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Protection Security Assessment for Large Power Systems

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***Abstract*-- Protection security assessment is an important task in nationwide power systems maintaining network security under changing network conditions. It can be reached preferably by a software assisted method of analysis which is presented in this paper. Existing protection systems have to be analyzed and checked under higher loading and contingency conditions. Adapted protection concepts should be evaluated applied to the network. Nowadays numerical simulation tools like PSS®SINCAL provide the possibility of a holistic simulation of network and protection behavior. This paper is presenting the proposed method of analysis and gives some results applying this method on a real transmission system.**

The collection of protection and network data has been done on the basis of data plausibility algorithms firstly. Numerous different network contingencies were investigated. The software assistance and the visualisation of the enormous amount of output data are described. Generic network and protection configurations leading to maloperation can be clearly detected.

***Index Terms*-- Holistic simulation, network security, protection coordination, protection security assessment, systematic protection check-up**

I. Introduction

THE complexity of power systems is increasing worldwide because of permanent network extensions and ongoing interconnections. Additionally the infeeds of distributed and renewable generation is requiring an increased transmission capacity and stability requirements in power systems. An important factor for blackout prevention is a regular review and if required an adjustment of the protection coordination concept [1,2]. In the field of transmission networks, protection coordination is developing more and more towards a task of handling nationwide power systems under continuous change and with numerous protection devices preferably graded by software tools. The aim of the presented protection coordination task was to analyze the condition of the protection equipment, to evaluate the used protection schemes and to check the selectivity of the protection system. Based on the identification of bottlenecks adapted settings should be derived improving the protection behavior under the changing network conditions. This leads to an important enhancement of the network security.

II. Individual Protection Coordination Steps

The proposed method of investigation needs different steps. These are illustrated in Fig. 1. The study begins with performing a network and protection data base by data collecting and data structuring work followed up by data plausibility checks. The contingency simulation is based on a system model including the network and the necessary protection functionality which is provided by PSS®SINCAL as a whole.

Fig. 1. Individual steps of protection security assessment

A. Data Collection

The data collection comprises data of primary and secondary equipment. Whereas the primary data collection is state of the art, the secondary data collection is a rather new challenge caused by its high number of devices and the high variety of types and manufacturer specific performances. Thus at the beginning a proper data structuring based on physical relay models is an indispensable step of this task.

In the protection data base all necessary details about the settings and the technical data of protection devices are collected. Each relay is assigned to one element (line, transformer, shunt reactor etc.) and has his individual parameters such as current or/and voltage transformer ratio, type of tripping characteristic, time delay, release current etc. Furthermore in each file it is possible to work with different setting groups. It enables the simulation and comparison of varied setting configurations.

B. Plausibility Check

Because of the big amount of data and to make the results of the study reasonable, a software assisted data plausibility check is necessary. With use of logic routines e.g. the settings of relays can be checked. Different levels of data checking are applied as the physical range check, the comparison with common setting strategies as well as the relay type requirements

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and the crossover check with other devices. During this procedure obviously wrong settings can be detected, reported and corrected. In addition missing data are retrieved and can be completed. The quality of these data checking routines is mainly determining the quality and reliability of the study results. Thus this step should be carried out by high diligence.

C. Contingency Simulation

In advance of the contingency simulation, the contingency scenarios of the network to be studied must be defined. These are dependent of the operation methods and operational scenarios of the network which must be discussed in close cooperation with the TSO. The contingency scenarios, that means e.g. which lines or transformers can be switched off or can be overloaded unexpected, must also be found with the TSO.

