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Real-Time Root Cause Analysis for Power Grids

Jan Eric Larsson, Bengt Öhman, and Antonio Calzada
GoalArt
Sweden

SUMMARY

The power grid is a complex and sensitive system, and its operation is essential to modern society. Power grid operation has a very high degree of reliability, but it is threatened by small disturbances developing into larger problems, ultimately leading to a complete blackout of the grid. Most of the large blackouts have been preceded by a short time period, from several minutes up to a few hours, where smaller problems occurred and fault indications and alarms started to pour in to the control room. The operators quickly became overloaded with information and were unable to understand the fault state and to plan and execute actions to save the grid.

If we provide operators with an intelligent system to help them understand the current (developing) fault situation, it would be possible to provide quick root cause analysis, which is important for reliable and efficient restoration of the grid. Sometimes, it could even be possible to avoid blackouts by quick actions in the time period during which the problems escalate from small to large.

The article describes a plug-and-play solution for a real-time root cause analysis system, based on multilevel flow models. This system has been tested in projects with EPRI and the Swedish National Grid. For example, it gives an immediate and correct analysis of the September 23, 2003 blackout in southern Nordel.

KEYWORDS

Alarm cascade, blackout, multilevel flow modeling, root cause analysis, situational awareness.

E-mail: janeric@goalart.com

INTRODUCTION

Interconnected power grids are probably the largest man-made systems that exist. Power grid operation has a very high degree of reliability, but it is threatened by small disturbances developing into larger problems, ultimately leading to a complete blackout of the grid. Several instances of this have occurred during later years. Most of the large blackouts have been preceded by a short time period, from several minutes up to a few hours, where smaller problems occurred and fault indications and alarms started to pour in to the control room. The operators quickly became overloaded with information and were unable to understand the fault state and to plan and execute actions to isolate parts of or reconfigure the grid.

If we provide operators with an intelligent system to help them understand the current (developing) fault situation, it would be possible to provide quick root cause analysis, which is essential to restore operation. It could even be possible to avoid large blackouts by quick actions in the time period during which the problems escalate from small to large.

THREE BLACKOUTS

There have been several large blackouts or near blackouts in the last few years. Most of them have large similarities, but they also differ in details. They all have the following properties in common.

- Several independent faults had to occur more or less simultaneously, in order to actually threaten the grid operation.
- Those faults caused an unclear alarm situation, there were a large amount of alarms, and the operators did not understand what was going on, in the time period preceding the blackout.
- The fault situations developed into fault cascades, caused by effects spreading through the grid, such as overload of parallel lines and automatic disconnection by protection relays. At some point, the fault cascade accelerated and became irreversible, causing a large blackout.

However, different blackouts have developed at different speeds, and in different manners.

September 23, 2003 – Southern Nordel

At 12:30 on Tuesday September 23, 2003, the Oskarshamn 3 nuclear power plant in southeastern Sweden had a valve fault, which lead to a routine scram. Only five minutes later, there was a severe internal short circuit in the Horred sub-station in southwestern Sweden. Both these faults were large, and together they lead to a situation where southern Sweden was externally supplied by only two sets of AC lines, which became severely overloaded. This situation lasted for about 100 seconds, after which the lines automatically disconnected. This, in turn, lead to an immediate and total voltage collapse in southern Sweden and eastern Denmark.

In this case, the operators knew about the Oskarshamn trip from when it happened, but did not locate the Horred fault for four hours, due to the large number of alarms in the control room. The time from the Horred fault to the irreversible cascade was only 100 seconds; too short for any preventive action. However, it could be argued that parts of the restoration and media information would have been more efficient if the Horred fault had been known at an earlier stage.

November 4, 2006 – European Interconnection

At 21:38 and 21:39 on Saturday November 4, 2006, E.ON Netz disconnected the Diele-Conneforde 380 kV line circuits one and two. This was in order to allow the cruise ship "Norwegian Pearl" to pass the Ems River to the North Sea. Once the line was disconnected, overload warnings started to pour into the E.ON Netz control center. Between 22:05 and 22:07, the 380 kV line Landesbergen-Wehrendorf overloaded. In order to remedy this, E.ON Netz connected two separated bus bars in the Landesbergen sub-station. This connection had an opposite effect from what was expected, and lead to an overload and disconnect cascade going south and east across the European interconnection from 22:10:13 to 22:10:32. The grid was separated into three independent but still working islands. The western part had the largest power deficit and 15 million households experienced the disturbance. Several attempts were made to re-synchronize the three areas, but they all failed because of large differences in frequencies. Finally, at 22:47, the first successful re-synchronization took place, and the European grid was reconnected around 23:57.

In this case, the operators had an unclear picture of the situation both before and after the cascading outage. The cascade itself was so quick that it would not have been possible to stop it by manual actions. It is not clear how useful a real-time root cause analysis for the cascade would have been. It is possible, however, that an immediate root cause analysis would have saved time in the restoration.

