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Changing Paradigms for Increased Productivity in Power System Restoration Studies: The Brazilian ISO Experience

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SUMMARY

By accepting that no power system is immune to blackouts, ONS, the Brazilian ISO, developed the Brazilian Interconnected Power System (BIPS) Defense Plan [1], which is based on three principles: minimize the probability of occurrence of large disturbances, minimize the propagation of unavoidable disturbances and reduce the time needed to restore power supply. Due to particular aspects of BIPS, ONS practices a two-stage restoration philosophy, breaking the process into fluent restoration and coordinated restoration. Fluent restoration is started by high-reliability hydro-power generators, keeping communication at minimum level, considering pre-defined priority load pick up and strictly observing generation/load balance. Coordinated restoration occurs under coordination of National and Regional Operating Centers and deals with the interconnection of previously restored geo-electrical areas. Despite the effort to avoid the occurrence of blackouts, they will occur from time to time and, in this case, restoration procedures must be planned and driven to restore power supply as soon and as safely as possible. To achieve this goal, system operators must have in hand detailed and precise operating instructions, generated after power flow, electromagnetic and electromechanical transient studies. ONS and CEPEL (Electric Energy Research Center) have been working together to speed up these studies, equipping ANAREDE, the power flow program used by most Brazilian utilities, with data and functions specifically oriented to restoration studies.

This paper describes new features specially tailored for power system restoration simulation implemented in the ANAREDE software, customized data edition and post-processing analysis tools, how these several software can be combined to speed up restoration studies and how a very simple evolution on the operational planning workstations may contribute to this. A general description of the various changes in processes, user interface, data flow, hardware and software is also provided.

KEYWORDS

Power system restoration, restoration plan, restoration strategy, power flow.

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1. INTRODUCTION

The two last major blackouts experienced by the Brazilian Interconnected Power System (BIPS) occurred in March 1999 and January 2002. On both occasions, full load restoration time was about 4 hours. As societal reaction to blackouts grows exponentially with load restoring time, ONS, the Brazilian ISO, strives to reduce restoration time in eventual future large disturbances. Among other actions taken to achieve this objective, a thorough review of all restoration procedures was initiated.

Restoration processes, be it partial or total, are defined by a set of instructions stating which actions must be taken by operators, utilities, regional operating centers and ISO regional and national operating centers to restore power supply. To generate the so-called operating instructions, a series of power flow, electromechanical transients and electromagnetic transients studies must be carried out. To periodically revalidate restoration procedures for each geo-electrical area a similar effort is demanded. The task of periodically reviewing all restoration procedures requires enormous effort and emphasizes the need for new and updated power systems analysis, data editing and post-processing analysis tools, equipped with specially tailored features for restoration studies. ONS requested CEPEL (Electric Energy Research Center) to develop some of these features in ANAREDE, the power flow software used in restoration studies. A graphical user interface (GUI) was created over the reliable ANAREDE core and new data blocks were created to host new data specifically related with restoration studies. A routine to evaluate the feasibility of user-defined restoration plans and a heuristic-search based routine to automatically determine restoration paths were developed. Two post-processing analysis tools and a customized data editing tool were also developed. The newly implemented features, together with the stand-alone post-processing and editing tools indeed speeded up some phases of restoration studies and even proved to be very useful to other types of studies (operation planning, maintenance scheduling, etc). However, it became evident that, to take full advantage of these new software tools, the standard engineer's workstation should be redesigned.

Real-time operators have long benefited from the availability of multiple CRT/LCD monitors in each system operator island of most EMS centers. These monitors allow access to different data bases (past, current, forecasted) and include many sophisticated real-time control functions. As real-time operation is a critical system function, the high cost of the associated hardware/software has always been fully justified. Off-line studies, when carried out in EMS centers, benefit from this lay-out. When it comes to operational planning studies, engineer's workstation lay-out is quite different. These teams usually work with single monitor workstations. Although this monitor can host multiple windows, the study engineer is obliged to continuously jump between various screens to perform his tasks. It is amazing that, despite the enormous reduction in hardware cost, the multiple monitor workstation concept has not yet permeated the operational planning studies area.

