DISTRIBUTION CONTROL CENTER EMULATOR FOR ADVANCED DISTRIBUTED AUTOMATION TESTS

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ABSTRACT

The current trend for evolution in power systems has integrated a great number of devices and operating conditions that demand efficient test strategies. Since the emergent challenge to obtain functional systems in scenarios with high diversity of "smart" strategies and devices could compromise the practical performance of the grid, lack of realistic testing tools conduce to develop high-cost prototypes or pilot projects. These test tools could highlight implementation risks related with the technical restrictions and characteristics of the current infrastructure; moreover, they could supply the necessary technological platform that supports the design process for control, communication and monitoring. In this paper the authors describe one methodological approach to design and implement control center emulators with distributed real-time hardware and algorithms founded in the Common Information Model.

INTRODUCTION

The Distribution Control Center (DCC) emulator musts provide a wide variety of characteristics that deals with the integration of new technologies and maneuver strategies. These features include the capability to generate the proper electrical signals and simulate large distribution systems with diversity of devices, distributed sources [1] and load models among others aspects related with the functional operation in control centers; as a result, the test tool should be designed and developed with a set of well-founded principles for data management, powerful simulators and high performance hardware with appropriate electrical interfaces in order to emulate the real operation of distribution systems [2].

Testing for Advanced Distribution Automation

The term Advanced Distribution Automation (ADA) arises as part of the IntelliGrid program developed by Electric Power Research Institute (EPRI). This program is an effort of operators, industries and manufacturers to increase the integration of intelligent control for power systems. The development group has established several action fields that are aimed for the interoperability of components at different levels of implementation (eg transmission, distribution, user, etc.), including aspects of communication, management and analysis of information, planning and implementation that in the past had been considered without a clearly defined policy.

The application of ADA for Distribution Systems (DS) is a well-structured alternative that provides a framework for integration of new technologies, including operation's tools and even connecting distributed generation [3]. However, this is a highly-versatile process and requires techniques that are designed according to the needs of each system. This flexibility in ADA design requires the development of methodologies and tools for each module in addition to accurate strategies for validation and debugging of each algorithm [4].

It has been identified a large list of functions to be integrated within ADA through a wide range of applications, including: the analysis and processing of information, continuous analysis of the system, coordinated volt/var optimization, fault detection isolation and restoration and feeders reconfiguration, among others. Because most of this applications requires real time control with continuous execution, the design stage usually includes computational time or communications frames as temporal considerations. This aspects of execution represent a challenge in simulation for debugging purposes, where the first alternative is the real implementation with pilot projects.

Hardware-software platforms represent an alternative that allows implementing models of large systems in a way that they can be simulated with practical constraints, achieving real scenarios in which information is exchanged between devices by analog and digital signals [5]. This approach yields on reductions in time, costs and risks related with design and validation of multipurpose strategies and algorithms. As a consequence, the design and development of a real time emulator of DCCs is a fundamental starting point for testing and validation of the strategies that make up the network automation [6].

DISTRIBUTION CONTROL CENTER EMULATOR

The architecture definition and information management in a standardized way is a main task to properly consider all the components involved in the DCC. Moreover, this principles afford the compatibility to connect external equipment and ensure its ability to maintain, upgrade or expand the platform.

Figure 1 presents some functional modules to be considered in the automation of the distribution network. Algorithms are developed on two independent platforms to build the emulator: first, the control center where automation applications are running and information management is performed, and last, the network where actuators, meters and communication equipment are simulated.

