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Avoiding Cascading Protection Tripping in Transmission Systems and Assessment of Quality and Security of the Protection System

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***Abstract*—This paper describes typical developments of blackouts from simple cause to cascading outages. The involvement of the protection system at the beginning and during the enlargement of the incident to the blackout will be shown. Measures to avoid cascading protection tripping will be presented. A new method will be proposed to assess the quality and security of protection systems which can be applied online and offline for systems with up to some ten thousand relays.**

***Index Terms*—Transmission system, blackout, blackout prevention, protection, distance protection, protection systems, cascading tripping, quality, security, selectivity**

I. Introduction

INCREASED consumption of electrical energy in recent decades worldwide has led to an expansion and spatial extension of synchronously operated AC networks and also to higher voltage levels. In Europe, the technical and economic advantages of hybrid operation have resulted in the synchronous operation of neighboring national networks in the UCTE (Union for the Co-ordination of Transmission of Electricity), and the DC interconnection to other asynchronous zones like NORDEL (Organisation for the Nordic Transmission System Operators).

In this way it has been possible to ensure the use of larger (and thus also more cost-effective) power stations, and likewise to reduce reserve power. At the same time, the transmission network has reached maximum possible reliability and availability.

Due to deregulation and privatization the load on the network is currently rising. This entails transmission bottlenecks and a detrimental influence on reliability. In view of global warming and the need to reduce CO_2 emissions, there will be a considerable transformation of the resources used and the energy mix. As the transmission and distribution network structures were adapted in the past to the previous generation and load structures, substantial structural and operational changes to the networks are now called for.

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Large-area outages and blackouts, not only in America and Europe, but also in countries all over the world, show that the operationally and economically favorable interconnection of neighboring networks also entails the risk of uncontrollable failures. In particular, stability and protection problems arise when there are very high loads on these networks in certain areas.

II. Blackouts and How they Occur

What distinguishes a blackout from a system incident?
"The term 'blackout' is used to describe a large-area breakdown of the power supply caused by a fault in the network or in the provision of electricity. By contrast, faults in the local distribution networks only lead to local supply interruptions."

If we assume that the transmission network is in a normal operating state, all equipment is operating within its design limits and the network is stable (likewise well inside its limits), then large-scale incidents always begin with a relatively simple initiating event. This might be a short circuit, the outage of a piece of equipment or the scheduled trip of a line. Now, if relays isolate the short circuit fast and selectively, or if correct operator decisions follow, the network will be able to return to a normal operating state. If this is not the case, cascading failures can occur.

This has been the case with a blackout in Italy, for example, where relay synchrocheck settings were wrong and prevented the automatic reclosing of the circuit breaker after distinguishing of the arc and, on top of that, the operators did not reach the right decision to disconnect the appropriate pump load.

The time line of the incident in Italy on September 28th, 2003, is typical for almost all blackouts. After all, a period of 20 minutes lies between the first initiating event and the cascading trippings, and this period could have been used to restore a normal network operating state.

When these cascading failures begin, a so-called 'point of no return' is reached after which the networks disintegrate into islands that can no longer be controlled, in which over- or underfrequency leads to a frequency collapse, or where due to reactive power problems a voltage collapse occurs.

If we compare this Italian blackout with the UCTE incident of November 4, 2006, we see that the UCTE network was intercepted before the 'point of no return' with formation of stable islands and with scheduled load and generation shedding, and that is was returned to the normal operating state within about 30 minutes. The Italian network, by contrast, collapsed into a complete blackout after isolation from the UCTE network.

III. Protection in Transmission Networks

Power system security (stability and protection of equipment) calls for fast and selective clearing of faults. To this end, all network elements are equipped with appropriate protection systems, which detect faults and trip the associated circuit-breakers. A fundamental distinction must be made between main and backup protection.

The main protection responds without delay and trips absolutely selectively; i.e. it isolates only the network components affected by the fault (e.g. transformer or line), thus minimizing its impact.

The classical protection methods are differential protection and distance protection with communication between the ends of the lines (permissive or signal comparison methods).

For safeguarding against protection failure, the main protective facilities in the transmission network are generally based on a redundant design with separate transformer cores, breaking circuits and battery terminals.

