TRANSIENT STABILITY TRANSFER LIMIT ESTIMATION USING THE SIGNAL ENERGY OF DIFFERENT NETWORK QUANTITIES: A COMPARATIVE STUDY

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KEYWORDS

Security; transient stability; transfer limit estimation.

ABSTRACT

Transient stability transfer limit determination typically requires the execution of numerous step–by–step time domain simulations. Though signal energy limit estimation has been developed for the purpose of accelerating the limit search process, it remains to be seen whether the signal energy of the time–varying voltage magnitude waveform represents the best quantity for limit estimation. Certain other network quantities such as voltage phase angle, system frequency and generator reactive power output also contain valuable information regarding the state of the system. The present paper therefore compares numerous limit estimates based on the signal energy of each of these quantities for normal contingencies on the 1991 Hydro–Quebec system. It is found that signal energy limit estimation based on voltage magnitude is indeed superior to that of other electrical quantities. Moreover, it appears that voltage magnitude integrates more information regarding the state of the Hydro–Quebec system, and does so earlier, than any other network quantity.

1. INTRODUCTION

The dynamic security limit of a transmission corridor is the most constraining of individual transfer limits associated with different contingency locations along the corridor. For a given contingency and location, a transfer limit is the highest power transfer not resulting in loss of load and respecting acceptability criteria [1,2,3]. Because of the complexity of modern power systems, it may be necessary to determine transfer limits on the basis of both transient [4] and long–term [5,6] stability in order to determine the lowest value. However, the implementation of either criterion requires lengthy iterative processes employing large numbers of step–by–step simulations and highly elaborate systems models.

In order to improve the efficiency of such processes in the off–line operations planning environment, software frameworks were originally proposed for automating many of the high–level tasks traditionally performed by planners in security limit determination in [4]. More recently, others have described an on–line dynamic security analysis system, based on an ingenious combination of time–domain simulations and the calculation of the transient energy margin, permitting the estimation of limits and reducing the number of simulations required to perform the limit search (i.e. the "second kick" method) [7,8].

Signal energy limit estimation, developed independently of transient energy function methods, also have the potential to accelerate the transient stability limit search process [9,10]. In particular, it has been shown that the signal energy of a power system's transient voltage magnitude response increases smoothly and predictably towards an asymptotic stability limit. However, this asymptotic behaviour holds not only for the signal energy of voltage magnitude, but also for many other physical quantities such as voltage angle, system frequency and generator reactive power output. A fundamental question therefore arises: is voltage magnitude the physical quantity which gives the best limit estimates? The present paper attempts to answer this question by comparing signal energy limit estimates obtained from each of these quantities for normal contingencies applied at different locations on a validated model of the 1991 Hydro–Quebec system. It is shown that, on this system, signal energy limit estimation based on voltage magnitude is indeed superior to that of any other electrical quantity.

2. SIGNAL ENERGY LIMIT DETERMINATION

2.1 Normal Contingencies

Normal contingencies are considered probable scenarios of unexpected events and are usually defined as the loss of any major power system component (i.e. transmission line, transformer, etc.), either spontaneously or preceded by a fault: this is frequently known as the N–1 criterion [11]. The security limits which circumscribe a power system's operation are obtained on the basis of the system's response to normal contingencies, without loss of load [2,3,11]. Utilities occasionally extend the definition of normal contingencies to cover system–specific conditions which might include HVDC transmission or back–to–back interconnections [12]. However, as the 3–phase fault/N–1 criterion usually results in a system design "capable of coping with a ... wider range of adverse events" [13] and is used extensively in dynamic security analysis, this paper will consider a normal contingency as a 3–phase fault followed by the loss of an EHV transmission line.