The use of automatic batch routines of the simulation software makes it possible to simulate different contingency scenarios without making any time-consuming manual changes in the data base of the simulation software. An appropriate method of the contingency simulation is the so called "running fault method". Here the behavior of protection system is routinely tested by the variation of fault locations through the entire network. Faults will be done on each line of the network e.g. in steps of 2% of the corresponding line length. In this way the fault is running effectively through the whole network. The simulation system calculates the response of all protection devices on each fault done in the network. The running fault method will be applied to different contingency scenarios

D. Evaluation of Results

The applied methods of contingency simulation are producing a big amount of output data. To use the whole information content of these data, appropriate evaluation methods are essential. Firstly the results will be previewed and reorganized by macro technique. This leads to a limitation and separation of relevant and irrelevant information. The human perception is mostly capable of processing graphical prepared data. That is why, beside a pure software assisted evaluation of the correctness of the protection responses, a graphical illustration has been developed to provide the whole relevant information to the operator at a glance. Evaluation criteria can be e.g. fault tripping at all, selective tripping, tripping in the first zone, tripping below a certain time limit etc.. This is depending on the requirements of the TSO.

E. System Improvement

The previous evaluation step shows clearly the bottlenecks of the protection system applied to the network to be investigated. The protection settings or protection functions can be adapted systematically achieving an improvement of the protection system behavior. The advancement as well as the worsening of such measures can be verified by re-simulation of the system. A solution which fulfills all requirements can not be found normally. But the best compromise of the protection behavior with regard to the network is achievable.

III. CASE STUDY

In order to assess the protection security in real transmission networks and checking a proposed protection coordination concept, a simulation environment was set up. Embedded simulations were carried out using the standard mathematic software MATLAB® in combination with the practice-proven power system planning and simulation software PSS™SINCAL [3]. The latter one was used for power flow, short-circuit and stepped-event protection simulation. PSS™SINCAL's protection device database includes all commonly used protection characteristics and relays from various manufacturers. Data is stored in an open MS Access database and is completely editable via a standard Open Database Connectivity (ODBC) interface. This enabled efficient batch-processing of the large-scale computationally intensive protection simulation.

A. Basic O/C-Characteristics

In this study the back-up overcurrent protection (O/C) will be checked exemplary. The standardized ANSI and IEC characteristics are commonly used. To set their pickup current I_p and their time multiplier T_p two basic setting-rules are essential:

1. Because the range of inverse operation of ANSI/IEC characteristics is between I_p and $20{\cdot}I_p$, T_p can be calculated at $20{\cdot}I_p$, regarding a minimum tripping time $t_{p,min}$ to be given from the coordination with unit protection devices.
2. I_p depends on the thermal limiting current $I_{th,min}$ of the weakest transmission line multiplied by a security factor s (1).

   $$I_p = s \cdot I_{th,\min} \tag{1}$$

   With this approach lines with higher loadability $I_{th} > I_{th,min}$ need individual pickup values $I_{p,ind}$ considering the higher thermal limiting current (2).

   $$I_{p,ind} = s \cdot I_{th} \tag{2}$$

   The characteristic of these lines will be cut off from the left side to prevent false tripping under load cases (Fig. 2a).

Reference [4] describes a non-standardised logarithmic characteristic. Its advantages are a user-defined wider range of inverse operation and a better performance regarding selectivity. The logarithmic characteristic is defined by (3)

$$t = a \cdot \log\left(\frac{I}{I_p}\right) + b \tag{3}$$

The basic setting-rules for the parameter I_p and b can be comparably adopted considering the wider range of inverse operation (Fig. 2b).

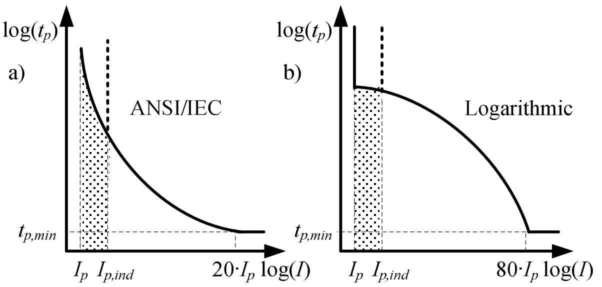

Fig. 2: Exemplary O/C characteristics

The choice of slope a such as the choice of concrete ANSI/IEC characteristics depend on the maximum tripping time to be allowed. It can be observed the steeper the gradient of the characteristic the higher the maximum tripping time and the better the performance regarding selectivity. In this study both characteristics will be investigated comparatively.

