A DMS PLATFORM FOR MONITORING AND ANALYSING LARGE DISTRIBUTION NETWORKS

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ABSTRACT

This paper deals with a Distribution Management System (DMS) platform developed by GILLAM (Belgium) and aimed at monitoring and controlling large distribution systems. The latter include both high and medium voltage levels in a mixed meshed and radial architecture. This project has involved the Electrical Engineering department of the University of Liège (Belgium) for the development of power network analysis algorithms. The most important features of the developed algorithms are their ability to handle large systems as well as perform computation in a single step on both the radial and meshed parts of the system. The platform is in use at the Usine d'Electricité de Metz (UEM), a French power utility from which examples are provided in this paper.

INTRODUCTION : PLATFORM OVERVIEW

The LYNX remote monitoring and control system, developed by GILLAM, has been designed to integrate power systems real-time monitoring and control functions (SCADA) together with a sophisticated DMS and a detailed study-mode module. Moreover, LYNX is built on an open software architecture and based on a highly structured real-time data base model, the global package providing the operator with an easy and powerful Graphic User Interface (GUI) system.

The study-mode module provides the operator with the following functions :

- power system analysis functions : load flow and short-circuit power calculation
- quality of service management (in the UEM case, service interruption counting based on number and duration analysis for the EDF Emeraude contract at each feeder of the distribution substations) : the study mode allows the operator to replay sequences of manœuvres performed within the context of system restoration after a failure
- preparation of complex manœuvre sequences.

These functions are run on system snapshots, acquired either from the real-time operating mode for real-time analysis and control or from the data base archive module for network operators training purposes. The GUI system is identical to that used in real-time monitoring and control except for colour codes.

This paper focuses on power system analysis functions and their environment. Its objective is twofold : (i) describe the flexible scheme adopted to integrate these functions in the overall platform; (ii) show how general power system analysis algorithms have been adapted so as to meet the specific requirements imposed both by the type of operation and the nature of systems to be handled.

Indeed, system modelling comprises both the High Voltage (HV) subtransmission system and the Medium Voltage (MV) distribution network. While the former is a rather small meshed system, the latter presents most usually a radial structure. This mixed meshed-radial structure has imposed the development of appropriate load flow and short-circuit power algorithms. Moreover, the overall system can comprise up to several thousands of buses. When dealing with a real-time system snapshot, real-time system analysis and control imposes very fast computations.

The first part of the paper presents the system modelling required by the power system analysis functions. The load flow and short-circuit power algorithms are described in the second part. Finally, Part 3 shows how these functions have been integrated the DMS platform.

PART 1 : THE STUDY MODE FOR THE POWER SYSTEM ANALYSIS FUNCTIONS

Preparation of system snapshots

The study mode relies on a copy of the data base in order to avoid interfering with real system operation. To start a computation, the operator has to define : (i) the part of the network concerned by the computation; (ii) the load and generation scenarios. Note that loads can be modelled either automatically or manually by the operator.

Network part selection. The study mode allows to define the boundaries of the system to be studied, retrieving information from a data base version which can be either a real-time or an archived snapshot acquired upon request (cyclically or on an event basis). Through the LYNX GUI, the operator can select the whole or a part of the network. In the example shown in Fig. 1 the operator has selected the whole HV subtransmission subsystem together with two MV distribution feeders. This is typical of situations where one is willing to test the consequences of closing the S switch (see Fig. 1), thereby creating a loop in the distribution system.

The boundaries of the studied system being defined, the operator can modify the topology as easily as in the real-time mode.

Automatic load modelling. Depending upon operators' needs, loads are modelled at various voltage levels. For instance, if one is interested in power flows on HV subtransmission lines (or cables) only, loads are represented at the corresponding HV buses (e.g. buses A, B, C, D in Fig. 1). On the other hand, if one is interested in power flows or voltage drops on some selected MV distribution lines, loads are represented :

- at MV buses for the selected part of the distribution system (e.g. buses G, H, I in Fig. 1)
- at HV or distribution feeder buses for the remaining of the system (e.g. buses B and E, F respectively).

