dead line charge, dead bar charge, power synchronise or synch-check) are allowed with respect to the safety and the stability rules, as well as equipment withstanding capabilities. The A/R for three phase faults may only be applied after ensuring that there is no possibility of jeopardising system security and stability due to the change of system configuration and substation run arrangement. The setting ranges for synch-check should be normally:

- ΔU=10-20%[8],
- Δf=0.030-0.5 Hz[9],
- Δa=10° - 60°,
- U< = 20 – 40% pu, dead bus or line,
- U> = 70 – 80%, live bus or line.

10 LINE DIFFERENTIAL (87L)

10.1 Current Differential protection applications

The line current differential protection together with the distance protection is considered the (trend of) preferred protection scheme for EHV and HV circuits [20]. A pre-condition is the availability of reliable telecommunication links. This principle of the protection scheme should always be used for multi-terminal(end) lines, where other protection principles, e.g. only distance protections, may not be able to guarantee the required selectivity or clearance time of the system. It can also be used for lines with tapped transformers.

Due to the fact that short overhead lines and/or cables may not have “enough impedance” for the distance relays, the current differential relay should always be used. When redundancy is needed, double line current differential protections could be used, but should be used from different manufacturers to avoid common failures. A short line is normally considered to be less than 5 km, as a general rule. The limit may be shortened, depending on the voltage level, the source impedance or characteristics of the voltage and current transformers. Another factor for assessing a line as a short one is the Source Impedance Ratio (SIR), which is defined as: SIR=|Zsource|/ |Zfault|
Classification of IEEE-Guide gives:

SIR > 4	short line
SIR < 4 and > 0.5	medium line
SIR < 0.5	long line

For a short line (large SIR), a differential protection is preferred, rather than for long lines (small SIR)

Cables should always use at least one line differential protection in order to guarantee the fast fault clearance while maintaining the security. The main reason for this is that there are many sources of errors associated with other protection principles, especially for ground faults in cables. For short cables, same as for the short lines, where redundancy is required, double current differential protections should be used.

Where a current differential protection scheme is used, it should have at least one distance protection as back-up when the protected object is a radial feeder. For the meshed networks

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[8] Other TSOs’ practice: ΔU=<33%, Δf=<0.15 Hz, Δa=40° - 60°

[9] Other TSOs’ practice: for synchronous setting is 0.02-0.05%, for the asynchronous setting of 0.4 - 0.6%.

and all other cases, they should be accompanied by distance protection functions serving as back-up protections and be coordinated with the rest of the transmission system.

The use of the line differential protections will guarantee the coverage of 150 Ohm or more high impedance fault under normal conditions. This is one of the reasons it should be used as a main protection in the redundant systems.

10.2 Current differential protection requirements

The current differential protections should be a reliable type (preferably digital/numerical) and phase segregated, i.e. be able to detect the phase where the fault is, therefore only trip the faulty phase (also to establish single phase A/R) for the single line-ground (SLG) faults. The synchronization of the measured values is done via a communication system (fibre optic preferable).

The differential protections should be, preferably, a biased current differential type which takes into consideration the measurement errors from the CTs, capacitive charging current of the OHL or cable, communication, and frequency deviation. The requirements for the CTs should comply with the relay manufacturer specifications but, in any case, CTs should not be saturated within the first 5 ms for the through faults to prevent unwanted tripping. The CT class should be at least 5P20, 30VA (better 5P60, 10VA) and it must be checked with calculations if the CT core fulfils the relay requirements for the protection functions in the relay. Optionally, PR cores with less remanent magnetization may be used.

The current differential relays used on 400 kV must have an operation time of less than 30 ms.

For the protection of the lines with tapped transformers, the differential protection should include some special features, such as:

- Ratio and vector group adaptation
- Inrush blocking

For this type of application, the maximum transformer feeder distance – as a practical rule - should be 1 km, as the burden may be introduced on the secondary winding of the CTs and make the differential protection unstable, using direct fibre optic as communication media.

10.3 Communication requirements for the line differential protection

The communication system for the line differential protection (87L) should be based on the fibre optic technology and associated equipment should comply with the IEC 60834. In general, the activation time should not be more than 30 ms for the communication between the protection relays of a current differential scheme. A TDM (Time Division Multiplexing) network is also acceptable for the line differential protections.

The synchronization method for the relays of the protected elements could be any type, except for the GPS (Geographical Positioning System), Glonass or Galileo, etc. due to the lack of control of the signals. The bit error rate (BER) of the communication system should be 99% of the time less than 10^{-6} s and 0.99% of the time less than 10^{-3} s (this reduced BER is not directly associated with a line fault).

When redundancy is a requirement and a double differential protection scheme is used, the communication channels should be fully and physically redundant, and not sharing the same physical path/cable.

For the differential protection (current or others), in order to synchronize the analogue measurements, the maximum delay of the communication system should be less than 10ms and the asymmetry in the pick-up times should be less than 1ms.