B. Program Sequence

For protection coordination examinations of an existing network model, faults have to be placed on every transmission line by hand. Detailed fault conditions can then be manipulated via ODBC by MATLAB® as described above. Knowing the exact assignment of lines and protection relays as stored in the database, a loop algorithm moves the fault location from one end to the other of all transmission lines. For each loop the simulation software is automatically started by the Windows Scripting Host to do the stepwise fault clearing calculations. The results come back to MATLAB® by ODBC to be further processed. In this way detailed information about selective fault clearing of each "moving fault" can be generated and illustrated.

C. Visualisation of Simulation Results

The different transmission lines are plotted on the y-axis whereas the x-axis represents the fault location related to line length. The colour value at every single point expresses the selective fault clearing time for a fault at this location. Moreover there are two special conditions: a white bar with two lines indicates non-cleared faults and a black-white bar represents unselective fault clearing. In this way protection coordination of widespread networks can be visually captured and assessed in one diagram (Fig. 3 to 6).

D. Case Study Results

A real transmission network was chosen and implemented in the simulation software. It is fed by three infeeds (short-circuit power S_{sc1}"= 1000 MVA, S_{sc2}"= 5000 MVA and S_{sc3}"= 133 MVA) representing adjacent transmission networks and by four power plants (rated power S_{rG1} = 465 MVA, S_{rG2} = 4210 MVA, S_{rG3} = 281 MVA and S_{rG4} = 281 MVA).

Except of three radial feeders, the network is meshed and consists of 23 transmission lines. Twenty lines are double-circuit lines and three are single-circuit lines. Four line types are applied (Table I). The network is solidly earthed.

TABLE I
APPLIED LINE TYPES

No.	Name	R'[Ω/km]	X'[Ω/km]	I_{th} [kA]
1.	GOOSE	0.1043	0.4231	0.580
2.	COOT	0.0430	0.3108	1.250
3.	REDWING	0.0448	0.3031	1.250
4.	XLPE Cable	0.0287	0.1830	0.884

For phase-to-phase faults O/C relays play the role of the final reserve. They are typically non-directional (51). From the suitability performance assessment the IEC Very-Inverse O/C-characteristic and a logarithmic O/C-characteristic from [4,5] are studied further on. According to the basic setting-rules the parameters for the tripping characteristics at each line type are summarized in Table II.

TABLE II
SETTING PARAMETERS FOR THE IEC VERY-INVERSE AND THE LOGARITHMIC CHARACTERISTIC FOR EACH LINE TYPE ACCORDING TO TABLE I

No.	s	I_p [kA]	$I_{p,ind}$ [kA]	T_p [s]	a	b [s]
1.	1.1	0.638	0.638	0.43	-3.61	5.0
2.	1.1	0.638	1.375	0.43	-3.61	5.0
3.	1.1	0.638	1.375	0.43	-3.61	5.0
4.	1.1	0.638	0.972	0.43	-3.61	5.0

Thereby the range of inverse operation is between I_p and $20 \cdot I_p$ for both characteristics and the minimum tripping time is assumed to be 0.3s.

Fig. 3 and 4 show the results. Selectivity can be ensured for almost all fault locations. For faults on lines 10, 19, 22 and 23 unselective tripping can be observed, i.e. more than two main relays tripped during the clearing time interval.

However the logarithmic characteristic can also clear line 19 selective but on average the clearing time is higher. On lines 17 and 18 the main O/C relays failed to clear the faults.