2.2 Signal Energy Behaviour of Voltage Magnitude Near the Stability Limit

The signal energy of the transient response of a power system to a normal contingency is defined as follows [9,10]:

$$E_{ij}(P) = \int_{-\infty}^{\infty} r_{ij}(t, P)^2 \; dt \qquad (1)$$

where $r_{ij}(t, P)$ is the transient response of the system to a normal contingency applied at location i and monitored at location j. The term $r_{ij}(t, P)$ is formally defined as all variations of the p.u. time–dependent voltage magnitude $v_{ij}(t, P)$ with respect to the post–contingency p.u. steady–state voltage $V_{ij}(P)$ at monitoring location j:

$$r_{ij}(t, P) = v_{ij}(t, P) - V_{ij}(P) \qquad (2)$$

Fig. 1 illustrates a typical limit search for a 6–cycle, 3–phase fault with subsequent loss of line on the 1991 Hydro–Quebec system (see Appendix) as seen through the perspective of four different system quantities: a) voltage magnitude at Duvernay, b) voltage phase angle at LG2, c) frequency at Duvernay and d) reactive power output at LG2. Focusing for the moment on voltage magnitude, an increase in power transfer on the James Bay transmission corridor clearly impacts the swing of the transient voltage response, causing it to increase until the system becomes unstable. The signal energy of the transient response of the individual $v_{ij}(t, P)$ waveforms of Fig. 1 a), calculated using (1) and (2), is plotted in Fig. 2 a) along with results obtained for other contingency locations. In all cases, signal energy clearly rises asymptotically with increasing power P to a limit L_i. Modelling the transient response, near the limit, as a third–order system [10]:

$$\begin{aligned} r_{ij}(t, P) = \; & A_{1ij} \exp(-\sigma_{1ij} t) \sin(\omega_{1ij} t) + \\ & A_{2ij} \exp(-\sigma_{2ij} t) \end{aligned} \qquad (4)$$

and assuming a linear relationship between power transfer P and dominant pole damping, σ_{1ij} and σ_{2ij}, the following relation for signal energy is derived:

$$E_{ij}(P) \simeq \frac{C_{0ij}}{(L_i - P)} \qquad (5)$$

For a given topology, C_{0ij} depends on contingency type and location, in addition to monitoring location, whereas the asymptotic limit L_i depends only on contingency type and location. Though a real network may have hundreds of poles and zeroes, this relation is found to estimate transient stability transfer limits with surprising accuracy. For normal contingencies on the Hydro–Quebec network, it has been shown that approximately 1% error can be expected in limit estimates provided that [10]:

$$\frac{\Delta E_{ij}'(P')}{\Delta P'} > 500 \qquad (6)$$

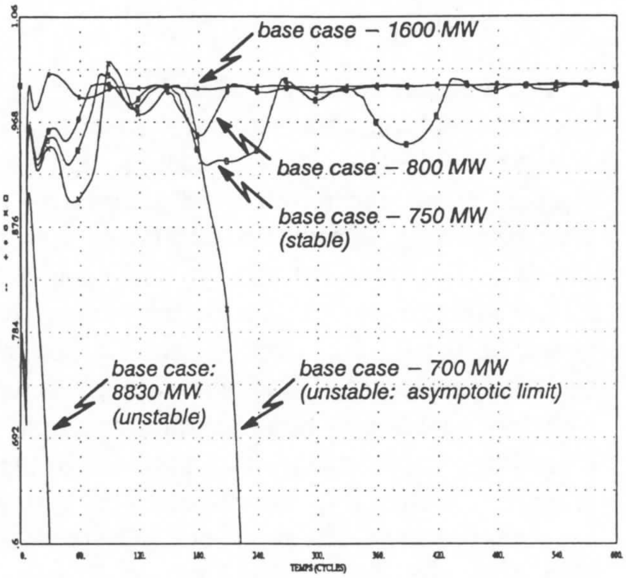

Fig. 1 a) Voltage magnitude at Duvernay

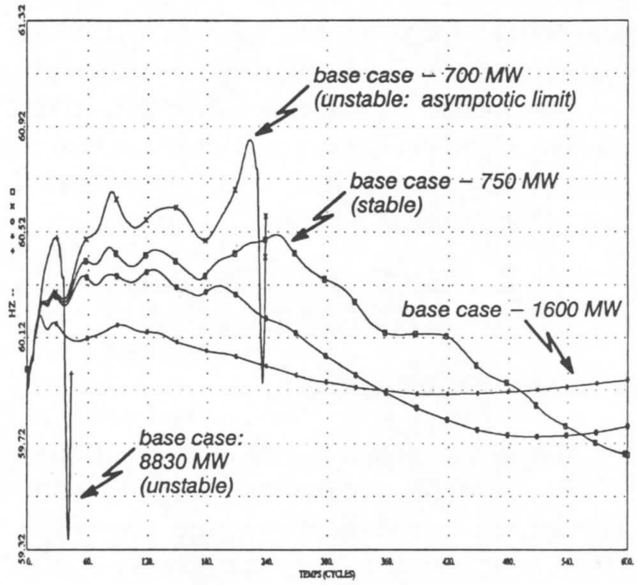

Fig. 1 b) System frequency at Duvernay

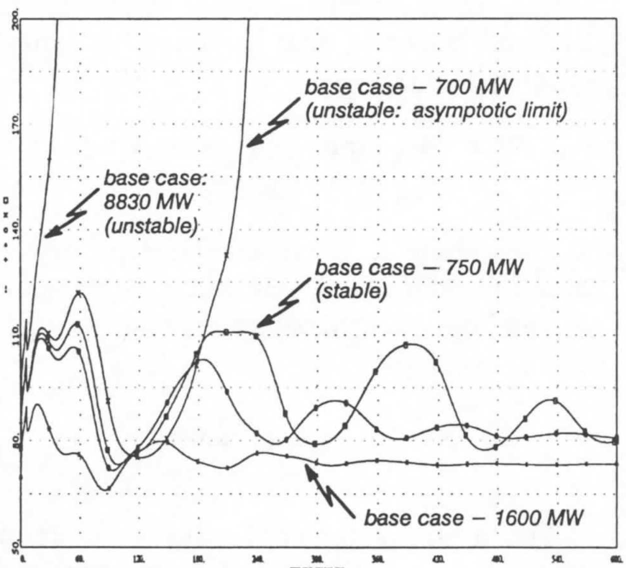

Fig. 1 c) Voltage phase angle at LG2

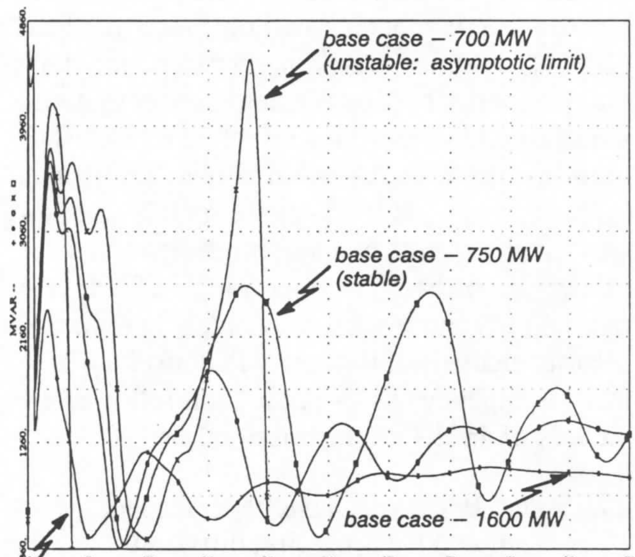

Fig. 1 d) Reactive power output at LG2

Fig. 1. Typical transient stability transfer limit search performed on the 1991 Hydro–Quebec power system for a 6–cycle 3–phase fault at LeMoyne with subsequent loss of line to Albanel: the asymptotic limit is found within 50 MW. The simulation time length is 600 cycles (10 seconds). This search is shown through the perspective of four different network quantities. The base case corresponds to a power transfer of 8830 MW flowing on the James Bay corridor. Note the effect of increasing pre–contingency power flow on the swing of each quantity. Note also that voltage magnitude reaches its post–contingency steady–state earlier than any other quantity.