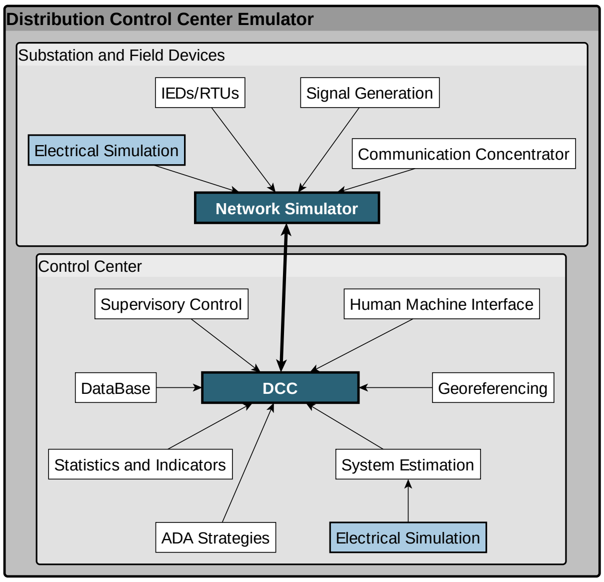

Fig. 1. Functional Blocks in the emulator.

One of the areas of greatest impact for the design of a suitable model of DCC is related to the need for exchange of information at different levels of the network infrastructure; this gives rise to the current regulations that standardize and facilitate system interoperability between its various internal components.

Standardization

The ongoing research about evolution and integration of Smart Grids has given the beginning to the standardization called Common Information Model (CIM) [7]. This integration framework, reflected on IEC61970 and IEC61968 standards, has been positioned as the core for future developments in this matter. Consequently, the inclusion of these protocols increases the applicability of the DCC emulator. The approach for this platform consider the electric simulator reports and results in a format compatible with CIM.

Dependencies related to components and equipment parameterization was established by the IEC61970 standard. For instance, every represented component have the corresponding label with a standardized format to represent the topology of the test cases. To achieve this purpose the platform uses class definitions that characterize the components by information extraction from the class classification of the electrical simulator (OpenDSS). The application of these format facilitates to scale the system, modify the characteristics of existing equipment and even communicate with external systems or devices with communication protocols programmed on the emulator's core.

Dependencies related to capabilities and applications of the control center was established by the IEC61968 standard. Therefore, the emulator has well-defined modules with specific channels to interchange information and perform analyzes to execute actions based on results. This methodology has been integrated as a main approach into the emulator by segmentation and concurrent execution of each function. In addition, algorithmic implementations of automation strategies are part of the core unit defined in this standard.

Purposes of Electrical Simulation

There are two major functions for electrical simulation in the platform: first, obtain the electrical information that support the IED's simulation, and second, asset the automation algorithms by an open loop estimation of the current status of the system. Although both cases could be performed by the same simulator in a multicore platform, the application should provide independent simulations at solver level for each function. The simulator should also guarantee that the open loop estimation with optimization purposes is not a particular iteration of the IED simulated power flow. The fact that the electrical simulator execute independent solving processes for the two functions contributes to the real emulation of the scenario composed by an electrical system and one offline estimation at the control center.

The open loop estimation could be accomplished by periodic execution of load flow calculations for the actual snapshot of device configuration and topology conditions. It is in this way that any changes applied to the system is automatically reflected in all modules that constitute the DCC. From this simulation it is possible to perform the calculation of indicators at each time (periods of 100ms), characterizing the operation of the network and presenting statistical results that allow the operator to identify critical conditions and take corrective actions in training activities.

One of the main aspects for the integrity of the platform is that the simulation engine includes relevant features of the mathematical modeling and resolution for systems of interest. Load flow tools oriented to transmission systems usually omit features such as the imbalance of load on users, or may even result in long processing times due to conditions of difficult convergence. Therefore, the OpenDSS specialized solver was selected in order to perform this task. This solver engine, developed by EPRI, includes fundamental models and characteristics to automation simulations; additionally, it can supply time-sequential results of load flows considering load profiles defined by the user.

Model of the DCC Emulator

It is necessary to define the functional blocks at different hierarchical levels of program implementation: at first level the electrical system simulation is sequentially running load flow calculations to supply useful information to other modules. The program follows a distributed model for functions that allow the inclusion of new blocks, applications or devices. This approach increases emulator's capabilities for modification of its features while preserving the independence of each task.