11 PROTECTING CABLES

In general, the principles described in the chapter “Protection Principles” should be applied to the cable protections [21]. One issue is the determination of the equivalent circuit of the cable for the studies. Most TSOs calculate zero sequence impedance according to manufacturer specifications, but some manage it by real time measurements. EHV- and HV-cables are normally protected by differential relays and, when necessary, also covered by the distance relays as backup protection from the remote cables and OHLs. The two protection schemes should be supplied by two different DC-supplies and two different CT-cores. The CBs should also have two separate trip coils which are used separately by each of the two protections.

For the reliability purpose, the practice of cable protections may be different for some utilities/TSOs. This is acceptable if a detailed examination and justification of the high reliability are carried out.

Additional protection functions, e.g. Residual voltage (U0), Directional O/C, Directional Earth Fault, Overvoltage (U>), circuit breaker failure (CBF) etc. may be required, related and according to studies for the anticipated phenomena of the cables during normal operation, as well as during short circuits.

For the benefit of the routine testing, the cable protection schemes should be equipped with test plugs or similar facilities. For heavily loaded cables, it should be possible to test one protection scheme with the cable in service while using other protection.

12 PROTECTING SHUNT REACTORS

The shunt reactors are an important element of the transmission grid. They are largely used for reactive power compensation purposes, can be connected as shunt devices directly to the HV, LV busbars or the tertiary (MV) of transformers. Shunt reactors are also used on the line side to compensate for the capacitive current of cables. They can be found in all (EHV, HV, MV) voltage levels. Similar to the power transformers, the shunt reactor protections normally have a separated selectivity and do not have coordination issues with other protections of transmission networks, depending of course on the grounding policy of both transmission system and reactor.
For the reactor protection [22] and switching, the IEEE Standards C37.015, C37.109, or other relevant IEC standards, should be used as references. Permissible permanent current overloading is described and specified in those documents.

The protection functions used for reactors normally include overall current differential, phase overcurrent, earth overcurrent, neutral overcurrent, overvoltage and residual voltage as well as Buchholz for mechanical protection etc. High and low impedance current differential protection, REF protection and distance protections may also be used.
A possible protection scheme proposed for shunt reactors bus-bar connected through their own bay is presented in Annex II. In some cases, automatic schemes are applied for the switching of the reactors. These schemes may be also designed for automatic ON/OFF-switching the reactor based on the BB-voltage and are intended as a backup function in the event of disturbance of the load dispatcher, SCADA or S/S control.
Other important matters to be considered for the shunt reactors include the necessity of a controlled switching mechanism for the main circuit breaker, per phase, to avoid switching over-currents when switching on or off the reactor, where the Point On Wave or Phase Synchronized Switching is applied.
The key point is that the phase current in the reactor has to be zero when switching it off.

13 PROTECTING SHUNT CAPACITORS

Shunt Capacitors are an important element of the transmission grid. They are largely used for reactive power compensation purposes. They can be connected at all voltage levels of a grid. Their protections should be designed according to the Standard IEC 60871 or equivalent [24], [25]. Permitted safe overloading etc. are described in the standards. Similarly, the shunt capacitor protections normally have a dedicated selectivity and do not have coordination issues with other protections of transmission networks. Therefore, they are not mentioned in other places in this document.

The Protection functions used for the shunt capacitors can include Overall current differential, phase overcurrent, earth overcurrent and neutral imbalance overcurrent, thermal overloading, overvoltage protection etc. Other protection schemes according to the recommendations of the manufacturer may be used, such as frequency protection (against dielectric overload). A possible protection scheme to eliminate the faults related to capacitor banks is presented as indicative in Annex III.

Other important matter to be considered for the shunt capacitors include the necessity of a controlled switching mechanism (similar to reactors, but when voltage is zero) for the main circuit breaker to avoid switching over-voltages, delayed re-energizing function (re-energize inhibit) and to assure the sufficient discharge of the capacitor bank.

When capacitor banks are connected in common medium voltage busbars, the inrush current due to neighbouring capacitor switching must be calculated to avoid the unwanted tripping of the instant overcurrent protection for the capacitor banks in service.

Where the shunt capacitors are directly connected to the high voltage busbars, attention must be paid to the automatic reclosing of the CBs with connection to the high voltage capacitors. The automatic reclosing is allowed after sufficient dead time as it is recommended by capacitor’ manufacturers.

Mechanically Switched Capacitors with Damping Network[10] connected to EHV grid, especially when they remain connected only with a transformer or with a houseload of a power plant, e.g. after a trip of EHV-lines, are subjected to high overvoltages due to high charging power [26]. In such cases, the addition of a dedicated overvoltage protection is recommended.

14 PROTECTION FOR RENEWABLES

The main issue of the protection in the grids with non-conventional generation plants, like a wind farm (W/P), photovoltaic farm (P/V) etc, is their behaviour in the event of short circuits [27], [28]. With an increased amount of renewable infeeds, a proper modelling of the behaviour of these, according to symmetric and asymmetric faults, will become increasingly important[11]. The controlled and non-linear characteristic of the power electronic interface of the renewables with the Systems must be considered. Appropriate equivalent models therefore need to be developed. The contribution of the plants to the system faults must be clearly known. Therefore, information on power plant transient performance during system faults should be available from manufacturers.

