Programmable Load Shedding Systems – Hydro-Québec's Experience

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***Abstract*--Programmable Load Shedding Systems (PLSS) are key elements of Hydro-Québec's Special Protection System (SPS). These systems perform control and monitoring tasks. They are programmable to offer customized solution to power system protection. They monitor power system frequency and voltage and can shed load on predefined conditions. Furthermore, these systems can receive load shedding orders from other systems. Operating conditions of the PLSS can be programmed on-site or remotely.**

A new generation of PLSS will be installed shortly in Hydro-Québec's substations. The replacement of the existing equipment was necessary to improve filtering characteristics and frequency measurement algorithm. Furthermore, the maintenance of this equipment has become complicated due to unavailability of spare parts.

***Index Terms*--Special Protection System, load shedding.**

I. Introduction

For more than 20 years, Hydro-Québec has used Programmable Load Shedding Systems (PLSS) specially designed to its own requirements. The biggest advantage of these systems is their programming features. They can support substation automation through ladder or pseudo-code type logic. Each system can thus be customized to offer unique solution to special protection needs. These systems can manage different type of data such as frequency, voltage value and even load shedding orders received from a remote system. This information is processed in accordance with the internal program. Depending on the result of this analysis, the PLSS may shed load.

In recent years, Hydro-Québec has decided to implement a new generation of PLSS. Two main reasons justified this decision. First, the installation of series capacitors on the main transmission lines has brought new phenomena such as subsynchronous and hypersynchronous resonance. These resonance cause problems to the frequency measurement precision because the existing PLSS uses zero-crossing algorithm. Thus, Hydro-Québec has decided to consider digital signal processing technology to improve the frequency measurement precision and filter out the undesired frequencies. The second reason to replace the existing PLSS is the need to improve the human-machine interface to program the systems.

In this paper, we will first describe Hydro-Québec's SPS because it helps to understand some of the PLSS features. We will next describe the new PLSS main characteristics and its programming features. Finally we will describe some examples and briefly discuss the coordination and the setting of the PLSS.

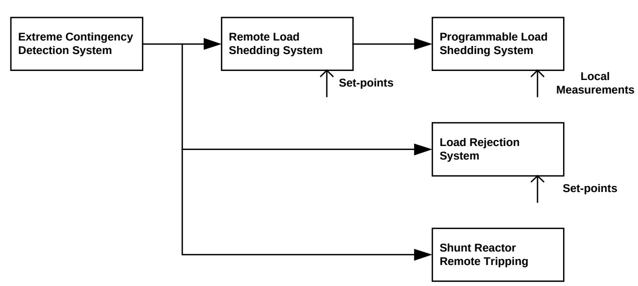
II. SPS at Hydro-Québec

SPS are designed to detect or anticipate abnormal power system conditions and initiate corrective actions to return power system parameters to a stable and recoverable state.

In 2000, a new SPS was commissioned as part of a new Hydro-Québec's defense plan [1]. The objective is to preserve the integrity of the electric system by using automatic emergency actions that are simple, reliable and safe for the system and provide the most extensive possible coverage against all possible extreme contingencies to improve the robustness of Hydro-Québec's power system. With this new defense plan, Hydro-Québec's transmission system has met the requirements and criteria in force in the NPCC (Northeast Power Coordinating Concil).

The new SPS is composed of the following elements :

- Extreme Contingency Detection Systems (ECDS)
- Remote load shedding System (RLSS)
- Generation Rejection Systems (GRS)
- Programmable Load Shedding Systems (PLSS)

