On the Comparison Between a Detailed Turbine-Generator EMTP Simulation and Corresponding Field Test Results

Bahram Khodabakhchian Gia T. Vuong Sylvain Bastien
Hydro-Québec
855 East, Ste-Catherine, 19th floor
Montréal, Québec, Canada H2L 4P5

ABSTRACT - The machines of the LG1 generating station may, under some circumstances, be isolated from the Hydro-Quebec system but remain connected to an unloaded transmission line. As a preliminary study indicated the risk of harmonic overvoltages, a more thorough EMTP investigation was performed in which the models and data were adjusted to reproduce recordings from a field test.

Results from these simulations pointed out the need to use detailed modeling for similar studies. Furthermore, experience acquired during the process led to the recommendation on models and data selection in order to guarantee more precise results. As a result, a test procedure to determine the parameters of a hydraulic turbine model is proposed.

Keywords: EMTP simulations, harmonic overvoltages, turbine modeling, load rejection.

INTRODUCTION

The new LG1 station in the James Bay generation complex is equipped with twelve 120 MVA hydraulic units which are connected to the Radisson substation via a 59 km double-circuit 315 kV transmission line (figure 1). It may be observed that whenever either of the two power autotransformers at the Radisson substation becomes unavailable (disconnect switch SR1 or SR2 open), contingencies involving breaker openings at Radisson (with or without a bus fault) may lead to the separation of LG1 and the unloaded line from the network. Such islanding conditions are potentially dangerous because power transformers and other equipments may be exposed to harmful sustained overvoltages.

A preliminary study involving frequency scans and EMTP simulations confirmed that there indeed exist many operating conditions for which low-order low-loss harmonic resonance between the generator transformers and the unloaded transmission line may occur. It was also decided that more detailed EMTP simulations were needed to investigate the effect of generator overspeeding on harmonic overvoltages.

Therefore, field tests were performed in order to obtain more precise parameters and to provide reference data against which results from EMTP simulations could be compared.

This paper summarizes the preliminary study, describes the field test, discusses various measures undertaken to refine EMTP models and presents simulation results.

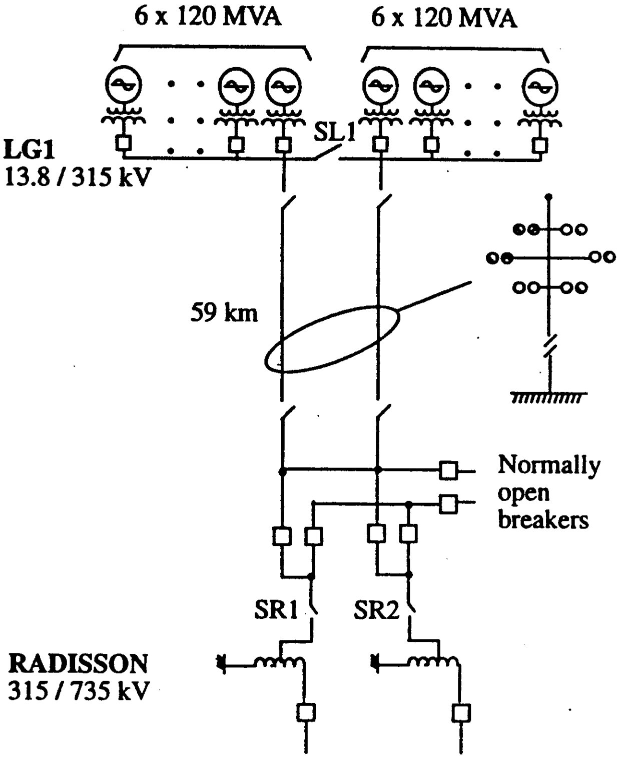


Figure 1: The LG1 - Radisson subsystem

PRELIMINARY STUDY

The LG1 station was designed for flexible operation i.e. generating units may be called upon in many possible combinations to meet specific needs: load requirements and scheduled maintenances.