Some companies apply the principle that plants with the fault ride through capability should have their high voltage busbars for connecting to the existing transmission grid via circuit breaker(s) and equipped with distance protection as a minimum requirement. In many cases, the renewables are connected at an EHV or HV line by a radial feeder. A possible protection scheme is shown in Annex IV (This configuration should be considered as an example only; is not mandatory at any case). The differential protection is used with the solid grounded neutral of the infeed transformer. For distance protection, autoreclosing of the lines feeding the busbars of the farm is allowed. In any case, the connection of the new plant to the system must consider and respect the operation specifications and conditions mentioned in the grid code, connection codes or other relevant technical documents. The owner of the generator must guarantee that all faults will be cleared by its own systems, which are reliable and dependable with built in redundancy. It is not the task of the transmission system protection schemes in the meshed grids to detect and clear (as back-up function) all faults occurring in the equipment of the renewables substations (i.e. between the main step-up transformer and the generators).

On the other hand, the protection of the renewables must respect the protection principles and the operating tolerances of the connected transmission systems and guarantee that they – at no time - will be tripped off unselectively or without coordination with the transmission system protections.

15 THREE-END LINES AND SPECIAL TOPOLOGIES

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[10] large shunt capacitor banks, arranged as a C-type (capacitive at fundamental frequency) harmonic filter, connected to the high voltage system to provide reactive compensation and harmonic control, but with reduced losses in the resistor at fundamental frequency by means of a resonance between the reactor and auxiliary capacitor

[11] ENTSO-E report: “short circuit contribution of new generation technologies and voltage drops expected during short circuits”, Topic 1 technical report, SG PE/StO/SOC.

The three (or more) ended lines and other special topologies are not forbidden, as long as the load dispatcher can handle it. Special teleprotection schemes or multi-end differential protection with a distance protection as remote back up should be applied. However, this kind of configuration should not be encouraged from the protection and system operation point of view as the sufficient selectivity of the protection and reliability of the communication paths may not always be guaranteed. For the benefit of cost efficiency and environmental purposes (saving of transmission paths etc.), the appropriate protection schemes should be fully discussed and agreed before being applied, in case these types of topologies are accepted in the system.

16 CONCLUSIONS – RECOMMENDATIONS

The increased penetration of renewable energy sources, the co-existence of different type of generations (conventional, non-conventional such as modern kinds of renewables etc), the demanding conditions of power transmission and the influence of electricity markets have introduced new challenges in terms of maintaining and improving the quality and security of power transmission function. The increasing restrictions concerning the expansion of the transmission components and infrastructures – due to environmental or financial reasons- consequently increase the need to reliably and safely maximise the capacity of existing apparatuses, within the operational limits.

Increased power flow and increased availability requires advanced and secure methods to protect transmission systems. In addition, the changes in system dynamics due to the establishment of power electronics at the transmission systems, can lead to more stressed conditions. These facts may cause difficulties or even incorrect operations under some complex circumstances. Therefore - and in parallel with all power transmission resources and pylons - the in-depth-reconsideration and rethinking of transmission-system protection principles and their permanent improving and optimization is of major importance. This edition of the present technical brochure has this as its objective.

The main specifications for the protection schemes are described in the national grid codes or in approved technical documents and standards. In addition, there are the ENTSO-E operation handbooks and policies and recently, the EU has issued Technical Lows, i.e. the regulations and guidelines.

This document describes the best practices of the European TSOs for protection, with considerations of security of supply and safety of personnel and equipment. The focus was on the protection of EHV AC and HV AC equipment, and in some special cases, other voltage levels as well, since the related components serve the purposes of the Transmission System.

Any protection system has to perform in terms of reliability, dependability and security. Overhead lines are generally protected by line differential relays and/or distance relays with tele-protection schemes. Power transformers are protected by instantaneous - typically current differential - relays and selective protections, such as back-up multi-stepped overcurrent relays. Additionally, distance relays may be provided on one (or both) side(s) of the power transformer, if the overcurrent relays prove to be inappropriate. Substations' busbars and directly connected equipment are primarily protected by extra reliable current differential protections. The criteria assuring the reliable operation of busbar protection were mentioned.

The level of redundancy was thoroughly analysed. The relationship between primary, secondary and backup protection and their mission was clarified. Recommendations and criteria, summarizing the TSO’s practices - for their selection were given.

Important protection issues such as: CBFP settings, Loss of Potential (or “VT Failure” or “VT circuit failure”), Autoreclosing Modes, Tele-protection schemes and Open Conductor Protection were analysed as they are considered very important features, because first they can affect the quality and the performance of overall protection and second they fight against conditions that are faults or can rapidly evolve to a short circuit.

The importance of high quality protection studies (e.g. short-circuit studies, relay coordination studies e.a.) was emphasized, so that the reliable operation and the security of the system is guaranteed. Tables, diagrams, formulas, e.g. the dependence to the SIR ratio, distinct values – or value ranges - calculation algorithms, even - commonly accepted - “rules of thumb” about crucial setting parameters were provided, with the aim of serving as a reference and as a supporting tool for the protection engineer in his daily work. Important protection study “constants”, such as the safe time margin between the main and back-up stages, were examined.