Presently, the MV/LV transformers are not modelled; each corresponding power is attached to the MV bus of concern.

Load modelling algorithms are different according to the voltage level at which loads are represented. Indeed, they originate from either real-time measurements (e.g. current telemetering on distribution feeders) or management parameters (e.g. industrial customer consumption).

After the network boundaries have been defined, the operator selects the load power calculation rules at each voltage level.

Obviously, these rules may differ from one utility to another. In the UEM case, MV loads are determined as follows :

- for each circuit leaving a distribution feeder, the downstream MV substations fed by this circuit are listed
- the power flowing into this circuit is derived from the available current telemetering
- this power is distributed over the listed MV buses according to participation factors derived from systematic measurements gathered in MV/LV substations
- both active and reactive powers (P, Q) are managed.

Beyond these general rules, the load power computation takes into account, among others, the specific behaviours of industrial customers for which various known management parameters allow more accurate computations (power, tariff, consumption habits, etc.)

Moreover, parameters such as time (week, day and hour), changes in temperature, and special tariffs influencing customer behaviour (e.g. the so-called "EJP") are taken into account.

Manual load modelling. Computed load powers can, of course, be modified by the operator, either globally through multiplication factors or individually by accessing through the GUI to the bus specifications.

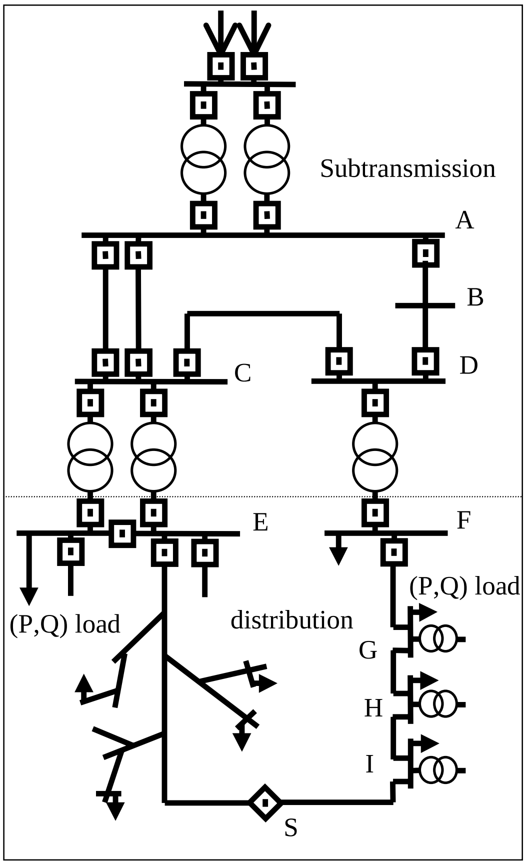

Figure 1 : Loop analysis

Generation modelling. Generators are easily represented, since they are most often remotely controlled (e.g. power telemetering is available). As for loads, power generations can be adjusted by the operator, who can then define for each group the active and reactive power, and the regulation mode (PV or PQ).

Computation requests

The operator has to select the type and options of the required computation. The request along with its options are further sent to the power system analysis module. Options and specifications to be met by the computation are the following.

Load flow. The operator can choose to either automatically adapt taps of regulating transformers or to let them fixed to their initial tap position. Real-time computation on the whole subtransmission plus distribution systems is needed if analysis concerns a real-time system snapshot.

Short-circuit power. The software is able to handle all types of shunt faults : single line to ground, double line, double line to ground and balanced three-phase. The following specifications are to be met :

- in real-time analysis : short circuit powers are to be computed at all system buses for three-phase nonimpedant faults, within a time delay compatible with real-time analysis;

- in training studies : the user can choose the location, the type and the impedance of the fault; at the maximum, voltages and short circuit currents and powers can be determined at any system bus for any fault type. Although real-time response is not required, the computation should be as fast as possible.

Results

Results can be accessed through two different ways.

The most important results, i.e. line currents and bus voltages in the load flow analysis, and bus short circuit powers are continuously sent back to the LYNX real-time tables. They are accessible through the real-time LYNX objects tables as well as displayed on the appropriate one-line network diagrams. Besides, special displays are made available such as the colouring of overloaded zones.