2. BRAZILIAN INTERCONNECTED POWER SYSTEM RESTORATION STRATEGY

Until late 1970s most Brazilian utilities used centralized restoration procedures, based on Operation Centers. After any disturbance, common problems were identified, such as high level of communication between substations and Operation Centers, lack of information about post-disturbance configuration, alarms overflow, etc, all this constituting clear evidence of the lack of effective restoration plans (operator instructions included) that could speed up the whole process. Due to ever increasing times to restore energy supply, utilities began to consider abandoning these centralized restoration strategies in favor of more reliable and faster alternatives. Following intensive studies, the basis of current Brazilian restoration strategy emerged. This strategy partitions the restoration process in two phases. During the first phase, called fluent restoration, previously defined operating instructions guide the restoration of geo-electrical areas, balancing load and generation in minimal network configurations. The second phase, called coordinated restoration, requires the intervention of regional and national Operation Centers to authorize additional load pick up and interconnection of already restored electrical islands.

The efficient implementation of such strategy requires precise and detailed restoration procedures, including a reasonable number of alternative routes to cater for unavailability of some devices that might be in maintenance or may have been damaged by the disturbance. Generating these procedures demand different kinds of digital simulations, particularly, power flow, electromechanical transient and electromagnetic transient analysis.

3. POWER SYSTEMS RESTORATION STUDIES

Various power system digital simulation tools are used to implement a restoration process, from initial studies that define the candidate restoration path to real-time implementation, by system operators, of the restoration strategy described in the operating instructions. These tools can be classified as [2]:

- Off-line power system digital simulation tools
- Operator training systems (OTS)
- Computational tools to support real-time restoration actions

This paper is focused on off-line computational tools, more specifically, how power flow programs can be best equipped, internally (new functions) and with the aid of post-processing analysis tools, to speed up restoration studies.

Feasibility analysis of candidate restoration paths begins with power flow studies, in which power generation availability must be determined. These studies consider n-1 generator units (n is the number of generator units in the power plant), assuming one unit to be undergoing maintenance (or a minimum number of synchronized units), to supply reactive power to compensate long transmission circuits operating under light-load conditions. To determine this amount of reactive power, the possibility of a sudden load rejection during load pick up and the need to avoid field self-excitation, the latter with catastrophic consequences, must be considered [3]. To keep bus voltages within specified limits during the restoration process, synchronous generators, shunt reactors, line reactors and intermediate load pick up can be used as sources of reactive power for voltage control. Shunt capacitors, static var compensators and synchronous compensators are not to be considered as sources of reactive power for voltage control during fluent restoration, except in very specific situations. Preferably, a fluent restoration path should be restored without intermediate load pick up and without voltage violation in any of its buses. Operating limits of transmission and generation equipment must also be observed in all steps of a fluent or coordinated restoration path. This is achieved by determining a minimum set of shunt and line reactors so that operating limits are not violated during the restoration of a given path.

Electromechanical transient stability studies check if switching actions simulated and proven viable during power flow studies are also viable from a dynamic point of view. Analysis of system frequency and voltage performance during the energization of lines and transformers as well as during load pick up and following equipment/load rejections demands simulation of voltage and speed regulators' action. Moreover, in face of loop or parallel closure, turbine-generator shaft torsional torques, dynamic overvoltages and system's electromechanical stability should also be checked.

Electromagnetic transients studies define maximum voltage for equipment energization and if it is possible to energize equipments without risk of transient overvoltage or system ressonance. These studies are focused on short term transient conditions such as line and transformer switchings and load rejections that may lead to severe equipment strain or damage and contribute with additional delays to restoration of supply.

3.1. Conventional Data and Work Flow in Power Flow Restoration Studies

Power flow restoration studies analyze system conditions in each step of the restoration process, ensuring that equipment's operative limits are observed and determining if a restoration path analysis should proceed to the electromechanical transient stability studies phase or not. Power flow data preparation begins with the creation of a case including one or more isolated systems, each one corresponding to a geo-electrical area. To create such a case, the engineer must delete all data, except for two buses, the one to which the black start generator unit is connected and the first bus of the restoration path. Over this case, successive power flows are executed, adding topological, load and generation changes to the previous case, checking operative conditions after each set of switching actions or, as usually named, restoration step. In face of an unsuccessful power flow simulation, remaining reactive power support alternatives are tested in ascending order of reactive power support, aiming to achieve operative conditions considered acceptable for a restoration process (bus voltage and line flow limits during restorative processes may be slightly different from those considered for normal operation). If acceptable conditions are achieved for the current restoration step, tests over a new set of switching actions, corresponding to the next restoration step, along with a new set of reactive power support are initiated. These studies, when carried out manually, involve intense error prone data manipulation, considering usual functionalities available in power flow programs. Besides, the trial and error approach described above raise difficulties, considering that switching equipments is usually represented by altering values associated with equivalent models of power system equipments. Starting from the premise that is much more adequate to alter operative status than modify values, a whole set of new functionalities were implemented in ANAREDE, allowing the power system engineer to concentrate in result analysis rather than in data edition. These new functionalities are described in the next sections.