The protection should be “set” not to trip under system transient and stable conditions where there are no short circuits as well as under abnormal but “foreseen” conditions (e.g. lower voltages). The performance requirements for the line protection during power swings (stable and unstable ones) were discussed. The system dynamic transients may lead to the start or operation of protection schemes, therefore they must be properly analysed. PSB functions or OOS tripping shall only be used if this is proved to be necessary after a detailed stability study.

Protection relays must allow the maximum possible “loadability” of the protected equipment, assuring flexible grids. Neighbouring TSOs may mutually agree on – due to protections and automations - limiting conditions for their common tie-lines.

Telecommunication aided protection should be used to ensure the safe, reliable and fast clearance of faults in any points of the protected line. Regarding teleprotection schemes, issues such as the technical requirements of the communication system and redundancy principles were examined.

Automatic reclosing should be applied for all overhead lines as it is usually also foreseen by the national grid codes. Automatic reclosing is normally suspended for cable faults, transformer faults, busbar faults and generator faults. In the mixed circuits (combination of overhead lines and underground or undersea cables) controlled auto-reclosing may be allowed for the overhead segment’s faults and their re-energization is foreseen to take place after the cable’s discharging.

The line current differential protection together with the distance protection is considered to be the preferred protection scheme for EHV and HV circuits. A pre-condition is the availability of reliable telecommunication links.

In general, the principles described in the chapter "Protection Principles" should be applied for the cable protections. The key factors for cables / mixed lines were mentioned.

Guidelines for protection of the shunt reactors were given. In some cases, automatic schemes are applied for the switching of the reactors. These schemes may be also designed for automatic ON/OFF-switching the reactor, based on the busbar voltage.

The protections of shunt capacitors should be designed according to the Standard IEC 60871. The necessary and specific functions used for the shunt capacitors protection were registered. Other protection schemes according to the recommendations of the manufacturer may be used, such as frequency protection etc. Shunt capacitors are related with features such as the controlled switching-on mechanism (similar to reactors, but when voltage is zero) for the main circuit breaker to avoid switching over-voltages, the delayed re-energizing function ("re-energize inhibit") to ensure the sufficient discharge of the capacitor bank, etc.

The main issue of the protection of Renewable Energy Sources' generating plants with "non-conventional" connection interface is their behaviour at the short circuits. The controlled and non-linear characteristic of the power electronic interface of the renewables with the systems and the behaviour according to the manufacturer must be considered. Appropriate equivalent models therefore need to be developed and given to the protection engineer.

Finally, the specific issue of protection of "three ended" or "T-type" circuits is briefly mentioned.

For most of the above-mentioned cases, schemes are given as appendices, figures, pictures and comprehensive diagrams.

We hope that the overall document may serve the protection engineer, in whatever position of the vertical protection chain he is engaged in and at whatever location – office, site, laboratory, control centre, factory etc.- as a guide and as a reference to improve and to standardize the daily work in favour of the reliable and safe overall performance of the electric power transmission system.

17 BIBLIOGRAPHY

1. J. M. Pond , Y. I. Lu, J. E. Mack ,"Dependability Versus Security: Finding a Reasonable Balance" (64th Annual Georgia Tech Protective Relaying Conference, Atlanta, Georgia, May 5–7, 2010)
2. "Network Protection And Automation Guide - Protective Relays, Measurement & Control", ed. Alstom Grid, 2011
3. C. R. Mason, "The art of science of protective relaying", GE, Retrieved 26-01-2009
4. "Power Plant and Transmission System Protection Coordination", NERC, Technical Reference Document, Rev.1, July 2010
5. R. Natarajan, "Computer-Aided Power System Analysis", Marcel-Dekker Inc., USA, 2002

