A SPECIAL CASE OF FERRORESONANCE INVOLVING A SERIES COMPENSATED LINE

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Abstract-- **Ferroresonance is a complex nonlinear phenomenon that can greatly affect high voltage power transmission system. This paper will explore and discuss the prevention of a special case of power transformer ferroresonance that is rarely reported in the related technical literature. A case of ferroresonance on a 230 kV series compensated power transmission system of Hydro-Quebec is described. Series compensation on a 210 km 230 kV transmission line, several power transformers at 4 power generation plants and insignificant local loads are the main elements creating ferroresonance. A sustained harmonic overvoltage up to 1.8 pu is observed in simulation because of ferroresonance, a constraint that can be harmful to power transformers and other equipment.**

EMTP-RV simulations and analysis of scenarios with low level of production may create sustained ferroresonance between generator transformers and series capacitors on the line. The ferroresonance phenomenon is confirmed by the typical 20 Hz component of the observed overvoltages.

The paper will also discuss the impact of varying the following parameters on the creation of the ferroresonance such the slope of the transformer saturation curve, number of power transformers, power transfer level and fault location.

An operational restriction was chosen to avoid the risk of ferroresonance and the associated harmful overvoltages.

Keywords: **Ferroresonance, Series Compensation, Power transformers, Harmonic overvoltage, EMTP-RV.**

I. INTRODUCTION

HYDRO-QUÉBEC power transmission system is composed of very long lines transmitting about 30,000 MW of hydro-electric power generated in the north to the main load concentrated in the south (Montreal, Quebec city and Trois-Rivières). To deliver this amount of power, series compensation on transmission lines is needed. This paper covers a phenomenon found on the Hydro-Québec's 230 kV network associated with a 210 km transmission line in a regional transmission system with several power plants. The study was initiated by the integration of a new small power generation plant Manouane Sipi of 20 MW at the top end of a 210 km – 230 kV line. During the studies, it was found that several power transformers at 4 power plants feeding the series compensated line and insignificant local loads contribute to the creation of this case of ferroresonance.

This paper will start by a brief history of ferroresonance involving series compensation and some theory on ferroresonance; it will describe the scenario led to the ferroresonance phenomenon and the models that have been used in EMTP-RV. Thereafter, system studies related to ferroresonance are investigated taking into consideration the slope of the transformers saturation curves, number of power transformers, power transfer level and fault location. The main purpose of this paper is to investigate a practical example of ferroresonance in power system involving series compensated line that has not been fully covered by the technical literature on ferroresonance.

II. HISTORY OF FERRORESONANCE INVOLVING SERIES COMPENSATION

Ferroresonance involving power transformers is addressed in technical papers [1]-[2] for load rejection scenarios. But the vast majority of the examples investigated in technical literature cover only the case of voltage transformers. Furthermore, practical examples given in some technical papers [3]-[4] don't consider series compensation (or covers it in a distribution network [5]), although these papers give multiple examples of real situations of ferroresonance.

But as experienced by Hydro-Quebec and reported briefly in a *IEEE* paper [6] about the Gaspesian region in eastern Quebec, and to a greater extent in internal Hydro-Quebec reports such as [7], series compensation combined with definite pre-conditions in a transmission system is likely to produce ferroresonance.

As mentioned in the detailed technical brochure [3], it is necessary to consider a sufficient margin to account for numerous parameters to limit a zone where ferroresonance shall not exist.

III. THEORY OF FERRORESONANCE APPLIED TO THE PRESENT CASE

Ferroresonance is a nonlinear resonance that can affect the safe operation of transmission networks. It always implies an electrical circuit with one or more nonlinear inductances (with saturable ferromagnetic material) and a capacitor supplied with a voltage source. The essential property and characteristic of ferroresonance is to present at least one stable regime that presents overvoltages or overcurrents.

For the Des Hêtres case presented in the next sections, the pole of ferroresonance at 20 Hz demonstrates a ferroresonant subharmonic mode. Ferroresonance in subharmonic 3rd mode has also been reported with inductive voltage transformers [8].

