High-Speed Power System Stability Simulation Using Analog Computation

Ira Nagel, Laurent Fabre, Rachid Cherkaoui, and Maher Kayal

***Abstract*—This paper presents a microelectronic emulation approach for high-speed power system computation. First, the problems of existing power system simulators are detailed. This shows that microelectronic emulation is a possible solution for solving the speed problems of existing simulators. Second, this paper presents one specific emulation approach, the so-called AC emulation approach. The ultimate objective of the AC emulation approach is the realization of a power system emulator which reproduces simultaneously a large number of phenomena of different time constants or frequencies with a much higher speed than real time. Frequency dependence of the elements is preserved and the signals propagating in the emulated network are the shrunk or downscaled current and voltage waves of the real power network. The models of the power network components are detailed. Special attention is paid to the generator model which was shown to introduce a systematic error. This systematic error is quantified, analyzed and optimized. Moreover behavioral simulation results confirm the feasibility of this approach which in turn lays the foundation for such an emulator.**

***Index Terms*—microelectronic emulation, high-speed simulation, power system transient stability, analog computation, ASIC**

I. Introduction

THE steadily increasing power consumption and the rising complexity of the power grid lead to a power system that is operating increasingly close to its operating limits. Of particular interests are stability concerns (transient stability, voltage stability and frequency stability) of the transmission power system; hence, stability of systems operating at very high voltage (i.e. 380kV and 220kV in Europe). In order to guarantee stability, security and reliability, it is of utmost importance to dispose of a high-speed power system simulator. High speed means that the simulator has to be able to reproduce different power system phenomena much faster than their real-time duration. With such a simulator the behavior of the power system can be anticipated and weak points can be identified. Finally, such simulators could be used directly connected to power system regulators as command units in order to dispose of a self-controlled power system which would consequently be much less susceptible to blackouts [1].

Fig. 1 illustrates the main challenge for power system simulators. They have to be able to simulate the behavior of thousands of loads and generators all interconnected to each other. Existing simulation methods are based on numerical algorithms, and are too slow for real-time applications. This is mainly due to the large number of interconnected nodes.

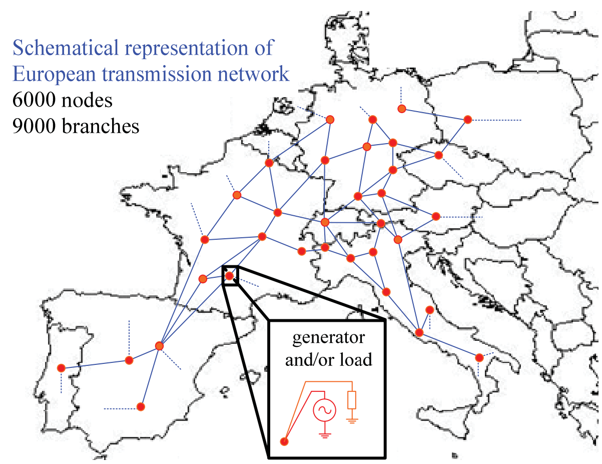

Fig. 1. Schematic representation of the European transmission network

Analyzing the problem of simulating the transmission power system reveals that there are essentially three components to model: generator, load and transmission line. In power system theory the generator is modeled using differential equations. Their number depends on the chosen model precision [2]. The transmission lines are connecting all loads and generators together. For the load, different models are known [2]. In a more abstract way, a power system simulator can therefore be seen as a solver of multiple sets of differential equations connected to each other. Hence, the reason why numerical simulators are not suited for real-time computation is that at each simulation step, the different differential equation solvers have to discern the results of the others. Thus, their simulation time depends on the number of nodes.

As the connection between all nodes is made by a grid of transmission lines respecting Kirchhoff laws, a more intuitive and much faster solution, than solving the Kirchhoff network equations by heavy numerical matrix algorithms, is to interconnect the multiple differential equation solvers by an emulated grid. This means that all of the computation blocks discern instantaneously the results of the others. This concept is shown in Fig. 2. Research is focused on two different

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All authors are with the Ecole Polytechnique Fédérale de Lausanne (EPFL), 1015 Lausanne, Switzerland (e-mail: ira.nagel@ epfl.ch).

approaches using emulation of the power system grid to accelerate simulation speed [3-9]. On the one hand, there is the so-called Phasor emulation approach [3-6] and on the other hand there is the AC emulation approach [6-9]. Phasor emulation consists in solving a mathematical representation of the real AC power system by analog computation. It provides the downscaled envelopes of the real power system signals. The power grid is implemented with analog components, whereas the generator and the load can be implemented using purely analog, mixed or purely numerical signals. In this context two prototypes have been realized that have proven the feasibility, the high-speed potential and the modularity of such emulation [4].