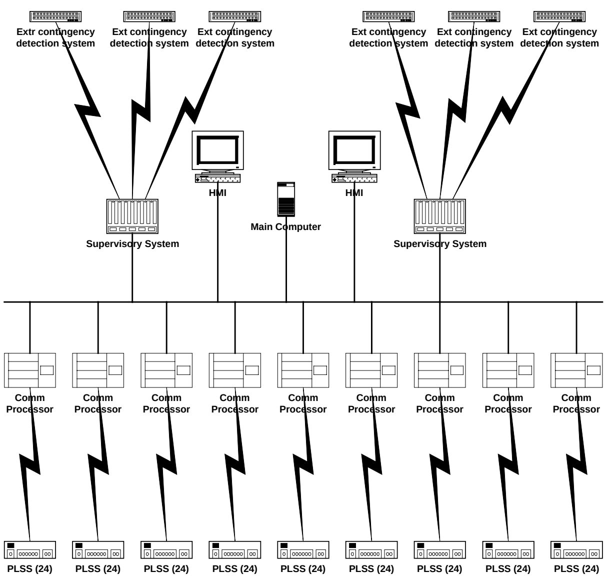


A. Extreme Contingencies Detection Systems

Installed in 735 kV substations, ECDS main task is to identify the occurrence of an extreme contingency such as power line tripping or series compensation bank bypass. When a contingency occurs, ECDS issues orders to GRS, RLSS and 735 kV shunt reactor remote tripping. ECDS includes line opening detection system for each line, series compensation bank bypass detection system and contingency composition unit.

B. Remote Load Shedding System

The RLSS analyzes data received from the ECDS. Depending on the type of events, it sends tripping command to the PLSS. This system is installed in the Hydro-Québec Control Centre and is composed of a supervisory system, a main computer, communication processors and the Human-Machine Interface.



The supervisory system processes all the events received from the ECDS. This system calculates the power to shed depending on the severity of the event. It makes sure that the rejected load is not greater than the allowed value within a time window.

The main computer monitors and controls the operation of the SPS. This system contains the database and off-line calculation such as power that can be rejected.

The communication processors poll the PLSS to get substation data and PLSS status. These processors also send the tripping command to the relays when the supervisory system detects a major event. Each communication processor communicates with 24 PLSS.

The power system operator uses the HMI to control and monitor the SPS. The HMI can be used to arm/disarm the system and to set manually analog values or digital status. Alarms are also shown on the HMI.

C. Generation Rejection Systems

GRS are located in power stations. These systems trip generating units when orders are received from ECDS. The number of units to reject (set-point) is function of the severity of the contingencies. The control center can adjust these set-points to an optimal value as a function of the status, loading and topology of the power system.

D. Programmable Load Shedding Systems

PLSS are installed in 140 distribution substations. PLSS can execute remote load shedding orders received from RLSS and/or execute load shedding as a function of local frequency conditions. PLSS can be programmed on-site to define tripping conditions. These conditions can be based on frequency, rate of change of frequency, voltage, rate of change of voltage, digital status and remote orders.

III. Description of the new PLSS

A. General Characteristics

The new PLSS was developed to meet the following objectives : reliability, security, performance and adaptability. It is obvious that security and reliability are important design criteria. Adaptability is another important criteria. It is important to be able to modify the system to realize new power system protection functions. For instance, new input/output boards should be easily installed in the system.

The PLSS has three main functions: local protection, remote load shedding and monitoring. The PLSS also has secondary functions useful for maintenance purposes: self-diagnostics, user interface.

1) Local Protection

The PLSS can be used to send commands to local devices when the power system is perturbed causing some measurements to exceed predefined values. The following measurements can be used for local operation:

- Digital input status
- Frequency value
- Rate of change of frequency value
- Voltage value
- Rate of change of voltage value
- DC analog values

From the preceding list, it can be seen that equipment status can also be used as a tripping condition. All the above data can be used in programming sequence to describe tripping conditions.

2) Remote Load Shedding

The PLSS can also accept orders from a remote system. Hydro-Québec has a centralized system, the Remote Load Shedding System, that send tripping orders to the PLSS. These tripping orders can be conditional to local values such as frequency or voltage level.

3) Monitoring

With its input/output capability, the PLSS can be used as a special monitoring device. The SPS can thus receive important data that can be used for its operation. The following information can be retrieved from a remote system:

- Digital input status
- Frequency value
- Rate of change of frequency value
- Voltage value
- Rate of change of voltage value
- DC analog values
- Oscillography waveforms
- Alarm monitoring
- Event recording.