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The study of the simplified schematic in Fig. 1 leads to the typical curves and equations corresponding to a periodic ferroresonance [9].

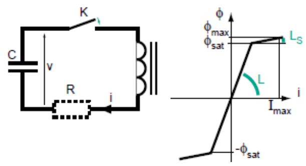

Fig. 1. Simplified network and φ(i) Characteristic

The flux oscillates between a saturated value and an unsaturated value with the frequency, as in (1):

$$\frac{1}{2\pi\sqrt{LC}} < f < \frac{1}{2\pi\sqrt{L_S C}} \qquad (1)$$

In the case of Des Hêtres with series compensation, we represented in EMTP-RV an equivalent circuit such as Fig. 1 to simulate the saturated and unsaturated poles of the circuit for two cases with ferroresonance (case 1 and 10 in TABLE I) and for one case without ferroresonance (case 3 in TABLE I). Fig. 2 shows the results of the simulations in the frequency domain.

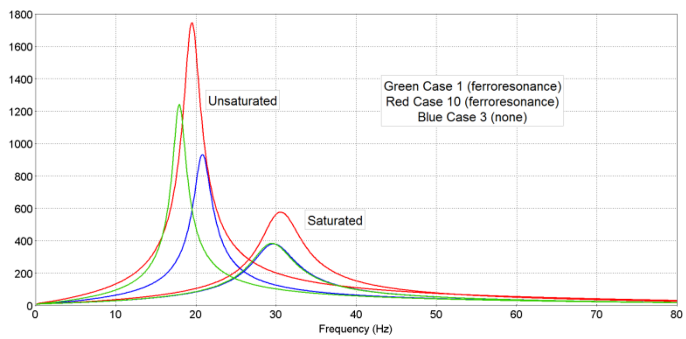

Fig. 2. Subharmonic poles in saturated mode (3 curves at the right) and unsaturated mode (3 curves at the left)

For the case without ferroresonance in Fig. 2, the unsaturated pole is around 21 Hz (just over 20 Hz). For the two cases with ferroresonance, we identified the subharmonic poles in unsaturated mode just under 20 Hz (18.5 et 19.5 Hz for each case). When the transformers are saturated, all poles move to a value of around 30 Hz.

The oscillation between the two values of frequency, saturated and unsaturated, leads to a periodic ferroresonance. As it will be observed further in this article about the Des Hêtres case, it leads to a ferroresonance state at 20 Hz (with the fundamental $f_o/3$).

IV. Scenario Description

Fig. 3 illustrates a simplified equivalent of the scenario simulated in EMTP-RV. The power system is represented by a 230 kV source with impedance at the Des Hêtres substation. Three sections of the line totalize around 210 km from Des Hêtres substation to Chute-Allard power plant and Manouane Sipi power plant. Series compensation is located at the beginning of the line at Des Hêtres substation.

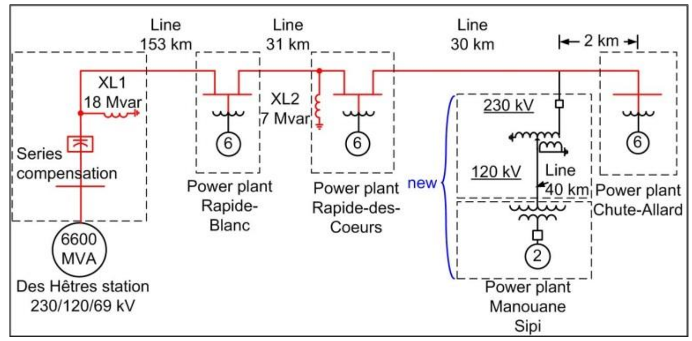

Fig. 3. Single Line Diagram of the analyzed power transmission system

Each transformer of power plant and substation of the scenario under study was represented in EMTP-RV: at Rapide-Blanc (6 transformers of 40 MVA each), Rapides-des-Coeurs (2 transformers of 44 MVA each), Chute-Allard (2 transformers of 35 MVA each) and Manouane Sipi (1 transformer of 25 MVA).