Backup protection supplements the main protection for the following reasons:

1. Despite redundancy, failure of the main protection cannot be entirely ruled out. Typical cases might be disasters (e.g. lightning strike, fire or failure of the battery voltage) or hidden hardware and software faults and human errors like incorrect relay settings.
2. Generally, busbar protection is not based on a redundant design; this is for cost reasons, and because the higher risk of overfunction is critical.
3. Circuit-breakers can fail, with the result that the short-circuit current has to be interrupted by upstream circuit-breakers.

Time-graded protection (overcurrent and distance) takes care of backup protection locally or in the neighboring stations.

Remote backup protection, however, is a problem in the transmission network because – with longer protection delay times – unselective trips of a larger area of the network can occur. Moreover, the backup zones must be set to long ranges and thus tend towards overfunction in the event of overload or high-impedance faults.

For each circuit-breaker, the circuit-breaker failure protection consists of a sensitively set current relay and a timer stage. This monitors whether the circuit-breaker interrupts the current within the specified switching time when a trip command is present. If deactivation is successful, the current relay is reset and stops the timer stage. In the event of a circuit-breaker failure, the time will expire and cause tripping of the circuit-breakers in the infeeds.

Thus, a shorter breaking time and improved selectivity are achieved in comparison with remote backup protection.

Overall, the following typical fault clearing times can be expected:

Main protection:	100 to 150 ms
Circuit-breaker failure protection:	300 to 350 ms
Backup protection:	400 to 500 ms in the first grading stage, plus 300 to 400 ms in each further grading stage

The transmission network in Germany is relatively stable, thanks to its distributed power station infeeds.

In compliance with the VDN Transmission Code, only short-circuits in the proximity of a power station need to be cleared in the quick-operating time mode (<150 ms). Delayed disconnection in a second zone with 400 to 500 ms is permissible for remote faults close to the line ends. It has thus been possible in the past to dispense with signal transmission in many cases.

Now, with the arrival of numerical protection and digital communication, differential protection is being introduced for all lines. This enables instantaneous fault disconnection over 100% of the line length.

Generally, the trend in Europe is towards two main protection units with communication in the 400 kV network and at least one protection unit with communication on the 230 kV level. Preference is given to digital line differential protection, which in all fault cases disconnects absolutely selectively and is completely insusceptible to overload and power swings in the network.

Considerably stricter regulations have always applied to extensive networks with long transmission lines. In those cases, doubled line protection with independent communication is the standard.

Thus, the grid code for the Brazilian network, for example, calls for a maximum fault clearing time of 100 ms for all short circuits in the transmission system.

IV. Cascading Protection Tripping

A. In the event of overload

Blackouts, especially in the USA, have shown in the past that the usual settings of the backup zones of distance protection devices can lead to unintentional protection trip overload situations /1/.

In the event of short circuits in the network the distance protection, as detailed in Fig. 1 and /2/, measures the line impedance Z_{LF} up to the fault location and the fault resistance (arc resistance) R_F. This results in the marked area of possible fault impedance.

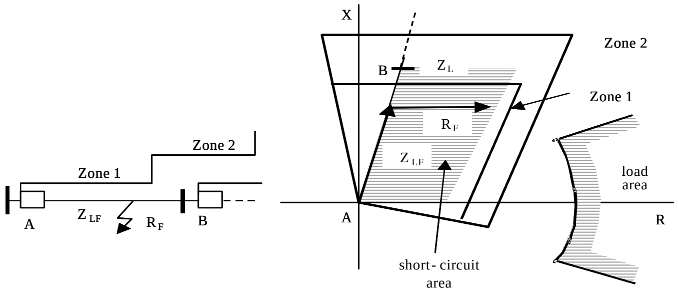

Fig. 1. Load and fault areas in the impedance diagram

In one sector, the impedance measured in the load state appears around the R axis in accordance with the active and reactive power:

$$\underline{Z}_{Load} = \frac{U^2}{S^2} \cdot (P + jQ) \qquad (1)$$

$$R_{Load} = \frac{U^2}{S^2} \cdot P \quad \text{and} \quad X_{Load} = \frac{U^2}{S^2} \cdot Q \qquad (2)$$

To clearly distinguish between the load and short-circuit states, the distance zones should cover the expected fault resistance values, but must not protrude into the zone of the load impedances, i.e. the boundary in the direction of R must pass between the fault and load ranges with a safety margin.