4. NEW GRAPHICAL USER INTERFACE, EQUIPMENT MODELS AND DATA BLOCKS

ANAREDE is being developed since the early 1980s and its original user interface was already interactive, but command line oriented. This characteristic made possible to wrap up ANAREDE reliable Fortran coded load flow engine with a modern C++ coded graphical user interface, including a versatile one-line diagram editor. Data input Fortran routines were slightly modified to directly communicate with C++ dialog callback routines (Figure 1).

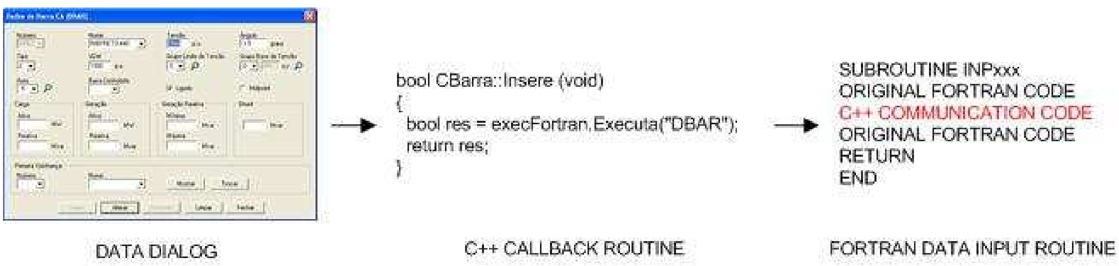

Figure 1 – Communication among data dialog, C++ routine and Fortran subroutine.

Similarly to other contemporary power flow programs, ANAREDE data blocks were designed to represent power system equipments as equivalent ones. This means that one only load, generator, shunt, etc, could be connected to each bus. That was acceptable at that time, to save memory, but useless on these days of cheap Gbytes. New data blocks implemented in ANAREDE take into consideration not only the need to model individual equipments, but also the need to represent groups of n identical units (with $m \leq n$ operating units). For data compatibility reasons it is still possible to use equivalent equipments, but users are strongly encouraged to migrate to individual models.

The need to rapidly switch whole groups of equipments led to the implementation of the operative status concept, which was extended to other equipment models, such as AC buses, transmission lines, transformers, DC links, etc. Obviously, this functionality is important to other types of studies, but it is particularly important to restoration ones. A clever usage of operative status feature allows the engineer to quickly start a restoration study using operation studies data by simply turning off parts of the power system. Figure 2 shows previous and current load model as an example of individual equipment model. In this particular case, individual feeders can be represented instead of modeling them as equivalent loads. Notice that individual loads can be switched as well as the whole group. More than one group of individual equipments can be connected to each AC bus.

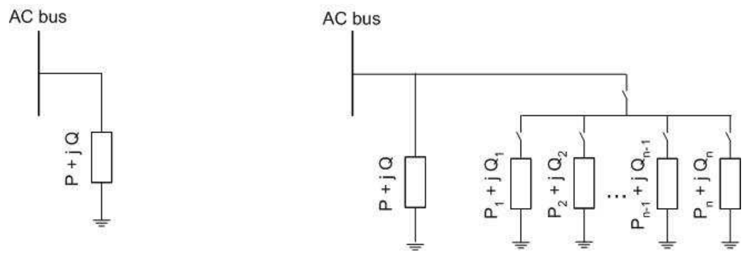

Figure 2 – Previous and current load model.

By using operative status data and other GUI features, the engineer can easily see the evolution of restoration actions along a restoration path and, at the same time, monitor bus voltages and line flows with the aid of configurable filters. It is also possible to visually distinguish live equipment from those that are deenergized (Figure 3).