In normal condition, when both transmission lines are available, LG1 is operated with switch SL1 opened and having up to 12 active units (two-line mode). Otherwise, it is operated with SL1 closed and having up to 8 active units, limited by the capacity of the remaining line (one-line mode).

Tables 1 and 2 present results of a frequency scan study covering all possible line-generator combinations, resonance frequencies being identified by the rank of the corresponding harmonics.

Table 1: Harmonic resonances, two-lines

L1 / L2	0	1 gen.	2 gen.	3 gen.	4 gen.	5 gen.	6 gen.
0	---						
1gen.	**2 nd**	3 rd					
2 gen.	3 rd	4 th	**4.5**				
3 gen.	4 th	**4.5**	**5 th**	**5 th**			
4 gen.	**4.5**	**5 th**	**5 th**	6 th	6 th		
5 gen.	**5 th**	**5 th**	6 th	6 th	**7 th**	8 th	
6 gen.	**5 th**	6 th	6.5	**7 th**	8 th	**7 th**	**7 th**

Table 2: Harmonic resonances, one-line

1 gen.	2 gen.	3 gen.	4 gen.	5 gen.	6 gen.	7 gen.	8 gen.
3.5	**4.5**	**5 th**	6 th	**7 th**	**7 th**	8 th	8 th

Dangerous overvoltages are characterized by resonance frequencies around the 2nd, 5th and 7th harmonics. It was observed that the resonnance impedance magnitudes average 13 k-ohms with a Q-factor of 10. These conditions correspond to the resonance frequencies highlighted with bold characters in tables 1 and 2.

This preliminary study proved that there are real risks of harmful overvoltages. Therefore, it was decided that more investigations are needed, mainly for two reasons:

- high frequency waveforms produced by EMTP are usually less damped than those observed in real life,
- the effects of machine overspeed following the islanding have not been simulated.

Consequently, some field tests and more detailed EMTP simulations were performed.

FIELD TEST

The field test was conducted for a one-generator one-line configuration (figure 2), classified not dangerous by the preliminary study. In this case, the load rejection phenomenon was simulated by an opening of breaker B2. As a precaution against possible damage to the equipements, breaker B1 was programmed to open 150 msecs after B2.

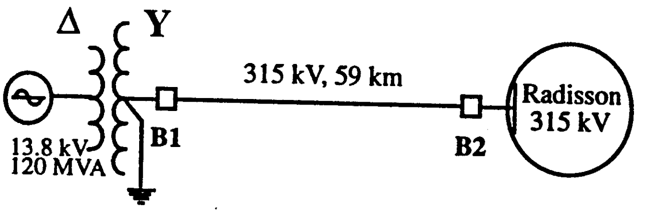


Figure 2: Field test configuration

The voltages and currents of the three phases at the 13.8 kV level were recorded, of which those of phase A are reproduced in figure 3. One may observe the breaker B1 and B2 openings at 3.93 s and 4.07 s respectively.

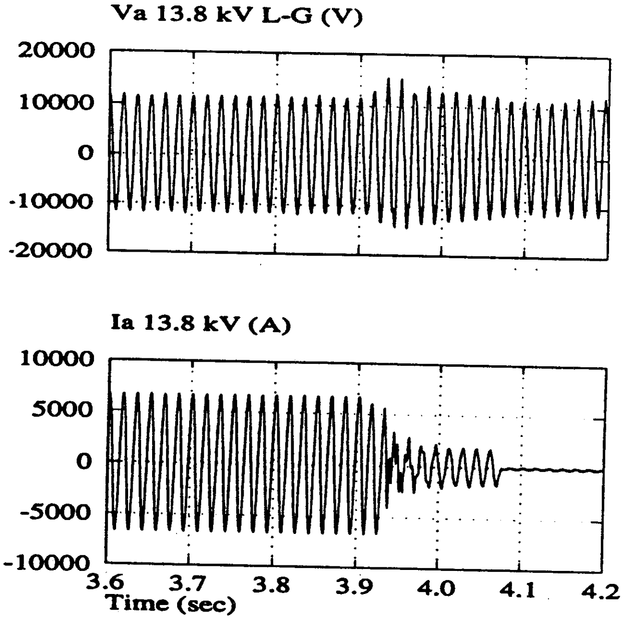


Figure 3: Terminal voltage and current, phase A

Other monitored variables included field voltage and field current of the machine. They are presented in figure 4, in which the voltage signal corresponds to the mean value of the saw tooth waveform as was registered during the field test.