6. S. Ward, e.a., “Redundancy considerations for protective relaying systems”, 63rd Annual Conference for Protective Relay Engineers”, 29.03.2010-1.04.2010, Texas, USA
7. C. S. Tuan Hoang, “Line Protection For A Sampled 230kv Power System”, Master Of Science, Electrical and Electronic Engineering, California State University, Autumn 2012
8. S. J. Mabeta, “Open Conductor Faults and Dynamic Analysis of a Power System”, Department of Electric Power Engineering, NTNU, Trondheim, June 2012
9. “Increase Line Loadability by Enabling Load Encroachment Functions of Digital Relays”, System Protection and Control Task Force, North American Electric Reliability Council Planning Committee, 7.12.2005
10. “Protection System Response to Power Swings”, System Protection and Control Subcommittee, NERC, August 2013
11. A. Abidin, A. Mohamed, H. Shareef, University Kebangsaan Malaysia “A New Detection Technique for Distance Protection during Power Swings”, 9th WSEAS International Conference on Applications of Electrical Engineering, 23-25.03.2010
12. V. Vittal e.a. “Representation, Modeling, Data Development and Maintenance of Appropriate Protective Relaying Functions in Large Scale Transient Stability Simulations”, Power Systems Engineering Research Center -PSERC Publication 17-05 September 2017. Arizona
13. N. Fischer e.a. “Tutorial on Power Swing Blocking and Out-of-Step Tripping”, 39th Annual Western Protective Relay Conference, Spokane, Washington, October 16–18, 2012
14. Q. Verzosa, Jr. “Realistic Testing of Power Swing Blocking and Out-of-Step Tripping Functions” Doble Engineering Company.
15. C. Sena, R. Franco, A. Giusto, “Assessment of power swing blocking functions of line protective relays for a near scenario of the Uruguayan system”, 2008 IEEE T&D LA Conference, August 2008
16. M. Zellagui, A.Chaghi , “Distance Protection for Electrical Transmission Line: Equipment’s, Settings Zones and Tele-Protection”, 29 June, 2012
17. A. dos Santos, M.T. Correia de Barros, P.F. Correia “Transmission line protection systems with aided communication channels—Part I: Performance analysis methodology”, Electric Power Systems Research, 2 July, 2015
18. L. E. Goff, “Automatic Reclosing of Distribution and Transmission Line Circuit Breakers”, Philadelphia, Pennsylvania, ed. GE Power Management, Canada
19. G. K. Gill, Nishu Gupta, “Automatic Reclosing – Transmission lines Applications And Its considerations”, International Conference On Deregulated Environment And Energy Markets”, DEEM 2011, 22-23.07.2011, Chitkara University, Punjab, India
20. G. Ziegler, “Numerical Differential Protection: Principles and Application”, Siemens, 2005
21. D. A. Tziouvaras, J. Needs, “Protection of mixed overhead and underground cable lines”, 12th IET International Conference on Developments in Power System Protection (DPSP 2014), 31 March-3 April, 2014 Copenhagen, Denmark
22. W. A. Elmore, “Protective Relaying: Theory and Applications”, 2004
23. G. Brunello e.a. “Shunt Capacitor Bank Fundamentals and Protection”, Conference for Protective Relay Engineers – 2003, Texas A&M University.
April 8-10, 2003, College Station
24. V. Lackovic, “Shunt Capacitor Bank Design and Protection Basics”, CED, Course. NY
25. “Protection of Capacitor Banks”, Section 8.10 of “Distribution Automation Handbook”, ABB
26. T.G. Martinich, M. Nagpal, A. Bimbhra, “Analysis of Temporary Over-Voltages from

Self-Excited Large Induction Motors 1.in the Presence of Resonance - Case Studies", International Conference on Power Systems Transients (IPST2013) in Vancouver, Canada 18-20 July, 2013
27. Dr. T. K. Abdel-Galil, e.a. "Protection Coordination Planning With Distributed Generation", June 2007, Canada
28. Z. Han, "Protection Coordination in Networks with Renewable Energy Sources", Thesis, University of Manchester (MPhil), Faculty of Engineering and Physical Sciences, 2014

18 ANNEX I Resistance values of the zones of distance protections related to the lines

Tab. 1 – Typical Resistance values of the zones of distance protections related to the lines HV with distribution function

$X_{ZONE\ 1\div3}$ [Ω/phase]	Measurement phase-earth (ϕ-N)	Measurement phase-phase (ϕ-ϕ)
	R/X	R/X
1.5 ÷ 3	5 ÷ 3	4 ÷ 3
3 ÷ 6	3 ÷ 2.5	3 ÷ 2
6 ÷ 9	2.5 ÷ 2	2 ÷1.5
9 ÷ 12	2 ÷ 1.8	1.5 ÷ 1.2
12 ÷ 24	1.8 ÷1.5	1.2 ÷ 1
24 ÷ 36	1.5 ÷ 1.2	1 ÷ 0.8
36 ÷ 48	1.2 ÷ 1	0.8 ÷ 0.7
48 ÷ 60	1 ÷ 0.7	0.7 ÷ 0.6
NOTE: values of the resistance phase-earth $R_{\phi\text{-}N}$ are valid for the coefficients of earth K_T with value in the range 0.85-1. For lower values they must be adequately increased.		

Tab. 2 – Typical Resistance values of the zones of distance protections related to the lines EHV with transmission function

$X_{ZONE\ 1\div3}$ [Ω/phase]	Measurement phase-earth (ϕ-N)	Measurement phase-phase (ϕ-ϕ)
	R/X	R/X
2 ÷ 4	4 ÷ 3	3 ÷ 2.5
4 ÷ 8	3 ÷ 2	2.5 ÷ 1.5
8 ÷ 12	2 ÷ 1.5	1.5 ÷1.2
12 ÷ 24	1.5 ÷ 1.2	1.2 ÷ 1
24 ÷ 36	1.2 ÷1	1 ÷ 0.8
36 ÷ 48	1 ÷ 0.9	0.8 ÷ 0.6
48 ÷ 100	0.9 ÷ 0.5	0.6 ÷ 0.3
NOTE: values of the resistance phase-earth $R_{\phi\text{-}N}$ are valid for the coefficients of earth K_T with value close to 1. For lower values they must be adequately increased.		

