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Recent Developments in ANATEM - A Comprehensive Program for the Analysis of Electromechanical Stability of Large Power Systems

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Summary

This paper describes some recent developments made in the ANATEM program, a comprehensive software for the analysis of electromechanical stability of large power systems. These developments improved the efficiency and flexibility of this software for the planning and operation studies of the Brazilian system, which presents many challenges due to its large size and complexity. Several modeling and methodological issues are discussed.

Keywords: transient stability - controller modeling - FACTS - switching logic controls - network solution methods - postprocessing

1. Introduction

The ANATEM program had, since its early days, an ample range of machine models and associated controllers (voltage regulators, governors and power system stabilizers models) [1]. As new kinds of equipment were installed and more stringent study requirements appeared, new models and features had to be provided.

The first major addition was a detailed model for the Itaipu HVDC link that delivers a huge amount of power (6300 MW) to the load center of the Brazilian southeast. Models for SVC equipment currently in operation, of different levels of complexity, were implemented next.

The recent interconnection of Brazilian's south-southeast and north-northwest systems posed new stability problems which had to be adequately coped with. The solution adopted was to interconnect the two systems with a 1000 km long, 500 kV compact transmission line having two TCSCs (one at each end of

the line). These TCSCs were needed to damp the low frequency oscillation (about 0.2 Hz) that emerged with this interconnection. Detailed TCSC models were then implemented in order to carry out the dynamic studies needed.

A couple of serious voltage stability problems that occurred in the São Paulo area in April 1997 also pointed out to the need to model phenomena in the mid-term range. Models for on-load tap-changers were then added as part of this effort.

Finally, the March 11th 1999 blackout in the Brazilian's south-southeast caused a highly intensive use of ANATEM in a comprehensive study aiming at the improvement of the system's overall reliability. The existing system protection and under-frequency load-shedding schemes were verified and system reinforcements and new emergency control schemes recommended. This required the implementation of new models for relays and automatic switching logic controls.

Initially, all equipment and controller models in the program were built-in. The constant need to update the existing models and create new ones made it essential to add a feature of user-defined control (UDC) modeling. The UDC models are built by the interconnection of elementary blocks. A large set of these basic blocks was then created so as to allow the detailed representation of all existing controllers in the Brazilian electric system.

Recent efforts have been focused on the modeling of new FACTS devices, in improving the speed and numerical performance of the program and in developing postprocessing tools to enhance the productivity of engineering studies.

2. Control Systems' Modeling

The ANATEM program can model the following equipment:

- 1) Synchronous machines, including their control system (voltage regulators, governors and stabilizers)
- 2) Induction motors
- 3) HVDC links and converters
- 4) On-load tap changers (OLTC)
- 5) FACTS devices
- 6) Static and dynamic loads
- 7) Relays

Built-in models were developed for the representation of all the above equipment and associated controllers. A built-in controller model is more computationally efficient but has the handicap of low flexibility and fixed structure. So built-in models were restricted to a few standard controllers. The remaining controllers are modeled using the UDC feature. Figure 1 gives an example of a simple UDC model developed for the static excitation system of the Itumbiara power plant, which incorporates a line-drop compensation block.

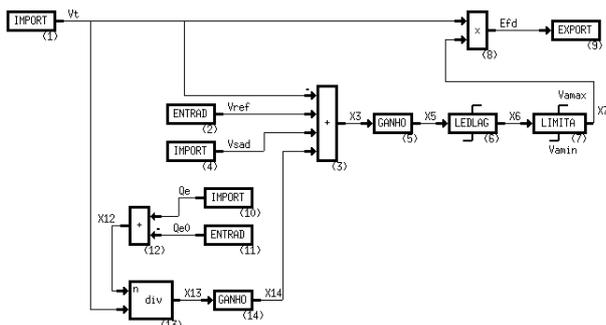


Figure 1 -Itumbiara UDC static exciter model

Recent developments made possible to represent all the above mentioned elements (with the exception of synchronous and induction machines) by UDC. It was not judged necessary to have UDC machine models since the several built-in models available fulfill all the requirements for a detailed electromechanical stability simulation [2].