Shunt reactors of 18 Mvar and 7 Mvar at 230 kV at two substations are represented (Des Hêtres and Rapides-des-coeurs).

V. EMTP-RV Models

A) Equivalent source and series compensation

As showed in Fig. 3, simulations were conducted in EMTP-RV with an equivalent network of 6600 MVA at the Des Hêtres station (impedance Z1 = 8 Ω and Z0 = 6 Ω) at 230 kV. Series compensation located at Des Hêtres substation is represented by an equivalent capacitor (transmission line compensated to 50 %).

B) Transformers

When analyzing a phenomenon such as ferroresonance, the representation of the transformer nonlinearity (magnetization data and saturation characteristics of the power transformer) is of high importance. Standard models of transformers from EMTP-RV library have been used.

The standard transformer model has been enhanced by using the proposed model in Electra 167 [10] to better represent the behavior of the power transformer, more precisely the transformer damping, in a rich harmonic environment. Also we have been a step forward by representing the magnetic losses of the power transformer based on [11].

Transformer nonlinearity (magnetization and saturation characteristics) is represented by the flux versus current within the transformer standard model in the magnetization data table (piecewise representation). To establish this characteristic, two parameters are determinant: saturation knee and the slope. The knee point varies and it is usually between 1,1 and 1,2 pu of the flux nominal value. The slope of the saturation characteristics beyond the knee saturation point corresponds to the air core inductance of the transformer.

For parametrization purposes, 5 sets of saturation data were used in the studies with slopes of the saturation characteristic of [12, 20, 26, 30, 38] %. The aim of this parametrization was to establish the sensitivity of the phenomenon to the saturation characteristics.

C) Transmission Lines and Shunt Reactors

Transmission lines were represented at first with a constant parameter model at 60 Hz and then with a frequency dependent model to determine the impact of the used model on the results. It is well known that the frequency dependent model has a better representation of the line when it comes to a phenomenon involving resonance and/or the damping of the line is of high importance.

D) Power Plants

Representation of hydraulic generating units and their specific controls at each power plant was necessary to study transient behaviors and over-voltages that can be observed after fault clearing and other perturbations in the system. Speed governors, exciters and stabilizers are represented to study the transient dynamic behaviors.

VI. Simulations Results

A) Case of ferroresonance observed in simulation on the Des Hêtres power transmission system

To illustrate the nature and the impact of ferroresonance observed in EMTP-RV on the Des Hêtres power transmission system, the following case is presented (case 1 from TABLE I).

- A 3 phase short-circuit is applied at the hydraulic generating unit side (11 kV voltage level) of Rapide-Blanc power plant followed by the elimination of the short circuit 100 ms after the loss of the generating unit;
- XL1 and XL2 in service on the line;
- One hydraulic generating unit out of 6 at Rapide-Blanc power plant is in service (all transformers are in service without any generation at the low voltage side because of the power plant normal operating conditions);
- One group respectively at Chute-Allard and Manouane Sipi;
- Transit on the transmission line is around 50 MW with series compensation at Des Hêtres;
- Transformers are represented with Electra 167 model [10]. Saturation curve of power transformers is represented with a slope of 26 %.

On Fig. 4 we observe the steady state before the event, followed by the short-circuit applied at 1 second and its elimination at 1,1 second. After the event, a new steady state with harmonic overvoltage occurs. That new sustained regime is due to ferroresonance. Harmonic overvoltage continues over several seconds without damping.

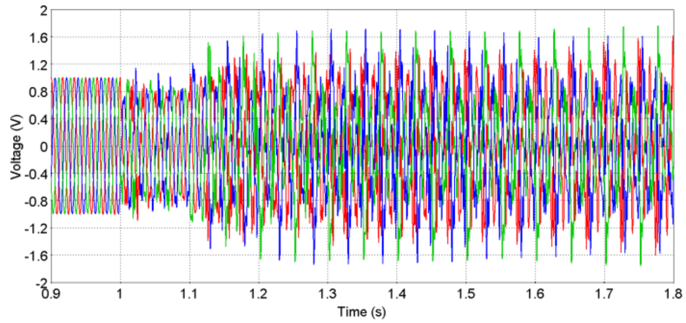

Fig. 4. Overvoltage observed on the 230 kV voltage level at Chute Allard.

