Integration of a hydraulic production plant in a weak power system on a long radial line

P. Larivière and M. Racine

An abstract-- Integrating power plants on long lines and weak power systems requires some care. To this effect, a study was conducted to determine if severe disturbances could result when a hydraulic production plant is integrated along a very long radial transmission line. Frequency responses were evaluated to identify possible resonant system operating conditions. Many events such as faults, transformer energizing and line opening were investigated. All power plant synchronous machines were represented including exciter and governor regulators. Impact of dynamic modeling of the load was examined. The study demonstrates that the overall protective strategy implemented will limit worst overvoltage constraints imposed to equipment and load within an acceptable level.

Keywords: Transmission lines, Electric Machines and Drives Temporary Overvoltages, Control Systems.

I. Introduction

THE hydro-Québec transmission system in the Province of Québec, Canada, integrates large production plants through an extensive 735 kV network over distances that exceed 1000 km. In many cases, lower voltage sub networks are often comprised of long lines and may be characterized as weak systems. One such case was examined to integrate a small hydraulic power plant. From the main grid substation, a 161 kV transmission line 340 km long feeds a total of 12 MVA off-peak loads over 6 substations (see table I showing distances from main grid and loads). The capacitive charging of the line is 20 Mvar between the main grid and location 3 substation and 12 Mvar for the rest of the line, explaining the need for a 12 Mvar shunt reactor continuously in service at location 3 substation. From a value of over 5 000 MVA at main grid 161 kV, the 3 phase short-circuit rating falls to 250 MVA at the integration point of the 42 MVA hydraulic power plant, 180 km away. Built over the Canadian Shield, the earth resistivity is around 4 000 Ω–m for this region.

The purpose of this paper is to present the required system studies when integrating a new power plant on a long radial line also used to feed small loads tapped along the line. To this effect, transient studies were performed to establish the worst overvoltage constraints imposed to sub network substation equipment and load when the production units are suddenly islanded on the sub network. Furthermore, protection studies were also performed to determine the best strategy to kill the island and limit overvoltage constraints imposed to equipment and load at acceptable levels.

II. Network Representation for Simulations

The network representation for simulations includes an equivalent for the entire Hydro-Québec network, the 161 kV transmission line, the hydraulic power plant with controls and a load model. This network representation must be adequate to represent the dynamic of the system at low frequency, including the dynamic response of hydraulic machines. All the simulations have been carried out with a time-domain electromagnetic transient software.

A. Equivalent for the Hydro-Québec transmission network

Since the main disturbance for this study is initiated by the opening of the line at the main grid substation, it is adequate to represent the Hydro-Québec transmission network by its fundamental frequency (60 Hz) equivalent at the main grid substation (network thevenin impedance). To do this, an ideal voltage source of 735 $kV_{ø\text{-}ørms}$ in series with an RL passive element is used. The representation of the 735-161 transformers was based on a fundamental frequency impedance equivalent model without any core saturation consideration.

B. 161 kV transmission line

The 161 kV line was represented by sections between substations, the longest section having 67 km. For the frequency range phenomena under study, the constant parameter model for the transmission line is adequate. For this length, a π model without hyperbolic correction would be fine too [1], except maybe, near the place where a fault is applied.

C. Load

The distribution of the load is described in table 1. This represents the off-peak load, usually present during the summer time. The hydraulic power plant will be integrated between location 3 and location 4 substations, 27 km away from location 3 substation.

The load at location 3 substation is the most important along the 161 kV line.

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TABLE I

VOLTAGE AND LOAD DISTRIBUTION ALONG THE 161 KV LINE BEFORE THE INTEGRATION OF THE HYDRAULIC POWER PLANT

substation	Distance from main grid substation (km)	Voltage ($kV_{\phi\text{-}\phi rms}$)	Active load (MW)	Reactive load (Mvar)
location 1	340	167.9	1.5	0.2
location 2	273	167.4	0.2	0.3
location 3	209	165.7	7.3	3.0
location 4	117	166.1	1.5	0.2
location 5	97	166.1	0.1	0
location 6	61	165.8	0.1	0
total load			10.7	3.7