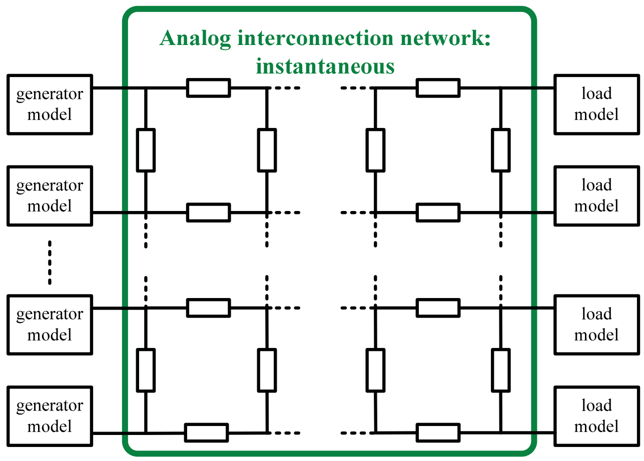

Fig. 2. Conceptional view of a power system with instantaneous interconnection between the generators and the loads by emulation of the power grid

Although considerable simulation time reduction compared to traditional numerical simulation is obtained, several limitations have been observed. The simplifications introduced during modeling, prevent the emulation of more than one phenomenon (first prototype). Moreover, mixed mode implementation can lead to unnecessary speed limitations, and frequency dependence of the elements is not taken into account [6].

Another important aspect is accuracy. With the two prototypes mentioned above it has been shown that using advanced circuit techniques for calibration a very good tradeoff between speed and precision can be reached [4].

Under these aspects another emulation approach has been investigated. Its modeling with systematic error analysis is presented in this paper. It aims to overcome the described limitations by one-to-one mapping of the elements of the real power network by emulating their behavior on a CMOS microelectronic ASIC. Corresponding to Fig. 2, this means that not only the power grid is emulated, but also the loads. Thus, frequency dependence of the elements is preserved and the signals propagating in the emulated network are the shrunk or downscaled current and voltage waves (AC signals) of the real power network. Therefore, this approach is referred to as AC emulation. Speed acceleration is obtained by frequency transposition. The emulated power system is working at a much higher frequency than the real power system (i.e. 50Hz in Europe), thus ensuring the emulated phenomena to be much faster than the real ones.

This paper is organized as follows. First we present the system architecture of the whole AC emulator based on the emulator principle presented in [6]. Moreover we explain its ultimate objective. In Section III the system level of each component, namely the load, the generator and the transmission line models are described. Then, in the following section the systematic error introduced by the generator model is analyzed and an optimized model is presented. Finally the theoretical statements as well as the validity of the presented models are confirmed by behavioral simulations.

II. System Architecture

Fig. 3 presents the system architecture of an emulator. It consists of an ASIC containing a matrix of reprogrammable atoms and an interface allowing a user to interact with it. A single atom includes an analog computed generator model, an emulated load and emulated transmission lines. Each one of these three components is designed with settable characteristics. Moreover, to guarantee reconfigurable interconnections, switch elements are added at every terminal of the components.

The switch elements at the terminals of the transmission lines link together the adjacent atoms. Through the user interface, any topology of the power system and the characteristics of its elements can be set. Moreover the scenario to be emulated can be chosen and the results can be observed and analyzed.

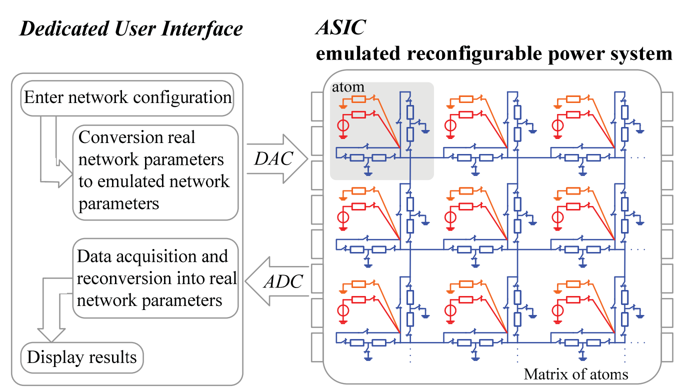

Fig. 3. System architecture of the whole emulator

The ultimate scope is that one emulator is able to reproduce different phenomena (i.e. transients, slow voltage drops and frequency changes). Or, another possible solution is to realize three different emulators for each phenomenon and to execute them in parallel. The latter has the disadvantage that it does not detect stability problems occurring by the overlapping of different phenomena.