In the course of system incidents involving increased line disconnection operations, increased loading of certain transmission lines occurs, frequently accompanied by a voltage drop due to reactive power problems. Fig. 2 shows the distance protection measurement of the Sammis-Star line during normal operation and during the blackout in Canada/USA in 2003. It can be seen how the impedance moves into the relay's trip area due to increased reactive power transmission almost in parallel with the imaginary axis.

In previous protection practice, setting of the protection was coordinated to the permissible thermal load of the line so that there was at least a reserve for increased active power transmission.

However, if large-scale incidents occur, the continuous thermal load can be exceeded, giving rise to tripping. The even stronger load on the remaining lines can then lead to a cascade of further tripping operations /3, 4, 5/.

In this connection, the circuit characteristics of the electromechanical relays are particularly critical because the R range cannot be set separately and, instead, it rises proportionally with the increase in the X range. Thus, if lines are long, this distance protection becomes very sensitive to overload.

The MHO circuits, which are preferably used in protection practice in English-speaking countries, are a typical example. They have contributed to a blackout in several large-scale incidents, as is shown in Fig. 2 /6/.

After an investigation of the blackout in 2004, the North American Electric Reliability Council (NERC) issued the following recommendation /7/:

Zone 3 (the most distant set zone) should not trip until 150% of the line's thermal limit current, 85% of the rated voltage and a load angle up to +/-30^{O} are reached. This requirement is intended to ensure exploitation of the lines' thermal short-time overload capacity for 20 minutes (response time of the network control centers).

As a consequence of this recommendation, in the USA several thousand relays had to be readjusted and, in a series of cases of older relays, the third zone had to be shut down.

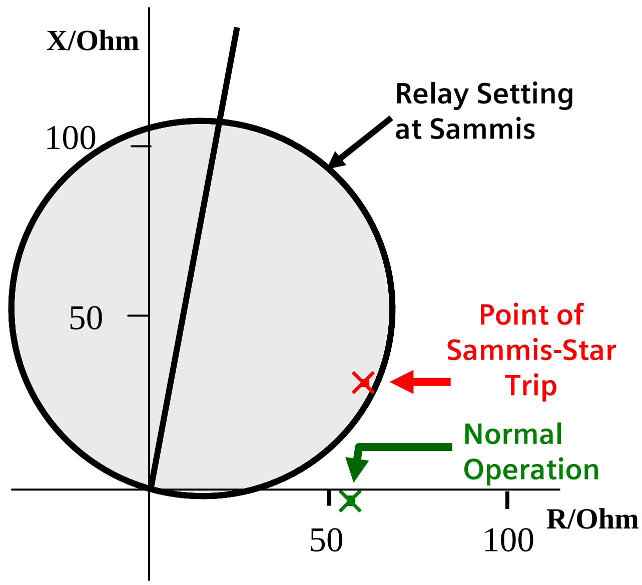

Fig. 2. Distance protection tripping in the event of overload (USA/Canada blackout in 2003)

The demands in terms of higher load carrying capacity can nowadays be met with digital technology. Modern relays are adjustable within wide limits and permit flexible design of tripping characteristics. On all common relays, a special load blocking sector can now be set that permits a high overload with large zone ranges, too.

B. In the case of power swings in the network

Stable and unstable power swings can arise from switching actions and also from the disconnection of network faults. These power swings can lead to situations in which the impedance measured by the distance protection runs through one or more protection zone(s). The relays will open the circuit-breaker according to the zone's set delay time. The result of this, however, is that the distance zones set selectively for a short circuit now lead to random disconnections from the network. In the past it was possible to tolerate this thanks to the high degree of meshing and the (n-1) - to (n-3)-safe network structure of the German transmission network.

Due to the expansion towards the UCTE network, the overall system, as studies show /8/, is becoming increasingly capable of oscillation with modes of increasingly lower frequency and reduced damping. The unscheduled load flows made inevitable by energy trading are an additional factor, as at present these can only be controlled to a limited extent. The resulting extremely high capacity utilization of certain network corridors will no longer permit this random disconnection in the future, because this could be the start of cascading tripping.