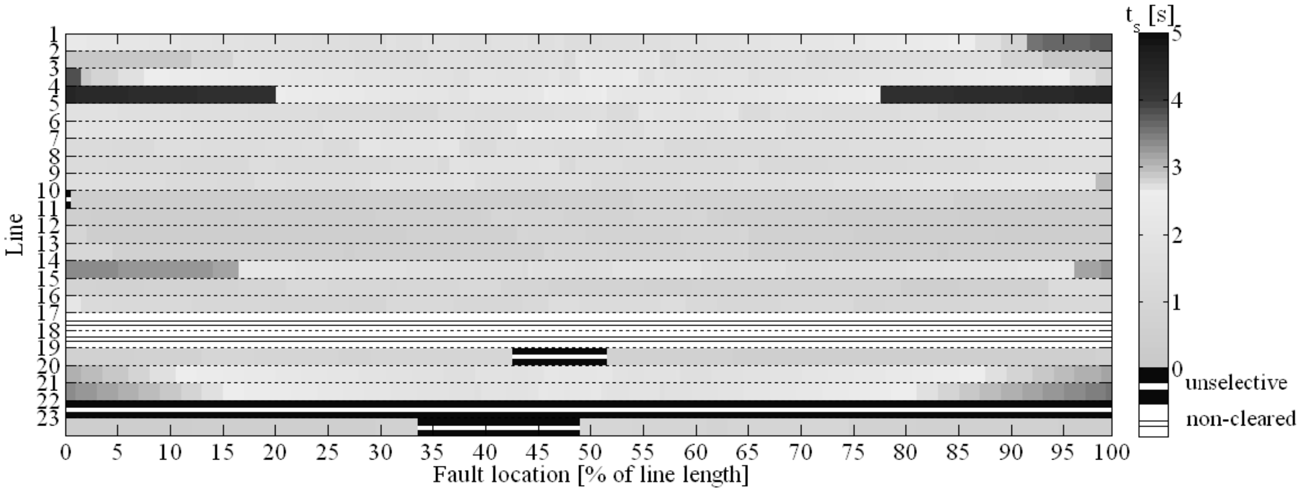

Fig. 3: Fault clearing chart with IEC Very-Inverse characteristic for phase-to-phase faults

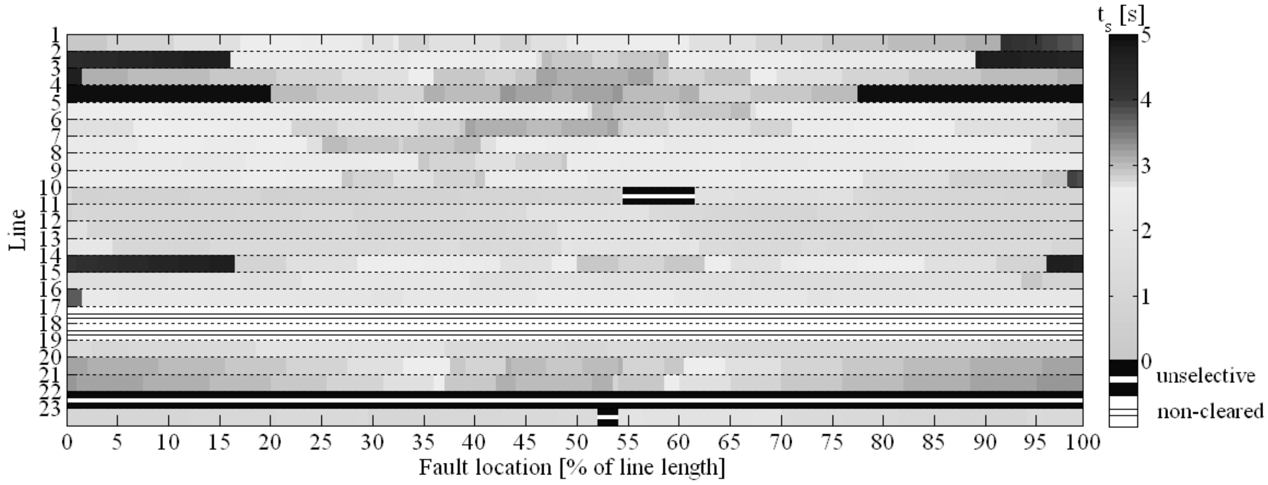

Fig. 4: Fault clearing chart with logarithmic characteristic for phase-to-phase faults