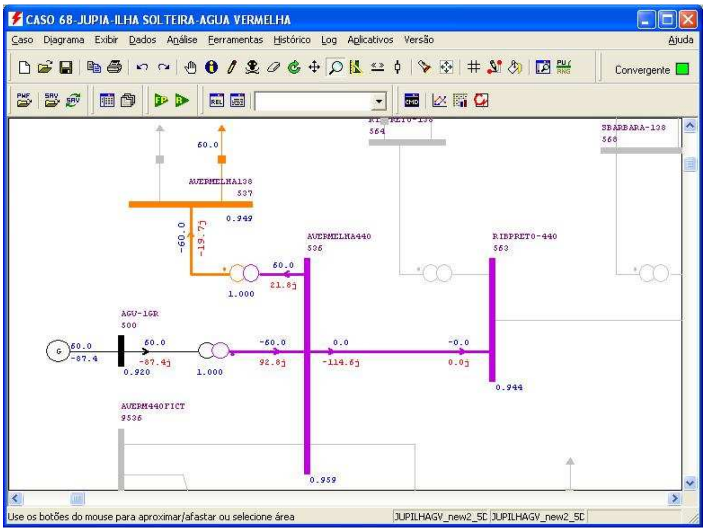

Figure 3 – Main window showing a partially restored power system.

5. AUTOMATIC RESTORATION PLAN EVALUATION AND AUTOMATIC RESTORATION PATH DETERMINATION

Detailed equipment models and the possibility to switch equipments are undoubtedly useful, but are not enough to significantly speed up restoration studies. It is necessary to concisely describe restoration paths, including all steps and related switching actions. Besides, it is desirable that the described candidate restoration path be automatically evaluated, checking the viability of the restoration strategy. Finally, it is important that this description can be reused in future revalidations of restoration strategies of the same geo-electrical area. To achieve these goals, restoration steps were modeled as an aggregation of switching actions, as shown in Figure 4, and described in an specific data block. To evaluate a candidate restoration path, the engineer selects a sequence of restoration steps and activates the automatic restoration plan evaluation function. The program considers the current state of all equipment as the starting scenario of the restoration plan, successively executing the following actions for all restoration steps: a) checks if pre-energization bus voltages are within specified limits; b) executes switching actions for all equipment belonging to the current restoration step, and; c) checks if post-energization bus voltages and line flows are within specified limits. If bus voltages or line flows violations occur, the restoration path evaluation is stopped and a report of switching actions and violations is generated. If voltages and line flows are within specified limits a history file case is recorded, so that all steps of the restoration path will be available at the end of the study. These cases may be analysed by post-processing analysis tools that generate a comprehensive set of reports and plots to help the engineer in the restoration planning studies phase.

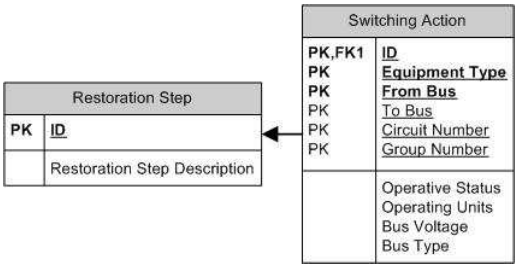

Figure 4 – Restoration Step / Switching Action Data Model.

Another recently implemented feature specifically tailored for restoration studies is an automatic fluent restoration path determination function. Given the bus corresponding to the black start generator unit and the objective bus to be reached by fluent restoration procedures, an heuristic search based routine scans the search space of potential solutions, organized as a search tree [4]. Starting from an initial node, corresponding to the power plant with black start capability, the routine expands promising candidate nodes into branches and prunes those branches that were found infeasible [5], narrowing the search space of this combinatorial problem. Due to space limitations and importance of the theme, the detailed description of this heuristic search implementation will be the subject of a future paper.

6. CUSTOMIZED DATA EDITOR AND POST-PROCESSING ANALYSIS TOOLS

Despite the previously described developments and all the data edition and result analysis and visualization tools, restoration studies would still demand intensive work. The joint CEPEL/ONS development team concluded that this work could be reduced with the aid of customized tools, capable of speeding up the data edition and result analysis phases.