The following figure shows typical trajectories of a stable oscillation with which disconnection from the network must not occur, and an unstable oscillation, with which disconnection should take place.

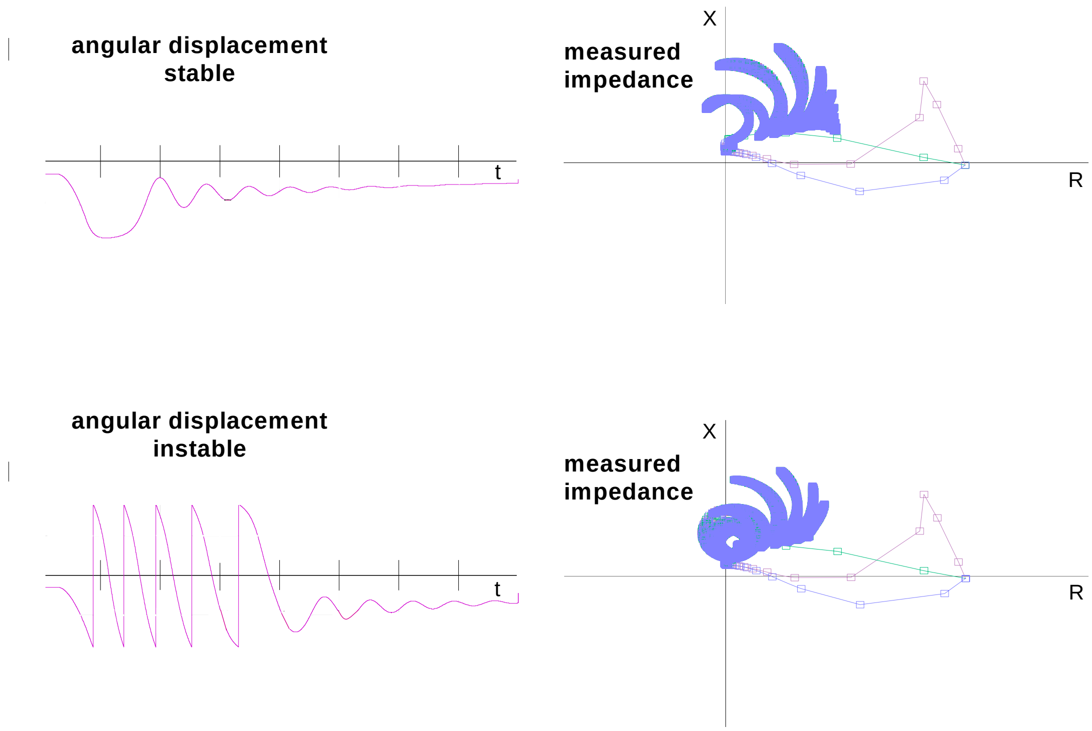

Fig. 3. Stable and unstable oscillations with rotor angle and the impedance profile measured on one line in the system

V. Avoiding Cascading Protection Tripping

Cascading protection tripping, and also protection tripping due to the causes described in the previous sections, can be avoided. In the design and calculation of the relays' settings, initially a clear distinction must be made between various network situations such as normal operation, overload, stable and unstable oscillation, and also short-circuits.

A. Dynamic overload limit

Nowadays, setting the overload protection usually is still oriented towards the thermal continuous load capacity of the equipment at a specified ambient temperature. Thus, possible reserves existing under favorable ambient conditions and a low prior load are not fully exploited .

Modern monitoring systems and numerical relays make it possible to exploit the dynamic load carrying capacity of the equipment /9/, which is explained in the following example of thermal protection of overhead lines.

The maximum permissible sag of the line between towers influences the thermal limit of an overhead line. It essentially depends on the ambient temperature, wind velocity, insulation and the characteristics of the conductors.

Today, a constant load carrying capacity that is based on worst-case conditions is almost exclusively assumed. It is a standard for the network control center so that the permissible sag is not exceeded.

From the past, overload protection consists of separate O/C-relays or, as in Germany, the O/C pickup stages of distance relays with a delay of a few seconds (end time tripping).