August 14, 2003, Eastern US and Canada

From 15:05 to 16:05 on August 14, 2003, the First Energy grid in northern Ohio experienced a slow cascading outage. It began when three 345 kV lines independently short-circuited against trees. It was a hot day, but none of the lines were heavily loaded. The reason for the short-circuits seems to have been bad tree management. When the three lines were lost, the lines in the underlying 138 kV grid gradually overloaded and tripped. After about one hour, the loss of lines overloaded another 345 kV line between Sammis and Star, and when this line tripped, there was a rapid fault cascade, which spread over the eastern US and Canada in a few minutes.

In this case, the First Energy SCADA/EMS system also experienced a problem. A software process that should transfer data from the signal database to the alarm system presentation hanged. Thus, the First Energy operators did not see any alarms, and were not aware of the developing fault situation.

The first, slow part of the cascading fault situation lasted for one hour, and during this time period, several actions could have saved the grid and avoided the blackout, had the operators been aware of the situation and understood the fault situation. Here one can argue that if the alarm system software had been working properly, a real-time root cause analysis could very well have enabled the operators to avoid the blackout and save the day.

REAL-TIME ROOT CAUSE ANALYSIS FOR NORDEL SEPTEMBER 23, 2003

During 2006, the Swedish National Grid and GoalArt performed a case study and pilot project on the September 23, 2003, Nordel blackout. The aim of the project was to create a pilot diagnostic system that could identify the root causes of the cascade in real time, thereby providing situational awareness for the operators from the beginning of the incident. The project comprised the following phases:

- Automatic generation of a multilevel flow model (the basis for the root cause analysis), from the Oracle database net list.
- Automatic analysis of the alarm and event list saved on September 23, 2003.
- Creation of a demonstration system with a human-machine interface to show the results of the analysis.
- Test and evaluation of the system's performance in the developing blackout cascade situation.

The resulting system is quite successful. It is possible to generate the knowledge database needed in a 100 % automatic fashion. The real time alarm and event input data can be used as produced by the SCADA system. The system identifies the two independent root causes *as soon as they arrive*. Thus, it provides the correct explanation for the fault situation immediately. If the system had been available in the control center on September 23, 2003, the Horred fault would have been known from the first minute, rather than after four hours. The project continues during 2007-2008, with the aim of integration with the control center SCADA and EMS system.

In another project, our system correctly analyses the start of the August 14 blackout, in the First Energy grid in Ohio.

PROBLEMS IN POWER GRIDS

We propose that there are a few main types of problems in power grids. These are:

- Protection shutdown cascades, which may cause large alarm cascades through consequential overloads and shutdowns, see for example [6]. It is interesting to observe that many of the problems are created by the protective systems, not the grid itself. We have seen that MFM can handle this kind of problem well in a number of examples.
- Voltage collapse problems, which are caused by lack of generation compared to loading. Due to the effects of reactive power, a grid does not loose power in a gradual fashion. Instead, there is usually a point, below which the grid looses all power in a sudden collapse. This type of problem is also handled well by the MFM-based algorithm.
- Frequency problems, which typically are caused by loss of sources, and where loads must be shut down. MFM is less needed here, because these problems do not present the same topological difficulty. The frequency is a globally available “sensor” for detection and diagnosis. It is easy to model frequency and its effects in MFM, though.
- Swing problems, typically caused by almost overloaded transmission lines and long distances between large sources and loads. Given that measurements are available, MFM can likely analyze swing situations too, but this needs to be further tested and evaluated in future projects.

MULTILEVEL FLOW MODELS

Multilevel Flow Models (MFM) is a graphically represented, formal modeling language, in which the intentional properties of a technical system are described. The purposes of the system and its subsystems are modeled with goals. The capabilities of the systems are modeled with flow functions, connected into flow paths. For a description of MFM, see [1-5].

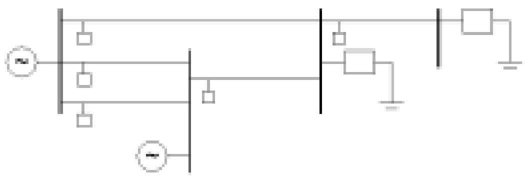

Figure 1. A simple example of a power grid.

MFM has a well-defined syntax and a well-described semantics [5]. There is a theoretical foundation behind the choice of flows and functions. However, in a short paper, the nature of MFM is probably best explained by an example. In Figure 1, we see a small grid. Each line is guarded by relay protection, (one relay and circuit breaker at each end). In Figure 2, we see an MFM model of this system. An MFM model of a grid can be created in a systematic way, from model fragments such as lines, N-way bus bars, etc. The details of MFM models and modeling have been thoroughly described in [1-5].

