An Advanced Distribution Automation System
Experience from Application Development and Project Implementation

I. PROJECT BACKGROUND

The CLP Distribution Automation project was first initiated during 1994/95 at which time the CLP DMS network operation could be characterised by manual procedures for system restoration and no real-time data acquisition (RTUs) in the DMS network.

Comparable studies at this time showed that CLP Power had, in general, a slower response time for system restoration. The conclusion was to initiate the CLP Distribution Automation project that besides the DMS system includes more than 6000 RTUs and the corresponding communication infrastructure (5). With the planned RTUs CLP Power intends to automatically supervise over 200,000 measured points and efficiently.

The execution of the DMS project has been done in close cooperation between CLP Power and ABB Automation. Although the supplier and the customer are situated on two continents (Europe and Asia), the work has proceeded in accordance to the original time schedule that stipulates a Taking Over of the final system in October 2000. A key factor to the success of the project has been two dedicated, strong and experienced project teams from both the supplier and customer working for one common goal.

Keywords: Distribution Automation - Distribution Management System - Fault localisation, Isolation and System Restoration - Project execution.

II. PROJECT SCOPE

An overview of the hardware configuration of the DMS systems is found in the Fig. 1. All major components are redundant and, in addition, a backup control system is included.

The SCADA applications are dimensioned for the very large data acquisition network and corresponding event bursts. They include:

- RTU communication infrastructure with 6000 RTUs
- Data acquisition and supervision
- Control capability
- Event/alarm handling
- Sequential control and real-time calculations
- Historical logs and reports

The need to access the DMS pictures by different categories of CLP users has led to a configuration whereby different tools are being used. With this approach the system is configured to cater for more than 80 simultaneous users;

- Unix Workstations; Allocated to users requiring the highest performance and with multiple screens.
- NT Workstations; Allocated to advanced DMS users that require full function access to the DMS master.
- Web enabled HMI; Allocated to the casual DMS user that now and then would like to view real-time pictures from the DMS system using a normal Web Browser from a standard equipped PC.

To provide additional redundancy and emergency facilities CLP Power required a Backup Control System (BCS) at a separate location in the original purchase. The BCS is continuously and automatically kept updated with all information coming into the main center from the process, from the operators as well as changes introduced by data engineering activities. In case of catastrophic failure of the main center CLP will manually switch over the RTU communication network to the backup system and take over the operation from the main system.
The CLP Power configuration includes a Utility Data Warehouse (HIS) for storage and retrieval of historical data. The Data Warehouse, which is based on a relational database (Oracle), stores data from the real-time process and from operator actions. These data can be used by various tools to present historical information in reports, curves or single line displays or to make calculations and analysis.

The Integrated Data Engineering System (IDES) is a Graphical Data Entry Tool combining ease of use with plausibility checks and productivity enhancements, e.g. predefined templates for complex power system objects. The integrated tools and procedures matched with the On-line Data Maintenance features enables a short turn-around time for add-ons and changes in the system database. A typical turn-around is less than 5 minutes for updating the real-time database and pictures in the DMS Master once the modified data has been entered in the Data Engineering tool.

The DMS system includes interfaces to the following external systems.

- Trouble Call and Outage System
- Customer Information System
- EMS (dual-ported RTU + ICCP (planned))
- General Application Programming Interfaces (APIs)

The scope of Network Applications, which are described in more details below, are:

- Topology Engine
- Dynamic Network Colouring
- Load Calibration
- Load Flow Calculation
- Fault Localisation, Isolation & System Restoration (FLISR)
- Interface to Trouble Call & Outage Management (TCOM)

III: NETWORK APPLICATIONS FOR THE DISTRIBUTION NETWORK

The base of the Network Applications is the centralised network model and topology determination. Figure 2 shows the different layers of the network applications. The basis is an Application Programming Interface that encapsulates all database access routines. A node branch topology is provided for all applications, based on the static network topology and dynamic switch status. A more detailed technical description and a technical background on the design of this patented topology model and engine is found in (1), (2) and (3).

