Development and Application of a Comprehensive Transient Stability Package Embedded in an Automatic Disturbance Analysis Multi-Agent System

Jonas Pesente, *Member, IEEE,* Felipe Crestani, Rodrigo Ramos, *Senior Member, IEEE,*
Miguel Moreto, *Member, IEEE,*

***Abstract*—This work presents a case of integration of a transient stability simulation algorithm in an Automatic Disturbance Analysis software. The transient stability simulation algorithm is presented in a step by step solution of a chosen case, and also was made available for free download[1], intending to others engineers to reproduce the results and to discuss the developed code. The algorithm was validated using a benchmark software, integrated to a multi-agent system for automatic disturbance analysis and had its performance tested using disturbance cases, presenting good results.**

***Index Terms*—Transient Stability, Multi-Agent Systems.**

I. Introduction

POWER ower system stability may be shortly defined as the capacity a power system has to recover to an equilibrium state after being subject to a disturbance [1].

Although power system stability refers to a single topic, where the admissible operational limits are simultaneously respected for all system quantities, for all system operation horizon and after any kind of disturbance, generally the instability phenomena is majorly related to a specific set of these attributes [2].

Thus, for analysis purposes, stability is commonly classified by: the *nature* of predominant phenomenon as voltage, frequency or angular; the *time basis* in short or long terms; and the *intensity* in large or small [3]–[6]. It is important to highlight that specific types of stability analysis may be related to particular mathematical tools and equipment models.

In this context, the *transient stability* term is defined as the class of stability main of angular nature, which occurs only a few cycles after power system being subjected to a large disturbance.

Stability evaluation is one of the main subjects of a disturbance analysis and considerable effort is made in the sense that every verified outage, the records are used to evaluate system performance. If any abnormal quantity excursion is then identified (limits violations, unpredictable behavior or incorrect models response), a stability study must be run. Examples are studies carried out after blackouts [7], [8].

J. Pesente was with the Superintendence of Operation, Foz do Iguacu, PR, 85868-140 Brazil e-mail: pesente@itaipu.gov.br.

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[1] The solution of the case presented in Matlab files is available in https://sites.google.com/site/jonaspesente/

This process may be time consuming and difficult to apply routinely. In the context of speeding up the disturbances analysis, automatic software has been developed, including routines of records gathering, classifying and transforming data into information for engineers has been evaluated and discussed in large blackouts [9].

The information processed from automatic disturbances analysis can be used to feed stability packages which will produce preliminary results and a set of files that establishes a starting point for further analysis of a specific disturbance.

In this context, this paper proposes an integration of a transient stability algorithm in automatic disturbance multi-agent system is presented. It is divided in the following sections: the general formulation of the transient stability algorithm is presented in Section II, the main aspects of the algorithm integration in multi-agent software in Section III, results in Section IV and conclusion remarks in Section V.

II. Transient Stability Package

This section is divided in a general view of the algorithm and in the solution of the system, as follows.

A. Descriptor System Equations

The general scheme of these equations that model the dynamical behavior of the power systems in transient stability studies is presented in Figure 1, where the interface between the differential and algebraic equations is highlighted: power flow equations are solved, the power of each generator feeds the dynamical equations, which are integrated, and the voltage solutions are used to solve a new power flow (alternately system solution).

According to the Fig. 1, the power system model basically comprises of a set of first-order differential equations and algebraic equations set which can be written as (1)-(3), assuming x as the states of dynamical system, u as algebraic variables, E and V, respectively as generators internal and terminal voltages and Y as the admittance bus.

$$\dot{x} = A.x + B.u \tag{1}$$

$$I\left(E, V\right) = Y.V \tag{2}$$

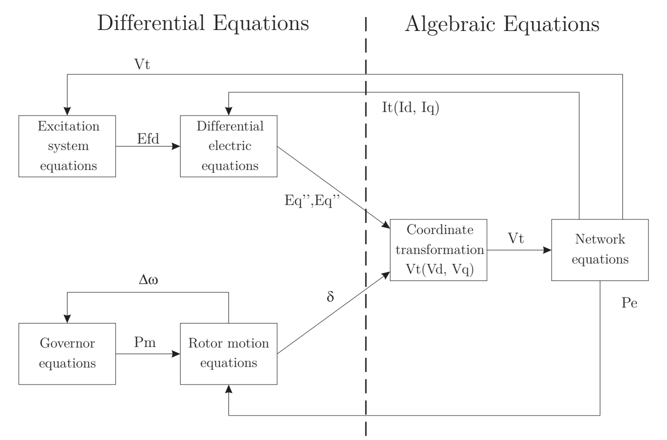

Fig. 1. General scheme of differential algebraic system solution flow.

$$u = h\left(E, V\right) \tag{3}$$

The procedure for solution of set of Equations used in this paper is described by Algorithm 1, as follows.