Line residual O/C relays are necessary as back-up protection for remote phase-to-earth faults and as protection against high resistance faults not detected by distance relays. They are typically directional (67N). The same characteristics as for phase-to-phase faults are studied.

Since a balanced operation causes no residual current the pickup current I_p can be adjusted more sensitive and equal for all line types. I_p is set to $0.2 \cdot I_{th,min}$. According to the basic setting-rules the other parameters for the tripping characteristics are (Table III):

TABLE III
EARTH-FAULT SETTING PARAMETERS FOR THE IEC VERY-INVERSE AND THE LOGARITHMIC CHARACTERISTIC FOR THE LINE TYPES ACCORDING TO TABLE I

No.	I_p[kA]	$I_{p,ind}$[kA]	T_p[s]	a	b[s]
1.-4.	0.120	0.120	1.69	-2.0	5.0

Thereby the range of inverse operation is between I_p and $20 \cdot I_p$ for the IEC characteristic and between I_p and $80 \cdot I_p$ for the logarithmic characteristic. The minimum tripping time is assumed to be 1.2s.

Fig. 5 and 6 show the results. One can see the IEC characteristic is less suitable for this concept. That is due to its narrow range of inverse operation and the wider range of the residual short-circuit currents. All O/C relays are measuring a residual current above $20 \cdot I_p$ trip (unselective) at the same time. On average the tripping time with the logarithmic characteristic is higher but selectivity can be ensured for almost all fault cases.

In comparison with Fig. 4 the same lines are in trouble and it is possible to summarise the maloperation of the protection coordination concept to few generic bottlenecks as to be discussed next.

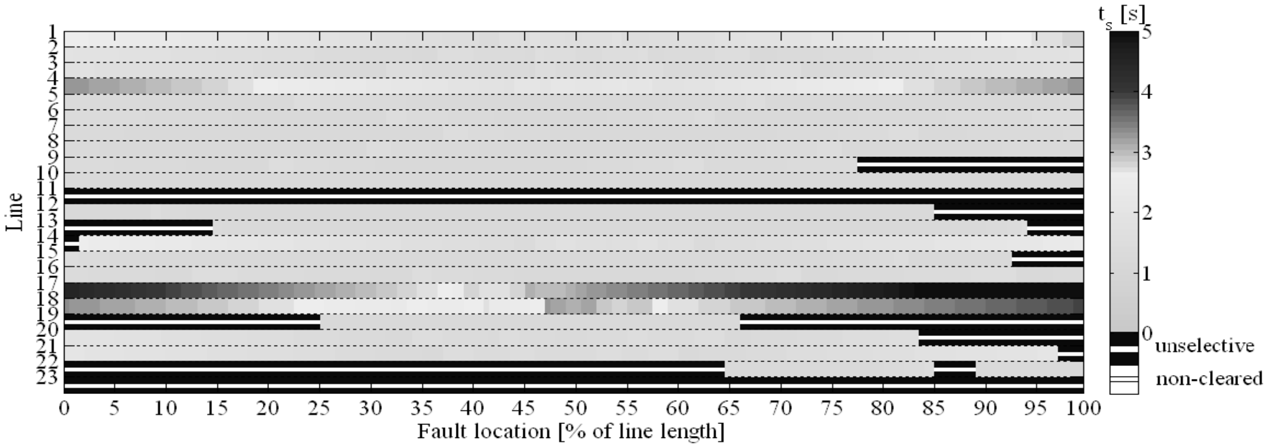

Fig. 5: Fault clearing chart with IEC Very-Inverse characteristic for phase-to-earth faults

