Operational Security Analysis of Interconnected European Network in Liberalized Market.

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***Abstract* — This paper discusses the problems of operational security analysis in context of a large power system consisting of international boundaries and heterogeneous electrical markets with different levels of liberalization. After analyzing the requirements of the operational security analysis, the paper presents the mechanism, which has been used to make a consistent network model for roughly 20 participating countries. The operational security analysis is split into several sub-problems, which include N-1 security analysis in day-ahead time frame and in on-line mode for operations. The computation of Network Transmission Capacity in advance and optimization of network operating condition in planning or on-line are also facets of the network security analysis. Since the security analysis process is mission critical, a method has been developed using state of the art information technology tools to automate the exchange of model and merge of data models from different participants.**

***Index Terms* — Power systems, network model exchange, congestion management, congestion forecast, power system tools, workflow control, contingency analysis, power industry.**

I. Introduction

The security analysis is a basic function to be performed by the system operator. This function has been historically performed in a vertically integrated electrical utility for snapshot of network state based on forecasted load and unit commitment of the generating plants. With the unbundling of electrical utilities and opening of markets the load forecasting and commitment of generation both are out of influence of transmission system operators. This problem reaches an acute proportion when the interconnected network is very large and transgresses multinational boundaries. This paper discusses basic problems and details experiences gained in making a comprehensive security analysis package when the system under consideration is a small part of the large system.

The proposed work first categorizes the network security problems from time and user perspective and then discusses the criterion, which were instrumental in choosing the solution. It is followed by the implementation experience.

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II. Network Security

The network security is composed of several sub-problems, which can be seen from the end user perspective and the time when it is operated. The four specific user groups within a Transmission System Operator (TSO) will look for network security in terms of long term planning, day ahead and on-line time frames. The specific requirements of these groups are briefly discussed in next section.

A. Net Transmission Capacity

The Net Transmission capacity (NTC) is a crucial security aspect in interconnected power system. The transits could be much more dominant for the network than the power flow caused by own loading and generation pattern. The European Transmission System Operators (ETSO) recommends a method to compute the NTC [1]. One of the major problems in determining NTC in planning phase is that due to very high degree of interconnections in the network, financial transactions and physical transactions could be far away from each other.

B. Long-Term Planning and Optimization

In the long term planning view it is seen more in terms of transmission reliability where expected load and generation patterns can be simulated to see the N-1 security criterion. Since the flows can vary over large fluctuation, the long term planning is more conservative in nature. In power industry brute force methods for simulation methods such as Monte Carlo have been used to determine the network security in long-term analysis [2], [3].

C. Day-Ahead Congestion Forecast

Most of the electricity markets require a day ahead scheduling system in the interconnected European system. Based on day ahead scheduling process of consumption and exchange with neighbors the production is planned and reported by the generators to the system operators. This input along with the planned network topology would give load flow situation and each of the planned points. If planning interval is one hour, the day-ahead scenario will contain 24 hourly snapshots, which will be basis of congestion forecast. The Day-Ahead Congestion Forecast (DACF) calculation rules [4] base upon the recommendations of DACF group and are also part of UCTE Operational Handbook [5].

D. Online Congestion Management

Due to differences in financial and physical transactions the on-line operation may show up some congestion, which was latent during planning phase. In the on-line congestion management the operator has to take measures to prevent such congestions. The basic mechanisms involve changes in network topology or shifting the generation location to relieve the congested part of the network. In the liberalized market this shifting of generation is based on financial incentives offered to generating companies.

III. Congestion Management in Large Interconnected Systems

Being situated in the middle of a highly meshed European network referred as UCTE (Union for Coordination of Transmission of Energy), Swiss network has transit flows, which are influenced by the international energy trade. The Swiss network takes a significant part of the total energy flow towards southern border loading its parts close to their physical limits. Under these circumstances it is very important to have a realistic congestion forecast and management system, which is not only computationally robust, but also utilizes the most recent information of the planned network status for the forecast period.