Since modeling of HVDC links has to be done in great detail (including CCA, VDCOL, VCO, CEC, etc) [2,3] and each HVDC plant has specific control features, the flexibility provided by UDC is highly useful. HVDC modeling by UDC also allows for the representation of industrial rectifiers. An example is the modeling of the ALUMAR Aluminum reduction plant which is an important load of the north-northwest Brazilian subsystem (about 680 MW).

Modeling of capacitor commutated converters (CCC) [4] was necessary for the stability studies involving the Garabi back-to-back DC station which will interconnect Argentina and Brazil and is expected to start commercial operation in March 2000.

Although load modeling can have a large impact on stability results [2], this has usually been done in a simplified way due to the difficulty to obtain or adjust parameters of more complex models. However, dynamic models which take into account load variation as a function of voltage and frequency have been proposed [2]. The dynamic load representation provided by the UDC feature in ANATEM can be used to investigate the adequacy of these models in specific studies.

A variety of elementary blocks (presently 67 different types), including arithmetic blocks, rational polynomial blocks (n(s)/d(s)), limiters, comparators, logic operators, selector blocks, timers, etc., provide large UDC modeling flexibility.

The system initialization is done in a completely automatic way, no matter the topological complexity of the various UDCs. The process starts from the known values of interface (input/output) variables. The algorithm proceeds by sequentially initializing block by block using the values of variables previously determined. When inputting the model data, instructions can also be added to initialize a variable with a numerical value or with the value of another variable that will be calculated during the solution process.

3. Modeling relays and special protection schemes

Proper relay modeling is essential to realistic simulation. They must monitor system variables (voltages, power flow, currents, frequency, etc) and trigger equipment, simulating the actions of protection schemes.

The relay models presently available in ANATEM are:

- 1) underfrequency relay for load-shedding
- 2) undervoltage relay for load-shedding
- 3) overcurrent relay for line tripping
- 4) impedance relay for line tripping
- 5) overvoltage relay for line tripping
- 6) overvoltage and undervoltage relays for shunt reactor/capacitor switching
- 7) out-of-step relay for detection of loss of synchronism between systems

The relay model 5 and 7 were recently developed for use in the March 11th blackout studies. Figure 2 exemplifies the operation logic of type 7 relay, used to sever the North-South interconnection under detection of out-of-step conditions. Operation occurs when the line impedance seen from one of its terminals enters consecutively the two rectangles in a time interval (t2-t1 in Figure 2) compatible with the chosen relay settings. The studies of the March 11th blackout determined the need for new system protection schemes to improve system reliability. These schemes will automatically switch several elements of the system. Therefore the UDC ANATEM feature is being

enhanced to allow for the simulation of these automatic switching logic controls.

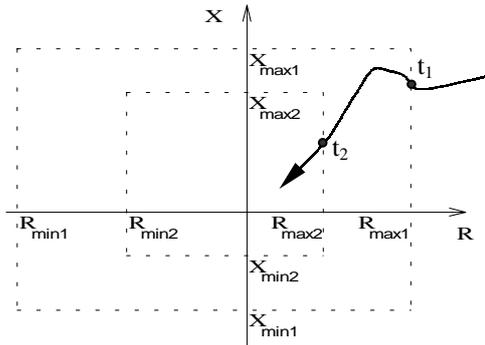


Figure 2 - Out of step relay diagram

Each element to be switched will be associated with a breaker, that can be triggered by single or multiple schemes. The breakers will receive a positive pulse to open and a negative pulse to close: some types of breakers (circuit, load and reactive shunt breakers) may be used to simulate time delayed reclosures. The breaker switching delay (one-cycle, for example) is modeled independently from the control logic.

In the case of multiple controls acting on a single breaker the program performs a check to avoid opposite commands. If this situation occurs simulation should be interrupted with a warning since either the model or the protection philosophy is incorrect.