For purpose of comparison, two models have been used for load representation. The first one is a RLC passive parallel element. The second one is a static load model, frequently used in stability soft wares, corresponding to the following equations [2] [3]:

$$P = P_0 * V^{N_p} * \left(1 + K_p * {(f - f_0)}/{f_0}\right) \quad (1)$$

$$Q = Q_0 * V^{N_q} * \left(1 + K_q * {(f - f_0)}/{f_0}\right) \quad (2)$$

Equations (1) and (2) describe the dependence of active and reactive power against voltage and frequency variations. P_0 and Q_0 are the nominal active and reactive power values, V the instantaneous amplitude of the 60 Hz voltage, f the instantaneous frequency, f_0 the nominal frequency. The parameters N_p, N_q, K_p and K_q are used to define different types of load. In this study, the values of these parameters are: N_p =1 ; N_q=2 ; K_p=0 et K_q=-2, corresponding to a general substation summer load.

D. Power plant

The new hydraulic power plant to be integrated will have 2 generators for a total of 42 MVA with two 13-161 kV step-up transformers. Because this hydraulic site will be subject to the presence of tides, the operation of only one generator has also to be considered. Since the purpose of the study is to determine if the acceleration of the turbine-generator will be to fast for regular protective scheme, the automatic voltage regulator (AVR) and governor/turbine must be represented. For the AVR, a model for brushless excitation system was used; refer to the AC5A excitation system model of [4]. For the governor/turbine representation, a classical approach was used for a hydraulic generator [5]. The generator was modeled as a synchronous machine [6].

E. ZnO arresters

It is well established that near transformers, for protection against surges, it is a good practice to install ZnO arresters. Those arresters have different VI curves depending of the type of perturbations: lightning surges, switching surges or temporary overvoltages at the industrial frequency. As we will see in this study, the overvoltages produced by the simulated perturbations are at the industrial frequency. For this kind of perturbation, the protective level is 1,7 p.u. for a current of 1 A in the arrester.

III. SIMULATIONS

The purpose of simulations during this study was to find the events that result in severe overvoltages along the 161 kV line. The assumption that those overvoltages will appear when the power plant is islanded with the long line and the small load was the starting point. To produce this, all simulations must include the opening of the circuit breakers of the line at the main grid substation.

Other considerations about voltage dips complete this study. For example, energization of a step-up transformer was also examined.

For purpose of analysis, threshold values of 1,4 p.u. (1p.u.=161*√2/√3 kV) for overvoltages, 63,5 Hz for frequency and 0,9 p.u. for voltage dips, were considered. Justifications will be given during analysis.

All the simulations have been performed with EMTP-RV version 2.01 (www.emtp.com)

A. Unpredicted opening (UO) of Circuit breakers (CB)

Fig. 1 illustrates the active and reactive power of the generators, the amplitude of the voltage for different locations along the line, the frequency and the field current of generators when an UO of CB at main grid substation happens at 0,2 s.

Before the perturbation, each generator produces 21 MW and absorbs 0 Mvar. The voltage along the line is at 1 p.u. and the load-flow indicates that 75% of the full production of the new power plant is injected at the main grid 161 kV bus. After the perturbation, the transient overvoltages are quite small, around 1,2 p.u., the dynamic overvoltages reach 1,4 p.u. and more 2 s after the event and the frequency reaches the value of 63,5 Hz 0,4 s after the event.

Some remarks about simulation considerations. It is important to check the polarity of the filed current (see Fig. 1). Beyond the zero-crossing point, the simulation is not valid. Physically, the polarity of this current is always positive, due to the presence of a rectifier. In the synchronous machine model, this particularity is not present. In reality, when the field current becomes zero, auto-excitation phenomena may arise. Remembering that the level of protection of ZnO arresters is 1,7 p.u., it becomes clear that it is unnecessary to include those arresters in the simulation. The active power is calculated by two different ways: by the product of v(t) and i(t) or by integration over one cycle of the fundamental frequency. Those two approaches give the same results. For the reactive power, a difference is observed between the results of the two approaches because with the integration, a constant delay of 0,25 cycle of the fundamental frequency is necessary. Since the fundamental frequency is changing, this constant delay introduces some errors.

