CUSTOM DISTRIBUTION FEEDER RECLOSER IED WITH HIGH IMPEDANCE PROTECTION FUNCTION

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ABSTRACT

This article presents the development of a custom Intelligent Electronic Device (IED) for distribution feeder recloser protection and automation. The IED was designed according to specific requirements of the overhead distribution networks from the Brazilian electric utility COPEL. The project aims to create a modular hardware and software solution, that could fit the today`s utility needs of a multifunctional device, such as a high-impedance protection function, and also future capabilities, in order to fit the newest Smart Grids scenarios of COPEL.

INTRODUCTION

Increased requirements for improved quality of power, and for fast dynamic operation of the electrical network, shifted the power system engineering point of view to a Smart Grids scenario, where automatic and decentralized decisions should be coordinately taken to assure the proper system response to events [1].

The power system distribution feeders play a major role in this theme due to its widespread service area and the inherently configurable connectivity between users, power system apparatus and the electrical utility. Thus, it is fairly common radial distribution feeders with several recloser devices installed along the network, with controlled breakers and switches that, according to protection and automation functions, can dynamically change the electrical topology to reroute and redistribute the energy among the users, to minimize power outages and guarantee the energy quality. However, besides these energy distribution networks, a necessary underlying communication infrastructure should provide all kinds of real-time data exchange for the protection and control functions to operate properly.

The extended use of such schemes allows smarter grids scenarios to take place. In this new era, new requirements urge for additional flexibility and functionality to improve the grid reliability, security and efficiency [2]. This can be achieved through the use of open systems, that can be easily programmed as needed, and communication standards, like the protocols and recommendations presented in IEC 61850 [3], that add easy interoperability and data exchange between existing devices and with SCADA systems.

Despite these overgrowing requirements, some kind of events in power system distribution networks, such as high impedance (HZ) faults, still pose as an unsolved protection problem [4]. The reason lays with the magnitude of the fault currents, which are usually smaller than typical load currents, and may not be detected by conventional overcurrent protection. Due to severe electrocution and fire hazards, the identification and detection of downed conductor situations, for example, are critical for safe feeder operations, and may be accomplished by the use of not one, but several complementary techniques [4].

For this purpose, it is highly advisable to apply a multifunctional IED that could be precisely adjusted to the network characteristics and which could be further improved or extended in the future to address new detection algorithms and fault identification methods.

In south of Brazil, the COPEL electrical grid serves around 4 million users in the State of Paraná, with a distribution network of more than 180,000 [km] of wires. Their variety of system configurations and network topologies inspired flexible protection and automation solutions, for example special algorithms for automatic recloser units and remote access capabilities for management, control and engineering. Thus, a specially designed IED was needed, to fulfill COPEL´s requirements for substation and recloser protection and automation, addressing problems such as the HZ faults in their overhead distribution networks, and also future needs for latter Advanced Distribution Applications (ADA) in Smart Grid operations [1], for example, distributed and decentralized energy generation resources (DER).

PROJECT REQUIREMENTS

The COPEL overhead distribution lines comprise many electrical network topologies, with both solidly and impedance grounded feeders, with primary voltages of 34.5 [kV] or 13.8 [kV]. To improve the energy quality indicators and further migrate to smarter grid scenarios, these feeders are being equipped with specially designed automatic reclosers. Each recloser is composed of a power unit and a control unit.

The power unit comprises a circuit breaker, a bypass switch and a set of instrumentation transformers and sensors, inside an enclosure tank. The control unit comprises an automation and protection IED, among other components, such as an uninterruptible power supply, network media converters, HIM units, push-buttons, etc. This control unit is housed within a compact and hermetic cubicle, installed under the power unit in the pole structure, as shown in Fig. 1.