Breaker status (open/close) should only be altered at the beginning of each time step, to avoid convergence problems in the iterative solution method. It is also important that the switching controls have a feedback of the operation state of system elements, so this kind of information should be made available to the UDC model.

4. FACTS devices and HVDC systems

The current version of the ANATEM program can model the following power electronic equipment:

- 1) HVDC links [2,3], including CCC [4,5]
- 2) Static Var compensators (SVC): thyristor controlled reactor (TCR) and thyristor switched capacitor (TSC) [2]
- 3) Thyristor controlled series capacitor (TCSC) and thyristor switched series capacitor (TSSC) [6]

These models are being used in the stability studies of the Brazilian system, which contains: a conventional HVDC link in operation (Itaipu), an HVDC/CCC link (Garabi) to begin operation in early 2000 (Figure 3), six SVCs and two TCSCs.

Models for voltage source inverters (VSI), which use GTO components, are being developed so that STATCON (static condensers) [7], CSC-GTO (series compensator with GTO converters) and UPFC (unified

power flow controller) [8] could be represented. These new devices, due to their flexibility, can improve system performance, when properly controlled.

The VSI devices consist of a set of GTO components linked to a fixed capacitor bank. The GTO firing control performs the switching of the capacitor bank among the phases of the ac bus producing the desired power control. According to the VSI device the control action may be done through reactive power changes (STATCON and CSC-GTO), or active power changes (static phase shifter, voltage source HDVC link) or both (UPFC). Another possibility is to use GTOs for active filtering.

Figure 4 shows the basic configuration of the elementary 6 pulse VSI. Several 6 pulse VSI can be connected by special transformers so as to obtain higher pulse VSI units. Figure 5 present the one-line diagrams for the STATCON, CSC-GTO and UPFC devices.

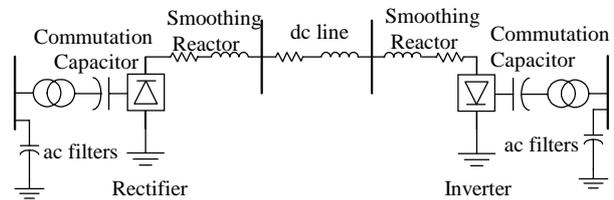


Figure 3 - HVDC/CCC Link

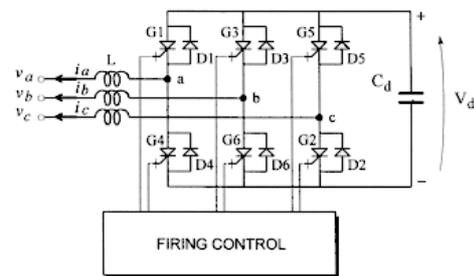


Figure 4 - Basic 6 pulse GTO VSI

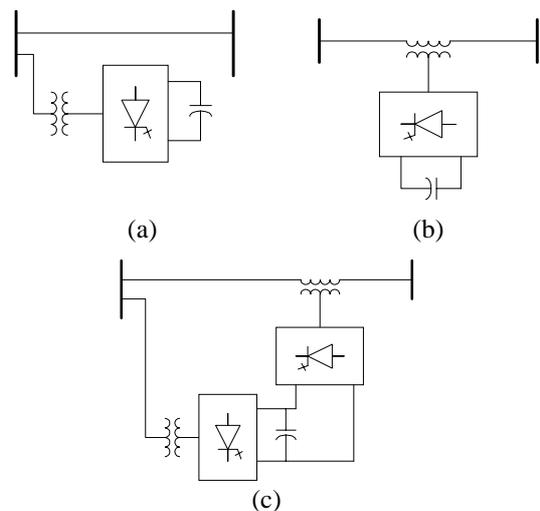


Figure 5 - One-line diagrams of STATCON (a), GTO-CSC (b) and UPFC (c)

5. Solution Methods

The ANATEM program currently uses the implicit alternate solution scheme. The integration method chosen is the implicit trapezoidal rule, which is numerical stable and does not introduce spurious damping in the solution [9], properties ideally suited to transient stability simulation programs. The ac network calculation is performed by the sparsity-oriented solutions of nodal admittance matrix problem, where the contributions of non-linear and of dynamic elements are modeled by injected currents to the ac buses (external injection method). The nodal admittance matrix which represents the network is kept constant between topological changes. Refactorization is only needed at these instants.