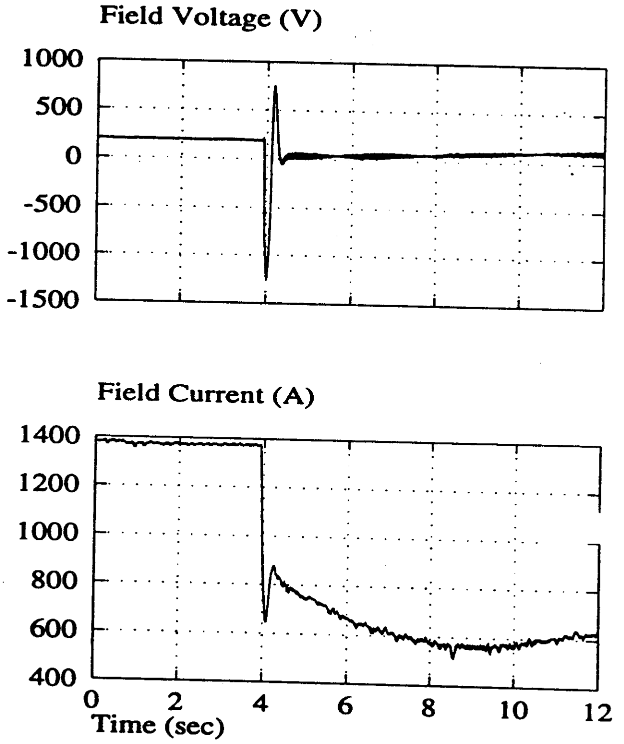


Figure 4: Field Voltage and Current

Three secondary variables computed from the recorded 13.8 kV voltages and currents complete the picture. The machine overspeed dynamics are captured in figure 5 which presents the computed frequency of the generator's output voltage; one may observe a peak value of 82.2 Hz. The two others are the generator's active and reactive output power, as presented in figure 6.