Algorithm 1: General scheme of DAE solution

1: Compute $x\left(t_0\right)$, $u\left(t_0\right)$
2: **while** $t < T_{max}$ do
3: $k = 0$
4: **while** $\|\Delta V\|^2 > \varepsilon$, do
5: Compute $V_{(t)}^{k+1} = [Y]^{-1}.\ I\left(E_{(t)}, V_{(t)}^k\right)$
6: Compute $\Delta V = \Delta V_{(t)}^{k+1} - \Delta V_{(t)}^k$
7: $k = k + 1$
8: **end while**
9: Compute $u_{(t)} = h\left(E_{(t)}, V_{(t)}\right)$
10: Compute $E^*_{(t+1)}$ by extrapolation
11: Compute $x^*_{(t+1)}, u^*_{(t+1)}$
13: Compute $x_{(t+1)} = f\left[x^*_{(t+1)}, u^*_{(t+1)}, x_{(t)}, u_{(t)}\right]$
14: Do $t = t + \Delta t$
15: **end while**

B. System equations solution

The differential equations of the Algorithm 1 are solved by implicit trapezoidal method which approximates the area over a function $x(t)$ by the trapezium formed by the interpolation of the 2 consecutive points as (4).

$$\int_k^{k+1} x\left(k\right).dk \approx \frac{\Delta k}{2}\left(x\left(k\right) + x\left(k+1\right)\right) \tag{4}$$

For a first-order differential equation $\dot{x}(t) + a.x(t) = v(t)$, the application of the method results in (5) and (6).

$$\int_t^{t+\Delta t} \dot{x} + \int_t^{t+\Delta t} a.x = \int_t^{t+\Delta t} v \rightarrow \tag{5}$$

$$\begin{aligned} x\left(t+\Delta t\right) - x\left(t\right) + a\frac{\Delta t}{2}\left(x\left(t+\Delta t\right) + x\left(t\right)\right) = \\ \frac{\Delta t}{2}\left(v\left(t+\Delta t\right) + v\left(t\right)\right) \end{aligned} \tag{6}$$

$$\begin{aligned} x\left(t+\Delta t\right) = \frac{1 - a.\Delta t/2}{1 + a.\Delta t/2}.x\left(t\right) + \\ \frac{\Delta t/2}{1 + a.\Delta t/2}\left(v\left(t+\Delta t\right) + v\left(t\right)\right) \end{aligned}$$

Using these concepts, the application of the trapezoidal method to generator results and for the AVR in the relations below.

$$\begin{aligned} \omega_{(t)} = \frac{1 - \frac{1}{2H}\frac{\Delta t}{2}}{1 + \frac{1}{2H}\frac{\Delta t}{2}}.\omega_{(t-\Delta t)} + \\ \frac{\frac{\Delta t}{2}}{1 + \frac{1}{2H}\frac{\Delta t}{2}}\left[\frac{\pi.f}{H}\left(P_{m(t-\Delta t)} - P_{e(t-\Delta t)} + P_{m(t)} - P_{e(t)}\right)\right] \end{aligned}$$

$$\begin{aligned} \delta_{(t)} = \delta_{(t-\Delta t)} + \frac{\Delta t}{2} * \\ \left(\begin{array}{c} \omega_{rotor(t-\Delta t)} \\ -\omega_{sinchronous(t-\Delta t)} + \omega_{rotor(t)} - \omega_{sinchronous(t)} \end{array}\right) \end{aligned}$$

$$\begin{aligned} E'_{q(t)} = \frac{1 - \frac{1}{T'_d}\left(\frac{X_d - X_l}{X'_d - X_l}\right)\frac{\Delta t}{2}}{1 + \frac{1}{T'_d}\left(\frac{X_d - X_l}{X'_d - X_l}\right)\frac{\Delta t}{2}}.E'_{q(t-\Delta t)} + \\ \frac{\frac{\Delta t}{2}}{1 + \frac{1}{T'_d}\left(\frac{X_d - X_l}{X'_d - X_l}\right)\frac{\Delta t}{2}} * \\ \left\{\frac{1}{T'_d}\left[\begin{array}{c} E_{fd(t)} + E_{fd(t-\Delta t)} + \frac{X_d - X_l}{X'_d - X_l}\left(E''_{q(t)} + E''_{q(t-\Delta t)}\right) - \\ \frac{(X_d - X'_d)(X''_d - X_l)}{X'_d - X_l}\left(I_{d(t)} + I_{d(t-\Delta t)}\right) \end{array}\right]\right\} \end{aligned}$$