III. Atom Architecture

Fig. 4 shows the system level of the emulated components of one atom.

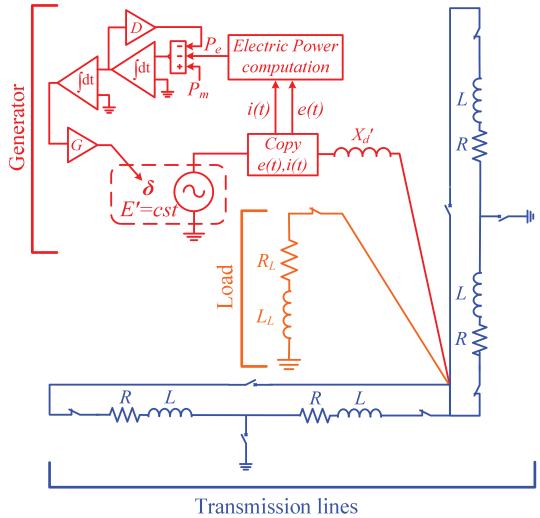

Fig. 4. System level of a single atom

As already mentioned in the previous section it contains the following three elements:

- Transmission lines (in blue):
  The behavior of the transmission line is modeled using resistive and inductive elements. This corresponds to the π-equivalent model neglecting the capacitors. In order to be able to emulate short circuits, the transmission line is split into two parts and a switch element is connected between the two parts and ground. Thus, considering that the values L and R are adjustable, short circuits at any distances of a node are possible.
- Load (in orange):
  The load has to be able to emulate active and reactive power variations. Thus, the load is modeled by means of a programmable RL-impedance. To change the amount of active and reactive power characterizing the load, the elements have to be reprogrammable in this case as well.
- Generator (in red):
  We have chosen the classical model for the generator [2]. This model allows studying the transient stability of a power system through the observation of the power angles δ_i of each generator G_i of the system. The information about stability of the system is then included in the first oscillation after default. In this classical model, the generator is represented as a voltage source ($E'_i\angle\delta_i$) with a constant magnitude E' behind a reactance X'_d. The behavior of the power angle δ is represented by a second order differential equation, called a swing equation, describing the rotor dynamics in the transient state:

$$M\frac{d^2\delta}{dt^2} = P_m - P_e(\delta). \tag{1}$$

M is the inertia factor, P_m is the mechanical power, and P_e the electric power provided to the power grid [7]. The inputs of the differential equation are the mechanical and the electric power. Contrary to the mechanical power which is constant and known, the electric power has to be computed using the information measured on the emulated grid, namely the transient current and voltage. In Fig. 4 this supplementary step is illustrated with the "electric Power computation" block. As this block does not reflect any reality, it introduces a systematic error. Section V is dedicated to the analysis of this error.

IV. First Realization

The first ASIC is under development in a CMOS 0.35µm technology and contains a simple power system topology based on the models presented in the previous section. Depending on the number and the type of phenomena one wants to reproduce with the AC emulator, the generator model to be implemented has to be carefully selected. This is the limiting point of our first ASIC. The other network components (loads and transmission lines) are one-to-one mapped from the real power network onto the emulator, thus adding no further restrictions as to the number and type of phenomena that can be observed. Despite being restricted, the generator model presented in the previous section allows the validation of our approach while serving as a starting point for further improvements of the model. The period of validity of the results is restricted to the first oscillations after the default and is therefore not increased compared to the one of the Phasor prototype. This is due to the fact that the amplitude E' is also kept constant during the dynamic simulation. Consequently, our first AC emulation ASIC only retains the advantages of the frequency transposition over its Phasor counterpart, resulting in faster simulation time.

