FAST TOPOLOGY DETECTION BASED ON OPEN LINE DETECTION RELAYS, A STRATEGIC FUNCTION IN POWER SYSTEM PROTECTION

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ABSTRACT

In the present deregulated and market driven energy industry, modern power systems need to be operated closer to their design limits. Moreover, their topology is becoming more complex due to additional interconnection links. Efficient defense plans are therefore more important than ever to provide fast, secure and reliable means of protecting these systems against their own contingencies or those experienced by their neighbours.

System topology monitoring is a strategic function to consider in the design of defense plans. Hydro-Québec transmission system is making extensive use of open line detectors to monitor system topology for the purpose of its most strategic SPS (Special Protection Schemes). A new version of these detectors, called DLO, have been recently developed.

The main characteristics and performances of these new DLO as well as their application on Hydro-Québec transmission system are presented in this paper.

Key words
Open line detection, topology change detection, fuzzy-logic based protection, defense plans.

1. INTRODUCTION

Power systems are operated to withstand normal contingencies and standard protection relays are designed to handle these usual events. On the other hand, extreme contingencies involving cascaded events such as multiple line outages will require system level protection actions to preserve stability or to avoid damage on expensive transmission equipments. In general, such contingencies will result in significant topology changes and affect the power system equilibrium. Remedial actions such as generator rejection and/or load shedding are often required to bring the system back to a new equilibrium.

In such a context, monitoring of the network topology is a strategic function to consider in the design of modern defense plans. To be efficient, it needs to be fast, reliable and secure. Its effectiveness will be decisive to avoid system wide power failures under extreme contingencies.

In its existing defense plan, Hydro-Québec has implemented this function on its 735kV transmission system using dedicated relays called open line detectors or DLO. In the recent years, a specific R&D project was launched to develop a second generation of these DLO for reducing the cost and complexity of the existing devices. Moreover, the selectivity of this new DLO has been improved by efficiently filtering the sub-synchronous resonances found on a series-compensated system.

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Characteristics and performances of the new DLO and its application on Hydro-Québec transmission system are presented in the paper which comprises seven sections.

Following the introduction, section 2 describes the open line detection problem itself, the underlying challenges and the performances required to meet the existing SPS (Special Protection Schemes) needs [5, 6]. The required line signals and the various configurations for which local and remote end detection are needed are also presented. Section 3 focuses on the detection principles that were used by the previous DLO and the main motivations behind the development of a new open line detector.

Section 4 is devoted to the functional description of the new DLO. The general principles of the fuzzy logic based algorithm, the auxiliary functions and the main characteristics of the digital platform are presented. The performances of the new DLO are demonstrated in section 5, with a series of field recordings and EMTP (Electro-Magnetic Transient Program) simulations corresponding to several line switching cases selected among those specified in section 2.

Section 6 is devoted to system considerations, briefly describing the key role played by the DLO in the existing special protection schemes. The conclusion, in section 7, brings back the key ideas found in the paper and presents the remaining steps required for completing the development work and for launching the new DLO.

2. THE OPEN LINE DETECTION PROBLEM

The DLO is a device made for detecting the line status (open or closed) of a radial (no mid-tap) transmission line. It must comply with a series of security, reliability and speed requirements as listed below:

**Security** :

False detections must be avoided in the following situations :
- low or zero power transfer on the monitored line
- distortion on line voltages and currents during faults
- fast variations in the power flow
- reversal of the power flow
- power swings
- sub-synchronous resonances resulting from the parallel combination of shunt reactors and series capacitors [12]
- presence of harmonics

**Reliability** :

The DLO must detect the line status for the following events :
- line opening at remote end
- line closing at local end when already open at remote end
- line closing or opening with a shunt reactor connected

**Speed** :

The DLO must detect any change in the line status in 35 ms or less. This response time includes the effect of the DLO internal filters, the delay of its output contacts and the magnetizing discharge of the current transformers.