Fig. 5 shows a zoomed part of the overvoltage waveform of the previous figure. We can see clearly that the peak value of the observed overvoltage is around 1,7 p.u. A sustained overvoltage of that magnitude is unacceptable on power system; the integrity of some equipment in term of insulation could be affected.

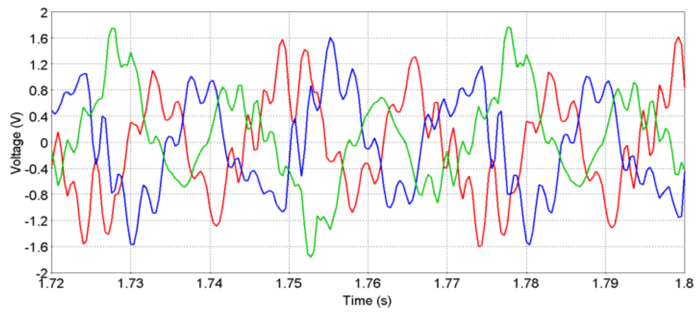

Fig. 5. Zoom on the overvoltage observed on the 230 kV voltage level at Chute Allard.

Fig. 6 illustrates the frequency spectrum (harmonic components) of the current through series compensation during the ferroresonance occurrence. We note that the $f_o/3$ component of 20 Hz exceeds largely the fundamental component of 60 Hz.

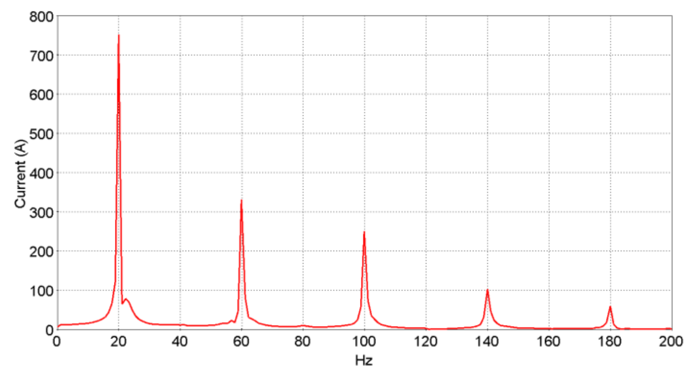

Fig. 6 Frequency spectrum of the current through series compensation

The previous analyzed case illustrates an example of ferroresonance for one topology of the Des Hêtres subnetwork. We have carried out sensitivity analysis to investigate the impact of different parameters on the ferroresonance phenomenon observed in our case; these parameters are:

- The nonlinearity of the power transformers, more precisely the slope of the saturation curve;
- The event (three phase or one phase to ground short circuit and/or loss of generation) and the location of the event on the analyzed subsystem;
- The number of power transformers with no load or no generation at the low voltage side;
- The transmission line transit (vary with the number of power plants on the 230 kV line).

TABLE I shows the results obtained with EMTP-RV simulations for different cases with different parameters.