Editing power system data and command files using a generic ASCII text editor is an error prone task. Aligning data in correct columns, as well as observing data block syntax correction, is so tedious and errors committed in this task are so common that they may significantly slow the pace of restoration studies. To address this problem, CEPEL developed a customized data editor, named EditCEPEL, that performs automatic on-line alignment and block syntax check. Besides, EditCEPEL allows the user to collapse data blocks, insert and remove comment markers, display hints to guide edition, etc. The editor can also be configured by the user to be compatible with the data format of different power system analysis tools developed by CEPEL. In Figure 5 it is possible to observe collapsed data blocks, a hint about restoration path data block, data columns marked and the line cursor during the edition of restoration path data.

ANAREDE can generate dozens of pre-formatted built-in reports related to the current case. However, restoration studies demand very specific types of report, often referred to a set of cases. For example, bus voltage reports, considering all steps of a restoration path, are useful to visualize the expected evolution of voltage profile during the restoration process (each step considered as a case, although recently implemented data blocks can pack everything in a single case). As content and data organization of these reports vary a lot, a report generator named FormCEPEL was developed. FormCEPEL allows the user to define a report structure, apply filters based on voltage levels, company name, bus name and an extensive set of attributes to this report and save report structure and filters for future use. Three types of reports are available: pre-defined reports, personalized reports and comparison reports. The first type relates to classical power flow reports and the others must be configured by the user. Saved report structures and filters can be loaded and applied over a single history file case or over a set of history file cases. FormCEPEL then generates reports as Microsoft Excel spreadsheets, allowing the user to perform further processing and formatting, code and execute macros, etc. Figure 6 shows a user defined voltage profile report, generated with FormCEPEL, in which the behavior of bus voltages during the fluent restoration of Ilha Solteira geo-electrical area can be observed.

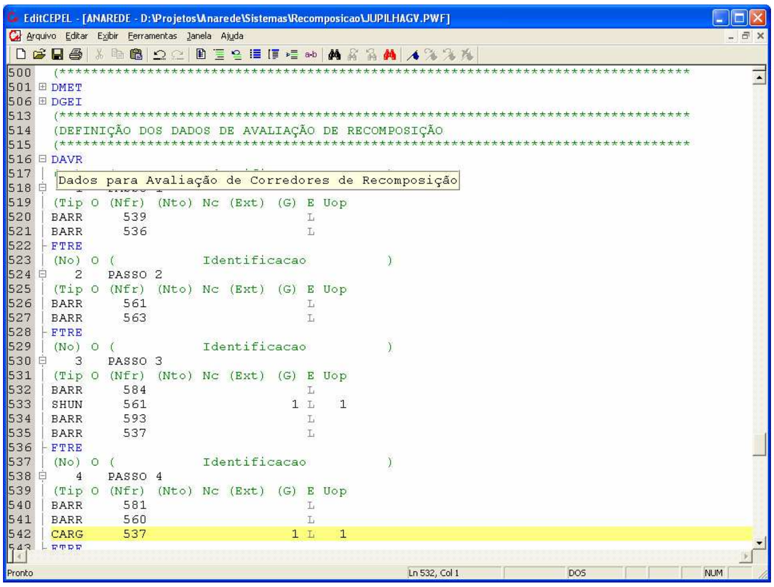

Figure 5 – Built-in EditCEPEL window used for restoration data preparation.

Comparação de Dados de barra - 11 casos												
Barra		Magnitude da tensão na barra [p.u.]										
Nome	Número	Etapa 1	Etapa 2	Etapa 3	Etapa 4	Etapa 5	Etapa 6	Etapa 7	Etapa 8	Etapa 9	Etapa 10	Etapa 11
ILS-6MQ	501	0,909	0,909	0,909	0,909	0,909	0,909	0,909	0,909	0,909	0,909	0,909
ILS-440	538	0,909	0,913	0,934	0,934	0,934	0,935	0,936	0,938	0,939	0,939	0,939
ARA-440	559		0,830	0,961	0,961	0,961	0,966	0,976	0,990	0,994	0,994	0,994
ARA-138	560			0,961	0,961	0,961	0,966	0,976	0,990	0,994	0,994	0,994
SAA-440	593			0,990	0,990	0,990	0,999	1,015	1,039	1,044	1,044	1,044
SAA-345	594						0,999	1,017	1,041	1,048	1,048	1,048
ITE-345	449						0,999	1,018	1,043	1,049	1,049	1,049
TPE-345	78							1,018	1,044	1,051	1,051	1,051
LEST-345	464								1,045	1,052	1,052	1,052
RRF-345	466									1,052	1,052	1,052
RRF--88	467										1,052	1,052