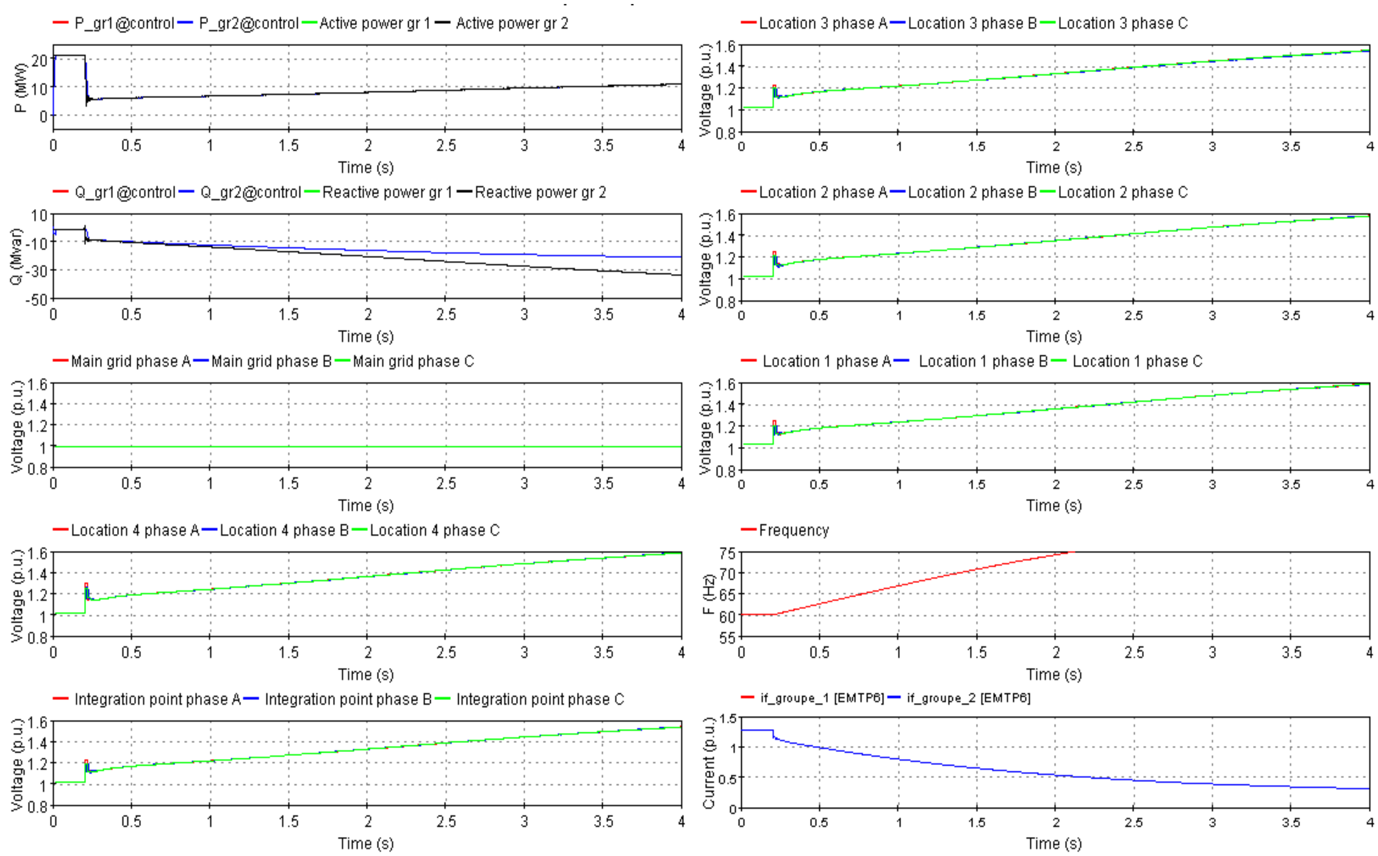

Fig 1. Power of generators, voltage along the 161 kV line, frequency and field current after unpredicted opening of CB at main grid substation.