$$\begin{aligned} E''_{q(t)} = \frac{1 - \frac{1}{T''_d}.\frac{\Delta t}{2}}{1 + \frac{1}{T''_d}.\frac{\Delta t}{2}}.E''_{q(t-\Delta t)} + \frac{\frac{\Delta t}{2}}{1 + \frac{1}{T''_d}.\frac{\Delta t}{2}} * \\ \left[\begin{array}{c} \frac{1}{T''_d}\left(E'_{q(t)} + E'_{q(t-\Delta t)}\right) - \frac{1}{T''_d}\left(X'_d - X''_d\right)\left(I_{d(t)} + I_{d(t-\Delta t)}\right) \\ + \frac{X''_d - X_l}{X'_d - X_l}\left(\Delta E'_{q(t)} + \Delta E'_{q(t-\Delta t)}\right) \end{array}\right] \end{aligned}$$

$$\begin{aligned} E''_{d(t)} = \frac{1 - \frac{1}{T''_q}.\frac{\Delta t}{2}}{1 + \frac{1}{T''_q}.\frac{\Delta t}{2}}.E''_{d(t-\Delta t)} + \\ \frac{\frac{\Delta t}{2}}{1 + \frac{1}{T''_q}.\frac{\Delta t}{2}}.\frac{1}{T''_q}.\left(X_q - X''_q\right).\left(I_{q(t)} + I_{q(t-\Delta t)}\right) \end{aligned}$$

$$\begin{aligned} E_{FD(t)} = \frac{1 - \frac{1}{T_A}.\frac{\Delta t}{2}}{1 + \frac{1}{T_A}.\frac{\Delta t}{2}}.E_{FD(t-\Delta t)} + \\ \frac{\frac{K_A}{T_A}.\frac{\Delta t}{2}}{1 + \frac{1}{T_A}.\frac{\Delta t}{2}}.\left(\begin{array}{c} V_{REF(t-\Delta t)} - V_{t(t-\Delta t)} \\ +V_{REF(t)} - V_{t(t)} \end{array}\right) \end{aligned}$$

It is important to highlight that the system of equations above uses quantities values of t and also of $t - \Delta t$, so it is necessary at least one variable to be extrapolated to initiate the process of integration. In this work, the load angle Euler extrapolation was made, as in (7).

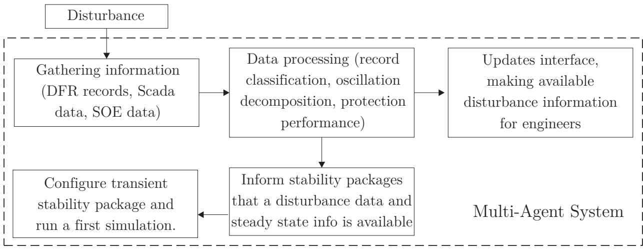

Fig. 2. General scheme of the integration of transient stability feature.

$$\delta_{(t)} = \delta_{(t-\Delta t)} + \frac{d\delta}{dt} \tag{7}$$

The algebraic equations solution of the Algorithm 1 was implemented by the Gauss-Seidel method, where the bus voltage is updated by the multiplication of current injection in the bus and the impedance connected to it, as in (8).

$$V_i^{(k+1)} = \frac{\frac{P_i^{def} - j.Q_i^{def}}{V_i^{*(k+1)}} + \sum y_{ij}.V_j^{(k)}}{\sum y_{ij}} \tag{8}$$

In the next section some aspects of the integration of the algorithm to the multi-agent software are commented.

III. Integration in Existing Multi-Agent System

The usage of multi-agent software in power system disturbance analysis has been successfully used, as described in [10]. Similarly, an automatic disturbance analysis was developed in Itaipu power plant, as presented in [11], including generators dynamic and protection performances evaluation. Every time a shutdown takes place at Itaipu power plant, this software gathers information from Scada, DRF and SOE, process this data and produce a set of analyses for engineers.

One of these features is the described transient stability package. The main scheme is shown in Fig. 2, where is illustrated that the whenever a disturbance takes place, the multi-agent system compute a steady state solution and make available for transient stability package, which performs the computation of interest and make available for engineers.