IEC-60870-5-101 is used as communication protocol.

4) Self-diagnostics

To insure high availability, the PLSS can execute a complete check of its internal operation, its inputs and its outputs. It features an auto-calibration that ensures high precision readings at all time. A logging facility stores all necessary information and four (4) alarm outputs can be used to remotely monitor the PLSS status.

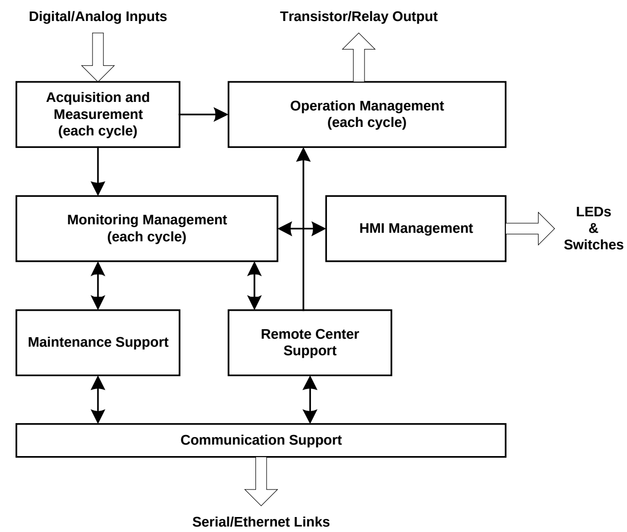
A Windows-based diagnostic software is provided to help accessing and analyzing the logs.

5) Human-Machine Interface

Each electronic board in the PLSS is equipped with the necessary LEDs to provide a quick overview of the general status and behavior of the device. For instance, the following status can be monitored from the LEDs:

- Operation mode
- Network signal status
- Watchdog
- Communication links status
- Failures
- Input/output status

B. Architecture of the PLSS



1) Acquisition and Measurement

Digital Inputs

The new PLSS has 8 digital inputs used to monitor status of substation equipment. There is a low-pass filter, for each input, adjustable from 1 to 30 ms.

For instance, Hydro-Québec uses these inputs to monitor the status of capacitor bank breakers. This information is used to estimate the total reactive power available for shedding.

Low Rate Sampling Analog Inputs

The new PLSS comprises four analog inputs sampled at 240 samples/s.

Hydro-Québec uses these analog inputs to measure the active power of distribution transformers. This information is used to estimate the load factor.

High Rate Sampling Analog Inputs

These inputs are used to monitor the power system AC signal. The sampling of AC signal is done at 2880 samples/s. A 16 bits A/D converter transforms the value in the digital domain. The frequency measurement is based on phasor estimation and Kalman filtering algorithm developed by Hydro-Québec's Research Institute (IREQ). The following values are calculated:

- RMS voltage (Vcy, V50, V200)
- Rate of change of voltage (Wcy, W50, W200)
- Frequency (fcy, f50, f150)
- Rate of change of frequency (Gcy, G50, G150)

Three different values are calculated for each measurement For instance, fcy is calculated over one cycle and f50 is calculated over 3 cycles. The precision for the different values are:

- fcy: 1,5%
- f50: 0,45%
- f150: 0,15%
- Vcy: 15,1%
- V50: 6,1%
- V200: 2,1%

The measurement ranges are:

- 0,01 to 2,0 p.u.
- 40 to 70 Hz
- -10 to +10 Hz/s.

2) Operation Management

In order to allow flexibility in the use of PLLS, its operation is fully programmable. Thus, any of the internal information can be used to define tripping conditions. The operation management module is responsible for the execution of the internal program. This module is activated at each cycle. Based on the results of the internal program, it activates output of the PLSS. The following data can be used:

- Digital input status
- Frequency value
- Rate of change of frequency value
- Voltage value
- Rate of change of voltage value
- DC analog values
- Remote Command

Some trigging conditions can be very simple:

if (f < 58.5 Hz)

In this example, the breaker will be tripped when the frequency will be below 58.5 Hz.