The starting resistance can be set with the following tables, which are the typical values of the fault resistance, depending on the value of X_{START}, respectively, for HV lines that carry out distribution function (Tab. 3) and EHV lines that carry out transmission (Tab. 4):

Tab. 3 - Typical starting values for distance protection lines with distribution function

$X_{STARTING}$ [Ω/phase]	$R_{STARTING}$ (ϕ-N)				$R_{STARTING}$ (ϕ-ϕ)			
	Characteristic of starting A (Fig.1)	Characteristic of starting B and C (Fig.1)			Characteristic of starting A (Fig.1)	Characteristic of starting B and C (Fig.1)		
	$R_{START\ \phi N}$ [Ω/phase]	$R_{START1\ \phi N}$ [Ω/phase]	$R_{START2\ \phi N}$ [Ω/phase]	Angle $\Psi_{\phi N}$	$R_{START\ \phi N}$ [Ω/phase]	$R_{START1\ \phi\phi}$ [Ω/phase]	$R_{START2\ \phi\phi}$ [Ω/phase]	Angle $\Psi_{\phi\phi}$
20	25 ÷ 35	25 ÷ 35	25 ÷ 35	0°	20 ÷ 30	20 ÷ 30	20 ÷ 30	0°
35			25 ÷ 35	0°			20 ÷ 30	0°
50			30 ÷ 45	45°			25 ÷ 40	45°
65			30 ÷ 45	45°			25 ÷ 40	45°
NOTE: values of the resistance phase-earth $R_{START\ \phi N}$ are valid for the coefficients of earth K_T with value in the range 0.85-1. For lower values they must be adequately increased.								

Tab. 4 - Typical starting values for distance protection lines with transmission function

$X_{STARTING}$ [Ω/phase]	$R_{STARTING}$ (ϕ-N)				$R_{STARTING}$ (ϕ-ϕ)			
	Characteristic of starting A (Fig.3)	Characteristic of starting B and C (Fig.3)			Characteristic of starting A (Fig.3)	Characteristic of starting B and C (Fig.3)		
	$R_{START\ \phi N}$ [Ω/phase]	$R_{START1\ \phi N}$ [Ω/phase]	$R_{START2\ \phi N}$ [Ω/phase]	Angle $\Psi_{\phi N}$	$R_{START\ \phi N}$ [Ω/phase]	$R_{START1\ \phi\phi}$ [Ω/phase]	$R_{START2\ \phi\phi}$ [Ω/phase]	Angle $\Psi_{\phi\phi}$
40	25 ÷ 35	20 ÷ 30	35 ÷ 45	45°	20 ÷ 30	15 ÷ 30	25 ÷ 35	45°
50								
60								
75								
100								
125								
NOTE: values of the resistance phase-earth $R_{START\ \phi N}$ are valid for the coefficients of earth K_T with value close to 1. For lower values they must be adequately increased.								