Figure 1 shows the configuration of a line in a substation with its capacitive voltage transformer CVT and current transformers (CT1, CT2 for breakers and CT3 for shunt reactor) that are used as the DLO inputs. The shunt reactor current is needed to avoid a false detection when the line disconnector is open while the line breakers are closed in order to feed the shunt reactor. The line could then be considered as closed.
Moreover, current and voltage transformers are not measuring at the same point if the line disconnector is open. The DLO must therefore take into account this discrepancy to avoid false detection.

3. THE EXISTING DLO

As presented in section 6 below, DLO are currently used in strategic 735 kV substations of Hydro-Québec transmission system. These devices are making use of three distinct methods to detect an open line condition:

1) trip signals coming from line protection relays
2) auxiliary contacts associated with breakers and disconnecting switches
3) low current measurements

The first method consists in monitoring all protection signals likely to order the opening of the line. This method is implemented in all the DLO. For the other line opening events such as a manual command, one of the two other methods are used. For tie lines that are subject to very low or reversing power flows, the detection method is based on direct monitoring of breakers and disconnecting switches positions as provided by their auxiliary contacts. For transmission lines with significant and unidirectional power flows, line opening events are detected by low current measurement. A line is considered open if its real current (active power) goes down below a given minimum. With the sensitivity of the existing undercurrent relays, this minimum is limited to a line current of 100 A. Some low-current measurements also incorporate a low power-flow monitoring function which inhibits false detection during low or reverse flow conditions.

These methods enable a DLO to detect line opening events at the local end only. In order to obtain the complete status of the line, a second DLO at the remote end together with a telecommunication link is required. Such a scheme allows for detecting the topology at either ends of a transmission corridor but it is a costly approach. The new generation of DLO has been designed for reducing both cost and complexity.

4. FUNCTIONAL DESCRIPTION OF THE NEW DLO

The functional diagram of the DLO algorithm is sketched in Figure 2. The five major building blocks illustrated are the following:

1) Acquisition unit: incorporates an anti-alias filter with a 400 Hz cut-off frequency. The nominal sampling rate is 32 points per cycle.
3) Pre-processor unit: computes and extracts the features to be used in the fuzzy-logic decision.
4) Logical unit: processes the output signal to lock the decision.

The Kalman filter as such is not new to power system protection [2]. However, lot of efforts have been invested since the mid-nineties in order to take full advantage of its most interesting and innovative properties in solving difficult filtering problems found in its series-compensated network [3, 12].

One of the applications for which Kalman filtering was instrumental in fulfilling the very stringent requirements imposed is the programmable load-shedding system [8]. Even if many factors advocate use of the Kalman filtering in general, its superiority, in the present application, over the Discrete Fourier Transform (or similarly, any full-cycle phasor measurement scheme) is its capability to provide signal components at spectral frequencies other than the fundamental and its harmonics. It then becomes an effective built-in self-diagnosis tool, taking advantage of both negative sequence component at fundamental and resonances that may transiently appear when a line is opened at both ends while its shunt reactors are connected.
4.1 Opening a line: steady-state aspects.

Per-unitization

For convenience, the various electrical quantities used in the pre-processor will be expressed in a per-unit system defined as follows:

- Base voltage (Vbase): the rated line to line voltage
- Base power (Pbase): the surge impedance loading (SIL)

The impact of applying this per-unit system to transmission lines of various rated voltage (110kV to 1100kV) and physical characteristics obtained from [10] has been investigated. The results are very interesting in that the line charging happens to be nearly a constant value in this SIL based per-unit system, i.e. 0.14 % per km. This means that we do not need to adapt the relay settings to a specific voltage level, since the measurements are self-adaptive to the transmission line characteristics through the proper selection of the base values.