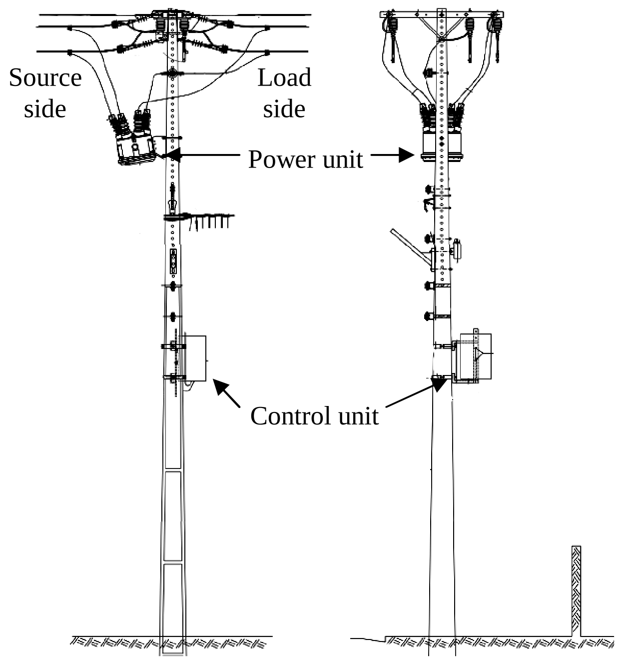

Fig. 1 – Typical pole structure and recloser installation.

The reclosers are installed both at substation and along the distribution feeder, using fiber optics network, for both horizontal (between devices) and vertical (between a device and SCADA systems) communications, with DNP3 and IEC 61850 protocols (MMS and GOOSE messages).

Nowadays, these custom reclosers use commercially available components and, therefore, usually require both hardware and software adaptations (mainly in the control unit IED), in order to fulfill COPEL electrical network operation needs.

Basically, the minimal requirements for the control unit IED inputs and outputs are: 4 analog inputs to source side voltage transformers (PTs) for each phase and an auxiliary input; 4 analog inputs to source side current transformers (CTs) for each line current and a ground current; 3 analog inputs to load side voltage transformers (PTs) for each phase; 4 digital outputs; 6 digital inputs; 3 independent communication ports (one to a front panel serial/USB connection, and two rear ports for fiber optics serial and Ethernet communications); support to IEC 61850 communication protocols and optional support to other legacy protocols, like DNP3 and ModBus; Human-Machine Interface (HMI) with at 16 configurable LEDs, 16 configurable function keys and a LCD display for system measurements, states and custom messages.

Internally the IED should have at least the following ANSI protection functions: conventional overcurrents (50/51, 50/51N, 50/51G, 50/51Q and 51V); directional overcurrent (67, 67N, 67G and 67Q); undercurrent (37); undervoltage (27); overvoltage (59, 59N and 59Q); under/over frequency (81U and 81O); under/over frequency variation (81df/dt); synchronism check (25); automatic reclose (79); directional power (32); breaker failure (50/62BF); vector shift (78) and High-Impedance (HZ). The protection algorithms should be executed at a fixed rate of at least 16 samples per cycle.

Besides these protective functions, the IED should also have user programmable logic with basic logic operators, a sequence of events recorder, a programmable waveform recorder for oscilography registers, a fault location function, IED autocheck and measurements of system voltages, currents, frequencies, active, apparent and reactive power.

Other important IED requirement is the ability to be remotely accessible through a wireless connection, by field based personnel, from inside the company maintenance vehicle, 50.0 [m] away from the control unit cubicle.

Instead of keep adapting commercial IEDs to fit their applications, COPEL motivated a R&D project with Power System Automation and Protection Research Laboratory – L.PROT – to create a compact, yet powerful and flexible, IED hardware and software architecture, with state of the art concepts and modular design, allowing both hardware and software evolutions and upgrades.

HARDWARE TOPOLOGY

To accomplish specifications for a compact control unit IED, a hardware topology was suggested combining a dedicated embedded electronic and a high-performance microcomputer.

The embedded electronics is called ACU (Acquisition and Control Unit) and was designed to act as a merging unit for all power system signals (voltages, currents and states), and the control of external devices, such as the switch breaker trip and close commands. An onboard Ethernet port in the ACU does the interface with the high-performance microcomputer unit.

The high-performance microcomputer, called PP (Processing Platform), executes the general IED processing tasks, such as: the execution of protection functions, programmable logic, communications tasks, and HMI. This unit also supports a several types of communication interfaces and protocols, such as: vertical, slow and old fashioned protocols (like ModBus RTU), and high-speed, low latency, real time communications, like IEC 61850 GOOSE messages.

Basically, the ACU acquires data from the power system, process and filter the information, resulting in a collection of samples, measurements and phasors (from voltages and currents), and digital states. This whole dataset is comprised in a custom GOOSE sampled values frame, and is sent to the PP for real time execution of the protection functions and programmable logic. The results are sent back to the ACU through a new GOOSE SV dataset, which is interpreted to proper operate the digital outputs according to the PP decisions. These data exchange is executed at a rate of 16 samples per cycle.