The less frequently used results, such as symmetric components, phase angles, etc. are provided in readable files that can be directly accessed in the study-mode.

PART 2 : POWER SYSTEM ANALYSIS TOOLS

They have been designed so as to meet the special features quoted in the Introduction, namely : system composed of both radial and meshed parts and comprising up to several thousands of buses.

Load flow

Efficient general purpose algorithms to solve the load flow problem in EHV meshed transmission systems are available [1,2]. Most are based on the Newton-Raphson method. For certain ill-conditioned cases, such methods can present convergence difficulties. Radial distribution MV systems have long been recognized as an example of such difficult case. The reason is twofold : (i) small X/R ratios for line impedance; (ii) presence of very short line sections. Moreover, the well-known electric $P\theta$/QV decoupling inherent to EHV networks no longer exists for systems comprising MV levels so that the widely used fast decoupled load flow algorithm reaches its limit of applicability.

Several load flow algorithms specially designed for distribution networks have been proposed in the literature [3,4]. They tend to improve numerical robustness as well as computational efficiency by taking advantage of the radial structure of distribution networks. Most of them however are not able to handle at the same time meshed and radial parts. Now, the presence of network loops is precisely a situation where load flow calculations are useful to operators.

As computers become increasingly powerful, computational effort is not the most important aspect when choosing a particular methodology. In particular one can now without difficulty resort to double-precision arithmetic. By so doing, numerical convergence of any algorithm is significantly improved. In particular, conventional Newton-Raphson method is able to successfully tackle most ill-conditioned distribution networks [3].

We have implemented the conventional Newton-Raphson method, handling in a single step both radial or weakly meshed distribution feeders and the meshed subtransmission system. Denoting by **x** the vector of nodal voltages, power balance at system buses can be written as :

$$\mathbf{f}(\mathbf{x})=\mathbf{0} \qquad (1)$$

The Newton-Raphson method solves eq. (1) through the following iterative procedure:

$$\mathbf{J}(\mathbf{x}^{k+1}-\mathbf{x}^{k}) = -\mathbf{f}(\mathbf{x}^{k}) \qquad (2)$$

In the latter expression, **J** is the Jacobian of **f** with respect to **x**. Convergence is achieved when all absolute power mismatches (right-hand side of eq. (2)) are below a specified threshold (solution tolerance). Full Jacobian formulation is used as the $P\theta$/QV decoupling property is not satisfied on distribution feeders.

Sparsity techniques are used to reduce the computational effort. More precisely, triangular factorization of the Jacobian relies on an optimal ordering scheme which limits at the maximum the Jacobian fill-in. This scheme automatically recognizes the radial parts of the system. In the presence of a radial structure, the ordering scheme orders buses from the leaf nodes up to the root one [3,4]. This avoids a large amount of computation and allows real-time load flow computation for systems comprising up to several thousands of buses.

Short-circuit calculation

The general methodology relies on symmetric components and on an admittance (Y)-matrix based formulation, which we briefly recall hereafter.

General Y-matrix procedure. The first step of the procedure consists in computing the Thevenin impedance Z_i^{Th} as seen from the faulted bus *i* in each sequence network. This requires to solve, for each sequence network, the following set of linear equations:

$$\mathbf{I} = \mathbf{Y}\,\mathbf{V} \qquad (3)$$

where **Y** is the node admittance matrix of the relevant sequence network and **I** is a vector of 0 except for the *i*-th element which is set to 1. The Thevenin impedance is given by the *i*-th component of vector **V,** i.e. :