V. Systematic Error Analysis

A. Original model

Equation (1) shows that the input of the feedback loop of the generator model is the electric power, i.e. the active power at the terminal of the generator. Because the signals propagating in the emulated grid of the AC emulation approach are the shrunken and downscaled current and voltage waves (AC signals) of the real power network, we have direct access only to the instantaneous current ($I\angle\varphi$) and voltage ($E'\angle\delta$) sine wave at the terminal of the generator. Hence, only the instantaneous power $p(t)$ is available quasi instantaneously by multiplying the current and the voltage sine wave. The relation between $p(t)$ and P_e is shown here below:

$$P_e = \frac{1}{T}\int_{t-T}^{t} p(t)\,dt, \tag{2}$$

with T, the period of the current and voltage sine wave, respectively. Out of this reasoning the first intuitive model of the generator was developed. Its system level is depicted in Fig. 5. Note that the signal at the input of the sine wave generating unit is not $\delta(t)$ but $\Delta\omega$ because this unit will be implemented using a VCO and the link between the angle $\delta(t)$ and the angular frequency $\omega_{osc}(t)$ of the VCO output signal is defined as follows:

$$\omega_{osc}(t) = \omega_o t + \underbrace{\int_0^t \omega(t)\,dt}_{=\delta(t)}, \tag{3}$$

Thus, the passage from $\Delta\omega$ to $\delta(t)$ is not necessary in the feedback loop as this operation is intrinsic to the sine wave generating unit.

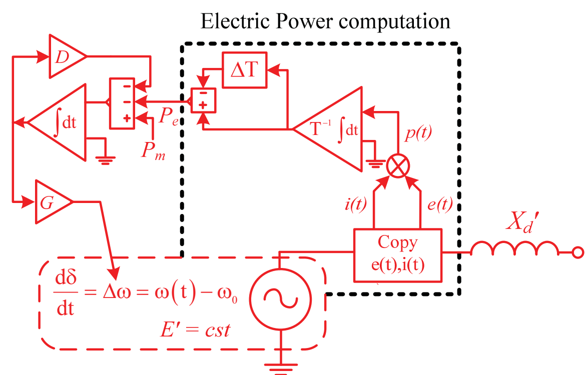

Fig. 5. System level of the generator model as introduced in [7]. G is a gain containing M and the shrink and downscaling factors.

The analytical analysis of this model shows that instead of solving (1), the following equation is solved by the emulated generator.

$$M\frac{\mathrm{d}^2\delta}{\mathrm{d}t^2} = P_m - \underbrace{\frac{1}{T}\int_{t-T}^{t} p(t)\,dt}_{=P_e} - P_D(\dot{\delta}). \tag{4}$$

Two supplementary elements appear. The factor P_D represents the damping power. It is proportional to $\Delta\omega$ according to the following equation:

$$P_D = D\frac{\mathrm{d}\delta}{\mathrm{d}t} = D\Delta\omega, \tag{5}$$

D is called damping coefficient.

The term P_D has been added to damp the oscillations for finding as fast as possible the steady state of the system after initialization of all parameters. During the emulation of a given scenario D is ideally set to zero, thereby not influencing the emulation result.

The supplementary integration needed to extract P_e introduces most notably a delay of at least one period in the feedback loop. The corresponding part is highlighted in Fig. 5. This delay does not reflect reality and consequently has to be considered as a systematic error.

In order to quantify this error, an open-loop characterization of both swing equation computation models, the ideal and the emulated one (both depicted in Fig. 6), was performed. In this process, the non linear sine wave generating unit was omitted as it is the same in the two loops. Moreover, for simplifying analytical calculations, the output was quantified in the Laplace domain and only the final result was then retranslated back to time domain.

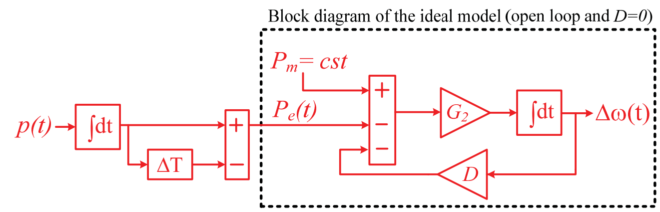

Fig. 6. System level of ideal and emulated swing equation computation

The output function of the ideal model $(D=0)$ is as follows:

$$\Delta\omega(t) = G\int_0^t \left(P_m - P_e(t)\right) dt. \tag{6}$$

Thus, ideally, the temporal weighting is uniform. In the emulated model, again with $D=0$, the present has no influence on the result. The weighting is linearly increasing towards the past (cp. (7)).