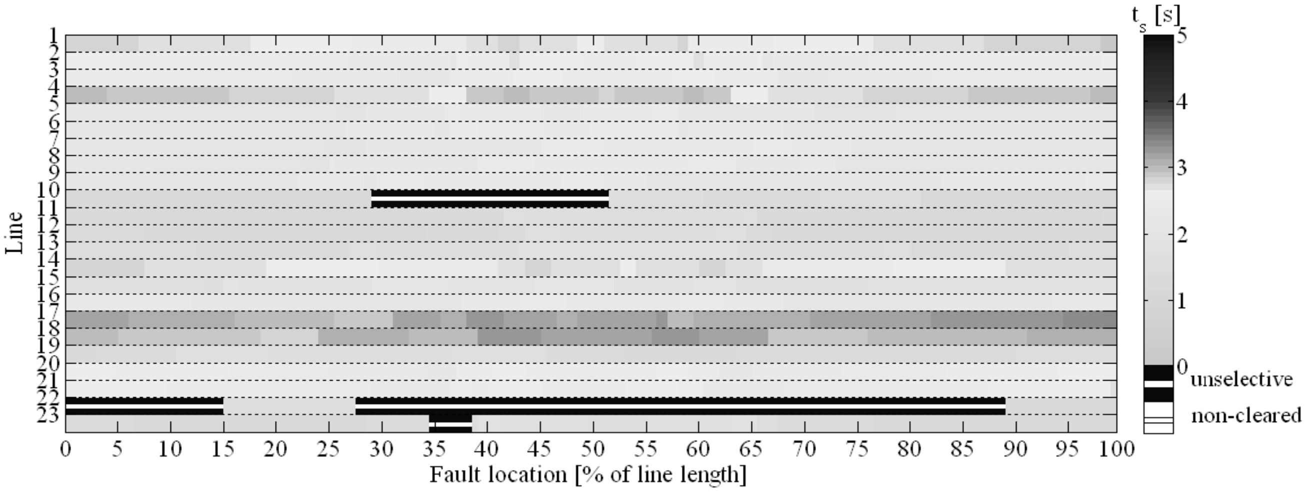

Fig. 6: Fault clearing chart with logarithmic characteristic for phase-to-earth faults

IV. DETECTED GENERIC BOTTLENECKS

A. Passive Radial Feeder

The proposed protection coordination concept ensures selectivity if a required minimum current difference exists. Lines without a local infeed at the remote bus can only be protected selectively if the remote bus has at least three feeders. Otherwise the short-circuit current is sensed equal at all relevant O/C relays (Fig. 7). That is the generic problem for line 22 in case of phase-to-phase faults.

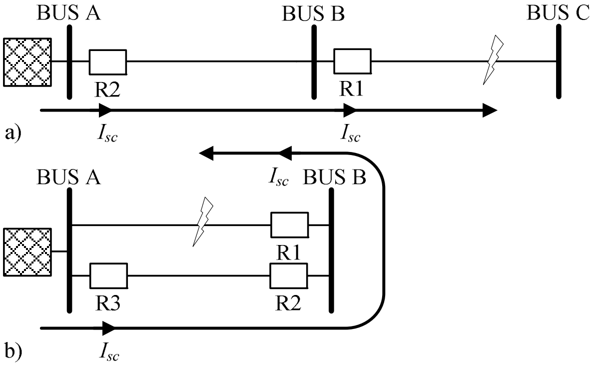

Fig. 7: Passive radial feeder

B. Long Lines with Weak Remote Infeed

However a local infeed at the remote bus does not ensure successful protection coordination. Its contributed short-circuit current must cause the required minimum current difference. That is rather achieved the higher the line impedance and the stronger the infeed. But for very long lines with weak infeed at the remote bus the coordination concept can fail dependent on the fault location if the seen short-circuit current gets below pickup. That is the problem with lines 17 and 18 in case of phase-to-phase faults.