where P' is the pre–contingency power transfer in the faulted corridor in p.u. of the asymptotic limit (i.e. $P' = P/L_i$) and E_{ij}' is the p.u. signal energy, obtained from rewriting (5) as follows:

$$E_{ij}(P') = \frac{C_{0ij}}{L_i} E_{ij}'(P') \quad (7)$$

where

$$E_{ij}'(P') = \frac{1}{(1 - P')} \quad (8)$$

2.3 Signal Energy Limit Estimation Based on Voltage Magnitude

Using the above model, a transfer limit estimate for a transmission corridor subjected to a normal contingency (i.e. within the same corridor) is obtained as follows:

a) two stable transient stability simulations are performed, each one corresponding to a different value of power transfer P. The time–varying voltage magnitude is obtained at an appropriate monitoring location within the same corridor, typically an EHV station near the contingency itself or near the corridor delivery point: this gives the two $v_{ij}(t, P)$ waveforms;
b) the post–contingency steady–state voltage $V_{ij}(P)$ of the monitoring location is then determined for each of the two values of power transfer. This is done either by means of a lengthy transient stability simulation, or through post–contingency power flow analysis;
c) the transient response of the system $r_{ij}(t, P)$ for each value of P is obtained using (2);
d) the signal energy $E_{ij}(P)$ of the transient response is obtained using (1) at each of the two values of power transfer P;
e) the two values of P and $E_{ij}(P)$ are substituted in relation (5), thus yielding a system of two equations and two unknowns, one of which is the asymptotic limit L_i.

2.4 Extending Signal Energy Limit Estimation to Other Network Quantities

As can be seen in Figs. 1 b), c) and d), the time–domain response of other electrical quantities such as voltage phase angle, electrical frequency and reactive power also increases in amplitude with increasing pre–contingency power flow. Let the transient response of the system for each quantity be defined as in (2) except that $v_{ij}(t, P)$ is now the time–dependent response of some arbitrary quantity and $V_{ij}(P)$ is the post–contingency steady–state value of this same quantity. If the signal energy of the transient response is determined for each of these quantities using (1), it can be observed, as plotted in Figs. 2 b), c) and d) for three different contingency locations, that the signal energy rises asymptotically to the limit. The above signal energy model, originally derived for the signal energy of voltage magnitude, is thus valid for other electrical quantities. The remainder of this paper therefore addresses the issue of comparing signal energy limit determination using each of these quantities, with particular emphasis given to the accuracy of each of the limit estimates.

3. RESULTS

3.1 Methodology

Tables I and II present a comparison of limit estimates made on the James Bay corridor of the 1991 Hydro–Quebec system. As can be seen, 8 different contingency locations are considered. The particular contingency applied at each location is a 6–cycle, 3–phase fault followed by the loss of a line south of the fault location (this coincides physically with the clearing of the fault). The limit estimates are made using the signal energy of the transient response expressed in terms of the different electrical quantities. Table I compiles data from 600–cycle simulations (i.e. a typical simulation time length performed by operations planners on the Hydro–Quebec system); Table II does the same for 1200–cycle simulations. The "true" limit is the asymptotic limit found within 25 MW: in comparison, acceptable transfer limits are found within 100 MW on the Hydro–Quebec system.