TABLE I
EMTP-RV SIMULATION RESULTS FOR DIFFERENT CASES AND PARAMETERS

Case	Saturation curve	Type of event and Site	Network	Transit	Ferro
	Slope		tx (MVA)	Des Hêtres (MW)	Yes / No
1	12, 20, 26	3ph R-B and loss 1 gr. R-B	276	50	Y
2	30, 38	3ph R-B and loss 1 gr. R-B	276	50	N
3	26	3ph R-B and loss 1 gr. R-B	276	80	N
4	26	3ph R-B and loss 1 gr. R-B	251	61	Y
6	20	3ph R-B and loss 1 gr. R-B	285	66	Y
8	20	3ph R-B and loss 1 gr. R-B	132	70	N
9	20	3ph R-B and loss 1 gr. R-B	276	70	Y
10	20	3ph R-B and loss 1 gr. R-B	399	70	Y
13	26	3ph C-A and loss 1 gr. C-A	399	60	N
14	26	3ph C-A and loss 1 gr. C-A	399	50	N
15	26	3ph R-D-C and loss 1 gr. R-D-C	329	53	N
16	26	3ph R-D-C and loss 2 gr. R-D-C	329	56	Y
17	26	Loss of 2 gr. R-D-C	329	56	N
18	26	1ph R-B and loss 1 gr. R-B	276	50	N
19	26	1ph R-D-C and loss 2 gr. R-D-C	329	56	N
21	20	3ph R-B and loss 1 gr. R-B	194	62	Y

* 3ph (3ph short circuit), 1ph (1ph short circuit)
R-B (Rapide-Blanc), C-A (Chute-Allard), R-D-C (Rapide-des-Cœurs)

B) Sensitivity of the ferroresonance phenomenon observed to the slope of the saturation curves

In the 1st and 2nd cases of TABLE I, only the slope of the saturation curve has been modified. The results from simulations are clear: in case 2 ferroresonance is absent (see Fig. 8) compared to case 1 (see Fig. 7). In case 1 we observe a sustained overvoltage around 1,8 p.u. representing a ferroresonance regime and in case 2 we observe a TOV (Transient Over Voltage) lasting less than 5 cycles with a peak value around 1,6 p.u.

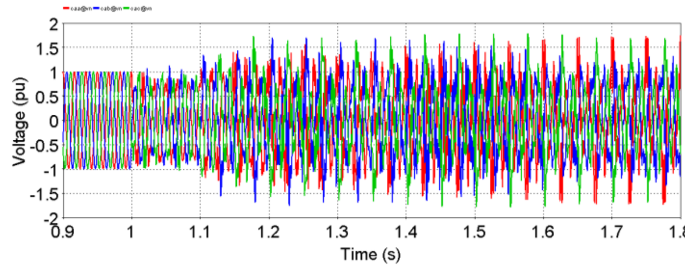

Fig. 7. Overvoltage obtained by simulation for case 1 with 20 % slope of saturation

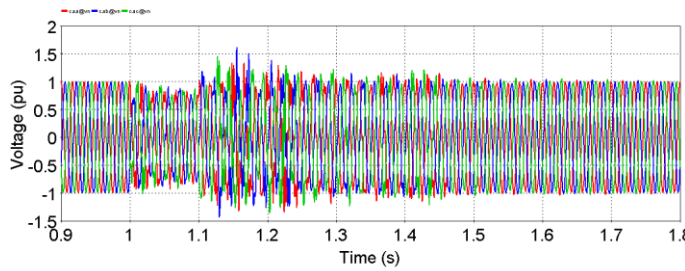

Fig. 8. Overvoltage obtained by simulation for case 2 with 30 % slope of saturation

If we analyze the influence of the slope of the saturation curve from the tab results in TABLE I, we can conclude that the slope is of high importance and influence the occurrence or not of ferroresonance. The real saturation curve of a power transformer is an unknown data unless it was measured during test (which is not a common practice). Because of its influence over the results, it will be necessary to take into account these uncertainties in the application of the solution.

C) Influence of the total MVA of power transformers

The number of power transformers (total MVA) present in the Des Hêtres subsystem also has a significant impact on the occurrence of ferroresonance. Transformers at the power plants may be in service even if the hydraulic generating units are out of service. This is likely to happen when we need to keep up the power plant supply of energy or for a fast startup of the hydraulic generating units because of the operational mode imposed by the initial design of the plant (no circuit breaker is present at the high voltage side of the power transformer).

Cases 8, 9 and 10 in TABLE I show the results of simulations obtained for different total MVA of power transformers (132, 276 and 399 MVA). For these cases we have fixed the slope of saturation (20%) and the transit on the transmission line (70 MW). A three phase short-circuit was applied at Rapide-Blanc Plant and it was cleared 100 ms later.