By measurement /10/, it has been found, that the load carrying capacity of the lines fluctuates considerably and, over hours, can amount to more than twice the static load value, as shown in Fig. 4.

A value of the order of 20 minutes was determined as the thermal time constant /11/. From this we can see that the conductor temperature in the event of overload rises relatively slowly and that, if the prior load is low (low initial temperature), there is a reserve of multiples of 10 minutes before the limit temperature is reached.

Modern sensor technology permits online monitoring of the relevant influences (pull forces, ambient conditions and conductor temperature) and continuous calculation of the short-time load carrying capacity. With this information, it can be pointed out to the network control center, for example, that the power of a particular line can be increased by 400 MVA for 10 minutes, 200 MVA for 20 minutes or 50 MVA for 60 minutes. Appropriate measuring equipment and monitoring systems have been available for some years /10, 11/. Pilot applications have been reported /9, 11/. In this way, in an emergency, line capacities can be dynamically exploited to a much greater extent.

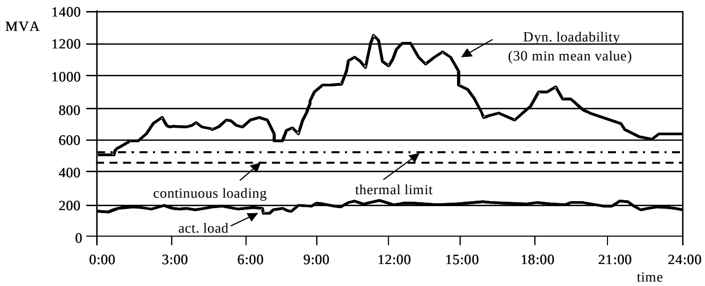

Fig. 4. Dynamic load carrying capacity of overhead line, results of measurements

The setting of the distance relays, however, must be adapted to the maximum short-time load /12/.

The NERC recommendation mentioned above (150% of the thermal limit current for 20 minutes) already considers a higher dynamic load. It must also be noted that the overload capacity of current transformers (CTs) has to be checked, because most CTs are only designed for 20% overcurrent.

B. Use of power swing blocking

For future protection of the transmission networks, a method is proposed here that (currently) is already being used by some UCTE members such as Transelectrica (Romania). It consists of a dedicated system for short-circuit protection and one for out-of-step protection. With the computing capacity of numerical protection relays, besides others, short-circuit, overload and out-of-step protection can be realized in one single device. As standard, these devices possess so-called power swing blocking that can distinguish clearly between a short circuit with a very fast impedance change dZ/dt and a power swing with a comparably slow impedance change dZ/dt and clearly observable swing trajectories. This functionality can be used for both distance protection and out-of-step protection.

1. Distance protection is selectively coordinated and parameterized as short-circuit protection.
2. Distance protection zones are blocked when a power swing is detected.
3. The optimum disconnection points in the event of power swings have to be determined by network studies.
4. Out-of-step protection, which opens the line only when a power swing is unstable, is parameterized at these specific points.
5. Coordination of distance and out-of-step protection can be ensured by using identical device algorithms for distance and out-of-step protection.

C. Automated protection security assessment

The so-called online or offline Protection Security Assessment (PSA), realized in the Siemens SIGUARD® as SIGUARD®–PSA is an important component in the avoidance of blackouts. Based on the current switching state of the network, a computer-assisted and thus automated analysis of the network and generator protection system's selectivity can be carried out. The functions of relays used, their characteristics and settings, and communication between the devices are, of course, also simulated. Using PSS®SINCAL as engine, all conceivable types of faults can then be automatically placed at locations moving through the entire network, and pickup and trip of the relays are simulated and evaluated in relation to, e.g., selectivity aspects /16/.

The diagram in Figs. 5a and 5b shows the extensive result data of a complete protection tripping simulation in a specimen network with 23 lines (Y axis), printed with 100% line length (X axis). The short-circuit moves through the entire network on all 23 lines in the grid, in steps of some percent of the line length (X axis).