$$\Delta\omega(t) = G\int_0^t \Big(P_m - \big(p(t-\tau) - p(t-\tau-T)\big)\tau\Big)\,d\tau \tag{7}$$

And finally the output function of the emulated model when the damping is added $(D\neq 0)$ is:

$$\Delta\omega(t) = P_m\frac{1-e^{-DGt}}{D} - \int_0^t \left(\big(p(t-\tau) - p(t-\tau-T)\big)\frac{1-e^{-DGt}}{D}\right) d\tau \tag{8}$$

The weighting also increases towards the past, but as opposed to the previous case, it tends towards a constant value. Fig. 7 illustrates these behaviors.

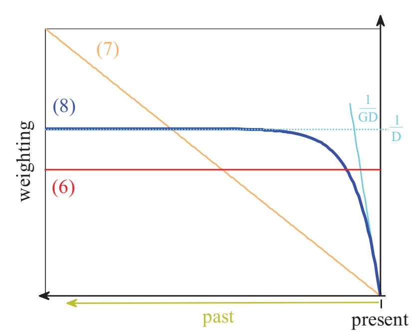

Fig. 7. Weighting as calculated in (6), (7) and (8) respectively

This analytical analysis emphasizes that: keeping a damping factor after the default considerably reduces the systematic error introduced by the electric power computation block. An optimal value (i.e. where the systematic error is minimal) for D exists. Nevertheless, with these formulas only an approximate optimal numerical value is obtained, because in reality all generators are interconnected, thus sharing their errors mutually.

B. Optimized model

The optimized model is shown in Fig. 8.

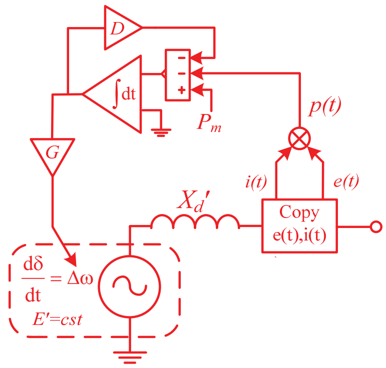

Fig. 8. System level of the optimized generator model

The difference to the original model is that the supplementary integration is omitted. Consequently the equation that is solved by the emulated generator is

$$M\frac{d^2\delta}{dt^2} = P_m - p(t) - P_D(\dot{\delta}), \quad (9)$$

with all the parameters as defined before. Supposing $P_D = 0$, and $p(t) = u(t)\, i(t)$ then the equation becomes

$$M\frac{d\omega(t)}{dt} = P_m - \underbrace{E'I\cos(\delta-\varphi)}_{=P_e} \underbrace{-E'I\cos(2\omega\cdot t+\delta+\varphi)}_{\text{systematic error } e}. \quad (10)$$

Obviously, a systematic error exists here as well. In order to be coherent, we also express the influence of this error on the output function $\Delta\omega$ (as done before for the original model). In this scope, we integrate the systematic error e found in (10), obtaining:

$$e_{\Delta\omega} = GE'I\frac{1}{2\omega}\left(\underbrace{\sin(\delta+\varphi)}_{\text{constant}} - \underbrace{\sin(2\omega\cdot t+\delta+\varphi)}_{\text{oscillating}}\right). \quad (11)$$

Both, the amplitude of the oscillating part of the error as well as the frequency-independent part of the error are negligible compared to the useful signal $\Delta\omega$.

- The error amplitude is $1/(2\omega)$ smaller than the amplitude.
- As the power system guarantees that $\delta+\varphi$ is small,

$$\sin(\delta+\varphi) \approx \delta+\varphi. \quad (12)$$

Thus the frequency-independent part results in a very small fraction of $G\,E'\,I\,1/(2\omega)$.

C. Discussion

The above analysis shows that the optimized model has the following advantages over the original intuitive model.

- No additional blocks not corresponding to a physical reality are added.
- The damping power is not used to qualitatively minimize the systematic error due to the added blocks. Results become more reliable.
- The solution is certainly stable on the system level. Indeed, as there is only one single integrator, the maximum phase shift at unity gain is $-\pi/2$. In the case of the original solution a design effort is needed to guarantee stability.