To achieve this goal, the congestion management process was established under the lead of ETRANS, which is the independent system coordinator of Swiss Transmission system. The process includes information collection and congestion forecast, followed by establishing the alleviation measures and their application [6].

A. General Concept

It is the ability to collect and use the most actual data and to reject the data that are erroneous or suspicious, that leads to stable trustworthy congestion forecast information, and corresponding alleviation measures.

To perform this function it is not sufficient to develop and took into the operation the corresponding software. The processes, involving the number of system operators in different countries, as well as wide number of internal and external systems, must be settled.

Congestion management system can be seen in the middle of the energy management process, utilizing the data from the Scheduling Management System, Topology Management System and network models provided by UCTE partner TSOs, and delivering the information to the own Network Control Center, surrounding systems and partner TSOs (Fig. 1.).

B. Main design aspects

The data model for medium and long-term elements may have elements, which do not exist in the current model. The known and planned extensions of the power system have to be modeled.

As close to the network model we reach in the on-line time frame, the data quality of own network improves. The state estimation provides an error free, time consistent network

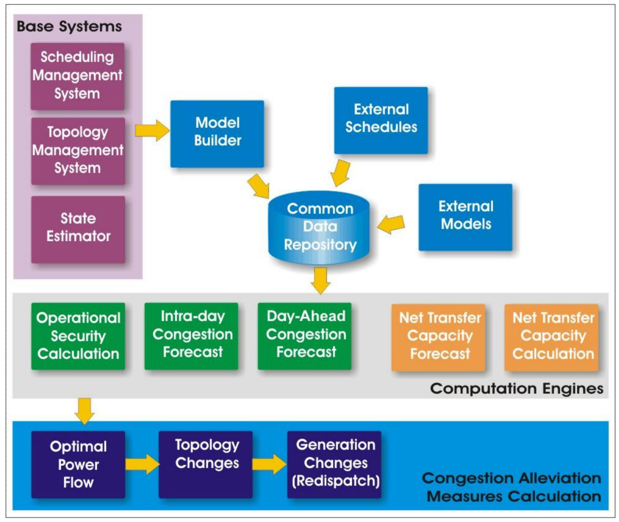

Fig. 1. Congestion Management System and Surrounding Systems

model [7]. However the quality of the models received from the day-ahead congestion forecasts is generally poor compared to the internal estimated data set.

C. Dynamic Model Generation

One of the main challenges in operational security analysis and forecast is obtaining an accurate model – e.g. the model that suits the situation under investigation as close as possible. This accuracy of the model is reflected in the efficiency and quality of results irrespective of the time frame for which situation is being analyzed.

At the same time, obtaining of the accurate model is a time consuming task. Manual creation of the model requires considerable manual work by qualified resources. Such a process may be acceptable for long term network planning, but is not practicable for the operational analysis, where the analysis time frame may vary from few minutes to few days. One of the possible solutions is to generate model dynamically using the state estimation results and merging them with the best available external network model. This approach is being used for the operational analysis, day-ahead congestion forecast, NTC calculations, and other activities. These models, when archived with appropriate tags, allow fast retrieval of a base case for future analysis.

Some of the important advantages of the dynamic model generations are:

1) Single source of data

All the models have the same origin: couple "base network model + state estimation results". This makes the model propagation through numerous processes transparent, permitting easier validation of the results. Additionally, it allows the easy substitution of the models across different processes (e.g. use of DACF models in NTC calculations, or the Redispatch models in DACF, etc.).

2) Most recent data

Use of dynamic model generation guarantees the use of the most recent data, as this model is generated every 5 minutes or even more often – in case of significant topology changes, or on demand. Of course, such high data volume demands proper archiving and data access systems.

One of the important steps in any modeling process is validation of the model to the real world. The comparison mechanism is facilitated if the models have the same origin and the same data format.

Main challenge in generation of the dynamic model is the superposition of state estimation on the static network model, extending the model by pseudo-estimation to cover unobservable network part, and merging it with external model.

Since state estimation is based on the bus breaker model and most of the application use bus branch model, some dynamic adjustments have to be done to provide reference between physical model and analysis model.