As an example, the backup O/C protection has been evaluated for an existing transmission system. The used relay characteristics in the system under evaluation are all inverse time characteristics. Graphical evaluation is performed according to the criteria of fault clearance time (color code light blue to red), non-selective tripping (dark blue) and no trip (white). Thus, the behavior of the overall protection system can be checked and assessed at a glance. Weak spots, such as non-selective tripping, can be investigated in greater depth and the selectivity can be reached by adapted settings, e.g. by

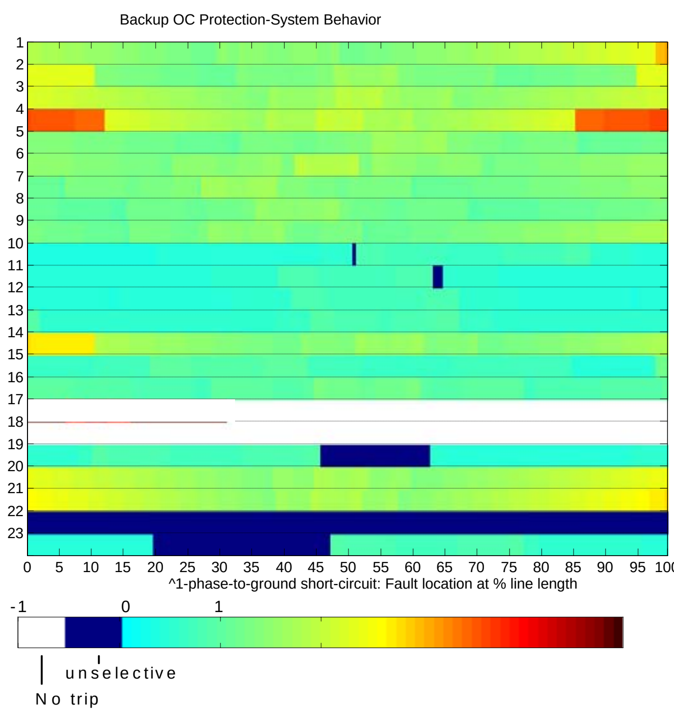

Fig. 5a. Graphic illustration of the security assessment results for the backup protection system with actual settings and characteristics in a transmission network

the use of expert systems /17/. Fig. 5b shows the result that can be obtained. All short circuits on all lines can be isolated selectively, except for on 2 lines, where the backup protection relays never trip. Detailed analysis shows that the installed backup O/C relays on lines 17 and 18, in combination with the high current transformer ratios, cannot be set to the necessary low pickup values. The relays have to be exchanged by new relays with a higher sensitivity.

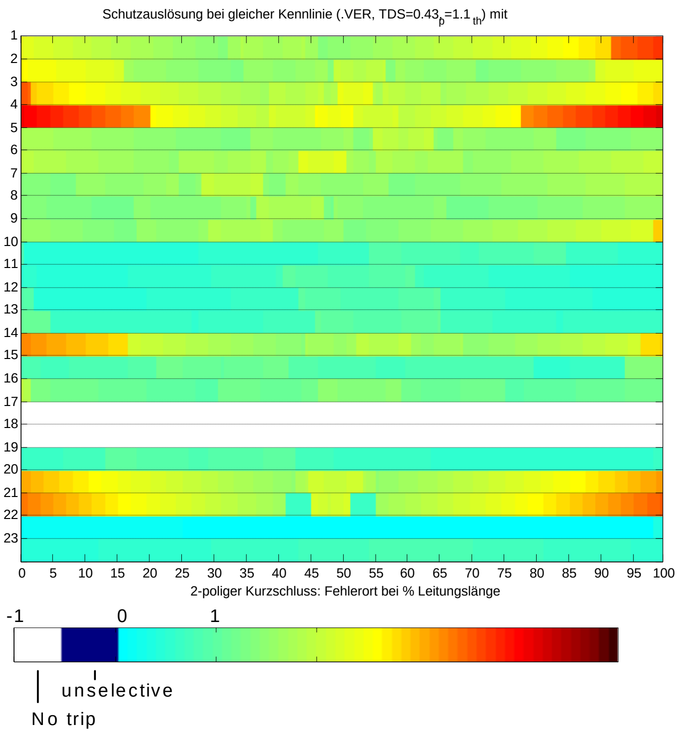

Fig. 5b. Graphic illustration of the security assessment results for the backup protection system with adapted settings and characteristics in the same transmission network

VI. CONCLUSION

Experience from evaluations of incidents and blackouts shows that cascading protection tripping occurs with highest probability when the transmission network is in a state of emergency and the equipment is loaded to its limits. A large number of such protection tripping operations is caused by the often inadequate separation of the protection functions for short-circuit, overload and out-of-step protection when designing and parameterizing the protection system.