Fig. 9 and Fig. 10 shows the results of simulation in EMTP-RV obtained for two extreme cases in term of total MVA of power transformers. In Fig. 9, which is case 8 (132 MVA), we observe a damped TOV with a peak value not exceeding 1,3 p.u.. In Fig. 10 which represents case 10 (399 MVA), a sustained overvoltage ferroresonance regime is observed with a peak value of 1,7 p.u.

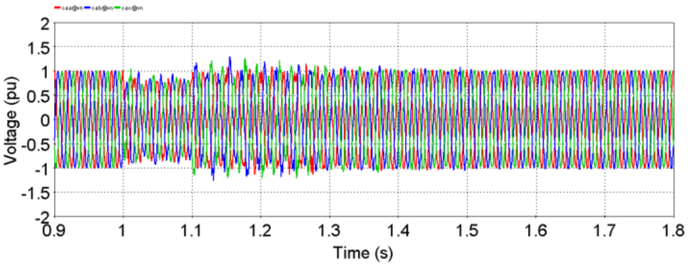

Fig. 9. Overvoltage obtained by simulation for case 8 (130 MVA)

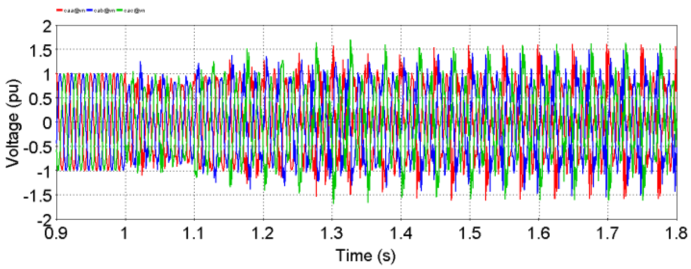

Fig. 10. Overvoltage obtained by simulation for case 10 (400 MVA)

It can also be observed from the frequency spectrum of the series compensation current in Fig. 11 that the 20 Hz component (1/3 of the fundamental) is considerably different in term of amplitude between case 8 (red curve, 25 Amps) and case 10 (blue curve, 525 Amps).

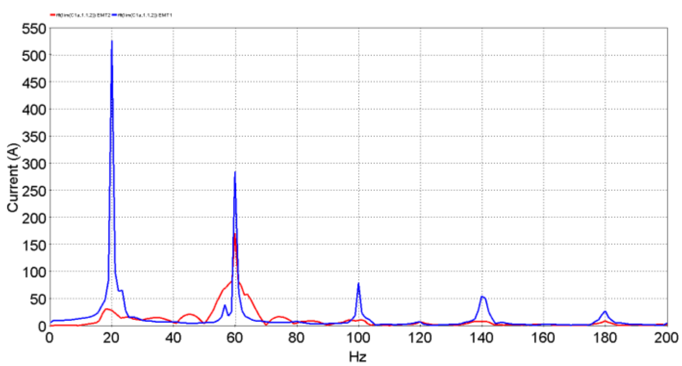

Fig. 11. Frequency spectrum of the series compensation current for case 8 with 130 MVA (red) and case 10 with 400 MVA (blue)

D) Influence of the short-circuit location and the type of event

The location of the short-circuit on the subsystem is certainly critical for the development of ferroresonance. In case 10 from TABLE I as opposed to case 13 it can be drawn that a fault associated with the loss of a bigger hydraulic generating unit (HGU) such as Rapide-Blanc (power plant of 6 HGU * 36 MVA) is more likely to create ferroresonance than a fault applied to a smaller HGU of Rapides-des-Coeurs (6 HGU * 14,5 MVA), Chute-Allard (6 HGU * 11,5 MVA) or Manouane Sipi (2 HGU * 10 MVA). The loss of a HGU at Rapide-Blanc might be riskier because of the loss of a bigger quantity of power and/or because of the proximity of Rapide-Blanc's power plant to the series compensation. Nevertheless, it is possible that the phenomenon occur for a short-circuit at a smaller power plant such as in case 16 from TABLE I. The short-circuit could be located on busbars that could lead to the loss of several hydraulic generating units. We note that a 3-phase fault eliminated in 100 ms (6 cycles) is sufficient to produce ferroresonance. From simulations results, the 1 phase fault does not seem to be sufficient to produce the ferroresonance phenomenon, as in cases 18 and 19 (see TABLE I).