3) Same Computation Engine

The advantage of the unified modeling approach can be additionally enforced by the use of the same tool in the different stages of the operational security analysis (Fig. 2.). In addition to cost reduction other advantages are lower educational costs, synergies in personnel allocation and robust system architecture, providing better system utilization.

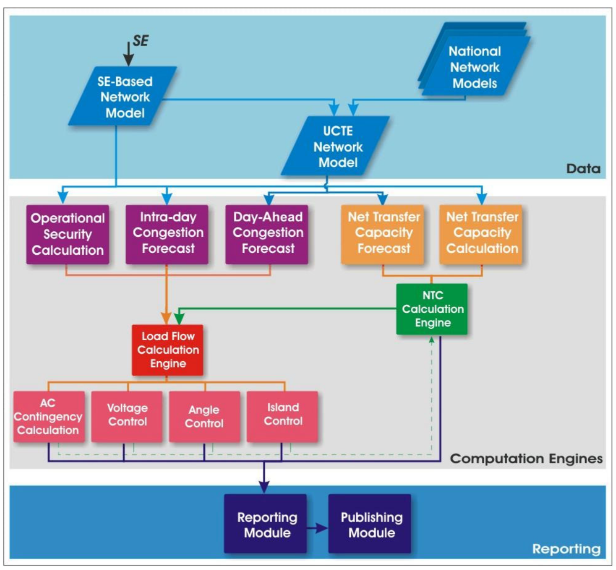

Fig. 2. Load Flow Calculation Engine Reuse for different tasks in Congestion Management Process.

The goal in this implementation was the use of the same calculation engine for Operational security analysis, Day-ahead congestion analysis, Net Transfer Capacity computation and Operational planning purposes.

Such an approach allows selection of best of breed software without sacrificing the advantage of user-trusted models. Using two high quality field proven packages provides possibility of cross checking the results and validates the model.

4) Consistent Data Set

Use of the standard formats at all stages of the congestion management process allows avoiding the data redundancy, as every process can access the data in system standard format. Absence of such standard causes the necessity of storing the same data (mainly network models, but also schedules, etc.) in different formats, what potentially results in damaging inconsistencies, increases data demand, and makes the process less transparent.

D. Calculations

The core of the security analysis is based on the principles of N/N-1 security.

1) N-1 Security

It is obvious, that, since its introduction in mid-seventies, the N-1 approach is well accepted in the network security analysis scene. The method is straightforward and comparatively fast; the results are easy to interpret, share and analyze.

The N-1 principle corresponds to the electrical networks design security concept, giving the operational congestion management system the same unambiguous criteria of network security that were used during its design.

From the practical point of view, the N-1 approach has various advantages. It may be executed in manual or automatic mode, efficient computation techniques could be used for the calculation accelerations, so, that even the security for the large networks can be calculated in the reasonably short period of time. For example, the security analysis of internal Swiss network with 300 contingencies, based upon the UCTE model with 3000 nodes, takes roughly 20 seconds on a 2 GHz Intel Pentium class processor. The time to generate calculation reports varies between few seconds to few minutes depending on the level of details to be included.

However, the N-1 approach has certain drawbacks:

- There is no universally accepted single definition, how the N-1 calculation shall be performed, which network elements must be tripped (e.g. in some cases generators are considered as contingency objects, in some not).
- The different models, used as a base case for contingency calculation may give different abilities for N-1 calculation: e.g. model of the generator transformers or distribution load.
- The element-by-element analysis may not correspond to the real life, where often several net elements are disconnected as a result of a single event.
- The time to allow overloading of some elements in post contingency case may change the N-1 security level of the network.

European model does not have a notion of Regional Transmission Operator (RTO) as established in the USA. Most of the work is done in work forces and task forces, which are formed by the specialists from participating TSOs. Congestion management procedure, a clear and accepted goal for all European TSOs, is a practical settlement of the common calculation rules. To make it possible for all the UCTE members to perform the calculations based upon the same network model, ETRANS shares the merged model that covers all UCTE countries (including the newly connected second synchronous zone) for the common UCTE use.