Such modular design allows many parts of the hardware to be improved and evolve to other solutions in the future, once their communications interfaces and protocols are kept

the same.
Both modules are powered by a flexible power supply (PSU), with both AC and DC input capabilities. The IED has additional support modules, such as fiber optics media converters (CIN) for the PP module communications interfaces (serial and Ethernet), a color LCD (VGA) monitor for HMI display, a custom keypad (KEY) with LEDs for user local command and supervision, and a 2.4 [GHz], serial RF wireless communication interface for field personnel remote access to the recloser control unit IED. This modules, as long as the PP unit and ACU are briefly shown in Fig.2.

Processing Platform

Previous experiences indicated that all IED processing tasks (protection and communication functions – at the desired data rate) could only be securely executed by a high-performance, general purpose, digital computer. A compact, common, x86 IBM PC architecture microcomputer was chosen: a industrial grade PC computer. This platform comprises a dual core Intel Atom processor, with 1.6 [GHz] of clock, 1.0 [GB] of RAM, 8.0 [GB] of FLASH based Solid State Disk (SSD), two ethernet ports, three serial ports and 4 USB communication ports.
The use of a such open processing plaform allows further hardware evolution and upgrades in the future, by the selection of newer, compatible platforms, besides the use of freely available real time operating systems (RTOS), such as real time Linux variants, and other commercial RTOS, like QNX.

Acquisition and Control Unit Electronics

A special hardware was created to support the acquisition of the specified number of analog channels, digital inputs and control of digital outputs, at the specified data rate of 16 samples per cycle, with the needed communication interface with the PP unit.
The designed ACU comprises a general purpose STMicroelectronics STR912F System-on-a-Chip (SoC), with 32 bits ARM9 architecture, with 96.0 [MHz] of clock, 1.0 [MB] of FLASH, 128.0 [kB] RAM, and a 100.0 [Mbps] Ethernet port, among other interfaces. This SoC is connected through a high speed serial port with a dedicated Analog Devices ADSP-21262 floating point digital signal processor (DSP), with 150.0 [MHz] of clock.
For both analog and digital input and output flexibility, the ACU was created in a modular “Eurocard type” rack, according to the IEEE 1101.1 standard, where the SoC and the DSP were positioned in a backplane of the rack (named BMI), along with the internal ACU power supplies and the Ethernet communication interface. This backplane implements a 4 slot expansions bus, supported by a XILINX SPARTAN-3 FPGA, for glue-logic and internal SPI communications, between the other system parts.
For the expansions slots, three types of cards were designed: DIN – a high-speed digital input card (DIN), for up to 16 digital inputs; DOF – a digital output card (DOF), with two high-speed, solid-state outputs, and 6 standard, fast relay contacts outputs; AIN – an analog sampling module (AIN), capable of acquiring up to 8 analog, low voltage (± 2.5 [V]), channels, with more than 128 samples per cycle, with 16 bits and simultaneous sampling.
Each complete set of instrumentation transformers signals (4 CTs and 4 PTs) are connected to the each AIN module through a conditioning and filtering module called AIE. The AIE module is responsible for the conversion of the secondary voltages and currents levels (115.0 [V] and 5.0 [A]) to the voltages levels of the AIN module inputs, with additional anti-aliasing analog filtering and protections.
Any combination of the previous cards could be arranged in the ACU backplane to establish the desired input/output configuration, allowing, for example, the acquisition of up to 8 power system voltages and 8 currents, with 16 digital inputs and 8 digital outputs. An example is show in Fig.3.

Housing

The custom IED received a specially designed mechanical structure to house all IED components in a single and compact unit, resulting in single 19” rack, with 4U, to be installed inside the recloser control cubicle.

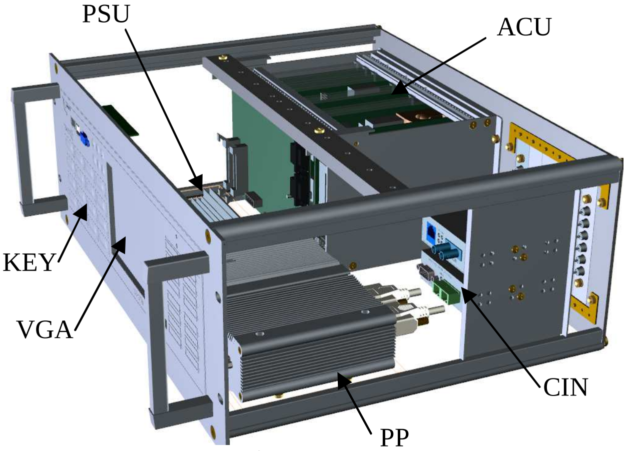

Fig. 2 – CAD view of the hardware inside its housing.