The network topology service kernel provides a complete network model for all network applications. This means that information about equipment data, measurements, static and dynamic topology, are shared by all applications. The advantages of this design are:

- The network model is kept only once in a shared memory area of the system memory and not multiple times in each application.
- The applications do not need to read the network information from the database and no separate network model is necessary.
- The functions for reading the network information from the database and constructing the network model are encapsulated in one location.
- The fact that all network applications use the same data structure for the network model makes it easy to exchange results between them.

One usage of the extended capabilities of the topology algorithms is the network analysis based on network partitioning. The basic idea of this analysis is to regard branches as open that fulfil special criteria. Such criteria could be:

- triggered fault or earth fault indicators on this branch.
- existence of flow measurement for the branch
- electrical or non electrical equipment

Based on a dynamic topology created by using one of these criteria, it is possible to draw conclusions for the individual network part based on the information of their separating branches.

An effective and accurate fault localisation algorithm based on network partitioning is described in the following. Figure 3 sketches out an example network with a few branches where the fault indicators have responded. If the fault happens on a branch with fault indicators on both ends (F1), the determination of the fault is trivial. Otherwise the network will be separated into sub-networks by assuming branches with triggered fault indicators as open branches. For the example (F2) in Figure 3 this separation will lead to four sub-networks, represented by the ellipse symbols. After that, a classification of the sub-networks will be done depending on the direction information of triggered fault indicators on the separating branches.

A sub-network where all fault indicators point out of it will be classified as faultless. A sub-network where some fault indicators point out and some into it will also be classified as faultless. Only those sub-networks where all fault indicators point into it will be classified as faulty.
The classification of the separating branches depends on the number and the location of the fault indicators on the branch. If the indicators at both ends of the branch have responded, then the classification will be trivial. Only if both indicators point into the branch will it be classified as faulty (F1). If the branch has only one responding indicator at one end, then the branch will get the same classification as the sub-network at the branch-end with a non-responding fault indicator.

A similar approach can also be used for load calibration. All branches with flow measurements are regarded as open. The total load of one network part can then be determined by building the sum of the flows on all branches that separate this network part from the rest of the network. Using this total load value, the sum value of the measured loads and the distribution factors, all loads without measurement belonging to the network part can be calibrated. The result of this load calibration can then be used as input for a load flow calculation.

Another advantage of the centralised network model is the possibility to derive the structure of the numerical matrix (e.g. Y-Bus matrix, Jacobean matrix) directly from the network model. The structure of the Jacobian is similar to the structure of the topology matrix structure. But for each element in the topology matrix the Jacobean will have a two-times-two sub-matrix. The values of Jacobean matrix are asymmetrical to the main diagonal. Therefore it is necessary to store to upper and the lower triangle of the Jacobian. This method enables extremely quick initialisation and recalculation times for the Load Flow.

In a Distribution Load Flow it is very important to model the voltage dependency of loads correctly. Therefore, the Load Flow uses a load model that is divided into three parts to describe the voltage dependency of the load. The three parts are:

- Constant Power
- Constant Impedance (quadratic voltage dependence)
- Constant Power (exponential voltage dependence)

IV. PRACTICAL USAGE OF THE NETWORK APPLICATIONS IN CLP POWER

This section gives examples how advanced network applications will be used by CLP in the operation of the medium voltage network. Certain feeders in the CLP Power network are normally coupled in a loop configuration, i.e. they are normally fed from two primary substations. Other feeders are normally connected in a radial configuration. The DMS system will, based on the dynamic topology, keep track of the normal configuration of all feeders and alert the operators if a switching operation brings a feeder into an abnormal configuration.

At every command operation the system will check if any loads are disconnected based on the dynamic topology model. If this is the case a warning will be issued in the command dialogue. The operator can override this warning if he so desires. The interlocks will also check if a switching operation would connect a live part of the network to an earthed part. This type of interlock can not be overridden.