It has been shown which methods can be used to handle these three mutually independent network phenomena with mutually independent methods of protection in order to avoid unintentional protection tripping.

Further protective measures can be necessary in addition to this optimization, but these have not been dealt with here.

In critical situations, networks must be relieved in good time by undervoltage and underfrequency load shedding. In stability-critical networks, cross-network protection systems so called “wide area protection systems”, “special protection schemes” or “system integrity protection schemes” must also be considered. These exploit the high-speed transmission of data by modern broadband networks to gather selected network data such as synchronous voltage phasors, and also central or decentralized evaluation in real time. If stipulated limit conditions are exceeded, programmed deactivation or changeover operations in the quick-operating time mode by remote control, within the range of seconds, can be triggered before the network control center can respond in the ten-minute range. This has been discussed on a worldwide scale for some time now and a few simple systems are already in operation /18/.

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VIII. BIOGRAPHIES

Rainer E. Krebs, born 1958 in Germany (member of VDE, CIGRE, IEEE, IEC and DKE), received his Dipl.-Ing. degree from the University of Erlangen in 1982. From 1983 to 1990 he worked as an assistant professor at the Institute for Electrical Power Supply at the same University. In 1990 he received his Dr.-Eng. degree in Electrical Engineering. 1990 he joined Siemens AG, Power Transmission and Distribution, System Planning Department. Since 1998 he is director of the System-Protection and System-Analysis Tools Department and since 2006 he is 'Principal Expert for Power Technologies'. In parallel he started in 2003 as lecturer at the University of Magdeburg. Since 2008 he is honorary Professor for System Protection and Control at the same University.

Gerhard Ziegler was born in 1939. He studied at the University in Munich and has then been working in the area of power system protection with Siemens in Erlangen/Nuremberg, Germany for a period of 35 Years. He was world-wide active in sales and application of relays. He has published numerous papers and contributions to conferences. He is the author of books on Differential and Distance Protection. He is past chairman of CIGRE SC34 Protection and Substation Control. He retired in 2002 but is still active as consultant for power system relaying.

Johann Jäger was born in 1964 in Erlangen, Germany. He received the Dipl.-Ing. and Dr.-Ing. degrees in 1990 and 1996 respectively in Electrical Engineering and Power Systems from the University of Erlangen. In 1990 he joined the Institute for Power Systems at the same University working on the analysis and calculation of FACTS-devices. From 1996 he was with the Power Transmission and Distribution Group and the System Planning department at Siemens AG in Erlangen, Germany. He was working on different fields of network planning and protections in worldwide projects. Since 2004 he is in charge of a full professorship for Power Systems at the University of Erlangen. He is member of VDE/ETG, IEEE and CIGRE as well as convenor or member of several national and international working groups.

Florin Balasiu, Director of the Protection and Automation Management Division of the Romanian Power Grid Company – Transelectrica.
He has an engineer diploma in Electrical Engineering from Polytechnic University Bucharest, Romania, 1979 and a Ph.D. diploma from Polytechnic University Timisoara, Romania, 1997.
He has almost 30 years of experience in the area of Transmission and Distribution protection and control systems engineering, commissioning and maintenance. He is an observer member of CIGRÈ, Study Committee B5 – protection and automation and has authored over 30 technical papers on protective relaying and is co-author of a Hand Book on Numerical Protection devices.

Felicia Mihaela Lazar, Chief Inspector for System Safety Romanian Power Grid Company –Transelectrica Bucharest – Romania. Diplomat engineer from 1981 when graduating from Polytechnic University Bucharest – Electro energetic Department. From the beginning of 1984 activated as an engineer in the Protection and Automation Department from National Dispatch Center. In 1994 gained the Expert in Protection and Automation position in the above mentioned department. In March 2002 was appointed as Head of Protection & Automation Department in the Romanian National Power Grid Company - "Transelectrica" S.A. From January 2009 was appointed in the position of Chief Inspector for System Safety.