The implicit alternate solution scheme yields good results, although it is known to be less robust than the implicit simultaneous scheme[10]. However, the latter scheme needs greater computational effort, since it is based on the Newton method solution of the nonlinear system equations. This method requires frequent calculations and factorizations of a large scale Jacobian matrix. The use of the implicit simultaneous scheme together with automatic variable step integration methods [11] may be attractive, but this has not yet been investigated in this project.

As an initial step to the simultaneous solution scheme implementation in ANATEM, an ac network solution by the Newton method was added. In this case a Jacobian matrix, representing the network and also the contributions of all the current injections of the non-linear and dynamic elements, is built and refactorized at each iteration of each time step of the solution.

The following solution variants were tested for the network Newton method:

- 1) "Full" Newton - Jacobian matrix built and factorized at all iterations of each time step.
- 2) "Dishonest" Newton - Jacobian matrix built and factorized only in the first iteration of each time step.
- 3) "Very Dishonest" Newton - Jacobian matrix built and factorized only in the first iteration of the time step and kept constant during several subsequent time steps.

It should be noted that the Jacobian matrix does not need to be totally rebuilt. Only the elements affected by the external current injections may be updated. However, the entire matrix factorization is needed.

A simulation of a disturbance in the Brazilian system was used to test these three options. The system model has 128 generators, 128 automatic voltage regulators, 105 governors, 49 power system stabilizers, 2465 buses, 3489 ac circuits, 1139 nonlinear loads. The disturbance was a short-circuit at one end of the Cachoeira Paulista-Adrianópolis transmission line (Southeast of Brazil), with subsequent line tripping after 80 ms. SVCs, HVDC

links and TCSCs were not represented to make simpler the comparative analysis.

Table 1 compares the performances of the two methods with respect to average number of network iterations per time step and total CPU time.

Table 1 - Comparison of network solution methods

Method	Average Number of Iterations	Time (s)
External Injections	8.35	231
Full Newton	3.01	510
Dishonest Newton	3.02	353
Very Dishonest Newton (after 10 steps)*	3.02	282
Very Dishonest Newton (after 100 steps)*	3.02	274
Very Dishonest Newton (after 500 steps)*	3.06	271

*The numbers inside parentheses indicate the frequency of updating and factorization of the Jacobian matrix.

In the Very Dishonest Newton method it was necessary to switch to the Dishonest Newton method during the first 200 ms after the disturbance, otherwise convergence could not be achieved.

The Full Newton method required the least number of iterations, although it consumed the largest computation time. The Dishonest and Very Dishonest Newton methods required a little more iterations but the reduction in CPU time was significant. The external injection method was the most efficient regarding CPU time. Its higher number of iterations may be an indication of lack of robustness, although convergence problems were not found in the tests.

Figure 6 shows the first 800 ms of the Cachoeira Paulista bus voltage which varies from 1.067 pu to 0.663 pu at the fault inception.

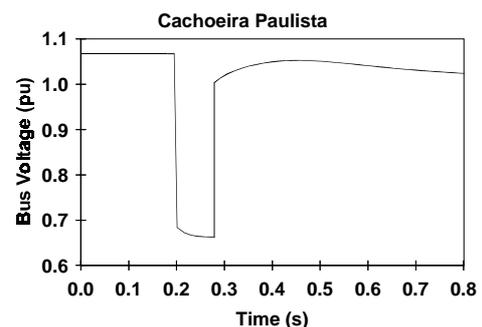


Figure 6 - Cachoeira Paulista bus voltage

Table 2 presents the number of iterations required for the network solution at $t=0.20s$ (fault inception) and $t=0.28s$ (fault clearance) by each method.