In addition to N-1 contingency approach, multiple contingency scenarios have also been implemented. This facilitates the special topological constellations (Y-nodes in the network), corridor contingencies or other scenarios.

2) Angle calculations

Most of the limit checks performed within the security analysis methods restrict themselves to thermal limits of the transmission lines and transformers. Some of the utilities are paying more attention to the dynamic limits imposed by the voltage collapse due to heavy network loads. In the system under consideration another type of limit was posing more stringent requirement on network limits. The re-closing of lines, which might have been opened due to temporary short circuits, cannot be performed before a synchro-check on the phase angles in the post contingency case. In the security analysis this feature has been added to check angle separation of the lines, which had been simulated as outaged.

IV. NTC

The NTC values provide the base information for the cross-border energy trade and have to be calculated several days in advance. The calculation is performed according to the ETSO guidelines that recommend several possible calculation algorithms. In the presented system the proportional generation shift with generation limits check is used. This method has been adopted by most of European TSOs, as being the closest to the reality.

The NTC values can be calculated for the purposes of long-term planning, short-term planning and operational control. The system under discussion performs all the types of NTC calculation with the help of the same software unit, which performs the automatic model creation with following generation shift and security analysis by each step. The latest valid day-ahead forecasted model is used as a base case for NTC calculations.

The NTC values for the Swiss borders are calculated daily for 3:30 and 10:30 for three days in advance, the calculation results are published on the web in extranet.

V. Day-Ahead Congestion Forecast

A. UCTE Standards Based Processes

As already mentioned above, the day-ahead congestion forecast is being performed according to the UCTE standard procedure. This procedure foresees the build of the common UCTE network model out of partial country datasets and the performing of the country-specific N-1 security and congestion analysis on its basis (Fig. 3.). The ETSO Electronic Highway Data Server (EH) is being defined as a global data repository for the DACF purposes.

B. Network Models for the DACF Process

The individual network model are generated by splitting each tie-line into two parts and creating a pseudo node with equivalent injections, referred as X-Nodes. In merging processes the flows from pair of X-nodes is removed to recreate the tie-line. The DACF procedure suggests, that each participating member has to provide 24 hourly models of the planned status of their power system for the day-ahead forecast process. National TSOs are striving to reach this goal. In current constellation minimum requirement is that these "X-node models" must be available for every day for at least one time point – 10:30, and at least once per week (Wednesday) – also for 3:30.

The DACF models are being stored on the ETSO Electronic Highway Data Server and shared among all the UCTE members for the day-ahead congestion forecast process purposes.

The technical aspects of DACF process realization at ETRANS can be found in [8].

1) Internal Network Model

ETRANS, as a Swiss network coordinator, prepares daily 24 hourly DACF models of the Swiss network (0:30 to 23:30). These models are built at 18:00 for day ahead planning purposes. The models are based upon State Estimator output, list of planned topology changes (taking elements out- and into the operation), Production plans and balance schedules, representing the total country energy exchange with the neighbors. In case parts of the information are missing or invalid, the most appropriate data are taken to perform the substitution.

2) UCTE Partner Models

According to the DACF process, all partial models are being downloaded from the EH Server and merged into the total UCTE network model, this process is being followed by the network security calculation.

As the network load/generation pattern changes over the day, as well as its planned topology and overall country energy exchange, one needs multiple models to be able to perform the accurate security analysis. That's why it is expected, that every country delivers 24 hourly models for the DACF purposes. Unfortunately, mainly due to the non-automated process of the DACF partial datasets, most of the countries are only able to deliver two models daily. In case of some countries, it is only the standard reference model that is available for the DACF purposes (being updated -twice per year).

Beside the models availability issue, one has also to fight with the model quality problems, as the UCTE network models standard format is fixed format, every data shift causing the format violations and model rejection.