Temporary devices, i.e. earth rods, line cuts and temporary lines, can be added to the network through on-line dialogues. Additions of temporary devices updates the connectivity model of the network and are considered in all applications like Dynamic Colouring, Load Flow and Fault Isolation and Restoration. In order to achieve fast, ergonomic response times for the operators the addition (and deletion) of temporary devices must update the connectivity models very efficiently.

The Distribution Load Flow will primarily be used for studies. In CLP configuration the DMS system has been configured for ten simultaneous studies. However, ten is not a limitation of the system but a practical limit set by CLP Power. The studies are used to test planned operations for possible overloads. Examples of operational aspects to study are command sequences, opening or closing of circuit breakers, etc. Save cases can be created at any time, either automatically or manually, and can be used to study alternative actions on historical network situations.

In the Fault Localisation, Isolation and System Restoration (FLISR) application the extremely quick calculation times of the described topology methods are essential. The FLISR application will, based on telemetered information from protection devices and fault indicators, calculate command sequences to isolate and restore the network after faults. Every possible network operation will be checked for overloads in the network with help of the Load Flow application and those operations creating overloads will be discarded. The FLISR application will generate approved command sequences for every fault situation and export these sequences to the Job Management application in the correct format. In Job Management the generated sequences can either be executed automatically by the system or step by step under the operators’ control.

CLP Power has a separate Trouble Call and Outage Management System (TCOM) in operation. The DMS system exchanges data with the TCOM system over a real-time link. Information of both planned and unplanned outages that affect supply to customers are sent to the TCOM system from the DMS system on every occasion. When an outage is detected by the DMS, it will send a list of de-energised load transformers to the TCOM system. The DMS system will also calculate the number of customers that are affected by the outage and send this to the TCOM system. The DMS system receives daily updated information on the number of customer connected to each load transformer.
V. RESULTS AND PERFORMANCE

CLP has throughout the project participated in the review of the distribution network applications. The distribution network applications have been very conscientiously tested by the CLP experts who have simulated a huge number of network operating scenarios. All tests, including the final acceptance tests, are successfully passed.

At the moment the network model for this metropolitan area contains 72,860 branches (22,500 lines, 360 transformers and 50,000 switches) connecting about 65,000 nodes. The DMS system is installed on a redundant computer system using DECserver 1200 computers. The initial establishing of the central network model uses about 10 seconds CPU time. Updating the network model after switch status changes is performed within a few hundred milliseconds CPU time. A complete load calibration for the whole network takes about 7 seconds CPU time, a load flow calculation is ready in 3 seconds CPU time. After a switch status changes, the load calibration and the load flow results for the affected network part are updated in 0.3 seconds respectively 0.1 seconds CPU time.

The execution time for the Fault Localisation, Isolation and System Restoration functionality depends on the size of the network part that was affected by the failure. In most of the cases the localisation and the isolation works in less than 1 second elapsed time and the system restoration takes less than 5 seconds elapsed time including load flow calculation to approve the proposed restoration sequences.

VI. PROJECT EXECUTION

The DMS Master project had a scope of over 65,000 hrs of project engineering and application developments and a time schedule with salient deadlines cemented in time that were determined by a joint understanding worked out during the contract negotiations. To cope with the challenge of managing this task within a 30-month time frame (+3 months availability test) several actions were taken at the supplier and client side (6):

- A detailed Project Plan with "fix" deadlines and built-in slack was agreed upon. An outline project schedule is found in Fig. 4.
- A Relationship Agreement with given rules for "grades" was defined to promote progress.
- Management involvement was encouraged as a part of the relationship agreement.
- Effective communication channels using e-mail and X.25 were established between the parties.