B. (UO) of (CB) with static load model

The same simulation was repeated with the static load model. The overvoltages and the elapsed time to reach 63,5 Hz are quite similar. In fact, the excursion of frequency to 63,5 Hz represents a correction factor of 0,1 for the reactive power. This small variation with respect to the size of the machines and the length of the line explain the slight variation in the results. Considering that, the RLC passive model will be used for the rest of the simulations.

C. (UO) of (CB) with only 1 generator in service

If the same perturbation is repeated with only 1 generator in service, we can deduce, from Fig. 2, that the overvoltages are less severe. This can be explained by a bigger damping effect of the load for 1 generator versus 2 generators. From this point, all future simulation cases will include 2 generators.

D. 3 phase fault at main grid substation

The results of the simulation of 3 phase fault at the main grid substation or in the first zone protection of the line are quite similar to those of Fig. 1, without significant transient overvoltages.

E. 3 phase fault on 161 kV line

A 3 phase fault at location 3 161 kV bus may conduct to the loss of the greatest load on this line; witch may result in the greatest overvoltages. Statistical simulations, using systematic opening order variation over 1 cycle of 60 Hz for the opening time of the CB at location 3, show that the maximum transient overvoltages at the integration point is 1,5 p.u. and reaches 1,9 p.u. at the location 1 substation.

F. 3 phase fault on 161 kV line with UO of CB

Fig. 3 shows that if a UO of CB following a 3 phase fault at location 3, the amplitude of transient overvoltages stays similar but the dynamic overvoltages rapidly reach 1,4 p.u., in 0,8 s after the perturbation. The 63,5 Hz is reached 0,65 s after the perturbation.

G. Single phase fault on 161 kV line with UO of CB

The single phase to ground fault produces the same transient overvoltage but the time to reach 1,4 p.u. for the dynamic overvoltages is quite longer: 2,5 s.

H. Transformer energization

The energization of the first transformer at the new power plant in this weak network has been simulated to evaluate the voltage dip that can appear. Fig. 4 shows the amplitude of the voltage for 3 locations when a severe case is simulated: remnant flux of -0,8, +0,8 and 0 p.u. for phase ABC and worst closing time (zero-crossing on phase A) on the voltage waveform.

Table II summarizes the duration of voltage dips under 0,9 p.u. deduced from Fig. 4:

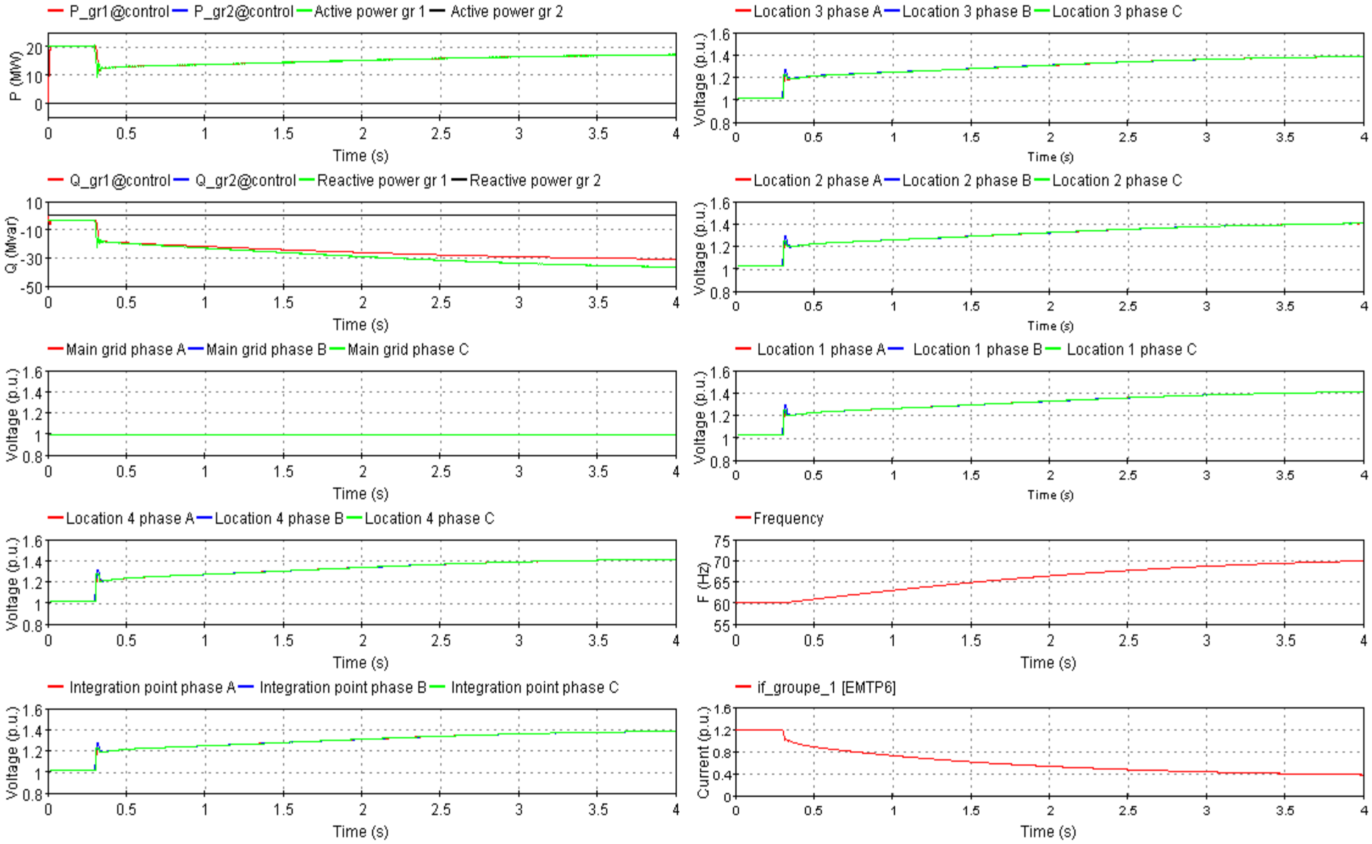

Fig 2. Power of generators, voltage along the 161 kV line, frequency and field current after an unpredicted opening of CB at main grid substation when only 1 generator is in service.