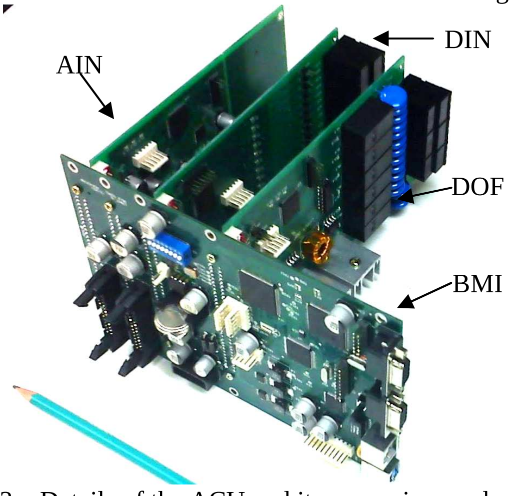

Fig. 3 – Details of the ACU and its expansion cards.

SOFTWARE TOPOLOGY

Besides the hardware infrastructure, a software topology was designed to allow easy development of all IED functionalities, involving all protection and automation functions and the user programmable logic. This scheme is also a modular concept, where parts of the system software can be later upgraded, once all data exchange between the modules are preserved.

ACU Executive System

The ACU has two executive systems (ES) running inside of the SoC and the DSP. They handle the real time data acquisition and communications between the power system and PP unit, and don`t require constant user modifications.

PP Real Time Operating System

The PP unit has a complete real time operating system to support all time critical protection and automation routines and network activities. Other secondary tasks are acomplished in non real-time, like the file system structure for data storage, graphical interface routines for VGA display and user keypad management, and wireless remote access. Both real time and non real time tasks are accomplished by a free hard real time framework for Linux called Xenomai.

Protection and Automation Functions

All protection and automation functions cited before were protyped in Matlab, for debuging, testing and analysis with a SimPowerSystem sample network to represent the feeder behaviour. Once tested, the routines are coded in ANSI C as basic functional blocks of a specially designed software framework called LPROTFRAME. This framework is an IEC 61131-3 function block diagram (FBD) runtime engine, with real time commitments, that allows the engineer to freely design the IED programmable logic, involving all protection and automation functions, IEDs digital inputs, digital outputs, user keys, HIM states, virtual (communication transfered) states, as long as basic logic building blocks (like timers, flip-flops, combinational logic, etc.). The resulting functional block diagram are compiled to an efficient byte-code image by the own IED system software, to be used during its in-service operations.
Custom or newer protection functions can be freely created by the user, with the available FBD basic building blocks, or through the creation of a new building block, directly inside the LPROTFRAME ANSI C source code.
The LPROTFRAME also supports mappings to ACSI services and data itens of IEC 61850 logical nodes presented in the IED.

High-Impedance protection function

The IED will include a specially designed high impedance protection function, based on secondary phase currents measurements and the precise monitoring of the feeder neutral CT. For this, the fourth channel of the AIE/AIN ACU module was designed with a smaller dynamic range (2.0 [p.u.]), allowing accurate tracking of the neutral current values, despite the phase CTs measurements (which have higher dynamic range, 20.0 [p.u.]). The algorithm basically relies on the perception of a broken conductor event, through constant monitoring of the primary feeder currents and sudden load rejections, and the subsequent behavior of the neutral current when a downed conductor reaches the floor.

PROJECT STATE

The project is being integrated in its mechanical housing, to be later subjected to EMI/EMC and functional testing. Final results are expected in the second half of 2013.

CONCLUSION

LPROT is developing a custom recloser IED with COPEL in order to fulfill present and upcoming requirements for the operation of their smart grids.
The IED hardware topology involves an autonomous merging unit, with IEC 61850 sample values protocol, that can be also used in further developments of process bus protection and automation systems in substation scenarios.
The IED is based in a high-performance PC compatible processing platform, running a real time Linux operating system, capable of handling protection and automation functions at a rate of 16 calculations per cycle, with support to IEC 61850 MMS, GOOSE and GOOSE SV protocols.
A real time software framework called LPROTFRAME was developed to support the user programmable logic and the execution of all protection and automation functions.
The modular hardware and software design, as long as the use of state of the art communications provided by IEC 61850, allow continuous development and constant improvements.
The initiative also improves the development of resources and technologies in Brazil, to locally support protection and automation engineering in the Smart Grid era.

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