E) Influence of the transmission line power transit through Des Hêtres substation

Finally, the transmission line transit through Des Hêtres substation, determined by the number of power plants on the 230 kV line, is another determinant parameter in the creation of ferroresonance. We see from the results of simulations done with EMTP that ferroresonance is created with a maximum of 70 MW (cases 9 and 10 of TABLE I). The transit limit (for which ferroresonance occur), does vary with several factors presented in the sections above: saturation curve of the transformers, quantity of transformation, types of event on the network and power transfer. That is the reason why it is important to apply a security margin, especially if the transit value ought to serve to discriminate potential cases of ferroresonance. A transit limit of 100 MW with an important margin of 30 MW was chosen to take into account the influence of these variable parameters.

In regards with transient simulations, ferroresonance was investigated with varying different parameters for network pre-conditions in Des Hêtres subnetwork. As a result and to prevent the phenomenon, it is important to avoid transit under 100 MW on the series compensated line. If transit line is under 100 MW, it is necessary to take action and put series compensation out of service.

VII. Solutions To Avoid The System Configuration Leading to Ferroresonance

To ensure a secure equipment operation conditions on this part of the power system, multiple solutions are possible. Indeed, for cases where a risk of ferroresonance is real, we ought to apply specific automatism as for example an automatism to bypass series compensation for an overvoltage peak value, introduce damping resistor or simply prohibit some network configurations.

For the Des Hêtres case, an operational restriction was chosen to eliminate transits at risk to produce ferroresonance. That solution has the advantage of efficiency, simplicity and low cost.

From the Des Hêtres transmission line transit history (Fig. 12), we observe that the transit drops to 100 MW often during the out of the peak load season and to 50 MW every year. These periods tend to concentrate during the summer time, which eases the application of an operational restriction. From the stability studies, series compensation on this part of the transmission system is needed for a transit on the line of 275 MW and up.

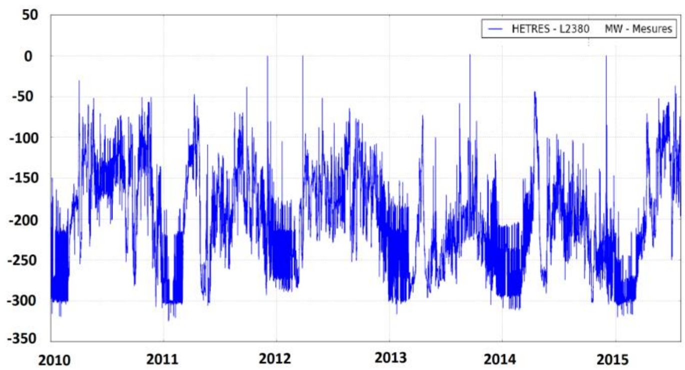

Fig. 12. Des Hêtres transmission line transit history (2010 to 2015)

The operational restriction that was chosen includes a margin and stipulates the following. When the transmission line transit is below 100 MW (the nominal transit of the line is 372 MW), it is mandatory to bypass the line series compensation.

VIII. Conclusion

From the technical literature we have noticed that ferroresonance involving power transformers and series compensated line with low transit are rarely reported. The practical example presented in this article covered a scenario of ferroresonance involving a series compensated transmission line, several power transformers at 4 power generation plants and insignificant local loads; these main elements creating ferroresonance.

System studies related to ferroresonance were conducted in EMTP-RV taking into consideration different parameters such the slope of the transformers saturation curves, number of power transformers, transmission line transit level and the fault location. A solution was proposed to avoid harmful overvoltages created by the ferroresonance phenomenon.

IX. Acknowledgment

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