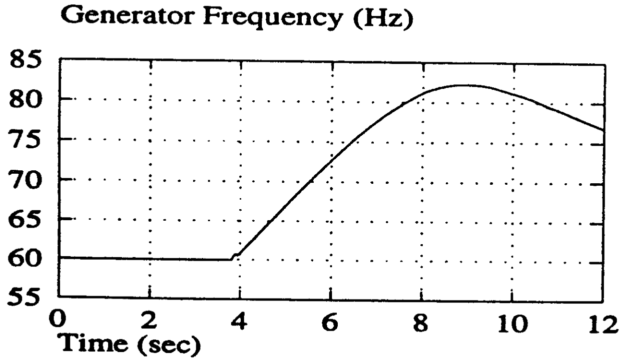


Figure 5: Generator frequency

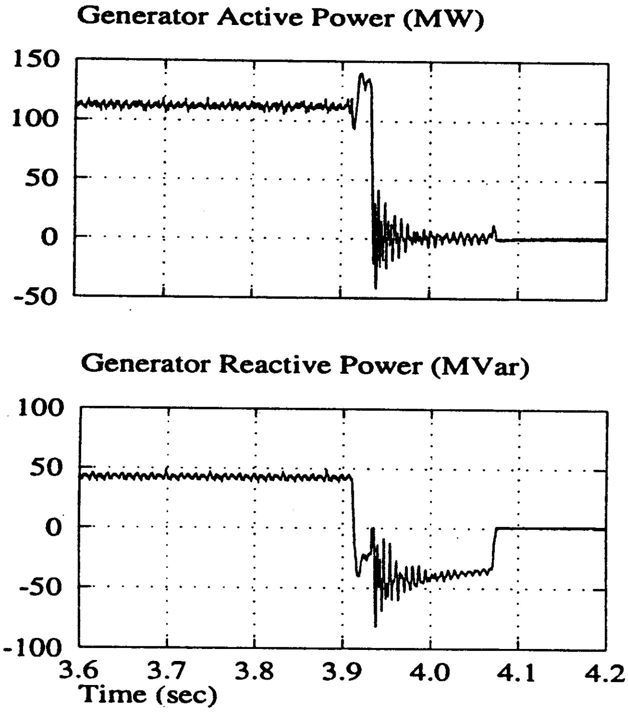


Figure 6: Active and reactive power output

MODELS AND DATA

The purpose of these simulations is to replicate the field test results and ensure that suitable models and accurate data were used.

Machine

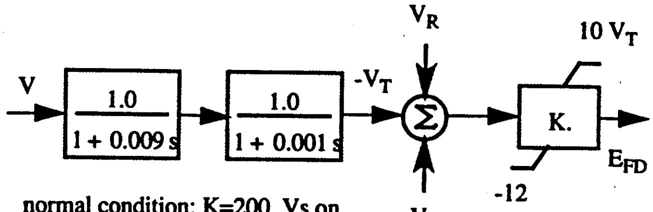
The characteristics of the machine under study are:

13.8 kV, 120 MVA, pf = .95, 85.7 RPM (84 poles)
H=4.29 (generator + turbine)
Ra = 0.004 pu
X''d = .290 pu, X'd = .400 pu, Xd = .900 pu
X''q = .268 pu, X'q = .400 pu, Xq = .670 pu
Xl = .190 pu, Xo = .135 pu
T''do = .036 s, T''qo = .102 s, T'do =5.41 s

Efforts to use the most appropriate data led to the following modifications: Xd was changed from .900 pu to .925 pu, the latter value was computed from acceptance test records and T'do was changed from 5.41s to 7.35s, computed from the field resistance as measured during the field test.

Furthermore, the saturation and short-circuit curves are obtained from records of acceptance tests..

Figure 7 presents the block diagram of the machine thyristor-controlled static excitor of which the stabilizer was disconnected, in accordance with testing conditions.



normal condition: K=200, Vs on
field test: K=33, Vs off

Figure 7: Excitation system

Speed governor and prime mover data

One of the main objectives of the planned detailed EMTP simulations was to study the effects of generator overspeeding on harmonic overvoltages. Although an accurate modeling of the prime mover and the speed governor was considered unnecessary for the short duration of interest following the islanding (1 sec.), detailed models were used so that the field test results could be replicated over their full duration.

Regarding the speed governor model (not shown), no special care has was taken to use very accurate data because, for the present case, a full load rejection, the governor output signal is limited by its lower bounds during most of the simulation time. On a previous load rejection test, these lower bounds were accurately determined as:

-13.9% per second for $.23 < g < 1.0$
- 2.8% per second for $0.0 < g < .23$

On the contrary, the prime mover, which is of the Kaplan type, needed to be accurately modeled with inputs from the flow rate and the water level. In order to represent the dynamics of the turbine over all loading conditions, a new model was developped. This model (figure 8) combined the features of hydraulic turbine models of two transient-stability programs: PSS/E [1] and ST600 [2].

Other equipments

All transformers are represented by an EMTP saturable transformer model.

Two line models were used: CP (Constant Parameters at a specific frequency) and FD (Frequency Dependent).

Finally, the 315 kV breakers are modeled as ideal switches, the one at Radisson being equipped with a 19 ms-insertion 1000 ohms opening resistor.