The systematic error of the optimized model is quantified and is small compared to the useful signal $\Delta\omega$.

VI. Behavioral Simulation

A. Description of the simulation method

Behavioral simulations are performed in the Cadence IC – Virtuoso environment. The used simulator is Spectre. This allows simulating power system topologies with the electronic models of the transmission lines and the load (as shown in Fig. 4) in combination with a purely behavioral generator model. The obtained results are compared to the results of a numerical simulator implemented in LabView. The numerical reference simulator has been validated using Eurostag.

B. Results

Three different types of results are presented in the following, all of them use the reference topology (1 slack generator, 2 generators, 1 load) depicted in Fig. 9. The characteristics of the components of the reference topology are listed in Table I. Most of the values are expressed in per unit [p.u.]. The per-unit system is the expression of the system quantities in fractions of a defined base unit quantity. Hence, in order to downscale the different characteristics on the microelectronic emulation, downscaling the base unit quantities is sufficient. Table II shows these downscaling factors between real and emulated world. Thereby it can be seen that the emulated frequency is transposed to 500kHz. Therefore the emulation is 10'000 times faster than real time.

The reference scenario selected for the comparison is as follows. 2.505 seconds after setting off the emulator, a short circuit is applied on the middle of the line between generator G_2 and the load L. A certain time t_{sc} later, the whole line is disconnected. Note that the times are given for the real world. In the emulated world they have to be divided by the time scaling factor (i.e. 10'000).

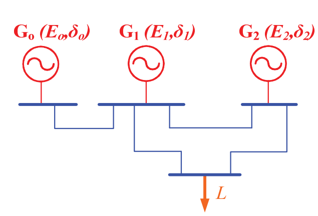

Fig. 9. Reference topology

TABLE I. CHARACTERISTICS OF THE REFERENCE TOPOLOGY

	Parameter	***Value***	***Unit***
Generator 1 G_1	Active power	0.7	[p.u.]
	Reactive power	0.25	[p.u.]
	Inertia	4.2	[s]
	Internal impedance	0.35	[p.u.]
Generator 2 G_2	Active power	1.1	[p.u.]
	Reactive power	0.4	[p.u.]
	Inertia	2.1	[s]
	Internal impedance	0.3	[p.u.]
Load	Active power	1.85	[p.u.]
	Reactive power	0.4	[p.u.]
Line G_B-G_1 200km	Line reactance	0.1	[p.u.]
	Line resistance	0.004	[p.u.]
Line G_1-G_2 370km	Line reactance	0.18	[p.u.]
	Line resistance	0.0077	[p.u.]
Line L-G_1 400km	Line reactance	0.2	[p.u.]
	Line resistance	0.0083	[p.u.]
Line L-G_2 200km	Line reactance	0.1	[p.u.]
	Line resistance	0.004	[p.u.]

TABLE II. DOWNSCALING FACTORS

	[p.u.]	***real world***	***emulated world***
U	1	380kV	50mV
I	1	263A	1.25µA
S	1	100MAV	62.5nAV
Z	1	1'444Ω	40kΩ
f	---	50Hz	500kHz

In order to force a fast convergence of the system to the steady-state values of δ_1 and δ_2, the damping factor D is set at a high value at the beginning of the emulation. Then, at the moment of the short circuit, its value is set to 0 or is considerably reduced (depending on the generator model used).

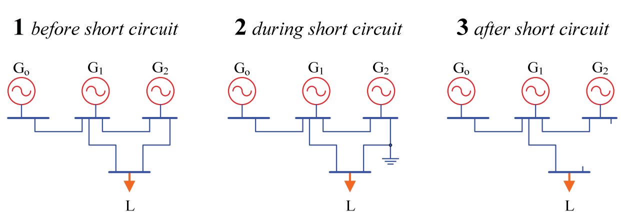

Fig. 10. Applied scenario

1) *First comparison: emulator vs. simulator*

Fig. 11 shows the comparisons of the behavioral emulation (top) with the results of the numerical simulator (bottom) while applying a short circuit t_{sc} of 70ms and using the original generator model with a damping coefficient D of 0.018. Considering the time axis of the two curves, the time scaling becomes visible. As predicted, as the emulator is working at 500kHz, its phenomenon is 10'000 times faster than the duration of the real time phenomenon shown by the numerical simulator.