Another problem is delivery of data before the gate closure time, which is being used by a number of other processes (like generation schedules acceptation/rejection procedure, NTC calculation, possible redispatch measures, etc.). It implies that the DACF process must be complete till the certain point on the timeline. Partial country data sets received after the defined time threshold (18:30), will not be considered in the process, causing poorer forecast quality.

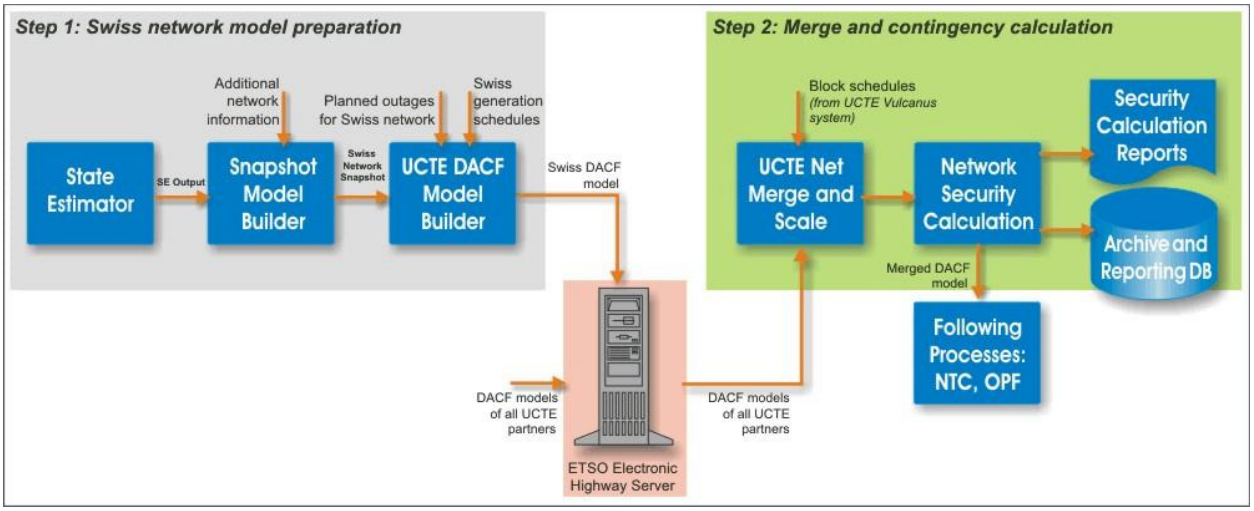

Fig. 3. Day-Ahead Congestion Forecast Process

To avoid these problems sophisticated data validation algorithm has been implemented to filter out as many different partial models problems, as possible. The missing or invalid data sets are replaced with the most appropriate ones, considering the weekday type, season, and hour, where applicable.

3) Experiences Gained

An accuracy of ±5% may be acceptable on the flow forecast. Since this value is used for congestion alleviation activation the network operation must have a good level of confidence in these values. This expected level of accuracy is only achievable by the corresponding quality of the input data that is, according to the performed studies and practical tests, is listed below in the order of importance.

a) Quality of the Internal DACF model

This factor depends mainly upon following information:

- ***Topology***. Topology is defined by the configuration of the base case model and information about topology changes for the next day. The wrong topology directly leads to the large errors at the particular places of the network model. This is especially true for the transmission lines close to border.
- ***Planned Production schedules***. These define the place and value of the planned generations and, so, are the inseparable parts of the DACF model. The impact of the missing or wrong generation schedules on the DACF model quality can vary from very small to very significant.
- ***Balance (exchange) schedules***. The exchange schedules show the planned value of country's total electric energy export or import. The country's DACF partial model is treated by the most partners as a kind of "black box", so, the correct total exchange of the country's network is of a major importance in this case.
- ***Load pattern***. Both correct generation and loads are important for the model quality. Though, while the generation schedules are submitted by plant operators, the energy consumption pattern can be treated as matching the one for the last similar day (it is being currently distinguished between weekday, weekend and holidays). As alternative, the load forecast system can be used.

b) Quality of the neighboring models

It is obvious, that the models of the immediate neighboring countries (in case of Switzerland – Germany, France, Italy and Austria) have the major influence at the security calculation results. The most important factor in this case is once again the topology of the neighbor networks, especially at the country borders.