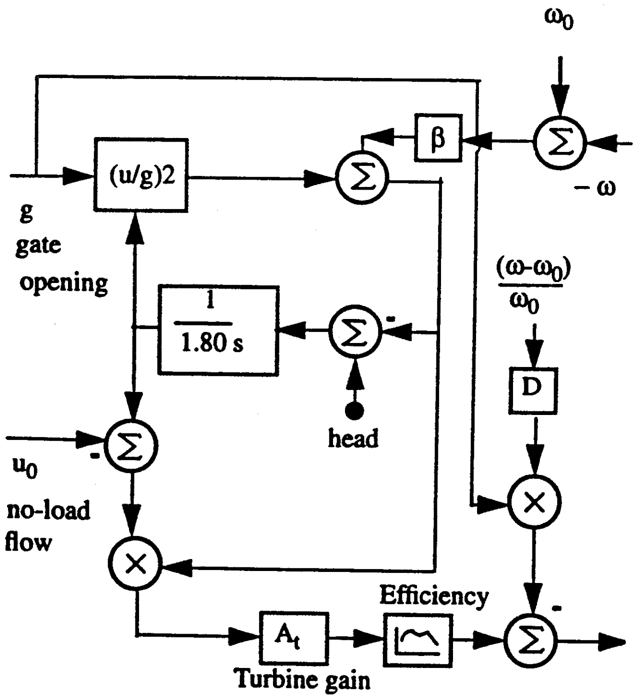


Figure 8: Block diagram of the prime mover

MATCHING THE SPEED CURVE

Initial data

This series of simulations using initially available data had been completed when a more accurate value for the inertia constant was obtained. Therefore, a second series of simulations was performed. Both set of results will be presented in order to highlight the influence of the inertia factor H on other mechanical parameters..

Based on an initial value of 4.29 for the inertia constant H, the purpose of this series of simulations is to find parameters which would permit a faithful replication of the overspeeding characteristics of the generator, as recorded during the described load-rejection field test. These parameters being the absolute-speed self-damping coefficient DSD of the turbine generator combination, the water pressure coefficient β and the damping coefficient D of the turbine.

It is worth mentioning that values for these parameters, even typical ones, are not readily available. Regarding β, no references has been found for Kaplan turbines. As for D, its value is either put within the range 1.0 pu to 3.0 pu in [3] or theoretically computed to be 1.0 pu at 100% opening and 0.35 pu at no-load operation [4].

The first simulation were made with DSD=2.0%, β=0.0 and D=0.0. The three parameters were then varied individually to observe their influences on the speed curve. In spite of the interdependency between the three parameters, one may observe thre following affinity relationships between them and the characteristics of the speed curve:

- DSD vs the descending slope
- β vs the peak value
- D vs the acceleration rate and the peak value.

Best results were obtained with DSD=1.8%, β=1.1 and D=.25. Attempts to find other suitable combinations failed.

Corrected data

For the first simulation, only H has been changed to the more accurate value of 4.11, all other parameters remain the same. Figure 9 compares the two speed curves (H=4.29 and H=4.11). It can be observed from the curves that while DSD is about right, there is need to find more appropriate values for β and D.

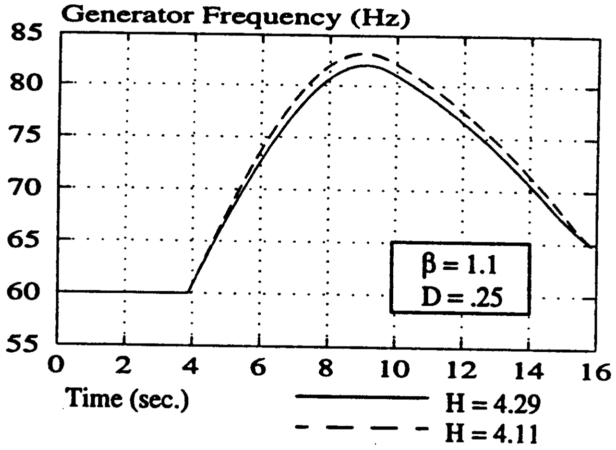


Figure 9: Influence of the inertia constant H

After many adjustments, it was found that best results were obtained with the combination DSD=1.8%, β=1.7 and D=.80. The corresponding speed curve is presented in Figure 10, against the one computed from field test recordings. One may note that the damping factor D, which get closer to its theoretical value, seems to endorse the fact that the new value of H is more accurate.