The multi-agent system developed uses the JaCaMo framework [12], which allows to deploy agents in the so-called belief-desire-intention model. Once the transient stability data refers to the entire system, it is manage and executed by the top level agent, in this case, defined as area agent. It is also important to note that this action is executed a single time each disturbance analyzed, using as much information the multi-agent system had gather. This and other actions deployed were compiled as Java packages, which are associated with agents through CArtAgO technology. Experiments performed and results obtained are presented in the next section.

IV. Experiments

The presented experiments are divided in a validation of the implemented algorithms using Anatem software as the benchmark, and a case of a reproduction of a disturbance and comparison with the simulation result.

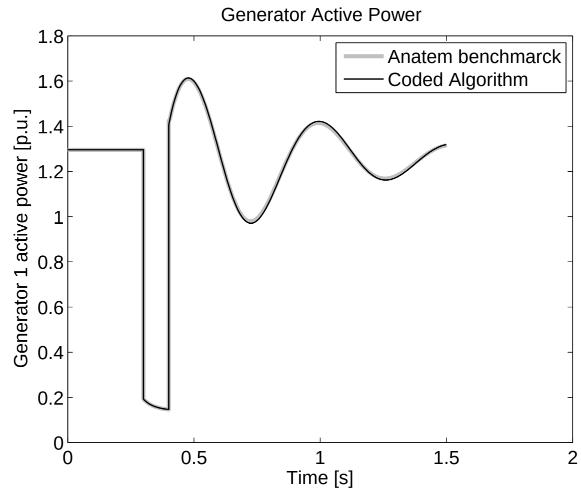

Fig. 3. Comparison between benchmark and coded algorithm.

A. Case 1: Validation

The power system data used in validation is presented in APPENDIX I along with a one-step equations solution. The comparison of a simulation of a three-phase short circuit in bus 2, at 300ms of simulating and during 100ms is presented in Fig. 3, for the generator 1 active power of coded algorithm and Anatem. It can be perceived the curves overlap, (the normalized sum of absolute differences of curves is lower than $4 * 10^{-4}$.

The remaining quantities presented a similar behavior to the active power showed in Fig. 3.

B. Case 2: Disturbance

The power system data used in validation is presented in APPENDIX I along with a one-step equations solution. The comparison of a simulation of a three-phase short circuit in bus 2, at 300ms of simulating and during 100ms is presented in Fig. 4, for the generator 1 active power of coded algorithm and Anatem. It can be perceived the curves overlap, (the normalized sum of absolute differences of curves is lower than $4 * 10^(-4)$).

Itaipu is a power plant placed in the border of Brazil and Paraguay and has ten generators of 60Hz/737MVA/18kV, and ten of 50Hz/826MVA/18kV, each group connected to a gas isolated substation. In 09/22/2015, four units were shut down after a disruptive discharge in the gas isolated substation of 60Hz. The sequence of events is presented in Table I.

The presented algorithm was used to reproduce the disturbance, receiving as the input the generators steady state condition and the simplified sequence of events shown in Table I.

It can be seen that the comparison of the step-by-step solution with the unit U15 record, as illustrated in Fig. 4, shows a good correspondence, encouraging its use as an automated routine.

TABLE I
SEQUENCE OF EVENTS OF DISTURBANCE.

Event	Instant after record trigger
Phase A short circuit	1.01 s
Short circuit extinguishing and shutdown of 4 units	1.13 s

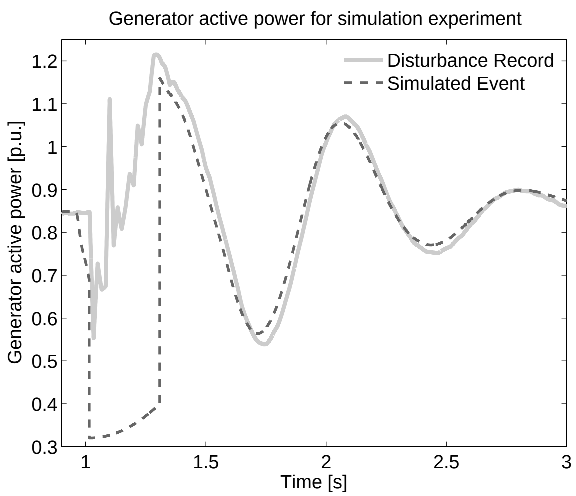

Fig. 4. Disturbance reproduction using software implemented.