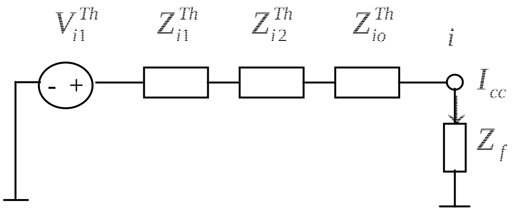

Figure 2 : single line to ground fault, equivalent system

$$Z_i^{Th} = V_i \tag{4}$$

Depending on the fault type, the short circuit current I_{cc} is derived after properly connecting the three sequence networks [5]. Assuming for example a single line to ground fault, and replacing each sequence network by its Thevenin equivalent, I_{cc} derives from the system sketched in Fig.2. Z_f stands for the possible fault impedance; V_{i1}^{Th} represents the Thevenin emf of the positive sequence[1]. It is of common practice in power system fault computation to set V_{i1}^{Th} to $1\angle 0$ assuming a flat voltage profile in the pre-fault configuration. With such an assumption, effects of loads are fully neglected. Another possibility is to fix V_{i1}^{Th} to the node voltage value at bus *i* in the pre-fault configuration. This requires a preliminary load flow calculation.

Both possibilities have been implemented, the choice being left to the user.

One short-circuit current computation requires to solve up to three systems of the type (3). Although **Y** is a sparse and symmetric matrix, this leads to a prohibitive computational cost, incompatible with real-time application, if fault calculation has to be done at each system bus. As quoted in Part 1, meshes are present in the rather small subtransmission system and in the distribution system during its reconfiguration. We now describe the method which has been implemented to exploit this network structure.

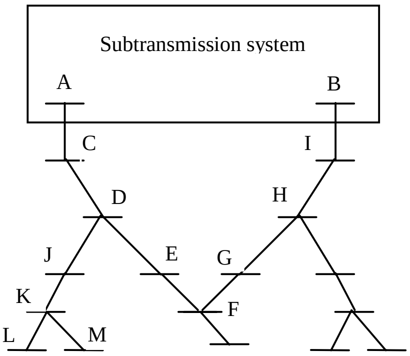

Figure 3 : a weakly meshed structure

Computation of Z_i^{Th} for radial structures.

Consider the small illustrative system shown in Fig. 3. It is composed of the subtransmission system and two distribution subnetworks connected to A and B. Moreover, the two subnetworks are looped through node F. Assume a fault at bus J, part of the radial tree DJKLM. The short-circuit “masks” the lower part KLM and, assuming that the Thevenin impedance at node D, Z_D^{Th}, is known, Z_J^{Th} at node J is simply given by

$$Z_J^{TH} = Z_D^{TH} + Z_{DJ} \tag{5}$$

where Z_{DJ} is the line series impedance of line section DJ. Once Z_J^{Th} known, the procedure can be repeated successively for buses K, L and M.

Eq. (5) relies on the following assumptions :

- the short-circuit is nonimpedant
- any shunt line capacitance is neglected
- no generator is connected to MV buses.

Note that the last two assumptions are quite reasonable for most distribution systems.

Assume now a fault located at some bus belonging to the loop, say bus D. The short circuit masks the lower part JKLMN but not part EFGHI of the loop and the above procedure is not valid. Z_D^{Th} has to be computed by the general Y-matrix formulation.

In radial parts and in case of nonimpedant faults, solving (3) can be conveniently replaced by the above simple procedure : computation of Z_i^{Th} at each bus is performed iteratively progressing from the root bus down to terminal buses by simply adding at each step the impedance of the line section crossed. The general Y-matrix formulation is only required on meshed parts of the system where the iterative simple procedure does not apply, namely : at each bus of the subtransmission system and at each bus of loops present in the distribution system (e.g. in case of the simple system of Fig. 3, at buses of the C, D, E, F, G, H and I loop).

This leads to an overall procedure composed of the following three steps:

- identify the meshed and radial parts of the system through a topological algorithm
- compute I_{cc} at each bus of the meshed part through the general Y-matrix formulation
- compute I_{cc} at each bus of the radial part according to the above iterative procedure.

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[1] since the system is supposed to be balanced in its pre-fault configuration, Thevenin emf only exists in the positive sequence

As illustrated below, this leads to a dramatic reduction of the total computational effort.

Illustration of performances

The load flow and fault calculation algorithms have been tested with respect to both computational efficiency and robustness. Computing times are assessed in terms of CPU time on a 300-MHz SUN UltraSparc-2 workstation.