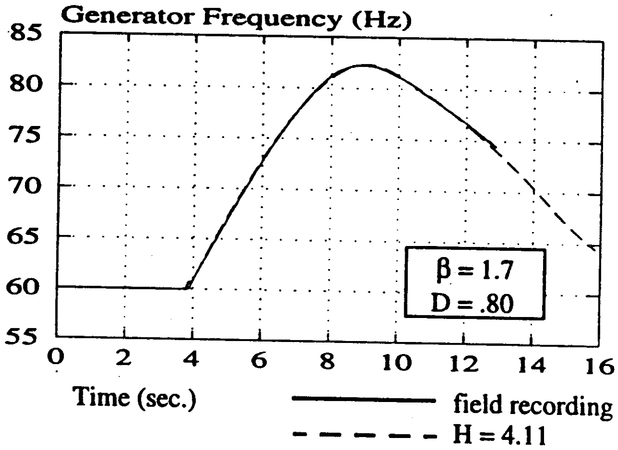


Figure 10: Final Speed curve vs recordings

MATCHING ELECTRICAL VARIABLES

Terminal voltages and currents

Since both simulated current and voltage showed less 4th harmonic damping than recorded signals, attempts were made to evaluate the series and shunt losses at 200 Hz.

At first, three line models were used: constant parameter at 60 Hz (CP60), constant parameters at 200 Hz(CP200) and frequency-dependent (FD). The current waveforms revealed that:

CP60: good agreement, less damping,

CP200: out-of-phase harmonics, high line charging, good damping,

FD: out-of-phase harmonics, less damping.

Based on these findings, it was decided to use CP60 model in which the resistive components are replaced with those at 200 Hz. Results with this hybrid model appeared to be best.

Next, the generator stator resistance was set to 4 times its value at 60 Hz in accordance with [5], and the transformer leakage resistance multiplied by 3.2 as suggested in [6]. Although the simulated currents with this set of data were quite satisfactory, the voltage waveforms showed much less damping than those recorded earlier. This shortcoming was corrected by gradually reducing the value of the shunt resistance representing the transformer core losses (Rmag). A very good agreement was found with Rmag set to 1/13 th of its value at 60 Hz. This choice seems logical since the Eddy losses in the core are a quadratic function of the frequency.

Field voltage and current

Simulations made with the updated data revealed that the simulated field current and voltage still differ significantly with field test recordings (figure 11).

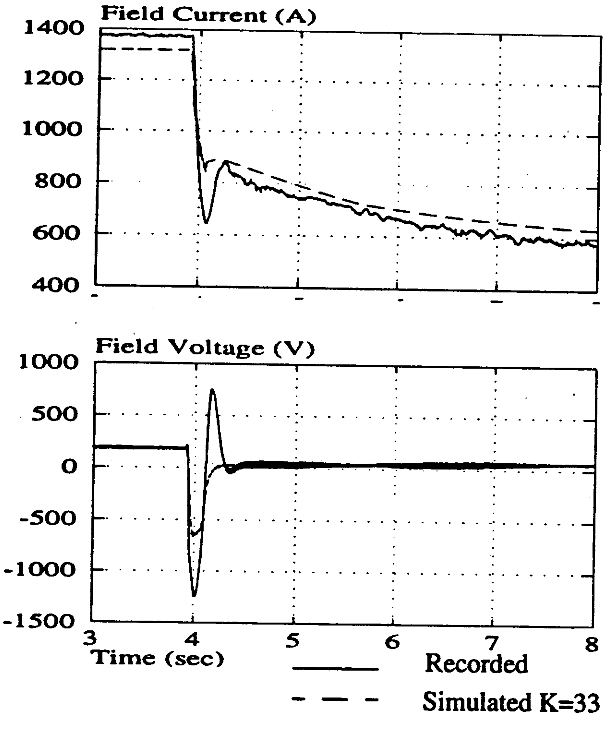


Figure 11: Field current and voltage for K=33

One may observe that:

- the steady-state value of the field current was reproduced with an error of less than 4%, which is quite satisfactory,
- the slower response of both simulated signals is an indication that the open loop gain (K=33) of the excitation system used is less than the real value during the field test.