V. Concluding Remarks

Automatic disturbance analysis software brings to the engineers the possibility to gather, classify and process larger sets of data then doing it manually.

Although these software process substantial amounts of data, much information related to disturbance analysis still remains not automated, as is commonly the case of disturbance reproduction in software simulation.

In this context, this study presented an algorithm that can receive from a multi-agent automatic disturbance analysis data of the disturbance and reproduce it in simulation.

Most of the cases analyzed did not fit perfectly data recorded from the disturbance. It is expected, since the disturbance reproduction may involve numerous details that cannot be automated. The coded algorithm, however, helped in the sense every disturbance processed result in a start case for simulation reproduction.

Appendix A
Power System Data and One Step Solution

The formulation and calculations presented in this paper were making for the sample case of the simplified power system illustrated in Figure 5 [13]. The parameters of generators are showed in Table A.1 and AVRs in Figure 6.

The power flow solution and data for Y_{bus} formation are presented in Fig. 5. The buses 6 and 7 are related to augmented power system, and are connected to generators

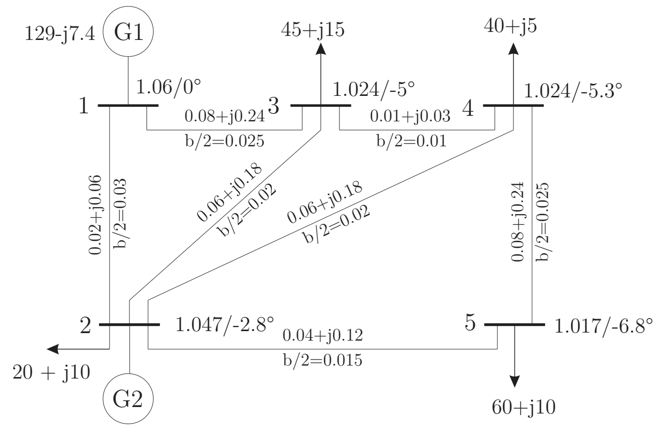

Fig. 5. Power system used to exemplify the algorithm implemented.

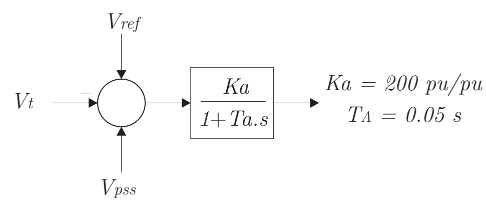

Fig. 6. Power system used to exemplify the algorithm implemented.

1 and 2 for the $X_d^{"}$ parameter, respectively. The resultant augmented Y_{bus} presented in (8).

$$Ya\,(1,1) = 6.25 - j22.3446$$

$$Ya\,(1,2) = Ya\,(2,1) = -5 + j15$$

$$Ya\,(1,3) = Ya\,(3,1) = Ya\,(4,5) = Ya\,(5,4) = -1.25{+}j3.75$$

$$Ya\,(1,6) = Ya\,(6,1) = Ya\,(2,7) = Ya\,(7,2) =$$

$$-Ya\,(6,6) = -Ya\,(7,7) = j3.6496$$

$$Ya\,(2,2) = 10.833 - j36.0646$$

$$Ya\,(2,3) = Ya\,(3,2) = Ya\,(2,4) = Ya\,(4,2) = -1.66 + j5$$

$$Ya\,(2,5) = Ya\,(5,2) = -2.5 + j7.5$$

$$Ya\,(3,3) = Ya\,(4,4) = -12.9167 - j38.695$$

$$Ya\,(3,4) = Ya\,(4,3) = -10 + j30$$

$$Ya\,(5,5) = 3.75 - j11.21$$

Step 1: generator 1 states initialization

$$E_t = V_t + j.X_q.\left(\frac{S_{pu}}{V_t}\right)^* = 1.2638.e^{j.34.6328^\circ}$$