Logical combination of trigging conditions can also be used:

if (df/dt < -0.5 Hz/s) and (f < 59 Hz)

In the above example, the breaker will be tripped when rate of change will be below 0.5 Hz/s and the frequency below 59 Hz. Rate of change of frequency is used as the main tripping condition and the frequency is used to validate the load shedding.

Trigger conditions can also be set for command received from the remote load shedding system:

if (command is received from main system) and (f<59 Hz)

The main reason for tripping is the remote load shedding system command and the frequency is used to validate tripping conditions. This trigger means "trip output if a command is received from remote load shedding system and the frequency is below 59 Hz".

The following outputs can be activated:

- 8 solid state outputs
- 4 relay outputs (2A @ 150 V. d.c.)

Four other digital outputs are used to send alarm to other systems such as RTU or Sequence of Event Recorders.

3) Monitoring Management

The monitoring management module is based on a realtime database to organize data management and data exchange between modules.

This module is also responsible for recording of events and oscillography waveforms. This last information is captured under the control of operation management module. For each event, the waveform is recorded from one second prior to the event to ten seconds after the event.

4) HMI Management

The HMI module is responsible for driving the LEDs on the front panel. It also gets information from switches used to change the mode of operation of the PLSS (test/normal/study).

5) Maintenance Support

A portable computer is used to program the PLSS. This computer contains software to prepare and define operating conditions of the PLSS.

The maintenance support module communicates with the maintenance computer. It transfers new database or program to the appropriate location in memory.

6) Remote Center Support

The PLSS has two telecommunication ports to allow data exchange with a centralized system (RLSS). IEC 60870-5-101 is used as communication protocol. The PLSS can transmit to the RLSS all its internal data. Furthermore, the PLSS can receive tripping orders from the RLSS.

IV. Examples of Applications

A. Two steps Under-frequency Load Shedding

In this example, the PLSS shall shed load 1 when frequency goes below 57 Hz and load 2 when frequency is below 56 Hz. Output 1 is used to shed load 1 and output 2 for load 2.

The following rules should thus be defined:

1. *If frequency is < 57 Hz then activate output 1*
2. *If frequency is < 56 Hz then activate output 2*

B. Rate of Change of Frequency Load Shedding

In this example, the PLSS shall shed load 1 when rate of frequency is below –0.6 Hz/s. Since the rate of change is subject to noise, the frequency value is used to validate the tripping action. Frequency should be under 59.5 Hz.

The following rules shall be defined:

1. *if df/dt < -0.6 Hz/s and freq < 59.5 Hz then activate output 1.*

C. Complex Load Shedding

In this example, the PLSS should trip load 1 with under-frequency criteria, load 3 with rate of change of frequency criteria. Moreover, the PLSS should shed load 2 when an order is received from the RLSS and capacitor bank breaker should be open when the voltage reach a certain value.

The following rules shall be defined:

1. *If freq < 58 Hz then activate output 1*
2. *if df/dt < -0.6 Hz/s and f < 59.5 Hz then activate output 3*
3. *If a tripping order is received from the RLSS and f < 58.5Hz then activate output 2*
4. *if voltage > 138 V. and f < 58 Hz then trip capacitor bank breaker.*

Note that in the preceding rules a frequency criteria is used to confirm tripping order for over-voltage and remote load shedding.

V. Coordination and Settings

The PLSS can initiate an action on a number of circumstances that can be local conditions or remote orders. Different conditions or events can lead to different actions, but in most cases the same action, or load, can be solicited by several events using the logical operator OR. For example:

1. *If (freq < 58 Hz) or (tripping order from RLSS) then activate output 1*
2. *If (freq <58 Hz) then activate output 1*
3. *If (tripping order from RLSS) then activate output 2*

All these cases rapidly lead to a very complex group of settings and a relational database becomes necessary to centralize, analyze and maintain all the settings of all the PLSS, as well as those of the RLSS.

Several factors are to be taken into account when adjusting the system as a whole.