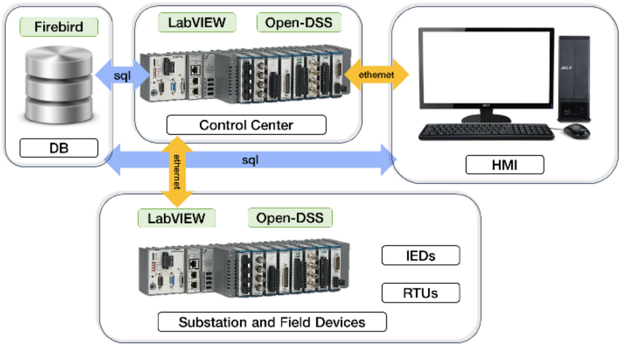

Fig. 2. Hardware and communication in the emulator.

The emulator architecture is shown in Figure 2, where arrows represent protocols with data connections between independent components. The database can be accessed from the DCC to store performance data, measurements and model's parameters; also, this information is accessible from remote HMI terminals where the operator is capable to evaluate and analyze the relevant indicators. Moreover, the electrical system simulation is performed outside the DCC core, and it is composed of four algorithmic cycles: the first is responsible for communication with the electrical simulator, the second simulates diverse network devices and their respective communication, and the last two are related to generation and acquisition of electrical signals by FPGA. Programming signal interfaces by cells' reconfiguration on FPGA ensures the determinism required for this function.
The HMI terminal (Figure 3) includes graphical interfaces for supervision control of emulated devices. The visual interface design is auto-configurable and incorporate numerical and graphical reports of real time performance statistics.

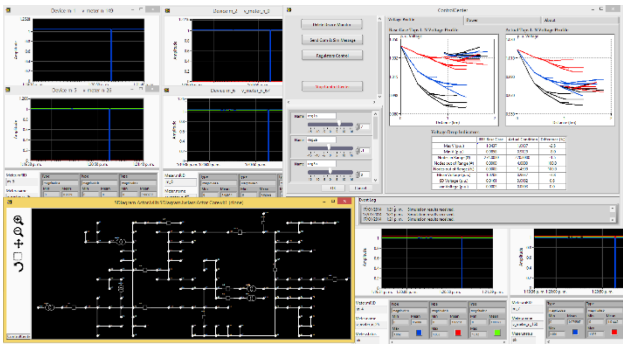

Fig. 3. DCC - Human Machine Interface.

Integration of ADA strategies

The DCC has an embedded console with controls associated to every controllable device in the system (voltage regulators, switches, capacitor banks, etc.) This method allows the platform to emulate the execution of changes decided by the operator or suggested by external algorithms. The ADA strategies are programmed as independent algorithms that exchange information with the DCC core by standardized messages. Moreover, the message schema supplies measurements generated from the simulated remote devices.
The emulation for electrical devices is implemented as algorithms that reproduce the behavior of a remote terminal unit (RTU). This devices are capable to perform measurements of various electrical variables obtained from the simulation engine, and to generate messages describing their status, measured values, time stamps, among others.

DESIGN AND IMPLEMENTATION

The implementation of this emulation approach was developed on LabVIEW platform. Design of several applications includes diversity of software models selected by hardware target or execution needs. Furthermore, any algorithm built in LabVIEW graphical language integrates elements of object-oriented programming, with proper attention to user events and information exchange between applications.