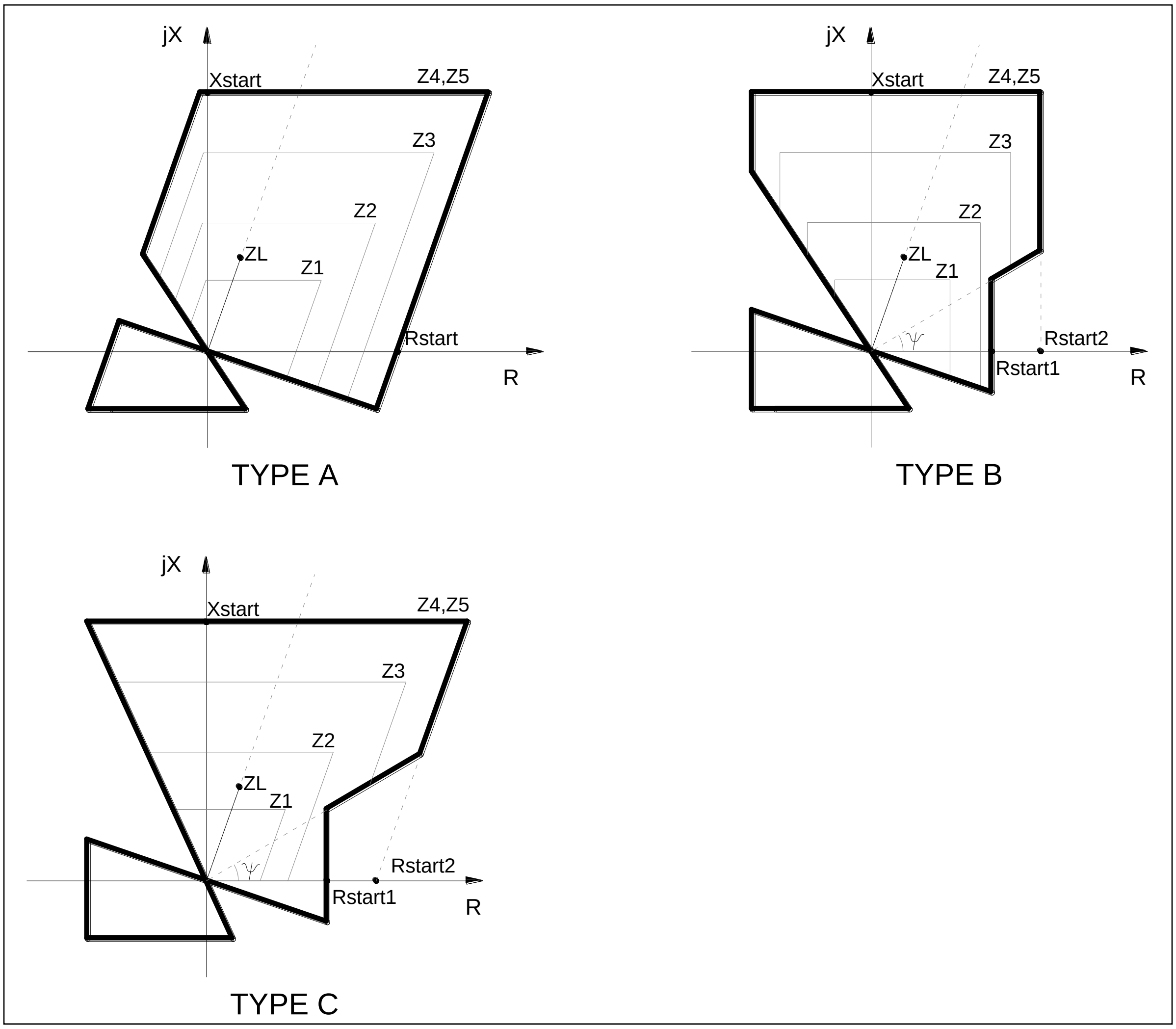

Figure: Main features of starting distance protection

Tab. 5. Primary values recommended for fault resistance, for OHL, with overhead earth wire. For other cases and/or if such an earth wire does not exist, these values could be increased

Zone 1	≥ 10 ΩPhase $_{\text{prim}}$
Zone 2	≥ 12 ΩPhase $_{\text{prim}}$
Z1 extension(overreach)	≥ 12 ΩPhase $_{\text{prim}}$
Zone 3	≥ 14 ΩPhase $_{\text{prim}}$
Starting	≥ 20-30 ΩPhase $_{\text{prim}}$

Note: The above specified arc reserve should be sufficient for most single- and three-phase faults. Under extreme conditions (low conductive and dry area), the distance protection schemes may be supplemented with a directional sensitive earth fault protection (U0/I0). In this case, it is not necessary to increase the fault resistance of the distance zones.

19 Annex II A possible protection scheme for shunt reactors connected to a bus-bar with its own bay

17.1 A possible protection scheme proposed to eliminate the faults related to the shunt reactor bay connected to the bus-bars is presented in figure I.

- Main protections: two low impedance (transformer) differential protection and two overcurrent protections/functions in the HV bay (I>> and I0>>)
- Back-up protections: two overcurrent protection/functions in the HV bay (I> and I0>) as well as two overcurrent protections in the neutral point

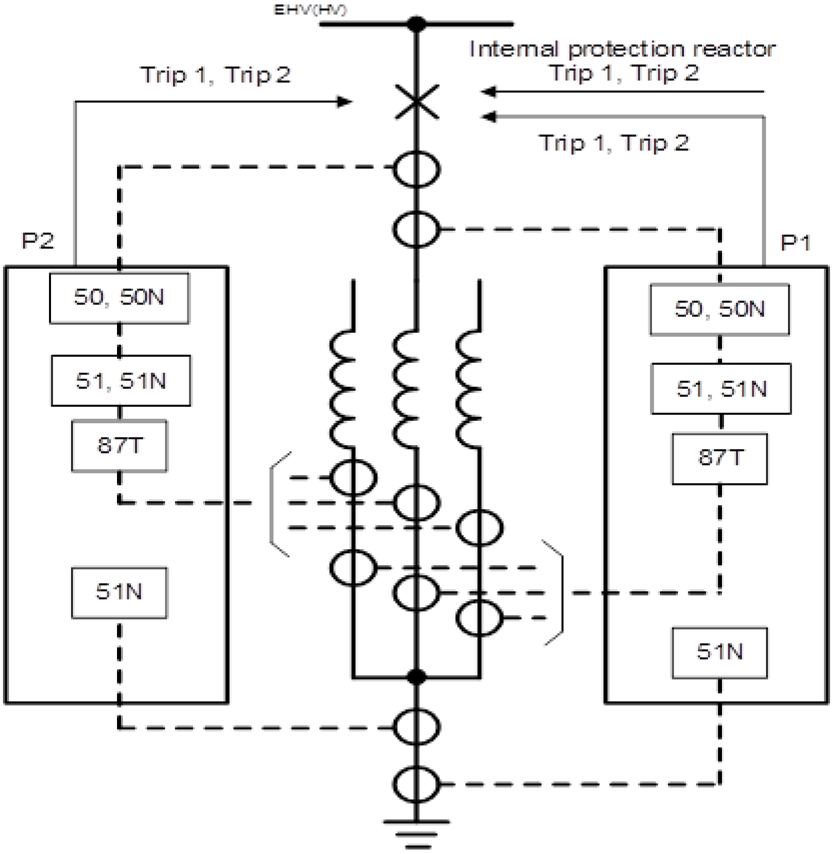

Figure I Example of a protection system proposed for a shunt reactor (indicative)

17.2 Aspects to be considered when choosing the protection scheme functions for a shunt reactor

The recommended protection functions for faults producing large increases in magnitude of phase currents are: the high impedance differential protection, the low impedance differential protection, the restricted earth-fault protection, the phase and earth-fault overcurrent protection and the distance protection.