Perfect equilibrium

While analyzing the physical process behind the disconnection of a line, we recognized that an open line is not so different from a closed one with no active power transfer. Therefore, it is important to understand, by theoretical computations, how critical measured variables such as the voltage and the reactive power are behaving when the active power of a connected line vanishes [9]. Figure 3 shows that, for a given line length, an operating point (consisting of the angle shift and voltage ratio between its ends) can be found so that, as seen from the sending end, both active and reactive powers vanishes.

Fortunately, even though this critical operating point is feasible, it is very sensitive:

For short lines (30km), the typical sensitivities are 45% MW per degree of angle shift and 25% Mvar per unit of voltage ratio. Therefore, this critical operating point is difficult to achieve and even more difficult to sustain in steady-state.

Generally, it will be matched transiently, and then the relatively large sensitivity of the Power-angle and/or Power-voltage around this point will force the power system to quickly exit the point.

4.2 Opening a line: transient state aspects.

At the heart of the DLO is a Delta_filter, which bears a physical meaning during a line disconnect process. It roughly corresponds to the rate of change of the positive sequence active or reactive power over a suitable time window. The behavior of DeltaP, where P is the active power, is illustrated in Figure 4 for two different situations:

- The power transfer is ramping from a positive direction to a negative direction, thus passing by zero in a manner that may mislead a crude open-line detector. At 4s, the power ramp crosses zero and DeltaP reaches a maximum value 30ms later. Interestingly, while the maximum value of DeltaP varies from 0.02 to 0.4 as the ramp slope is increased from 0.5 p.u./min to 60 p.u./min, this maximum is reached nearly at the same time, i.e. about two cycles after zero-crossing.

![Figure 3: Critical operation point: Sending end active and reactive powers are both zero.](image-url)
At various power transfer levels ranging from 1% to 100% of the SIL, the line is suddenly opened. DeltaP then increases sharply from its zero-steady-state value to its maximum value close to 1. Whatever the prior power transfer level is, the later value is reached about 2.5 cycles after the switching.

From these empirical observations, it clearly appears that opening a line suddenly with a breaker results in "large" maximum values of DeltaP, while power transfer reversal through slow ramps results in comparatively low maximum values. The threshold to discriminate between these two situations is about 0.5 and the time needed before an unambiguous decision is about 2 cycles.

4.3 The DLO’s Fuzzy Decision System

Although fast and reliable relaying algorithms can be achieved by applying conventional Boolean logic, conflicts may arise in doubtful cases. For instance, during line energization at no-load, CVT (Capacitive Voltage Transformers) induced electro-magnetic transients may suggest that the active power is not zero (line closed) while the line is actually open. Experience has demonstrated that such a conflict can be more easily resolved using a multi-criteria Fuzzy Logic based approach [4, 7], which results in the following interesting properties:

1. Tripping decision is based on several criteria with adaptable weighting factors
2. Uncertainty with respect to signals and settings is modeled quantitatively
3. Delay of tripping initiation depends on the amount or inflow of information related to relaying signals, and through them, to the disturbance analyzed by the protection.

A sample general structure of the fuzzy decision system is shown in Figure 5. It consists of three main steps:

1. Fuzzyfication of 10 selected decisions features from the pre-processor
2. Fuzzy logic inference on these features, using twelve rules or criteria
3. Crisp decision sent to the output

Fuzzyfication is a necessary step prior to a fuzzy-logic based reasoning system [7]. It consists in transforming the crisp variables provided by the pre-processor in Figure 2 into categories easily described by linguistic spellings from the common language such as "Normal", "Small", "Large", "Very Large" and so on. Figure 6 illustrates this fuzzyfication process for two typical variables: the Active Power and the DeltaP. The first feature is defined as "SMALL" when its crisp value is below a given threshold ($\theta_L$) while the DeltaP feature is defined as "BIG" for crisp values higher that ($\theta_S$). Obviously, the active power threshold should reflect the steady-state accuracy limit of the measurement system while the DeltaP threshold is 0.5 as previously explained in paragraph 4.2.
The set of rules operates on these fuzzy variables according to basic physical principles. We can for instance define "Reliability rules" to specifically assess the open-line condition and "Security rules" to target closed-line situations.