As already mentioned above, the partial DACF models are available from the most of the countries for 1-2 hours per day instead of 24, and even these are from time to time missing or coming with delay – mainly due to the resources problems (manual creation), or some technical problems. In all these cases the substitution algorithm is being used. It was experimentally proven that only DACF, performed on the base of the model, containing the correct partial datasets of the Swiss neighbors provides the results that correspond to the accuracy requirements.

c) Availability of the European energy exchange schedules

The energy exchange schedules are being used to perform the control of the countries' generation-to-load balance. As already described above, in case of absence of partial DACF models they will be substituted and scaled to fit the planned inter-countries energy exchanges. The delayed delivery of the energy exchange schedules causes their substitution, what can negatively influence the results quality.

d) Quality of the models of other countries

In the most cases one can obtain the good forecast results without considering the actual models of the non-neighbor countries. This is though not valid for the case of large transit flows caused by energy exchange between the non-neighbor nets, and flowing through the country of consideration. A sensitivity analysis is being done to determine which partner models have the highest influence on the Swiss load forecast.

VI. Optimization and Planning

Being a major network security process by itself, the Day-Ahead Congestion Forecast also delivers the models, which are intensively used by the following processes, including operational Optimal Power Flow (OPF) and short-term net optimizations.

A. Operational Optimal Power Flow

The operational OPF performs network optimization with the following controls:

- Generator Redispatch;
- Switching;
- Transformer Regulations.

OPF can perform optimization using all control variables either in one pass, or sequentially, making it possible to perform validation of intermediate results. The objective functions can be a security-constrained optimization, fulfilling N or N-1 security criteria, or in addition perform cost optimization.

The whole process of OPF model creation on the basis of UCTE DACF model (as, obviously, OPF model should contain more data than the power flow one) is highly automated, allowing the network engineer to perform optimization calculation in the fast and easy manner by selecting the base network model and specifying some the control possibilities.

The preliminary runs of the redispatch process were performed, where the main goal was to test the redispatch concept. The corresponding system included following functionality:

- Bidding of redispatch capacity by plant operators
- Automatic OPF model creation on the base of DACF file, considering the redispatch bids;
- Automatic OPF calculations with the means of generators redispatch for all the N-1 insecure cases resulting from DACF.
- Creation of corrected schedules and ordering the redispatch at the plant operators.

The test operation verified the functionality of the software system and at the same time showed the complexity of organization of the connected business process. It also pointed out a limitation of available national controls for heavily loaded transit networks.

B. Short- and Long-Term Net Optimization

Short-term optimization is being performed with the same technical means, as operational OPF, but may include different target functions, as well as simplified or, vice versa, more complex model of generator participation in redispatch.

VII. Online Congestion Management

The on-line network model provided by the state estimation is characterized by a very close matching to the actual network conditions. Since the topological and measurement data from a ring of two node distances around internal network are acquired using TASE.2 protocol from neighbors over the Electronic Highway, the external network model also reflects the latest realistic network model of the external network. The flows and exchanges outside the observable area are adjusted on the basis of the measured values.

If the capacity allocation and day-ahead process operate as designed, the on-line congestion management does not have to be activated. However the difference between financial and physical transactions, unanticipated transit flows force some actions necessary for on-line congestion management.

VIII. Interfaces

A. System Interfaces

System interfaces play a dominant role in effective implementation of congestion management schemes and must be carefully planned and designed.

Currently, the following groups of interfaces are being used in the operational security analysis system:

- Network configuration interface
- Generation planning interface
- Capacity allocation system interface
- Bidding system interface
- Support Systems interface
- User Interface

Below is given the short characteristics of the corresponding system interfaces.

1) Network configuration interface

Over this interface the system gets the information about current, past or future status of the network condition: topology, physical parameters, loads/generations patterns, etc. The main source of the information: state estimator, reference models, maintenance database, outages planning database. But also the load and generation forecast systems can be included into this group.