Test system. It is derived from the UEM power system and is composed of :

- the 63-kV meshed subtransmission network : it comprises 55 buses, 39 lines and 34 transformers among which 21 feed distribution networks
- one connection to the 225-kV transmission system
- 8 local generating units
- 4x21=84 radial distribution subnetworks connected at the 17.5-kV bus of the 63kV/17.5kV transformers. For testing purposes, the same structure is reproduced at each 17.5-kV bus and is composed of 4 trees comprising respectively 9, 28, 66 and 100 lines and buses.

Overall, this leads to a system model with 4318 buses, 4302 lines and 34 transformers.

Loads may be either connected at the 63-kV level if distribution subnetworks are not represented in computations or at the 17.5-kV distribution stations if the computation includes the corresponding subnetworks. The system load is 296 MW, of which local generating units produce about 10%.

Load flow computation. We consider the whole system with 84 distribution subnetworks and evaluate the overall computing time. It is of 1 s, which is perfectly compatible with real-time use. Note that a load flow computation on the subtransmission system only takes less than 0.01 s.

Numerical robustness is mainly dictated by the minimal X/R ratio and the minimal line section length. The minimal X/R ratio is about 0.3. To test algorithm robustness, we have varied the minimal length of some line sections from its initial value of 20 m down to only 1m. Table 1 presents the number of iterations obtained when decreasing the solution tolerance. The latter corresponds to the maximal (kW or kvar) power mismatch allowed at each system node. Decreasing line length leads to one additional iteration only and, as expected, decreasing the solution tolerance slightly increases the number of iterations.

Table 1 : number of iterations

l_{min}	solution tolerance (kW/kvar)		
	1	0.1	0.01
20 m	5	6	7
1 m	6	7	8

Short-circuit current calculation. The computational efficiency of the proposed method is assessed in the context of real-time application. Hence, we consider :

- a nonimpedant three-phase fault
- applied at each of the 4318 system buses.

As indicated in Table 2, the overall computation through the general Y-matrix takes 280 s while the proposed strategy is 56 times faster, with a short-circuit calculation at each of the 4318 system buses performed in 5 s only. Note that treatment of the meshed subtransmision system takes 0.4 s.

We then consider a possible reconfiguration leading to one or several loops in the distribution system. Each loop includes 55 buses. Table 2 reports the computing times obtained for respectively 1 and 5 loops. Although increasing with the number of loops, the computational delay remains perfectly acceptable. Moreover, the gain with respect to the general Y-matrix procedure is still significant.

Table 2 : CPU times

full Y-matrix (4318 buses)	280s
no loop, fast procedure (meshed part : 139 buses, radial part : 4179 buses)	5 s
1 loop, fast procedure (meshed part : 194 buses, radial part : 4124 buses)	7 s
5 loops, fast procedure (meshed part : 414 buses, radial part : 3904 buses)	18 s

PART 3 : INTEGRATING THE POWER SYSTEM ANALYSIS MODULE IN LYNX

The parameters strictly necessary for power system analysis are extracted from the LYNX data base (real-time or archieved data base). These parameters can be classified into :

- static parameters which correspond to equipement characteristics (e.g. line and transformer reactances, …) and are fixed as long as the system is not physically modified by adding new elements
- topological dynamic parameters which characterize the breakers status and enable to determine the current network topology
- operating point dynamic parameters which characterize the load and generation pattern or some other parameters which can vary during system operation (e.g. tap position of regulating transformers)

Static parameters are extracted once for all and coded in ASCII files while value of dynamic parameters are get in real-time from the data base.