For each contingency location, a limit is estimated using each of the different quantities: these are of course taken from the same transient stability simulations, as in Fig. 1. The simulations used to perform these calculations are identified by means of their pre–contingency power flow in p.u. of the "true" limit. From this information, it can be seen that many combinations of

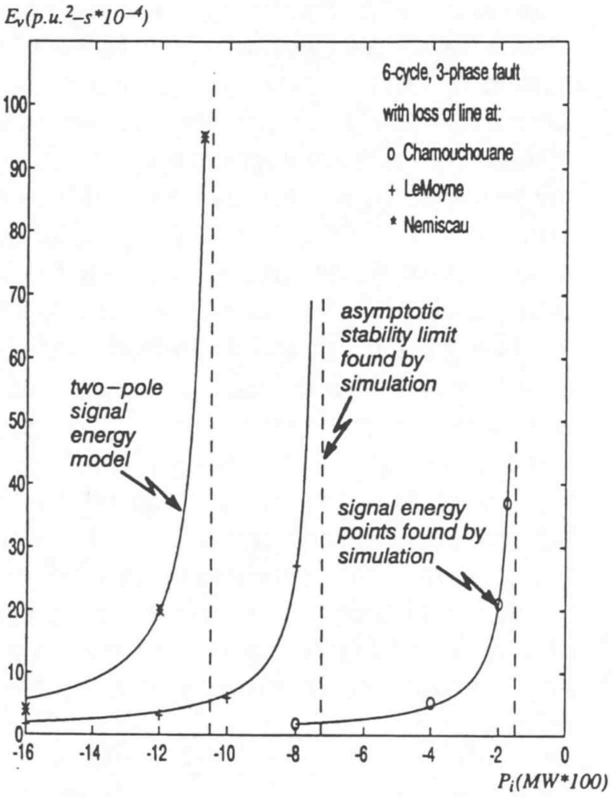

Fig. 2 a) Signal energy of transient response based on voltage magnitude at Duvernay

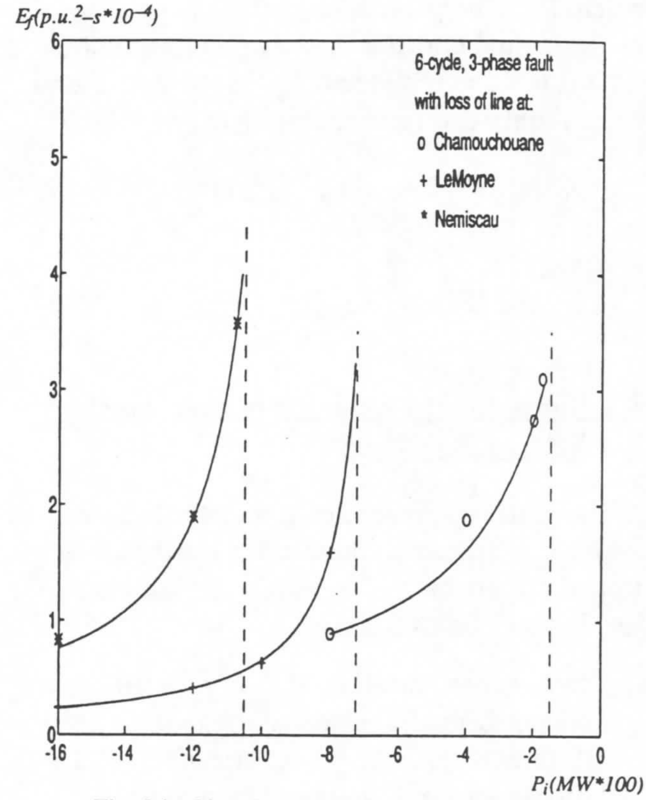

Fig. 2 b) Signal energy of transient response based on system frequency at Duvernay