Most of the actual information about the generators "Commitment" in the very short (hours) or short (days) perspective can be obtained from the scheduling system, containing the up-to-date information not only about the production schedules, but also about regulation blocks and zones exchange schedules. This information helps to perform the necessary tuning of the model, especially in absence of load forecasting system.

2) Capacity allocation system interface

The congestion management process provides the NTC values which is used for the allocation of the transmission capacity for the market players. The capacity, which has already been allocated, is deducted from the NTC giving the Available Transmission Capacity (ATC).

3) Bidding system interface

The bidding system provides the important information for the optimization process, giving the possible generation variation capacities, as well as energy prices.

4) Support Systems interface

Under support system interfaces we understand the interfaces to the IT systems, which support the reliable functioning of the system under discussion.

Here one can list the process- and application monitoring software, process data archiving and reporting systems and others.

5) User Interface

a) Network Control Personnel

The network control specialists are the main users of the operational congestion management system; hence, the information provided must be unambiguous and clear. The user interface for this customer group includes the text and graphical reports and network diagrams for different system states. Additionally, they get the information about the state of the process, availability and quality of data, as this information is important to be able to undertake the corresponding measures, and to evaluate the results quality.

b) IT Personnel

The IT department is responsible for the system operation from the IT point if view. To simplify the process control and diagnostics, the special monitoring facilities are being developed, that integrate the standard application monitoring tools with process-specific information.

c) Process Owner

The whole system is controlled with the means of workflows, which are implementing significant part of process logic. It is very important, that process owner, being normally an electrical engineer and not necessarily a software specialist, can control and modify by necessity the logic of the process, as well as its other parameters (data to be considered, calculation settings, etc.) The well-developed workflows interface plays an important role for these people.

d) External Partners

The information about calculated planned NTC values, forecasted national network security and other results, obtained during operational congestion management process are of the major importance for the national and international partners of TSO. This data is published in the secure web site area, allowing the partners the constant information access.

IX. Conclusions

The complex process of network security analysis can be split in different objectives serving in different time frames and user groups. Standard established products of network analysis could be used if the work and data flow can be organized to solve part problems. The modular handling of data models and algorithms allow an open system where the user may profit from solutions from different suppliers. It reduces dependence on a single supplier and provides investment protection.

X. Acknowledgment

The authors gratefully thank all team members and especially Marc Emery for his contribution to DACF Process in UCTE, and ETRANS AG for giving permission to publish this work.

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XII. Biographies

Nisheeth Singh (SM'1986) has over 30 years experience in power system control and operation. He has worked for BBC / ABB in field of network control and energy management system in different positions starting from research engineer, product development, project management, training, product management and finally as senior consultant. He joined ETRANS AG in Laufenburg, Switzerland 2001. In his present capacity, he is leading the project management group in ETRANS, which is heavily involved in new applications and new technologies.

Dr. Singh is senior member of IEEE and an active member of CIGRE WG39 for system control performance and has a Dr. Sc. degree from Federal Institute of Technology, Zurich in Electrical engineering. He is on several Task Forces / working Groups for European Transmission System Operator (ETSO) and Union for Coordination of Transmission of Electricity (UCTE). He has over 30 publications in reputed conferences and journal in his field of activity.

Dmitri Tchoubraev (M'2004) has worked over 15 years in the area of computer technologies application in electrical systems.

After completion his doctor thesis on computer-aided modeling of electromechanical devices at the Institute for Electrical Machines of the Swiss Federal Institute of Technology in Zurich, Dr. Tchoubraev worked in the area of telemanagement systems software development. From 2000 to 2003 he has worked at ABB Switzerland as manager of electrical SCADA engineering and development group. From 2003 till now Dr. Tchoubraev is a project manager by ETRANS AG, Switzerland, responsible for the design and realization of the operational congestion management system for the Swiss transmission network.

Dr. Tchoubraev is IEEE member and author of 10 publications in the area of modeling and calculation of electrical machines and the methodology of informatics systems development in electrical engineering.