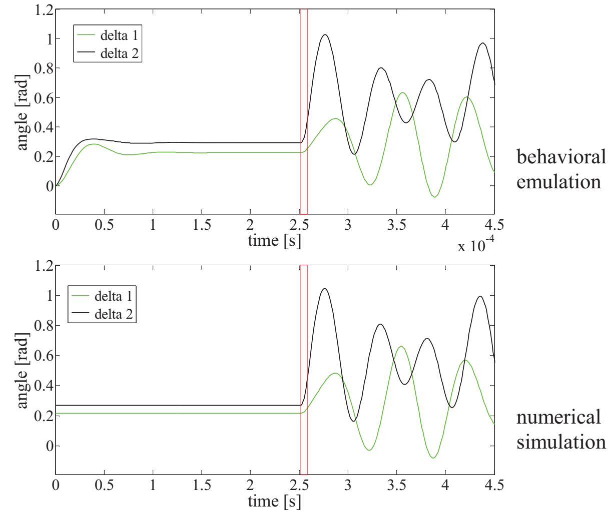

Fig. 11. Comparison between the results of the behavioral emulation (top) and the numerical simulator (bottom); t_{sc} = 70ms at 2.505s

2) *Second comparison: generator model*

Fig. 12 depicts the behavior of the electrical angles just before and after the default of 70ms for the different generator models. Table III shows the absolute error of the emulations compared to the reference simulator. Note that for these comparisons all the results are converted into real world values. Hence the speed enhancement of the emulator is not visible in the result comparison.

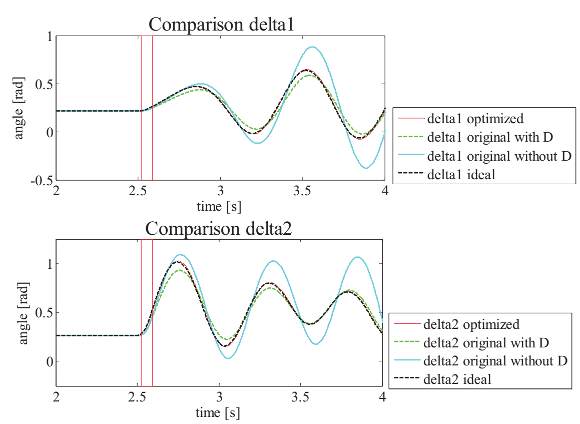

Fig. 12. Comparison of different generator model emulations; t_{sc} = 70ms at 2.505s

TABLE III. ABSOLUTE ERROR WITHIN 1S AFTER DEFAULT

Emulator		***D*** [-]	Δ_{min} [°]	Δ_{max} [°]
Behavioral emulator, optimized	δ_1	0	-0.49	0.75
	δ_2	0	-1.18	0.95
Behavioral emulator, original	δ_1	0	-3.96	4.93
	δ_2	0	-4.68	6.30
Behavioral emulator, original	δ_1	0.018	-10.00	8.35
	δ_2	0.018	-14.30	9.18

3) *Third comparison: critical short-circuit time t_{crit}*

The main function of a transient stability power system simulator is to determine the critical short-circuit time t_{crit}. It is defined as the longest possible short circuit on a transmission line before the power system loses its stability. The critical short-circuit time of the line between G_2 and L is compared in Table IV for the different generator models. Fig. 13 illustrates the behavior of the electrical angle when stability is lost.

TABLE IV. CRITICAL SHORT-CIRCUIT TIME t_{crit} COMPARISON

Simulator / Emulator	***D* [-]**	**t_{crit} [ms]**	**Δ [ms]**
Numerical reference simulator	0	181	---
Behavioral emulator, optimized	0	184	+3
Behavioral emulator, original	0	183.5	+2.5
	0.018	193	+12

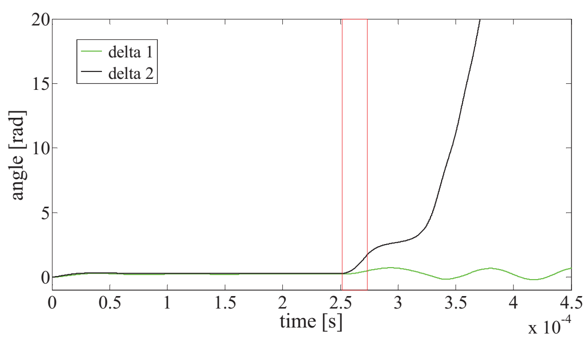

Fig. 13. Behavioral emulation results for t_{sc} =196ms where generator G_2 desynchronizes and the original generator model has been used.