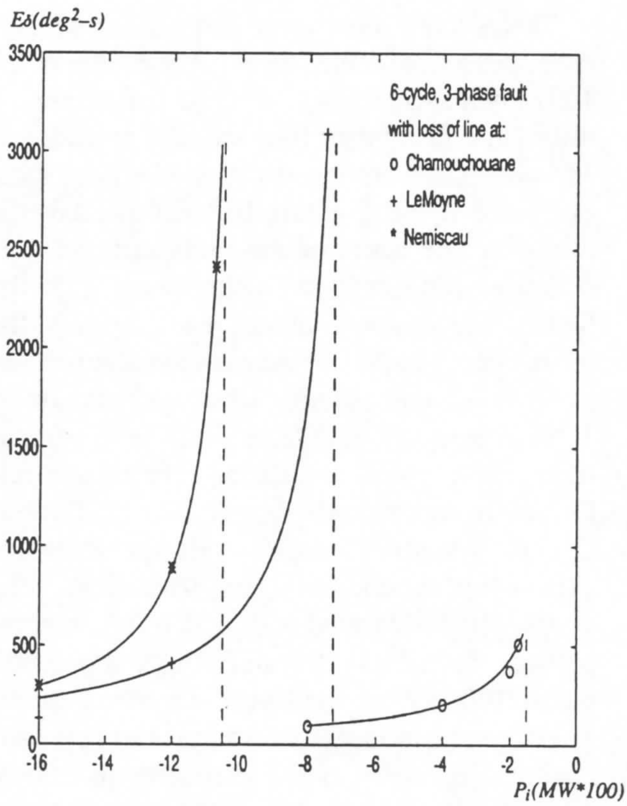

Fig. 2 c) Signal energy of transient response based on voltage phase angle at LG2

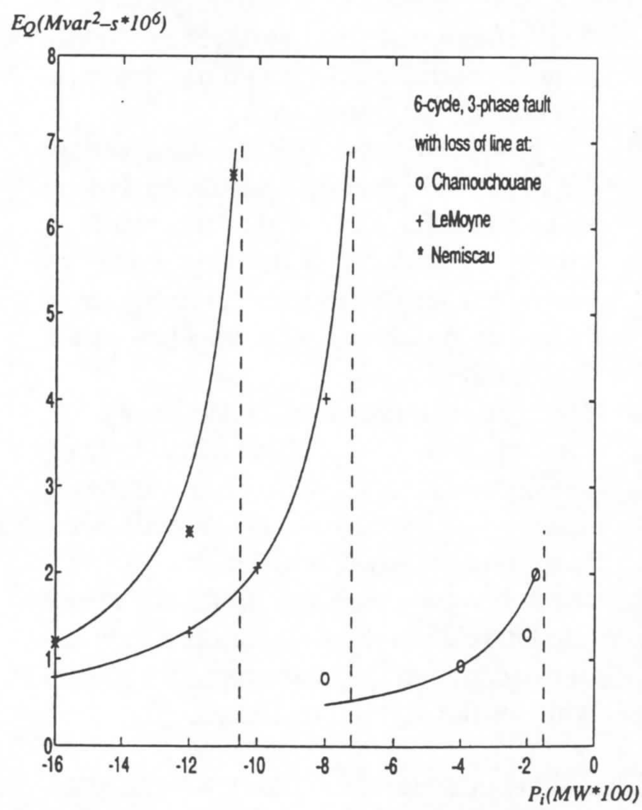

Fig. 2 d) Signal energy of transient response based on reactive power generated at LG2

Fig. 2. Signal energy behaviour of the transient response of different electrical quantities (600 cycle simulations). The zero on the power axis corresponds to a base case of 8830 MW flowing in the James Bay corridor. All quantities show an asymptotic approach to the limit. The curves are plotted using equation (5): the coefficients of (5) are obtained using the two points (simulations) identified on Table I.

points were used to estimate the limits, at various distances of the "true" limits.

The limit estimates based on the different quantities are identified as follows: voltage magnitude: L_V, frequency: L_f, phase angle: L_δ, and reactive power: L_Q. The error in % made with respect to the "true limit" in the case of each quantity is identified as ε_V, ε_f, ε_δ and ε_Q, respectively. The slope of the p.u. signal energy with respect to p.u. power is also shown for each pair of points in order to perform error correlation. Voltage magnitude and frequency are monitored at Duvernay 735 kV switching station, one of the delivery points of the James Bay transmission system, near the main load located at Montreal. Voltage phase angle and reactive power are monitored at LG2, the largest power plant on the system. These monitoring locations were selected after trials at a number of different locations in order to present the most favourable limit estimates for each quantity.