Concurrent execution (Actor Framework)

The programming technique used in this development is known as LabVIEW Actor Framework (AF), a proprietary programming model based on actors' deployment. This technique allows concurrent computations by applications known as *actors* who are responsible for specific functions and can share information in an organized manner.
The general approach to implement actors in this emulator is conceived from the standardization principles discussed in previous sections. Each actor is built from two types of classes: first, one class that characterize the actor's tasks, and second, one class defining the messages exchange pattern. Each of these classes include some legacy methods to define the response to global events, start of tasks execution, etc. The core actor of the emulator is responsible for centralizing all internal communication. This is the only one that can send or receive messages from other components; therefore, standardizes the CIM of any internal or external message from the control center.
This model prevents the information loss within the concurrent tasks using queues and independent memory blocks for each actor. Essentially, any messages sent or received by a component of the control center obtains a space in the queue to be processed, and to preserve access control to these memory spaces each actor only has access to their own queue and one specific shared-queue of the core actor. This implies that the core is the only entity with access to the modules' queues and is not possible for applications (actors) to store or modify information without central management.

High determinism (FPGA)

Real-Time (RT) simulations require an execution time frame that preserves synchrony with the time of the simulated phenomenon. This property allows external devices or users to obtain results as signals continuously extracted from a real system and not as a result of previous simulations; As a consequence, responses from external equipment could be considered into the model, closing close the simulation loop (Hardware in the Loop - HIL).

To achieve the requested synchrony between simulation time and execution is necessary to use proper computational platforms with concurrent programming. These devices not only include multi-core processors, but also their data buses and storage devices are designed to increase the speed and reliability of the whole operation process. This implementation include real-time equipment from National Instruments; the model cRIO9082 are high-performance devices for industrial environments composed by one Intel Core-i7 processor with 4 threads and Field Programmable Gate Array (FPGA) Xilinxs Spartan 6. The FPGA was programmed with measurement and generation routines that reproduce the simulation results with strong time frames. In this application were used the NI9225, NI9227 and NI9269 modules that are responsible for generating voltage signals and measuring voltages and currents, respectively.

Test cases of ADA

Various implementations of case studies were conducted through the process of evaluation and design of ADA algorithms. The first stage of these implementations is intended to apply big combinatorial problems on optimization functions, which includes advanced automation algorithms on IEEE test feeder of 34 and 37 nodes. Required algorithms was designed to meet the automation needs of tested distribution systems, so they can be evaluated with the platform. These algorithms are proposed by the authors in base of several optimization methods using the properties of centralized information management.

Test case 1: System reconfiguration

This strategy could be defined as an optimization problem of the operation process which seeks to establish the best radial topology reducing the power loss in lines and transformers. Sudden changes of loading conditions such as balance, scale and type of consumption can lead to considerable increase in power losses; as a result, this phenomena could degrade the equipment operation and economically impact the system operation. The inclusion of strategies for automatic reconfiguration allows the DCC to mitigate these effects from coordinating switches to establish optimal and operational topologies.

Although there are several methods of calculation and measurement to determine the magnitude of power losses, operators often use one estimation from the difference between the logged energy supply and the billed charge as final user consumption. When DCC has the availability of current and voltage estimation with full observability of the electrical system, it is possible to perform detailed calculations of losses in real time, and evaluate optimal alternatives for grid configuration.

It should be noted that the absence of electrical loops must be ensured by restricting the mathematical model, and this way the strategy can use this feature to discard a great number of possibilities for reconfiguration.

The proposed algorithm exploit the fact that the mathematical problem retains similarity to the shortest path problem in graph theory. As a consequence, the method seeks for the path of minimal cost that allows the connection between the source node and all the targets (loads) without loops.

However, there is a nonlinear relationship between the costs and the possible shortest paths trees, constituting a major constraint to use linear methods such as Dijkstra's algorithm. One compound approach proposed in this platform includes multipurpose nonlinear optimization techniques applied over the Dijkstra Algorithm (DA). The first part makes use of DA as a search mechanism for low cost paths between nodes in the graph, so the radiality and typical transport considerations should not be included in the nonlinear optimization. The last component uses the Differential Evolution algorithm as nonlinear method searching for optimum results in total system losses [8]. This meta-heuristic method presented excellent results given the complexity of the electrical model, with other benefits as the adaptability to other distribution systems.