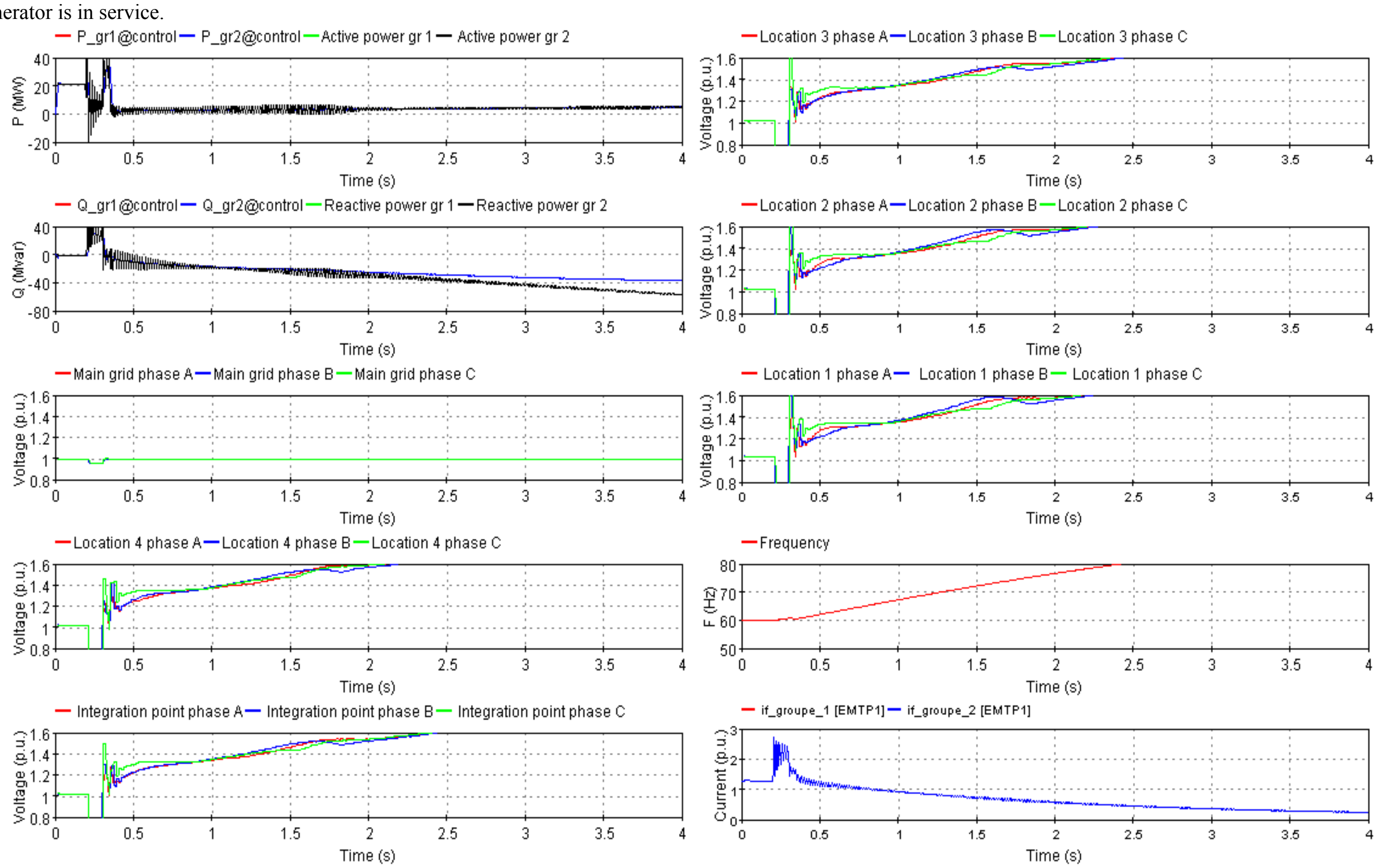

Fig 3. Power of generators, voltage along the 161 kV line, frequency and field current after a 3 phase fault at location 3 161 kV bus and an unpredicted opening of CB at main grid substation.

TABLE II

DURATION OF VOLTAGE DIP UNDER 0,9 P.U. DURING ENERGIZATION OF FIRST TRANSFORMER

substation	Duration (s)
location 1	0,135
location 2	0,145
location 3	0,180
Integration	0,160

This simulated case is one of the most severe. The same case with a closing moment at full voltage of phase A does not produce a voltage dip under 0,9 p.u

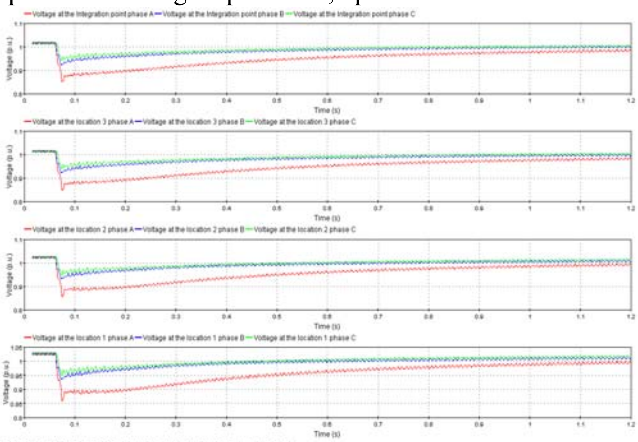

Fig 4. Voltage at the integration point, location 3,2 and 1 substations for the energization of the first transformer.

I. Frequency response of network impedance

To verify the sensitivity of those simulation results to the possible variation of the network impedance, a frequency response study has been performed. Fig. 5 shows the amplitude and phase angle of the impedance at the integration point.

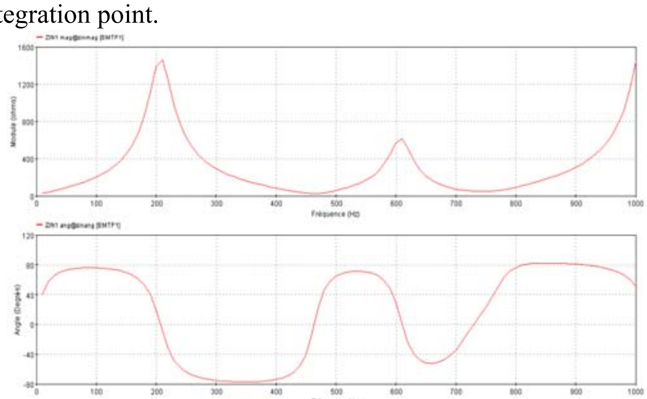

Fig 5. Module and phase of the network impedance at the integration point of the new hydraulic power plant.