3.2 Discussion

Table I shows that, on average, signal energy limit estimation based on the transient response of voltage magnitude yields limit estimates with the lowest error (i.e. 0.55%). With an average error of 1.43%, voltage phase angle is its closest rival, followed by frequency (3.35%) and reactive power (4.72%). As seen in Table II, increasing the duration of the simulation by a factor of 2 does not change this trend, though the error is reduced in all of the estimates: reactive power is most favourably affected in this respect, the error being reduced by 32%, followed by voltage phase angle (20%), system frequency (15%) and voltage magnitude (11%). An interpretation of this result is that voltage magnitude integrates more information on the state of the system, and does so earlier, than any other system quantity. Fig. 1 clearly substantiates this claim as voltage magnitude does indeed reach its post–contingency steady–state value earlier than any other quantity. On the Hydro–Quebec system, this may be due to the action of numerous static VAR compensators which tend to control the voltage on the James Bay transmission system. However, this may also be true for many other systems, particularly where rapid generator excitation systems are widely employed. This point is worthy of further study.

As can also be seen in both Tables, there is a clear correlation between the slope of the p.u. signal energy with respect to p.u. power and the error in the estimate obtained from voltage magnitude (ε_V) and angle (ε_δ): the higher the value of this slope, the lower the error in these limit estimates. In the case of frequency and reactive power, another trend emerges: the error in the estimate increases as the contingency location moves south, away from LG2 (where reactive power is measured), towards the other end of the corridor (where frequency is measured). This appears to indicate that limit estimate accuracy based on either of the latter quantities is highly dependent on monitoring location.

As a final remark, limits were also estimated using the real power output of the LG2 power station (which is injected into the James Bay corridor). The error in these estimates was found to be so far in excess of that of all other quantities that these results are not presented here.

4. CONCLUSION

The present paper addresses a fundamental issue in signal energy transfer limit estimation: which physical quantity gives the best transfer limit estimates? Based on numerous limit estimates employing voltage magnitude, voltage phase angle, system frequency, and real and reactive power, voltage magnitude limit estimation is shown to be superior, on at least one power system, to all other electrical quantities. The limit estimate error, based on voltage magnitude is, on average, less than half that of its closest rival (i.e. voltage phase angle) and is not significantly affected by monitoring location. The corollary to this is that, for both of the quantities which are relatively insensitive to monitoring location (i.e. voltage magnitude and phase angle), the error in the estimate clearly correlates with the slope of the p.u. signal energy with respect to p.u. power: the higher the slope, the lower the error. As a final point, voltage magnitude appears to integrate more information on the state of the Hydro–Quebec system, and seems to do so earlier, than any other network quantity. Future work will attempt to explore the generality of this statement and also determine the minimum simulation time requi-

COMPARISON OF LIMIT ESTIMATES OBTAINED FROM DIFFERENT ELECTRICAL QUANTITIES

TABLE I

Simulation time length: 600 cycles

Contingency location	Points[2] (p.u.)		$\Delta E'/\Delta P'$	True[1] limit (L_t) (MW)	L_v[3]	L_δ	L_f	L_Q (MW)	ε_v[4]	ε_δ	ε_f	ε_Q (%)
LG2	.8602	.9792	344	8405	8360	8549	8404	8523	0.53	1.72	0.01	1.41
Le Moyne	.8920	.9661	273	8105	8030	7953	8199	8201	0.92	1.87	1.15	1.19
Némiscau	.9293	.9968	4420	7780	7778	7828	7914	7870	0.02	0.62	1.72	1.16
Albanel	.9293	.9807	733	7780	7724	7834	7948	8036	0.72	0.69	2.16	3.28
Abitibi	.9117	.9874	899	7930	7878	8020	8220	8737	0.65	1.14	3.66	10.17
Chibougamau	.9787	.9970	1565	8205	8219	8290	8434	8280	0.17	1.03	2.79	0.92
Chamouchouane	.9251	.9942	2302	8680	8688	8828	9169	9575	0.08	1.70	5.63	10.31
La Vérendrye	.9217	.9635	350	9580	9708	9842	10509	10473	1.35	2.73	9.69	9.32
Average error									0.55	1.43	3.35	4.72