$$I_d = sin\left(\measuredangle E_t\right).R_e\left(I_t\right) - cos\left(\measuredangle E_t\right).I_m\left(I_t\right) = 0.6754$$
$$I_q = cos\left(\measuredangle E_t\right).R_e\left(I_t\right) + sin\left(\measuredangle E_t\right).I_m\left(I_t\right) = 1.0214$$
$$V_d = sin\left(\measuredangle E_t\right).R_e\left(V_t\right) - cos\left(\measuredangle E_t\right).I_m\left(V_t\right) = 0.6343$$
$$V_q = cos\left(\measuredangle E_t\right).R_e\left(V_t\right) + sin\left(\measuredangle E_t\right).I_m\left(V_t\right) = 0.8493$$
$$E_d^{''} = V_d + R_a.I_d - I_q.X_q^{''} = 0.3544$$
$$E_q^{''} = V_q + R_a.I_q + I_d.X_d^{''} = 1.0343$$
$$E_q^{'} = E_q^{''} + I_d.\left(X_d^{'} - X_d^{''}\right) = 1.0587$$
$$\emptyset_t = A.e^{\left(B.\left(\left|E_q^{'}\right| - C\right)\right)} = 0.2718$$
$$E_{FD}^0 = \left(I_d.\left(X_d^{''} - X_l\right) + E_q^{'} * \frac{\left(X_d - X_l\right)}{\left(X_d - X_d^{'}\right)} - E_q^{''}\right) *$$
$$\frac{\left(X_d - X_d^{'}\right)}{\left(X_d^{'} - X_l\right)} + \emptyset_t = 1.7600$$
$$E = E_q^{''}.e^{j.\measuredangle E_t} + E_d^{''}.e^{j.\left(\measuredangle E_t - 90^\circ\right)} = 1.0934.e^{j.17.8395^\circ}$$
$$X_{ad} = X_d - X_l = 0.946 - 0.202 = 0.744$$
$$I_{fd} = E_{FD}/X_{ad} = 2.3656$$

Step 2: solution for a three phase short circuit at bus bar 2, applied at 5ms of simulation, cleared at 10ms
In the step time that there is a net change (fault applying and clearing), two solution (before and after switching) are calculated. So the time vector for this simulation becomes

$$\left[\begin{array}{ccccccc} 0 & 0.005 & 0.005 & 0.010 & 0.010 & 0.015 & 0.020 \end{array}\right]$$

In $t = 0.005$ the fault is applied and $V_2 = 0$. The power flow solution in step 3 for the augmented system and internal generator voltages E_t returns voltage from showed below.

$$V_{bus(t)} = \left[\begin{array}{c} 0.1795 + j0.007; \\ 0 + j0; \\ 0.0447 - j0.001; \\ 0.0356 - j0.0004; \\ 0.0116 - j0.007 \end{array}\right]$$

The initialized values define values for $t = 0$ or step 1, afterwards, the values are updated by relations that follows.

The values of Vbus are used to calculate generators internal voltages, axis voltage and currents and active power, as shown below.

$$I_{t(t)} = \left(E_t - V_{bus(t)}\right)/j.X_d^{'} = 1.1969 - j.3.1436$$
$$I_{d(t)} = 3.2349$$
$$I_{q(t)} = -0.922$$
$$V_{d(t)} = 0.1018$$
$$V_{q(t)} = 0.1480$$
$$P_{(t)} = R_a\left({I_{d(t)}}^2 + {I_{q(t)}}^2\right) + V_{d(t)}.I_{d(t)} + V_{q(t)}.I_{q(t)} = 0.1928$$

Then, the extrapolation for derivatives of the quantities is determined:

$$SAT_{(t)} = A.e^{\left(B.\left(\left|E_q^{'}\right| - C\right)\right)} = 0.2718$$

$$\Delta E_{d(t)}^{''} = \frac{1}{T_q^{''}}\left(-E_{d(t)}^{''} + \left(X_q - X_q^{''}\right).I_{q(t)}\right) = -4.8169$$

$$\Delta E_{q(t)}^{'} = \frac{1}{T_d^{''}}\left(\begin{array}{c} E_{fd(t)} + \frac{X_d - X_d^{'}}{?\bar{a}_d^{'} - X_l}E_{q(t)}^{''} + \frac{X_d - X_l}{X_d^{'} - X_l}E_{q(t)}^{'} \\ -\frac{\left(X_d - X_d^{'}\right)\left(X_d^{''} - X_l\right)}{X_d^{'} - X_l}I_{d(t)} - SAT_{(t)} \end{array}\right) =$$
$$-0.1335$$

$$\Delta E_{q(t)}^{''} = \frac{1}{T_d^{''}}\left(\begin{array}{c} -E_{q(t)}^{''} + E_{q(t)}^{'} \\ -\left(X_d^{'} - X_d^{''}\right)I_{d(t)} + \frac{X_d^{''} - X_l}{X_d^{'} - X_l}\Delta E_{q(t)}^{'} \end{array}\right) =$$
$$-2.0086$$

$$\Delta\delta_{(t)} = \omega_1 - 2.\pi.60 = 0$$
$$\delta_{ext(t)} = \delta_{(t)} + \Delta\delta_{(t)}.\Delta t = 36.75^\circ$$
$$E_{ext(t)} = E_q^{''}.e^{j.\measuredangle E_t} + E_d^{''}.e^{j.\left(\measuredangle E_t - 90^\circ\right)} = 1.0934.e^{j.17.8395^\circ}$$
$$\Delta E_{FD(t)} = K_A\left(V_{REF(t)} - V_{t(t)}\right) = 0$$