An example for each type of rules is given below:

- **Security**: if (ActivePower is not SMALL) LINE is CLOSED
- **Reliability**: if (DeltaP is BIG) LINE is OPEN

Overall, the inference engine contains 12 such rules evenly divided into 6 rules for detecting the open-line status under various circumstances ("Open" rules), and 6 rules for detecting the closed-line status ("Closed" rules). In each category, the rules can be further classified in terms of transient and steady-state rules. For instance, the reliability rule above is a transient one while the security rule is a steady state.

All the rules for detecting the closed-to-open switching action of line breaker rely on the Delta-filter principle recognized in paragraph 4.2. Additionally, the steady-state "off" rules heavily depend on steady-state indicators with sufficient redundancy and the short-term memory of the line past status. Any inconsistency in the voltage signals (cf. Figure 2) is reflected in an excessive negative sequence voltage
Vn(fn) and an excessive sub-synchronous voltage V(dc), which are expressed in fraction of the positive sequence voltage magnitude. These variables are used in two complementary rules in order to rapidly detect the open line condition while the line is still discharging into shunt elements at both ends, with or without sub-synchronous resonance present on the line voltage. The last step in figure 6, called defuzzification, consists in converting the evaluation results of the 12 criteria into a single decision. Each criteria states that the line is open or closed with a given probability and defuzzification really aims at reconciling all partial decisions using an aggregation procedure as described in [7].

4.4 Description of the digital platform

The DLO algorithm described above has been implemented on a modern digital relay platform [11]. Its hardware block diagram is shown on figure 7. It comprises 6 modules which are the main processor board, the coprocessor board, the input module, the IRIG-B board, the future communication board and the power supply module.

The main processor board performs both the protection and communication functions except for those that are run on the coprocessor. It supports user interface functions with its LCD and keypad, its programmable LED indications, a serial port and a parallel port. It also provides an interconnection bus for interfacing with other boards.

The serial port supports functions within the relay by providing the ability to program settings off-line, configure the programmable scheme logic, extract and view event, disturbance and fault records, view the measurement information dynamically and perform control functions. The parallel port is used to download the firmware or to perform tests on the relay. A battery is provided to backup disturbance memory and real time clock.

The input module comprises both analogue and digital input circuits. The analogue circuitry is responsible for converting up to four power system voltage waveforms and up to nine power system current waveforms. Out of these, the DLO algorithm requires three voltages and six currents. Currents as low as 0.01 p.u can be measured in order to detect very low power transfers. The last three channels are required for self-testing. The digital circuitry provides a set of eight opto-isolated inputs.

As for the main board, a digital signal processor TMS320VC33-150 is used on the coprocessor board. It runs the DLO algorithm itself at a rate of 32 samples per cycle. The IRIG-B board decodes a 1 kHz sine wave, modulated with time of year data to a resolution and time frame of one second as defined by IRIG time code. The board provides the processor board with an accurate time for time tagging of events. The board also contains a fibre optic transmitter and receiver pair for communication over a fibre optic IEC870-5-103 network.

Provision is made for future expansion of the system’s communications facilities. It consists of a reserved group of addresses on the communications bus and mechanical provision for a board which can be fitted instead of the IRIG-B board. This future board will support the new IEC 61850 protocol.

The power supply module consists of four parts: the power supply circuits, an RS485 port, a watchdog relay and output relays. The RS485 port provides isolated half-duplex communications suitable for several standard protocols while the watchdog relay monitors the status of the system. A set of seven fast relays (1ms closing time) is available for main and auxiliary output signals.
The digital platform inherently supports a series of self-testing functions to check the adequate operation of the DLO: a) Integrity of power system voltage and current inputs (loss of 1 or 2 phases); b) analog to digital conversion; c) code integrity via checksum; d) relay settings integrity; e) real time operation (watchdog); f) power supply outputs. The performance of the DLO algorithm has been extensively assessed on a realistic database. In the sequel, sample cases from this assessment study will be used to demonstrate the good performance of the new device.