- Available load (MW and Mvar)
- Load factor
- Load priority
- Regional distribution of the load
- Coordination between remote and local actions
- Customer satisfaction

A. Cascade principles

On the occurrence of a major network event, and depending on the severity of the event, the course of action builds up as follows:

1. Generation Rejection
2. Remote Load Shedding
3. Local Load Shedding

It is also possible that an undetected or minor event does not lead to generation rejection or remote load shedding. Should the frequency change be high enough, only local load shedding will be initiated.

1) Generation Rejection

For the first level of severity, such as the loss of one or two 735 kV lines, GRS will be the only action executed and the PLSS will not be solicited. The amount of rejection is preset and controlled by the control center as a function of the actual status of the power system.

2) Remote Load Shedding

When a network event is severe enough, for instance the loss of more than two 735 kV lines, GRS alone is not sufficient and can even cause network instability. It is then necessary to restore the generation/load equilibrium with load shedding.

Load shedding can be conditional or unconditional.

For security reasons, it is necessary to protect the network against false signals and undesirable load shedding. In general, if the RLSS receives an event from only one ECDS, it then sends to the PLSS what we call “conditional tripping orders”. The PLSS must then validate the order with local conditions before executing the action. Most of the time, this condition is that the frequency must go beyond a specific range, typically [59.9 – 60.1Hz].

If the RLSS receives the same event from two or more ECDS, it is then considered as validated and an unconditional order is sent to the PLSS. No frequency check, nor any other, is done locally and load shedding automatically takes place.

3) Local Load Shedding

In all cases, remote load shedding settings are adjusted to a minimum necessary to maintain network stability. But it is possible that the amount of power taken out is not sufficient and that the network conditions continue to worsen. Each PLSS might then execute local load shedding if the conditions reach the appropriate criteria.

B. Coordination

For this cascade of actions to work, load must be available at each step. Several factors affect the availability of the load:

- Most of the load is shared between several criteria
- The available load is limited
- The available load decreases with load factor
- Regional distribution must be taken into account
- Load priority
- Customer satisfaction (if possible, it is best to avoid disconnecting the same customers every time)

The load is then divided according to thresholds. The fastest and most sensitive thresholds are activated first. This allows the local load shedding to operate in relatively small steps, avoiding unnecessary drastic actions. This also facilitates the coordination between remote and local load shedding. Whenever a remote load shedding is required, the order in which the RLSS selects the individual loads is important and must follow a pattern that saves, if possible, a certain amount of load available for local load shedding, should it be necessary. A typical order is:

G1 -> F3 -> G3 -> F4 -> G4 -> F1 -> F2 -> G2 -> F5 -> F6

Most sensitive threshold	Protected thresholds	High priority loads

Thresholds Frequency		MW	Mvar
58.5 Hz	F1	800	800
58,0 Hz	F2	1200	800
57.5 Hz	F3	1200	800
57.0 Hz	F4	1200	800
56.5 Hz	F5	1550	0
56.0 Hz	F6	1560	0
Rate of change of frequency			
-0.4 Hz/s at 59.8 Hz	G1	600	600
-0.6 Hz/s at 59.5 Hz	G2	600	600
-0.9 Hz/s at 59.5 Hz	G3	1200	800
-1.2 Hz/s at 59.5 Hz	G4	1200	800

VI. Conclusion

For more than 20 years, Hydro-Québec has used PLSS for emergency load shedding in its substations. Its programming features have allowed the realization of special protection system as required by the expansion of the power system and the needs to operate power system components to their full capacity. The adaptability of this system has proved to be highly beneficial to Hydro-Québec. For instance, the base system has been modified to allow three phases measurement.

Wiser for this experience, Hydro-Québec has developed a new generation of PLSS and has used the same design criteria as of the previous one: reliability, security, performance and adaptability. It has improved the frequency measurement precision and adopted user-friendly programming tools.

References

[1] G. Trudel, S. Bernard, G. Scott, "Hydro-Québec's defense plan against extreme contingencies", *IEEE Transactions on Power Systems*, Vol. 14, No 3, August 1999, pp. 958-966.