ROOT CAUSE ANALYSIS

Larsson [1] presented an algorithm for root cause analysis based on MFM. It solves the problem of finding root causes in large cascades of events, where most events are consequential faults caused by a few primary root causes.

In MFM, there are only a few syntactically legal connections between the model objects. The root cause analysis algorithm has a small table of causation rules fore each legal connection. Whenever the fault status of an object changes, the algorithm calculates whether this is a root fault or caused by a neighboring fault, simply by looking at the fault state of the neighbor objects, and applying the rules of the relevant causation table. An entire fault situation is analyzed step by step by pair wise comparisons. This way of implementation makes the algorithm very simple and fast.

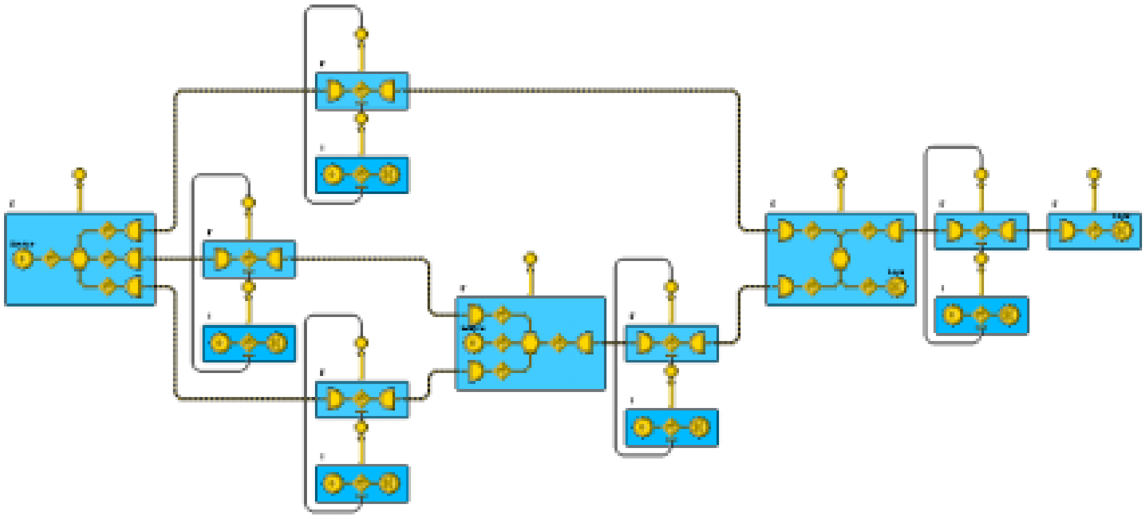

Figure 2. An MFM model of the example grid. Each generator, line, bus bar, and load is modeled in a standardized way. A model like this can be generated automatically from a topology database. The MFM objects used in the model above have been explained in detail in [1-5].

The details of the MFM-based root cause analysis have been given a more formal description in the thesis [1] and the article in Artificial Intelligence [3]. A number of additional features have been developed by GoalArt, whereof some have been published. Several developments are proprietary to GoalArt. The algorithm has been industrially proven in several applications, in conventional and nuclear power, for medical and chemical systems, and for electrical and control systems in vehicles. It has a number of interesting properties, which make it well suited for realistic size diagnostic problems.

- It provides a single, correct analysis of every possible combination of inputs allowed by MFM. This was not true for the previous versions, but has been developed by GoalArt in later years.
- The root cause analysis algorithm is independent of timing information. Thus, it can handle situations where the faults arrive in out-of-time order, which is necessary for any real system.
- The algorithm can handle varying magnitudes and directions of flow, as the current grid status changes. This is true even when flow directions change in the midst of developing situations.
- The algorithm can handle all possible combinations of faults, multiple independent root causes, circular dependencies, etc. Most other methods cannot handle such cases.
- The algorithm is efficient and it is possible to calculate worst-case time and memory demands. A large fault situation with several thousands of events can be analyzed very quickly. For example, a complete root cause analysis on a large power grid takes less than a second.
- The size of an MFM model grows linearly with target system size, and the time and space demands of the algorithm grows linearly or less than linearly with MFM model size.

HUMAN MACHINE INTERFACE

The root cause analysis allows an immediate presentation of the originating faults in a complex fault situation. It allows the operators to know what happened at a single glance, see Figure 3, and they can maintain situational awareness through a complex event, and avoid a blackout, perform a graceful save, or restart more quickly.