C. Short Double-Circuit Lines with Strong Remote Infeed

A meshed topology must be examined in detail if a bus with high short-circuit power (BUS B, Fig. 8) is connected via a short double-circuit line with adjacent buses (BUS A).

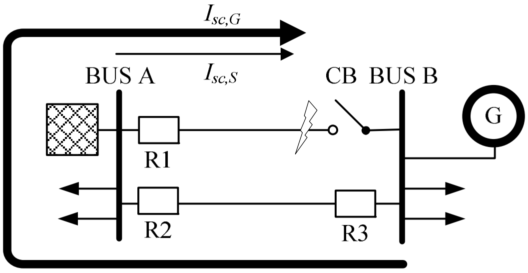

Fig. 8: Short double-circuit line with strong infeed at the remote bus

Despite the required current difference should be sufficient, the strong infeed at the remote BUS B determines the sensed short-circuit current of the relays R1-R2 or R1-R3 to be coordinated respectively after operation of the circuit-breaker CB. The short-circuit current contribution $I_{sc,S}$ of the remaining network at BUS A is decreasing and the required current difference is not sufficient to ensure selectivity after CB has been switched off.

D. Timer Sequence

The previous statements consider the network topology. The dynamic protection simulation with PSS™SINCAL made it possible to detect a practical constraint caused by the timer sequence of the O/C protection devices.

Assuming that after a delayed O/C relay trip, the circuit-breaker is switched off and the short-circuit current is steeply increased due to the changed topology. At this moment the tripping times t_p of the O/C relays are decreasing caused by an increasing short circuit current. However the protection coordination keeps selective as far as the actual timer state T is below the adjusted tripping time t_p . In other case, actual timer state T is above the adjusted tripping time t_p , the relays trip instantaneously and unselectively.

V. CONCLUSION

It could be shown that the protection security can be improved by a software assisted protection coordination method. Different concepts can be checked using only one simulation setup.

The evaluation gives rather reliable results based on real transmission network data. An appropriate visualisation method has been developed to illustrate the enormous amount of output data clearly arranged for further investigations. Based on these visualisation diagrams, practical constraints of protection coordination concepts can be easily detected and systematic solutions can be proposed. In this way a protection coordination concept can be evaluated properly and the procedure as well as the existing bottlenecks can be found clearly. This is fully supporting the protection security assessment in transmission systems.

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VII. BIOGRAPHIES

Johann Jäger received the Dipl.-Ing. and Dr.-Ing. degrees in 1990 and 1996 in Electrical Engineering from the University of Erlangen respectively. From 1996 he was with the Power System Planning department at SIEMENS in Erlangen, Germany. He was working on different fields of FACTS devices, 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 and task forces.

Rafal J. Lubiatowski received his double diploma (M.Sc. and Mgr inz.) in Electrical Engineering at the Wroclaw University of Technology and the Otto-von-Guericke-University Magdeburg. Since 2007 he is working at the University of Erlangen as scientific assistant on field of network protection analysis.

Rainer E. Krebs, born 1958 in Germany (member of VDE, CIGRE, IEC and DKE), received his Dipl.-Ing. degree from the University of Erlangen. 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 (Grad. Eng), born in 1939 and has been working in the area of power system protection with SIEMENS AG in Erlangen/Nuremberg, Germany for period of 35 years. He was active in the areas of product support, application and project planning, marketing and sales, on a worldwide basis. He retired in 2002 but continues to work as consultant. G. Ziegler has published numerous national and international contributions in the area of power system protection. He served in international organizations for many years. From 1993 to 2001 he was the German delegate to the IEC TC95 (measuring relays and protection equipment). He is past chairman of the Study Committee 34 (protection and local control) and Honorary Member of CIGRE.