Figure 4 provides a schematic representation of the power system analysis module. The latter is continuously running a loop waiting for the possible (1) to (6) events, each one of

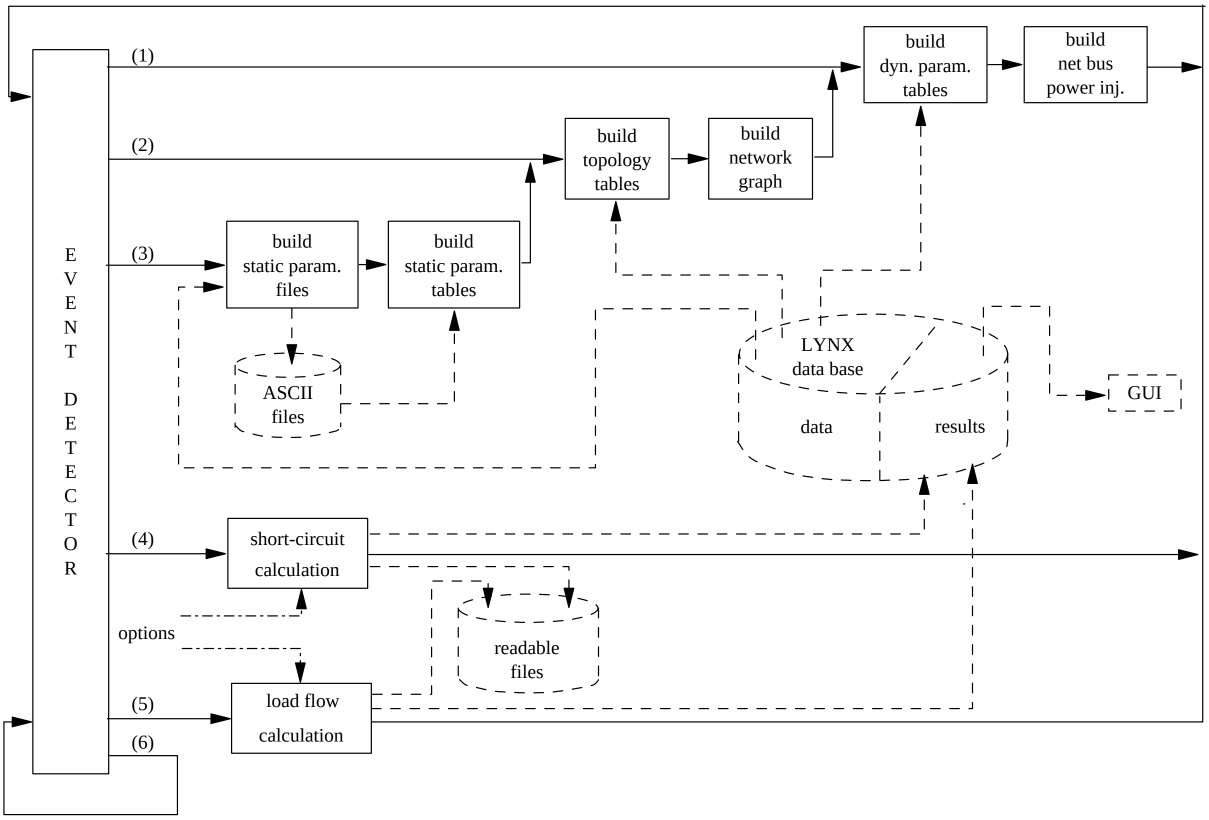

Figure 4 : power system analysis module

them triggering appropriate actions. Possible events and their corresponding actions are the following :

(1) change in operating point dynamic parameters : triggers the update of the dynamic parameters and the computation of net bus power injections necessary for load flow computation; the previously built topology is kept unchanged

(2) change in topological parameters : triggers the update of the topological dynamic parameters and a new determination of the network graph; since topology has been modified, the loads and generations must be subsequently updated

(3) change in static parameters : triggers the interface module converting static parameters in ASCII files; this has to be followed by a whole system operating point update : topology, loads and generations

(4) request for short-circuit calculation : options concern the fault type(s), the fault location(s) and the fault impedance

(5) request for load flow computation : an option can specify to adjust taps of regulating transformers or to keep them fixed during the load flow computation

(6) no event : waiting loop.

As already quoted in Part 1, results are output on readable files and most important ones are sent back to the LYNX data base to be possibly displayed by the GUI.

This very flexible scheme allows to limit at the maximum delays inherent to data flows and makes the power analysis module independent of the platform architecture.

Acknowledgement. The authors are grateful to Mr. F. Grosmangin from the Usine d’Electricité de Metz for his valuable contribution.

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