Therefore, this open loop gain was gradually increased until a good match is attained (K=100). This may be explained by the malfunctioning of the thyristor firing control, which was reported later by the testing personnel. After this last parameter adjustment, a quasi-perfect match was obtained (figures 12 and 13).

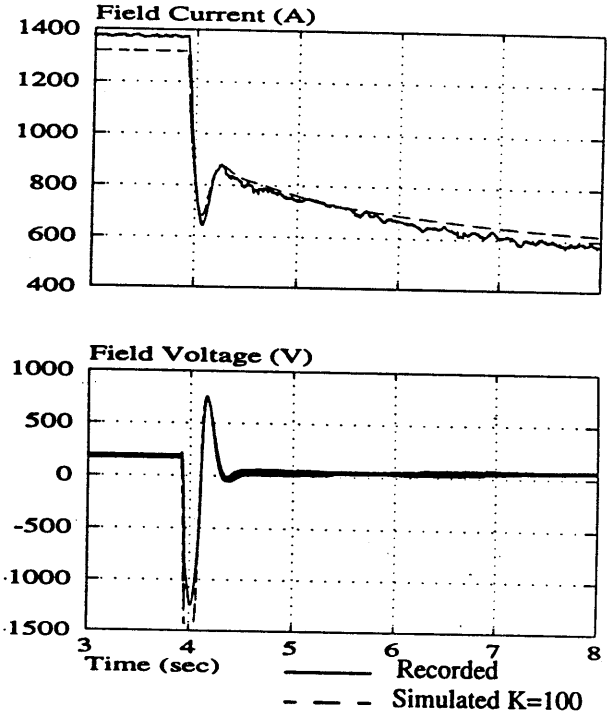


Figure 12: Field current and voltage for K=100

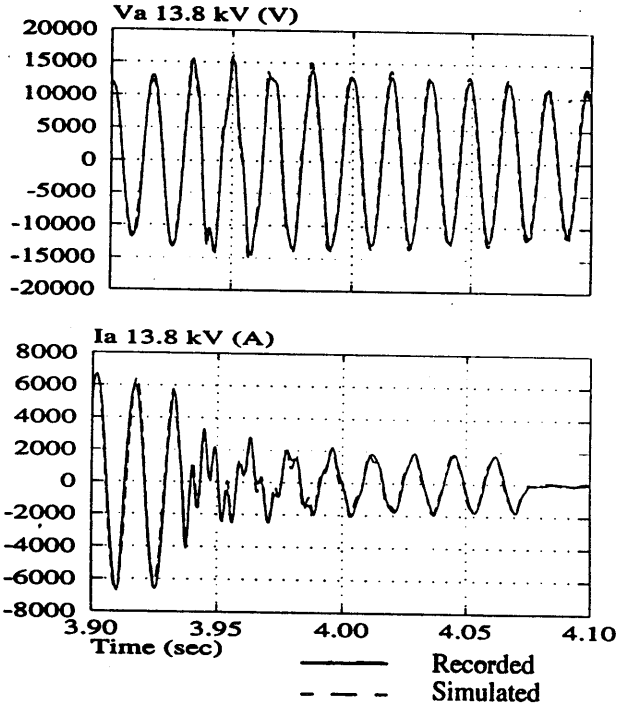


Figure 13: Terminal voltage and current, phase A

DETAILED STUDY RESULTS

The series of simulations done in the preliminary study was repeated with the validated turbine-generator model and data. As expected, some of the cases became much less severe than they were previously, thanks especially to the fact that high frequency losses are now accounted for. Surprisingly, however, some of the cases showed much severe behavior than before. For example, figure 14, which corresponds to a 3-machines / one-line configuration, shows overvoltage peaks of up to 1,85 pu while they were only around 1.45 pu from preliminary results.

Actually, the resonance frequency for this particular configuration is around 310 Hz, which corresponds to 5.16 times the synchronous frequency (60 Hz), slightly offset from the 5 th harmonic. Therefore, when the overspeeding is properly simulated, there exists a point (around 62 Hz) where the resonance becomes exactly tuned to the 5 th harmonic, amplifying the harmonic overvoltage phenomenon.