The Full Newton method presented the best performance but some convergence problems may occasionally occur at instants of the simulation where the initial values are very far from the solution (mainly

post-contingency instants). The external injection method must then be used in the first three iterations to overcome this difficulty. Following this initialization procedure for the case shown in Table 2, the number of iterations in the Full Newton method came down to 4 for $t=0.20s$ and $t=0.28s$.

Table 2 - Comparison of methods at discontinuities

Method	Number of Iterations	
	$t=0.20s$	$t=0.28s$
External Injections	25	26
Full Newton	6	5
Dishonest Newton	9	18

6. Postprocessing and visualization of results

Large scale systems studies generally involve simulation of hundreds of cases and monitoring of a large number of variables. This requires postprocessing and visualization tools that enable easy manipulation of the results in the form of graphics and tables, and easy generation of reports. A graphic analysis tool is therefore being developed in the Microsoft Windows environment, which will enable integration with the majority of editing and graphic manipulation programs available for this platform.

The visualization tool will be able to combine results from different simulation cases, each containing numerous variables. Figure 7 shows the selection window for cases and variables to be used when producing graphical results. The box on the right shows a tree representing the results chosen to be graphically displayed.

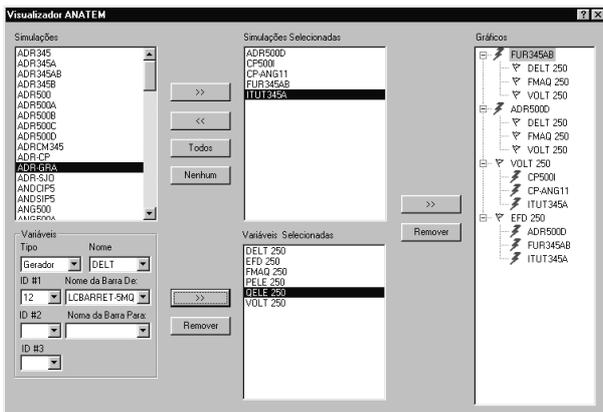


Figure 7 - Dialog window of the postprocessing manager program

It often happens that an important variable is not previously selected for monitoring, requiring a new program run. The solution adopted to avoid this problem is to store all information needed and reconstruct network variables from the bus voltages and topological changes.

Integration and plotting steps have to be chosen adequately to obtain precise simulation results, taking

into account the frequency range of the involved phenomena. Since stability models usually require time steps in the range of 1 to 10 ms, plotting intervals generally do not exceed 20 ms and simulation time is usually between 5 and 20s, the amount of data stored for postprocessing of all variables of a large system can be excessive regarding present hard disk and memory capacities.

Automatic variation of time step integration may reduce the amount of stored data since time step and plotting interval tend to be naturally increased when faster transients are damped out. However this may not be effective: if a fast transient is present in only a few variables, time step will not be sufficiently increased resulting in unnecessary data stored for the remaining variables.

So, a filtering algorithm was developed to reduce the number of points stored for each variable to the minimum necessary to capture all the relevant dynamics. This algorithm is based on the variation of the derivative and on the local maximum and minimum points of each signal. Figure 8, Figure 9 and Figure 10 show the results of application of this algorithm to three curves obtained in the simulation of a disturbance in the large scale Brazilian system. Each figure contains two superimposed curves: one before and other after filtering. The dots correspond to the points retained in the filtering process. The curve of Figure 8 has a more oscillatory behavior than those of Figure 9 and Figure 10. It can be seen that the filtering did not significantly alter the pattern of the curves.