C. *Discussion*

As the validity of the chosen generator model is restricted and the information about stability is contained in the first oscillation, the functionality of this approach has been proven. Moreover also the time scaling has been emphasized.

The second series of results confirm what is described in Section V; the systematic error of the original model can be considerably reduced by maintaining damping during and after the short circuit (cp. Table III). On the other hand maintaining this damping factor leads to an overestimation of the critical short-circuit time which is better estimated with no damping. Be aware that this result has to be regarded with suspicion, because of the simplicity of the reference topology. Indeed, for more complex topologies, the large error on the behavior of the electrical angles could influence much more t_{crit}. However, the results for the optimized model are very accurate, thus confirming its validity and the negligible character of its systematic error.

VII. CONCLUSION

This paper introduces the difficulties related to power system simulators. Our analysis shows that microelectronic emulation is a possible solution for the speed problems of existing simulators, using emulation of the power grid to build an instantaneous connection between multiple differential equation solving blocks, each one using the results of the others.

Moreover, AC emulation is presented in detail. Aiming to overcome limitations shown by emulation approaches developed earlier, frequency dependence of the elements is preserved and the signals propagating in the emulated network are the downscaled current and voltage sine waves of the real power network transposed to a higher operating frequency. Our ultimate objective is to create a power system emulator which simultaneously reproduces a multitude of phenomena of different time constants at a much higher speed than the corresponding real-time phenomena, using purely analog implementation.

For a first realization AC models of power system's components limited to transient stability are developed. The operating frequency of the emulator has been set to 500kHz. Hence the first realization will be 10'000 times faster than real time. Moreover the systematic error of the original generator emulation model has been analyzed and an optimized solution has been worked out. Therein, the swing equation is solved using the instantaneous power instead of the active power. It has been shown in this paper that the systematic error introduced by directly using the instantaneous power is quasi negligible and particularly better quantifiable and smaller than the systematic error of the original model. Moreover, as its topology is less complex, containing only one integrator, stability is intrinsic.

Finally, the model is fully analyzed and waits to be confirmed by a microelectronic ASIC realized in a CMOS 0.35µm technology.

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Ira Nagel received her B.S. and M.S. degrees in electrical engineering from the Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland in 2005 and 2007 respectively. She is currently working towards the Ph.D. degree at the same institute. Her research interests include analog and mixed-signal microelectronic emulation for high-speed power system simulation.

Laurent Fabre received the B.S. degree in Microengineering from the school of Business and engineering Vaud, Switzerland, in 2000. He worked for three years as an R&D engineer in blood separation tools for Biofluid Systems (Nyon, Switzerland). He received the B.S. and M.S. degrees in electrical engineering from the Ecole Polytechnique Fédérale de Lausanne, Switzerland in 2005 and 2007 respectively. He is currently working towards the Ph.D. degree at the same institute. His research is related to high-speed mixed-signal power system emulation.

Rachid Cherkaoui (M'05-SM'07) received both the M.Sc. and Ph.D. degrees in electrical engineering in 1983 and 1992, respectively, from the Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland. Since 1992, he is senior scientist at EPFL. His research and teaching interests are in electricity market deregulation, in distributed generation and storage and in power system vulnerability.

Maher Kayal received the M.S. and Ph.D. degrees in electrical engineering from the Ecole Polytechnique Fédérale de Lausanne (EPFL, Switzerland) in 1983 and 1989 respectively. He has been with the Electronics laboratories of the Ecole Polytechnique Fédérale de Lausanne (EPFL, Switzerland) since 1990, where he is currently a professor and vice dean for education of the school of engineering. He has published many scientific papers, is coauthor of three text books dedicated to mixed-mode CMOS design and he holds seven patents. His technical contributions have been in the area of analog and Mixed-signal circuits design including highly linear and tunable sensor microsystems, signal processing and CAD tools for analog design and layout automation. M. Kayal is a recipient of the Swiss Ascom award in 1990 for the best work in telecommunication fields; He is author and co-author of the following paper award in: ED&TC conference in 1997, IEEE-AQTR in 2006, Mixdes conference in 2007 & 2009, Powertech conference in 2009. M. Kayal received in 2009 the Swiss credit award for best teaching.