In general, if the resonance frequency is slightly lower than 120 Hz, 300 Hz or 420 Hz, the resonance is detuned further away by the generator overspeeding, yielding less severe overvoltages. Conversely, if the offset is positive, the overvoltages will be more severe.

Overall, the detailed study showed that many of configurations are still theoretically dangerous to be operated. Therefore, it was decided to install a fast acting protection device which monitors the status of the various breakers and switches at Radisson in order to trip the 315 kV transmission line should an islanding occur.

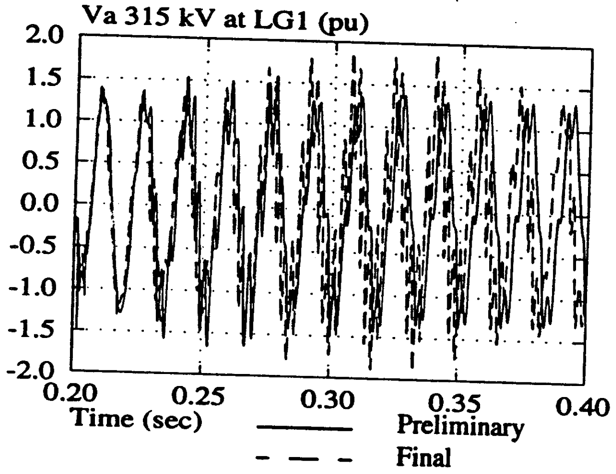


Figure 14: Harmonic overvoltage for 3 mach./one line configuration, phase A

CONCLUSION

The need for an in-depth investigation of islanding of the generating station LG1 led to an effort to replicate the results of a field test. Experience gained during detailed EMTP simulations provided many insights. It was founded that TACS feature in EMTP is a powerful means to produce transient-stability like excitation systems, governors and prime movers.

While matching the overspeed characteristics of the generator, it was found that:

- the proposed prime mover model is very appropriate to reproduce the field test overspeed recording over its entire time frame;
- provided that an accurate value of the inertia constant H is used, a full load rejection test is a valuable means to determine prime mover parameters such as the damping factor (D) and the water-pressure coefficient (β) which are very difficult to find otherwise.

Similarly, matching the electrical variables revealed that, in the range of 60 Hz to 420 Hz:

- lines are best represented by their CP60 model where the resistive components are replaced by those computed at the predominant harmonic frequency,
- high frequency losses of machine and transformers must be properly accounted for by multiplying their series resistances by a frequency-dependant factor,
- transformer Eddy current losses must be accounted for by decreasing its equivalent magnetizing resistance by a factor proportional to the square of the predominant harmonic frequency.

Moreover, simulations made with the more accurate model reported here showed that in similar cases, one must take into account the correct frequency dynamic of the generators. This may therefore confirm that the time frame use of EMTP may be extended to cover post-transient phenomena. Studies are currently being undertaken at Hydro-Quebec to the use of EMTP in some three-phase transient stability simulations for the entire network.

REFERENCES

[1] Power Technologies Inc., "PSS/E Program Application guide", Vol. 2, 1993.

[2] IREQ, "Programme de stabilité ST600, manuel d'utilisation", version 701, 1987.

[3] P. M. Anderson and A. A. Fouad, "Power System Control and Stability", Iowa State University Press, 1977.

[4] G. Anderson et al., "Influence of Hydro Units Generator to Turbine Inertia Ratio on Damping of Subsynchronous Oscillations", IEEE Trans., Vol. PAS-103, August 1984, pp 2352-2361.

[5] G. Croteau, "Mesure de l'impédance opérationelle d'un alternateur à la centrale LG-2", Hydro-Quebec internal report R-8571 (Région Maisonneuve), July 1985.

[6] IEC, "Determination of Power Losses in High Voltage Direct Current Converter Stations", New Work Proposal 22f (USA), 1994, p. 23.

ACKNOWLEDGEMENTS

The authors wish to thank M. Michel Granger, Dr Benoit Dubé and Dr Vijay Sood for their much appreciated contributions.