The different project phases from the initial CLP Power study to final taking over can be summarised as follows;

- Pre-Contract (1994-1997)
  - Study
  - Pre-qualification
  - Tender & Evaluation Phase

- Contract Preparation (Dec 1997 - Jan 1998)

  - Functional and Design specification documents
  - Data Engineering style guide and training

- Implementation (Dec 1998 - Sept 1999)
  - System configuration
  - SW Development
  - CLP Data Engineering (Database and pictures)
  - Test Procedures

- Factory Verification period (Oct 1999 - April 2000)
  - System Test
  - Pre-FAT
  - FAT
  - FAT updates and re-test

- Site Commissioning & Acceptance Test (May-Oct 2000)
  - System Installation
  - SAT
  - SAT updates and re-test
  - RTU Commissioning (parallel to DMS Master activities)
  - Database update (bringing CLP data to current status)
  - Availability Test

VII. PROJECT ORGANIZATION

Team set-up

The ABB and CLP Power team organisation has had a similar structure with "kernel" teams at both the supplier and client side. On the ABB side the kernel team consisted of 12 members with different areas of responsibilities e.g. Team Leader (Project Manager), Technical Lead, Hardware Responsible, Head Integrator, Data Engineering Support as well as sub-team leaders for the development projects. Beside the kernel team, specialists were used for different areas when required making the total number of people involved approximately 50.

Customer participation

CLP Power has participated actively in the project in the following fields;

- Data Engineering activities
- Documentation Review
- Change Management
- Site Preparation
- Installation
- Verification activities in Factory and at Site

Responsibilities

A clear line in the division of responsibility in the DMS Master project has been the software delivery and the customer database production. ABB has taken full responsibility for all aspects of the software production with the exception of customer reviews. Correspondingly CLP Power has taken full responsibility for the database definition and the corresponding work to enter all the data using the
IDES graphical data entry tool. To make this task effective it required that CLP Power (after training) first reviewed and planned how the system behaviour should be configured since a SCADA/DMS system has many levels of configuration freedom.

After 6-7 months of training and prototyping the system behaviour (in parallel to the specification activities) the CLP Power decisions were documented in a CLP style guide to be used by all persons involved in the actual data entry. It should be emphasised that this planning and prototyping phase saved considerable time later in the project by eliminating questions of picture/object design or usage of database parameters.

Relationship Agreement

To encourage co-operative team efforts at both the supplier and client side a separate relationship agreement was signed in addition to the basic contract. The purpose of the relationship agreement was to define a framework of contacts between the two organisations as well as to establish measurement methods for the DMS project. These measurements are included in “Key Performance Indicators”, see Figure 5, whereby such items as the Project Schedule for overall project progress and development tasks, Quality and Team consistency over time are measured.

![Figure 5 - Example of Key Performance Indicators](image)

Although the relationship agreement in itself is not contractually binding it has had a positive effect on the project teams in focusing on key parameters (e.g. by audits) as well as establishing useful contacts on the management levels.

Project Challenges

The project has had many different challenges to overcome but most of these can be grouped into the following three main categories;

A. Ambitious Time Schedule

The overall project goals and the urgency of a quick and timely project execution combined with approximately 20 man-years of new development presented at times the need for extraordinary actions by both the ABB and CLP teams.

B. CLP Data Engineering in a changing world

Due to the changing nature of a distribution network and especially for CLP Power, a two step approach was used. The initial phases of the project, up to and including the FAT, a snapshot of the system state was used for testing purposes. Combined with other data from the client, a realistic set of data could be achieved for the testing of SCADA and DMS applications. After SAT the database was updated to reflect the status at the time of taking over.

C. On-line Database Maintenance

The size of the CLP network combined with the high pace of changes in the distribution network makes it necessary to have the data entry/engineering tools well integrated with the DMS Master with performance matching the high set project goals.

- Frequency of database updates; 5-10 changes per day
- Turn-around response time for typical change < 5 min.

Business Partners Co-operation over two continents

The idea of having a business partner halfway around the world may discourage some people. However, in this time and age of Internet, the experience is quite different, it is actually in some sense an advantage compared to having your business partner next door. It does, however, require some basic rules to be successful;

- The use of email as primary means of communication to promote formal and informal contacts and with the advantage of almost immediate delivery to the person addressed.
- One correspondence log with defined rules of correspondence identification. Even when traditional means of communication such as letters or fax are used, a notification and/or copy via e-mail is recommended.
- “Long days effect” due to Asia/Europe time difference enabled “shift-work” within a 24-hrs period. The time difference between Hong Kong and Europe is 6/7 hrs, i.e. when the engineer at the CLP site prepares to finish the day, his partner in Europe is about to start activities.