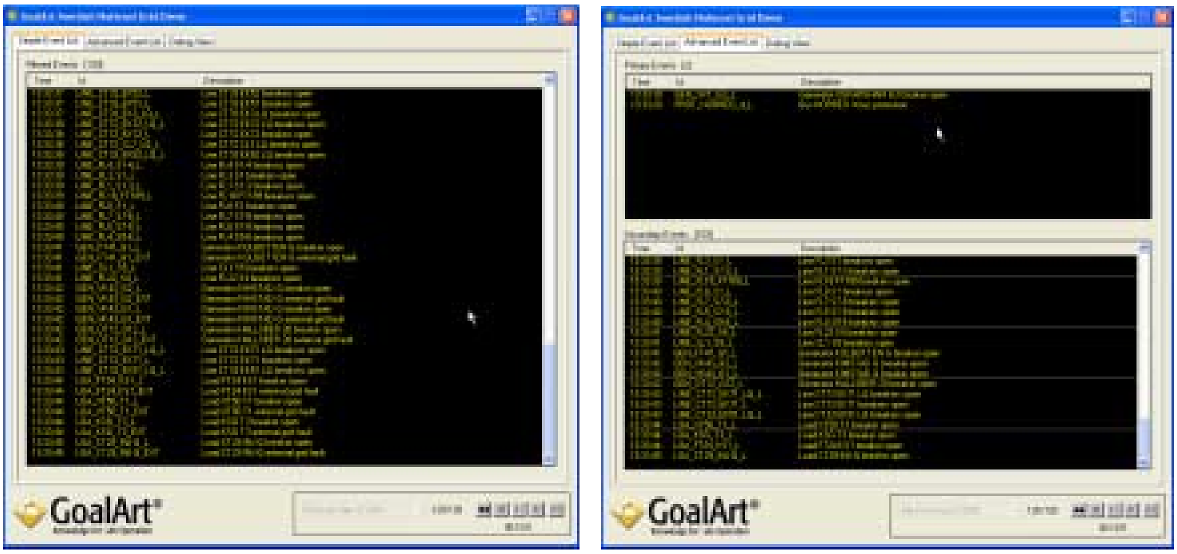

Figure 3. To the left, we see a standard alarm list, where the root cause alarms are very difficult to find. To the right we see a dual GoalArt alarm list, where the root causes are shown in the upper list. This allows the operators to recognize the causes of the entire cascade in a single glance. Based on this, they may be able to take actions to mitigate the fault situation immediately.

AUTOMATIC MODELING ALGORITHM

GoalArt also has developed an algorithm that can build MFM models automatically from database information about nodes and branches. In essence, all grid objects are seen as generators, lines, bus bars, or loads. For example, a transformer corresponds to a line element, since it is a power-transporting device. The MFM model is automatically built from model fragments for each of these four object types, and those model fragments are reused over and over again, see Figure 4.

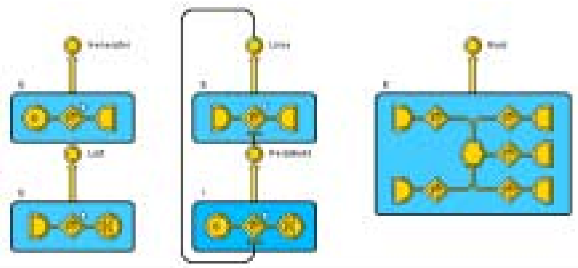

Figure 4. Each grid component has a corresponding MFM model solution. Thus, generators, lines, bus bars, and loads are modeled in a standardized way, which allows automatic generation of an entire MFM model.

The information needed can be obtained from a grid topology database, and each time the grid and database is updated, the automatic model generation algorithm is executed, to provide an updated model. In this way, the MFM-specific knowledge engineering is limited to creating new types of grid components when needed. The rest of the modeling work is completely automated.

INPUT DATA

The root cause algorithm uses the same alarm and event inputs as are presented to the operators in the control room. These data come from circuit breakers, power flow measurements, protection relays and similar equipment, and some data may come from on-line state estimators. Thus, the GoalArt system should be connected to the SCADA and EMS system in the control room. The automatic model generation algorithm should be connected to the grid topology database, and executed whenever this database is updated. Minimally, the algorithm needs breaker positions and power flows only, but it can also use other data, such as, for example, protection relay signals.

ROOT CAUSE ANALYSIS FOR AN ENTIRE GRID

The MFM-based root cause analysis algorithm has a number of interesting properties:

- MFM can handle large models. Currently, some of the larger models of, for example, nuclear power plants, contain some 50 000 objects, and the worst-case execution time of the analysis is less than a second.
- The worst-case time and memory demands increase linearly or less than linearly with model size.
- MFM provides sub-models to structure large models in an efficient way, and sub-model libraries to handle efficient reuse of models.
- Execution times in our current power grid examples, such as southern Sweden, are less than a second.

We contend that it is possible to perform root cause analysis for large areas of the power grid, for example, the entire area controlled by an Independent System Operator, (ISO), which are the organizations that operate the US interstate grids. MFM models can be structured in sub-models and the algorithm distributed over several processors, so it is possible to envision a solution, which can perform root cause analysis for very large parts of the grid using GoalArt technology.

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