In comparison with the high impedance differential protection, the low impedance Kirchhoff differential protection offers the following advantages:

- the relay can be applied with a different type of CTs at the reactor HV side and at the reactor star point (the CTs don’t have to be identical);
- no galvanic connection is necessary between the CTs from the HV side and the one at the star point;
- in case of an internal fault, no high voltages will appear in the CT secondary wiring.

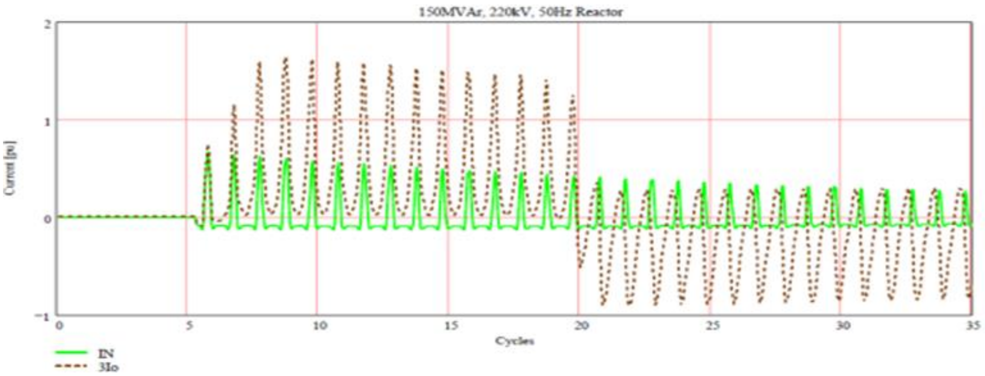

Figure II. Zero-sequence currents during the shunt reactor switching on

The principle of the REF protection consists in calculating the differential current as a difference between zero-sequence currents at the reactor bushings (calculated from the phase currents) and the reactor neutral point current. There are cases where a shunt reactor protection of this type operates incorrectly. The problem arises, as presented in figure II, when one or more phase CTs saturate and a false earth fault current appears at the reactor bushings. Unfortunately, this manifests as the current of opposite polarity in comparison with the neutral point current, which causes the REF to malfunction during reactor switching. For this reason, this protection type may be considered as not sufficiently reliable for the shunt reactors.

A phase overcurrent protection can be a useful back-up in the event of large magnitude internal faults. The protection will be tuned to respond to the fundamental frequency only, and should be set higher than the maximum current that can flow in the reactor during transient condition.

An earth-fault overcurrent protection function is necessary for more common winding to core and winding to tank faults and generally for faults involving earth. The magnitude of the current resulting from this type of fault is dependent upon the location of the winding to ground fault, in relation with the reactor bushing. Bushing failures within or external to the tank can result in significant increases in the magnitude of phase current. A high set earth-fault stage is useful to detect the faults located in the HV bushings vicinity.

For the detection of turn-to-turn faults, the differential protection (low or high impedance type) and the restricted earth-fault protection are not efficient and the overcurrent protections might not be sufficiently sensitive due to the fact that the currents are very small in such cases. A relatively safe protection solution to detect turn-to-turn faults and faults with low current could be represented by the Buchholz relay and the over-current protection on the neutral side of the shunt reactor. As a back- up protection to detect these faults, delayed stages of phase and earth-fault overcurrent with lower current settings could be used.

20 Annex III A possible protection scheme for capacitor banks (indicative)

A possible protection scheme proposed to eliminate the faults related to the capacitor bank is presented in the following Figure:

- Main protections: two overcurrent protections in the HV bay (I>> and I0>>)
- Back-up protections: two overcurrent protections in the HV bay(I> and I0>) and overcurrent protection which measures the current unbalances

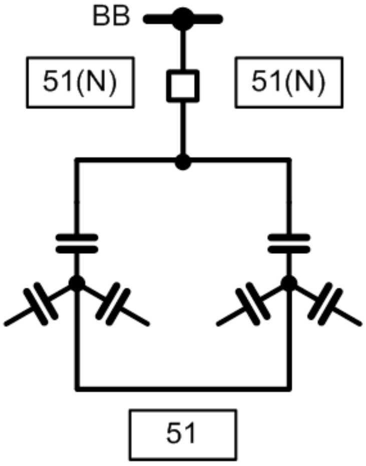

Figure: Example of a protection system proposed for capacitor banks

21 Annex IV: Protection Schema for connection of renewables (Example – indicative; figures are also indicative)

1) Distance protection with impedance starting and differential protection
   - Protection of the transformer and the MV lines
   - The distance protection is additional backup protection for 2), 3) and 4)

   Two separate trip commands are recommended
2) Buchholzrelay
   - transformer protection
3) Differentialprotection
   - transformer protection
4) Time over-current
   - protect the MV busbar with 0.5s delay
   - backup protection for 6).
5) Directional earth fault detection (needs cable type current transfomer)

   - to detect the residual resistive current in huge compensated grids or the capacitive earth fault current in small insulated grids

   - earth fault detection for the machine connected cable
6) Time over-current
   - protect the machine connected cable with 0.1s delay
7) Starting comparison and circuit breaker failure protection
   - Trip in case of starting of 4) and no starting of 6)

   - Switch off the 30 kV breaker at the end of the first tripping time and the EHV breaker at the end of the second tripping time
8) Earth fault monitoring

protection scheme
windfarm-substation