The Figure 4 presents the graphical interface for this module. It includes graphical tools to review the quality of service and topology indicators with proposed changes.

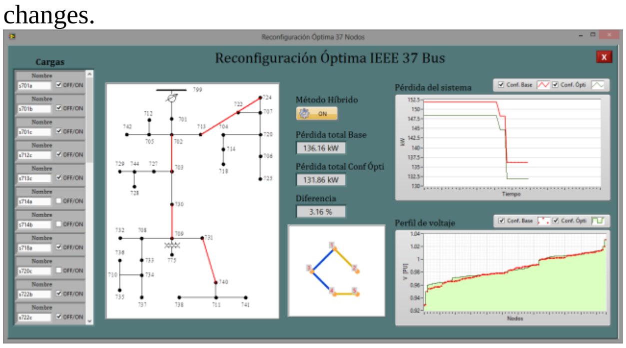

Fig. 4. System reconfiguration interface.

Test case 2: Voltage and reactive power Control

This feature is fundamental in the grid operation due to the variable nature and diversity of loads that degrade the voltage profile; besides, this reduction on quality of service increases the costs of the operation. Voltage regulation techniques usually consider local control rules and tele-operation of regulation devices. Although, both alternatives are effective according to the objectives, ADA implementations contemplate integration of

centralized strategies to improve quality throughout the system. Therefore, DCC must have the ability to execute commands or change settings to remote control devices as a result the global grid performance.
This optimization problem seeks to establish the best configuration of regulator's taps and needs for connection of capacitors compared to the current load condition being evaluated. This optimization problem is solved by making use of differential evolution technique referred in the previous section. The mathematical approach includes several objective functions that must be solved simultaneously, including the minimization of the amount of voltage out of range and its variance. The model restrictions for tap regulators define the range of integer values for each phase, and connection status of available banks on capacitor's case.
The Figure 5 presents the graphical interface for this module. It is composed of three main parts: (1) the edition panel for load conditions, (2) the control console and (3) the performance indicators system.

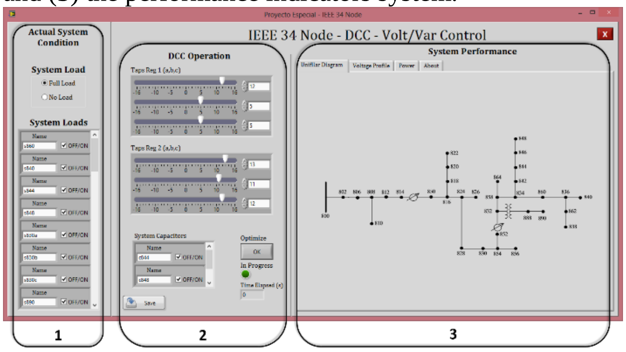

Fig. 5. Interface for voltage and reactive control.

Conclusions

Design and implementation of the DCC emulator include several aspects related to programming architectures for specific purposes; the approach to deal with complex data interchange and modular automation was based on the Common Information Model and proper standardization.
The platform is supported by computer with real-time architecture, where processing time benefits are available to provide the experience of being a real power system operation.
The proposed model, based on actor framework, for CIM on control center emulation has the ability to integrate new components and applications without information loss. This approach also supplies characteristics for concurrent execution and propitiates the modularity for future developments or tests. The independency on tasks execution allows HMI interfaces to supply several indicators for decision assessment without loss of determinism.
Given the emulator's ability to generate and acquire electrical signals in RT, the user can design controlled test scenarios for validation or calibration purposes. Since the simulator can obtain electrical information from any point in the system, the physical restriction is only defined by the magnitude and power of the signals that can be reproduced.
Proposed automation strategies presented positive results in various applications for typical test feeders documented by IEEE. The profile characteristics and compliance of voltage limits and power losses were tested on the emulator under real time execution.
Other strategies of advanced automation can be integrated as separated algorithms; once implemented these strategies can be evaluated by supplied test cases or even using models from other systems of interest.

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