Fig. 6 shows a resonance at a frequency of 200 Hz. At that frequency, this resonance does not represent any problem. If this resonance can be moved at 180 Hz, the third harmonic of 60 Hz, some special care may be needed. One way to obtain this shift is by adding capacitive shunt compensation on the main grid substation. Even with a new 200 Mvar shunt capacitor bank added on the main grid, the resonance stays near 200 Hz.

IV. ANALYSIS

For all simulation cases with the opening of the circuit breaker at the main grid substation, see Fig. 1 to Fig. 3, the dynamic overvoltages may be describes as unacceptable because they are high and most importantly, they never decrease. This rapid built-up of voltage can be explained by the relative importance of the reactive charging of the line versus the rating of the power plant. In the case of 1 generator, the rising rate of voltage is less, because the damping effect of the load is greater.

An overvoltage of 1,4 p.u. is acceptable for air gap insulated extra high voltage equipments when perturbation duration is 6 s or less [7]. This is in concordance with typical characteristics of power system electromagnetic phenomena [8].

Considering that a network with an important frequency excursion will become unviable, the over frequency protection usually set at 63,5 Hz has been used for analysis.

Considering the range and duration of overvoltages along the line, the characteristics of equipment and the sensibility of load, we conclude in the necessity of an automatic action scheme to prevent or limit the duration of this situation.

From the simulations, we can extract the response time needed for the automatic action: the 1,4 p.u. is reached in 0,8 s and the 63,5 Hz in 0,65 s.

A. Strategy for protection systems

The analysis of results indicates that the dynamic overvoltages obtained are very severe and actions must be taken to quickly limit overall constraints with an automatic power rejection scheme. Automatic actions will be initiated when the line opening is detected at the main grid substation. When the line opening condition is detected, automatic power rejection will be initiated. Actual power rejection will be achieved within 150 ms with the use of a telecommunication link. Power rejection is achieved by opening the main breaker at the power plant substation.

In the absence of the telecommunication link, a combination of an overvoltage and an over frequency protection will open the main power plant substation breaker. The overvoltage protection set at 1,4 p.u. for 200 ms will limit the duration of the severe overvoltage constraints imposed on substation equipment and load. The over frequency protection set at 63,5 Hz without delay will rapidly eliminate any islanding condition when overvoltages are less severe. When an island is formed, mismatch between production and load is sufficient to cause acceleration of the machines that will reach the over frequency protection setting within 500 ms.

B. Analysis of transformer energization

Voltage dip is usually defined for short duration (0,5 – 30 cycles) and rms value between 0,1 and 0,9 p.u. [8].

Table II summarizes voltage dips obtained for a rare and severe case of transformer energization. For a more regular case, since the rms value of the voltage does not go below 0,9 p.u, no mitigation technique such as a control switching system is necessary. Field experience will inform us in the near future if some load can be affected by this first transformer energization.

V. CONCLUSIONS

Simulation studies of transient phenomena are a very useful tool to determine if special protection schemes are necessary for the integration of a new hydraulic power plant in a weak transmission network.

The main purpose of those simulations was to establish the overvoltage built-up rise. To do this, the dynamics of automatic voltage regulators and governors/turbines must be represented.

For faults and unpredicted opening of circuit breaker simulations, the observed dynamic overvoltages are sufficiently severe to justify the implementation of an automatic power rejection scheme in order to limit overvoltage constraints imposed to substation equipment and load to an acceptable level.

The proposed protection strategy includes a telecommunication link between the main grid substation and the power plant for an automatic power rejection when the opening of the circuit breaker of the line at the main grid is detected. In the absence of the telecommunication link, a combination of an overvoltage and an over frequency protection will open the main power plant substation breaker.

VI. ACKNOWLEDGMENT

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VIII. BIOGRAPHIES

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