TABLE II

Simulation time length: 1200 cycles

Contingency location	Points (p.u.)		$\Delta E'/\Delta P'$	True limit (L_t) (MW)	L_v	L_δ	L_f	L_Q (MW)	ε_v	ε_δ	ε_f	ε_Q (%)
LG2	.8602	.9792	344	8405	8360	8535	8396	8517	0.53	1.54	0.10	1.34
Le Moyne	.8920	.9661	273	8105	8040	8136	8180	8200	0.80	0.38	0.92	1.17
Némiscau	.9293	.9968	4420	7780	7779	7838	7868	7860	0.01	0.75	1.13	1.03
Albanel	.9293	.9807	733	7780	7730	7880	7921	8019	0.64	1.29	1.81	3.08
Abitibi	.9117	.9874	899	7930	7880	7985	8155	8163	0.62	0.69	2.83	2.93
Chibougamau	.9787	.9970	1565	8205	8220	8258	8337	8267	0.18	0.65	1.56	0.76
Chamouchouane	.9251	.9942	2302	8680	8693	8790	9108	9575	0.14	1.27	4.94	6.04
La Vérendrye	.9217	.9635	350	9580	9676	9835	10501	10465	1.00	2.66	9.61	9.24
Average error									0.49	1.15	2.86	3.19

1 *"True" limit obtained within 25 MW*
2 *Points used to estimate limits (in p.u. of true limit: P/L_t)*
3 *Limits estimated from the different quantities*
4 *Error relative to true limit*

red for acceptable limit estimation on this and other networks.

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APPENDIX

The transient stability simulations were made on a validated model of 1991 Hydro–Quebec system shown in Fig. 3 (700 buses including 55 generating stations, 1000 lines at voltages from 13.8 to 735 kV, active non–linear voltage–support elements such as SVCs, synchronous condensers, static excitation systems, power system stabilizers, etc.). The RP600 and ST600 power flow and transient/long–term stability software [14] are driven by the ELISA dynamic security analysis framework [4] to determine the "true" transfer limits.

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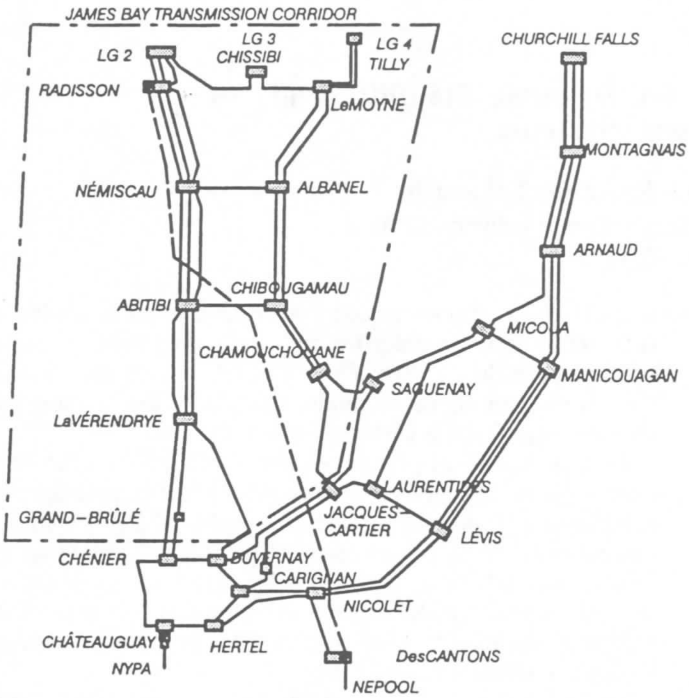

Fig. 3. Hydro–Québec's 735 kV transmission system.

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