Etapa 1 - Energizando UHE ILS com 6 Unidades
Etapa 2 - Energizando até a SE de ARA-440
Etapa 3 - Energizando até a SE de SAA-440
Etapa 4 - Energizando a SE de ARA-138
Etapa 5 - Tomando 0MW de carga na SE de ARA-138
Etapa 6 - Energizando até a SE de ITE-345
Etapa 7 - Energizando até a SE de TPE-345
Etapa 8 - Energizando até a SE de LEST-345
Etapa 9 - Energizando até a SE de RRF-345
Etapa 10 - Energizando até a SE de RRF-88
Etapa 11 - Tomando 0MW de carga na SE de RRF-88 - Corredor Completo

Figure 6 – Voltage profile during fluent restoration of Ilha Solteira geo-electrical area generated by FormCEPEL.

During restoration, synchronous generator units operate in particularly critical conditions, with low terminal voltage, high reactive power absorption and low active power generation, to compensate long transmission lines operating under light-load conditions, since initial fluent restoration steps are performed without feeding any load. To adequately represent these operating conditions, the synchronous generator model must include an optional capability curve model. If the capability curve data is available, accurate reactive power limits are calculated and this information used to automatically energize new generator units, if necessary. The program generates capability curve points and allows visualization of generator units operating points for each step of the restoration path (Figure 7) with the aid of PlotCEPEL [6], a customized plotting tool for all power system analysis software developed by CEPEL. In Figure 7 the blue asterisk indicates the operating point for Água Vermelha generator units on the 7th step of fluent restoration of the geo-electrical area with same name.

The ever increasing CPU processing power of the engineer workstation has not been followed by a corresponding improvement in the visualization devices. Until recently, power flow restoration studies were conducted using a command-line oriented power flow program in a single monitor, single CPU workstation. Three satellite applications that effectively speed up restoration studies were described in this section. Obviously it is possible to use them together with a power flow program, switching windows in a single monitor workstation. However, it has negative impact on data edition and result analysis activities, slowing down the whole process. We envision the use of multi-core multiple monitor workstations as the ideal environment to perform restoration studies using the above mentioned computer applications.

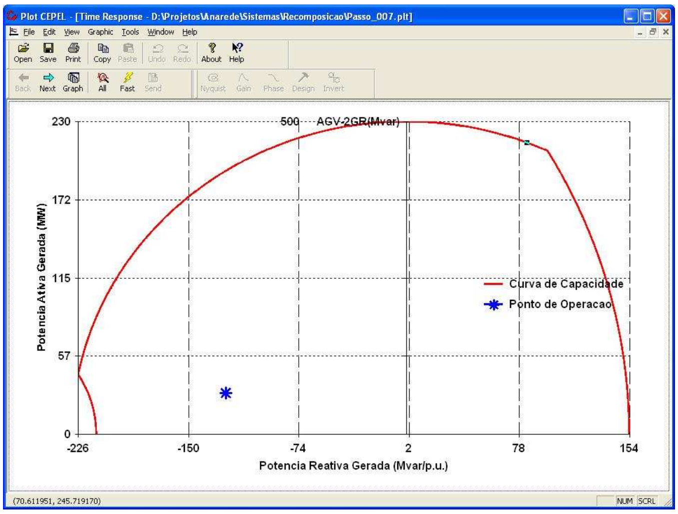

Figure 7 – Capability curve for Água Vermelha generator units on the 7th step of the restoration path.

7. CONCLUSIONS

Restoration studies are critical activities that demand intensive data preparation and post-processing analysis work. These labor-intensive tasks may be automated to a significant extent, resulting in the speed-up of the whole process, and creating the possibility to test multiple alternatives. Customized computer applications together with new graphical user interface, equipment models, data blocks and functionalities incorporated into a production grade power flow program, effectively speeded up BIPS restoration studies performed by ONS, improved the quality of results and made possible the reuse of restoration path data for periodical restoration strategy revalidation.

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