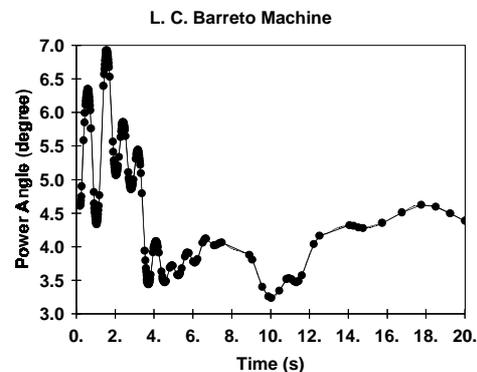


Figure 8 -Filtering of L.C.Barreto power angle curve

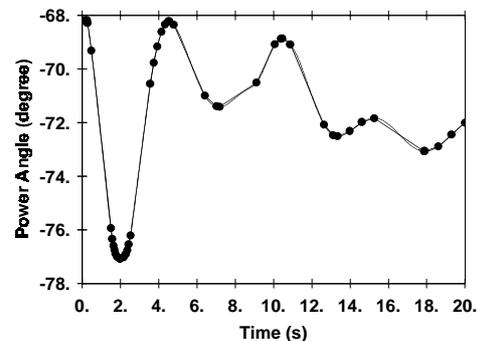


Figure 9 -Filtering of Xingó power angle curve

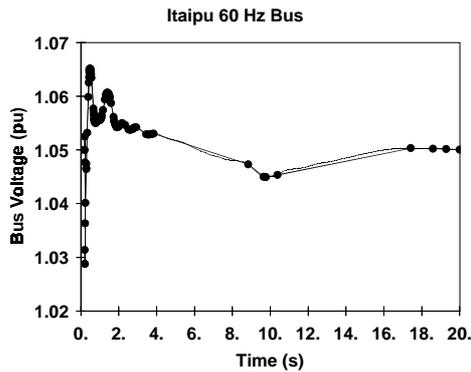


Figure 10 -Filtering of Itaipu bus voltage curve

The original curves contained 1341 points (discontinuity points also included), corresponding to a 20 s simulation with a 3 ms integration step and a 15 ms plotting interval. The filtering algorithm reduced the curves of Figure 8, Figure 9 and Figure 10 to 230, 49 and 82 points respectively, producing significant savings in stored data.

7. Simulation of the March 11th Blackout

The March 11th 1999 blackout was partly reproduced by simulations using ANATEM. The event was initiated by a bus fault at the Bauru substation, followed by the simultaneous loss of 5 lines (440 kV). The subsequent tripping of a sixth 440 kV line (I. Solteira-Tres Irmãos) caused instability and collapse. Figure 11 shows simulation results which reproduce the chain reaction leading to the blackout.

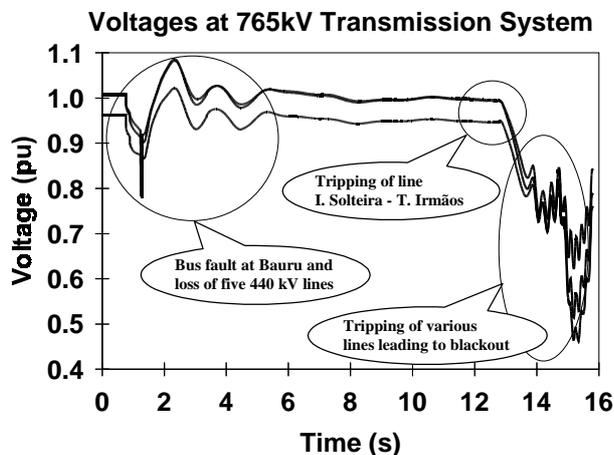


Figure 11 -Voltages at the 765 kV system

8. Conclusions

The recent developments in the ANATEM software involved improvements in modeling, numerical robustness, flexibility of use and visualization of results. Several of these enhancements were discussed in this paper.

ANATEM has been recently used in many studies of the Brazilian system, and constant feedback from the electrical companies, helped the development team to

make the software suitable to the stringent requirements of the electrical energy sector.

Advanced features are currently under development, including these:

- Integration into a power system package, including power flow, small signal analysis, short circuit calculation, etc., by means of a data base management system.
- Implementation of a script language to model complex special protection schemes as an alternative to the UDC modeling.
- Enhancement of equipment models to allow mid-term stability simulations, including AGC action and secondary voltage control schemes.

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