Re-computingload flow of augmented system using E_{ext} results in the solution of $V_{bus(t+\Delta t)}$:

$$V_{bus(t+\Delta t)} = \left[\begin{array}{c} 0.1795 + j0.007; \\ 0 + j0; \\ 0.0447 - j0.001; \\ 0.0356 - j0.0004; \\ 0.0116 - j0.007 \end{array}\right]$$

Then the algebraic quantities are re-calculated, this time already referring to $t + \Delta t$:

$$I_{t(t+\Delta t)} = \left(E_t - V_{bus(t)}\right)/j.X_d^{'} = 1.1969 - j.3.1436$$
$$I_{d(t+\Delta t)} = 3.2349$$
$$I_{q(t+\Delta t)} = -0.9220$$
$$V_{d(t+\Delta t)} = 0.1018$$
$$V_{q(t+\Delta t)} = 0.1480$$
$$P_{(t+\Delta t)} = R_a\left(I_{d(t+\Delta t)}^2 + I_{q(t+\Delta t)}^2\right) +$$
$$V_{d(t+\Delta t)}.I_{d(t+\Delta t)} + V_{q(t+\Delta t)}.I_{q(t+\Delta t)} = 0.1928$$

Further, using the extrapolated and algebraic quantities calculated, the values of $t + \Delta t$ quantities are estimated, and then its derivatives are updated:

$$E_{d(t+\Delta t)}^{''} = V_d + R_a.I_d - X_q^{''}.I_q = 0.1112$$

$$E_{q(t+\Delta t)}^{''} = V_q + R_a.I_q - X_d^{''}.I_d = 1.1253$$

$$E_{q(t+\Delta t)}^{'} = E_{q(t)}^{'} + \Delta E_{q(t)}^{'}.\Delta t = 1.1380$$

$$SAT_{(t+\Delta t)} = A.e^{\left(B.\left(\left|E_q^{'}\right|-C\right)\right)} = 0.2707$$

$$\Delta E^{''}_{d(t+\Delta t)} = \frac{1}{T^{''}_q}\left(-E^{''}_{d(t+\Delta t)} + \left(X_q - X^{''}_q\right).I_{q(t+\Delta t)}\right) = -4.8169$$

$$\Delta E^{'}_{q(t+\Delta t)} = \frac{1}{T^{'}_d}\left(\begin{array}{c} E_{fd(t+\Delta t)} + \frac{X_d - X^{'}_d}{X^{'}_d - X_l}E^{''}_{q(t+\Delta t)} + \frac{X_d - X_l}{X^{'}_d - X_l}E^{'}_{q(t+\Delta t)} \\ -\frac{\left(X_d - X^{'}_d\right)\left(X^{''}_d - X_l\right)}{X^{'}_d - X_l}I_{d(t+\Delta t)} - SAT_{(t+\Delta t)} \end{array}\right) = -0.1334$$

$$\Delta E^{''}_{q(t)} = \frac{1}{T^{''}_d}\left(\begin{array}{c} -E^{''}_{q_{ext(t)}} + E^{'}_{q_{ext(t)}} \\ -\left(X^{'}_d - X^{''}_d\right)I_{d(t)} + \frac{X^{''}_d - X_l}{X^{'}_d - X_l}\Delta E^{'}_{q(t)} \end{array}\right) = -2.0086$$

Finally, the integration of the quantities is made:

Rotor speed

$$B_n = 1 - D/H = 1$$

$$B_d = 1 + D/H = 1$$

$$B = B_n/B_d = 1$$

$$\omega_{(t+\Delta t)} = B.\omega_{(t)} + \frac{\Delta t}{2.B_d}\left(\frac{\pi.60}{H}\right)\left(\begin{array}{c} 2.P_{mec} \\ -P_{(t)} - P_{(t+\Delta t)} \end{array}\right) = 377.28$$