5. DLO PERFORMANCE: SOME RESULTS

The first case, shown in Figure 8, is from an EMTP simulation of Hydro-Québec transmission system and illustrates the behavior of a long line which is opened at its remote end without a fault.

Figure 8: DLO operation on a remote line opening at low (left) and high (right) power transfer

Figure 9 confirms the good security of the DLO for two typical adverse conditions: reversal of power flow at nominal voltage and unstable power swings with repeated zero crossing of active power.

Figure 9: DLO is secure when power flow is reversed (left) and during unstable power swings (right)

Several COMTRADE files recorded in Hydro-Québec transmission network were also replayed to check the DLO performance.

Figure 10 illustrates two security cases. The first one shows that, on a short tie line at low power transfer, severe 30-Hz switching transients caused by a fault on the system do not induce false tripping (left). In the second case (right) the DLO is able to maintain its open status during unloaded energization of a long line.
6. APPLICATION OF THE DLO IN HYDRO-QUÉBEC TRANSMISSION SYSTEM

In the nineties, Hydro-Québec has devoted substantial efforts to analyse the reliability of its transmission system. This analysis led to a more stringent design criteria and to the establishment of an extensive program to strengthen the existing infrastructures. The most attractive solution for satisfying this new criteria was to add series compensation, shunt reactors and SPS (Special Protection Systems). RPTC (Rejet de Production et Télédélestage de Charge) and SPSR (Solution Permanente pour la Séparation du Réseau) are two strategic SPS in the existing defense plan that are making extensive use of the DLO for their operation.

RPTC: This Generation Rejection and Remote Load Shedding System [5] detects extreme contingencies in 15 substations of the 735 kV system, performs generation rejections that can be as much as 5000 MW in four different sites and includes a remote load shedding system that can shed up to 3500 MW of load and 1500 Mvars of shunt capacitors. Extreme contingencies correspond to major topology changes like multiple line losses or capacitor bank bypasses on series-compensated lines.

As mentioned earlier, DLO are detecting line losses. All generation rejections and load shedding actions are modulated in real time by the system control centre to produce appropriate actions in all system conditions.
SPSR: Unexpected events may create system instability. Even if such events are highly unlikely to happen because of RPTC preventive action, equipment damages could occur if no additional precautions were planned. Following a system separation, severe temporary overvoltages (TOV), due to the Ferranti effect, appear on long unloaded lines still connected to the generators. Strategic equipment must be protected against these TOV in order to ensure that system restoration can be achieved. All measures deployed to protect strategic equipment in relation to electrical constraints are combined under the name of SPSR [6].

This system relies on overvoltage protection and on special switched metal-oxide surge arresters. Should a system separation occur, unloaded lines will be removed rapidly by overvoltage protections and TOV magnitude will be limited by the surge arresters. To ensure safe operation, over-frequency and open-corridor detection (initiated by the loss of all lines in the same corridor) will activate the SPSR. DLO must allow fast and reliable detection of such open-corridor conditions.

7. CONCLUSION

In the context of actual interconnected and heavily exploited power systems, fast detection of topology changes is considered an efficient means to trigger fast remedial actions and to defend a power system against contingencies of unusual severity.

The paper has presented the characteristics and performances of a new open line detector based on an original fuzzy logic algorithm. This new relay, called DLO, can detect opening of a line at either ends in less than 35 ms using only the line voltages and currents at the local end. Transfers as low as 0.01 p.u. of line rated power are detected thanks to its sensitive current inputs.

Being implemented on a modern digital platform, the new DLO offers a set of flexible auxiliary functions for user interface, communication, programmable scheme logic, self-verification, event and disturbance recording. The pre-series version was delivered end of 2003 and it is planned to conduct certification and field tests in 2004 in order to implement this new relay in Hydro-Québec transmission system.

8. REFERENCES