The time difference actually turned out to be more a benefit than a disadvantage since a kind of “parallel” engineering was possible. Questions or comments issued during the working day at one location could be answered until the start of the working day at the site of the originator. Even software problems reported during the working day in Hong Kong could via remote X.25 connection be resolved until the client team was back to work during the next day.

CLP Data Engineering and Training

CLP Power has been responsible for the Data Engineering part of the project (7). For this purpose a graphical tool for Data Engineering (IDES) has been used which enables definition of objects, connectivity and the graphical representation in one single step. The Data Definition work has mostly been done in Hong Kong after training in Europe. Also on-the-job training has been extensively used with CLP Power engineers working within the ABB project organisation in Europe. These engineers have performed some of the local training in Hong Kong for operators and system engineers before system Taking Over.

CLP Power defined at an early stage the magnificent target of installing 1000 RTUs per year. During 1999 this target was achieved and the long-term goal for year 2000 and beyond is to accelerate the pace. Such an ambitious target makes it necessary to enter the data for 3-4 new RTUs each working day in average. This goal can only be achieved using suitable tools such as the IDES/On-line Data Maintenance.
functionality that enables incremental add-ons into the real-time DMS database without disturbing the operation of the rest of the network.

The above tasks can also be illustrated by the CLP Power achievement of successfully entering the following amount of equipment data within a period of 6 months, by temporary employing 5-6 data clerks to do this work.

<table>
<thead>
<tr>
<th>Single line pictures:</th>
<th>1,400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Stations:</td>
<td>120</td>
</tr>
<tr>
<td>Sub-Stations:</td>
<td>18,000</td>
</tr>
<tr>
<td>Transmission Lines:</td>
<td>30,000</td>
</tr>
<tr>
<td>Transformers:</td>
<td>357</td>
</tr>
<tr>
<td>Switches:</td>
<td>66,000</td>
</tr>
<tr>
<td>Measurements:</td>
<td>33,000</td>
</tr>
<tr>
<td>Indications:</td>
<td>58,000</td>
</tr>
</tbody>
</table>

The above achievement was possible due to good preparation work by CLP Power and by the use of the easy and intuitive IDES tool as well as an excellent co-operation between the CLP and ABB engineers working out concepts and templates for the data entry.

The separation of engineering tasks (Data entry style guide; "rules") from the daily data entry work enabled the optimal use of CLP Power personnel. Data entry clerks following defined rules set-up in the style guide combined with lead data entry engineers supervising the work entered all of the CLP data.

VIII. SUMMARY - PROJECT SUCCESS ATTRIBUTES

The project goal to reduce outage time and to improve restoration procedures is now in its initial months of operation. Previous testing in FAT and SAT has shown that significant improvements can be expected using the basic Distribution Automation facilities as well as from the Advanced Network Applications available to the operators.

The overall experience gained in this project working on two continents has been very positive both on the supplier and the customer side. With a close co-operation between two motivated project teams it has been shown that the original time schedule could be kept for a project of this size and complexity.

To achieve the above milestone, a common understanding of the project goals and their importance to the CLP business environment has contributed to a "one team partnership approach" in which each party has contributed to the success of the project without loosing sight of the client/supplier relation - a true win-win co-operation. The spirit of this co-operation was founded on three basic items;

- A knowledgeable client that via pre-studies and earlier experience has shown a professional handling of internal as well as external issues.
- The supplier using a well-proven formula - to give the client what he expects on the agreed terms and conditions.
- Despite the good intention of all parties involved - surprises and unexpected events are a part of every project. The common project goals as well as flexibility from both sides is essential in resolving issues along the way.

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