Rotor angle

$$\delta_{(t+\Delta t)} = \delta_{(t)} + \left(\omega_{(t)} - 2.\pi.60 + \omega_{(t+\Delta t)} - 2.\pi.60\right) = 36.79^\circ$$

Voltage $E^{''}_d$

$$B_n = 1 - \Delta t/2.T^{''}_q = 0.9821$$

$$B_d = 1 + \Delta t/2.T^{''}_q = 1.0179$$

$$B = B_n/B_d = 0.901$$

$$E^{''}_{d(t+\Delta t)} = B.E^{''}_{d(t)} + \frac{\Delta t}{2.B_d.T^{''}_q}\left(X_q - X^{''}_q\right).\left(I_{q(t)} + I_{q(t+\Delta t)}\right) = 0.3679$$

The determination of the value for $E^{'}_q$ demands an additional step, since the determination of its derivative is a non-linear function of $E^{'}_q$:

$$\frac{dE^{'}_q}{dt} = \frac{1}{T^{'}_{do}}\left[\begin{array}{c} E_{fd} + \frac{X_d - X^{'}_d}{X^{'}_d - X_l}E^{''}_q - \frac{X_d - X_l}{X^{'}_d - X_l}E^{'}_q \\ -\frac{\left(X_d - X^{'}_d\right)\left(X^{''}_d - X_l\right)}{X^{'}_d - X_l}I_d - A_{sat}.e^{B_{sat}\left(\left|E^{'}_q\right|-C_{sat}\right)} \end{array}\right]$$

In this work, the solution of the last equation was obtained by a Newton-Raphson loop, which includes the updating of the $E^{'}_q$ quantity using relations of the following equation, where only the final (converged) value for $E^{'}_q$ is presented.

$$B_n = 1 - \left(\frac{\Delta t}{2.T^{'}_d}\right)\left(\frac{X_d - X_l}{X^{'}_d - X_l}\right) = 0.9979$$

$$B_d = 1 + \left(\frac{\Delta t}{2.T^{'}_d}\right)\left(\frac{X_d - X_l}{X^{'}_d - X_l}\right) = 1.0021$$

$$B = B_n/B_d = 0.9958$$

$$E^{'}_{q(t+\Delta t)} = B.E^{'}_{q(t)} + \frac{\Delta t}{2.B_d.T^{'}_d}\left(\begin{array}{c} E_{fd(t)} + E_{fd(t+\Delta t)} + \\ \frac{X_d - X^{'}_d}{X^{'}_d - X_l}\left(E^{''}_{q(t)} + E^{''}_{q(t+\Delta t)}\right) \\ +\frac{X_d - X^{'}_d}{X^{''}_d - X_l}\left(I_{d(t)} + I_{d(t+\Delta t)}\right) \end{array}\right) = 1.0508$$

Voltage $E^{''}_q$

$$B_n = 1 - \Delta t/2.T^{''}_q = 0.9479$$

$$B_d = 1 + \Delta t/2.T^{''}_q = 1.0521$$

$$B = B_n/B_d = 0.9010$$

$$E^{''}_{q(t+\Delta t)} = B.E^{''}_{q(t)} + \frac{\Delta t}{2.B_d}\left(\begin{array}{c} \frac{1}{T^{''}_d}\left(E^{'}_{q(t)} + E^{'}_{q(t+\Delta t)}\right) - \\ \frac{1}{T^{''}_d}\left(X^{'}_d - X^{''}_d\right)\left(I_{d(t)} + I_{d(t+\Delta t)}\right) \\ +\frac{X^{''}_d - X_l}{X^{'}_d - X_l}\left(\Delta E^{'}_{q(t)} + \Delta E^{'}_{q(t+\Delta t)}\right) \end{array}\right) = 1.0248$$

Field Voltage E_{FD}

$$B_n = 1 - \Delta t/2.T_A = 0.9048$$

$$B_d = \Delta t/2.\left(1 + 2.T_A.\Delta t/2\right) = 0.0024$$

$$E_{FD(t+\Delta t)} = B_n.E_{FD(t)} + \frac{K_A}{T_A}.B_d\left(\begin{array}{c} \left(V_{REF(t)} - V_{t(t)}\right) + \\ \left(V_{REF(t+\Delta t)} - V_{t(t+\Delta t)}\right) \end{array}\right) = 1.0248$$

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Jonas Pesente works in Itaipu Binacional at Operation Superintendence, Electrical Studies and Standards Division, and has received M.Eng. in Aeronautical Engineering 09', M.Eng. in Power System Engineering 10' and is current pursuing Ph.D.