A Quasi Dynamic Model Applied to a Ramp Load Increase Study

Valério O. Albuquerque, R. Coradi Leme, *Student Member IEEE,* B. Isaias Lima Lopes, A. C. Zambroni de Souza, *Senior Member IEEE*, Otavio A. S. Carpinteiro, Rodnei Dias dos Anjos, Pedro P. Balestrassi

Abstract **– This paper employs a quasi dynamic model for transient and long term analysis. The set of equations considered permits to calculate the solution by using the Newton-Raphson´s method. The simplicity of the model allows one to obtain some pieces of information required to take preventive control actions. A particular case of interest is the ramp load increase. For this sake, a real Brazilian system is employed, so the transient, long term and voltage collapse studies are carried out with all limits considered.**

Index Terms: **load margin, quasi dynamic model, transient and long term response.**

I. INTRODUCTION

The literature shows that voltage collapse problems are real and the consequences may be dramatic. If the system reaches the collapse point as a function of successive load increases, a power flow model may be enough to analyse the system behaviour [1,2]. In a situation like that, the equilibrium is lost in a point identified in the literature as a saddle-node bifurcation [3].

Several researchers have identified voltage collapse point by using a static model. The focus is on the identification of the system load margin, critical bus, control actions to avoid the problem and contingency screening. A power system, however, may reach a voltage collapse point as a consequence of a contingency. If the transient period is the focus, the differential equations involved must be integrated in order to assess the system trajectory. On the other hand, if a longer term is considered, a quasi dynamic model may be employed, as proposed in [4-8]. Based on the fact that the transient characteristics may be neglected, the set of equations becomes algebraic, enabling one to employ the Newton´s method to find the numerical solution.

Manuscript received October 29, 2008. This work was supported in part by CNPq, CAPES, FAPERJ and FAPEMIG.

Valerio O. Albuquerque is with Cemig and Unifei. E-mail voa@cemig.com.br.

Rafael C. Leme, B. Isaias Lima Lopes, A C. Zambroni de Souza and Otavio A. S. Carpinteiro are with the Federal University of Itajubá. Av. BPS, 1303, Pinheirinho, C. P. 50, 37500-903, Itajubá, MG, Brazil (corresponding author. Phone: +5535 36291242; fax: +5535 36291365; e-mail: isaias,zambroni@unifei.edu.br).

The second and last authors are also with the Federal University of Itajubá. E-mails: leme, otavio@unifei.edu.br and ppbalestrassi@gmail.com

Such an alternative yields accurate results in a much smaller computational time. This quasi-dynamic model is used here.

Using this model enables one to study the following scenario: A contingency takes place, and the system is able to sustain the impact during the transient period, reaching a stable post fault equilibrium point. A low voltage level is detected in some buses, and control actions are taken in order to restore the acceptable operating conditions. The actions are executed according to the sequence: local shunt capacitors switching, load tap changes and AVR´s set points adjustment. If, after the whole sequence is executed, the voltage level is still low, load shedding is triggered. The load shedding strategy adopted in this work is based on the existence of a low voltage profile. Therefore, frequency deviation is not considered for this purpose.

The contingency considered here consists of a ramp load increase, so the system dynamics may be evaluated. This is tested with the help of a real Brazilian system with all the limits considered.

II. DYNAMIC SYSTEM AND QUASI-DYNAMIC MODELS

The general dynamic model is first introduced. In order to link to the quasi-dynamic model, the system behavior is decomposed in various time scale, which permits to separate the equations and the associated variables as follows:

long-term behavior, consequence of load evolution:

$$w = \phi(t) \qquad (1)$$

discrete dynamics, associated with LTC tap and OXL (over excitation limiters) :

$$z(k+1) = f(x,y,z(k),w) \qquad (2)$$

transient dynamics, associated with synchronous machines, voltage regulators, etc. :

$$\dot{x} = f(x, y, z, w) \qquad (3)$$

topological conditions, given by the network equations:

$$0 = g(x, y, z, w) \qquad (4)$$

Note that equation (4) represents the network characteristics, i.e., the power flow equations. Equation (3) is associated with the vectors of transient state variables. Equation (1) represents the load evolution in time and equation (2) shows the discrete dynamics associated with the LTC.

978-1-4244-2235-7/09/$25.00 ©2009 IEEE

As for equation (3), the machine model used here is the IEEE (1.1) model. Such a model consists of 4 differential equations for each generator. The simple model IEEE Type 1 represents the voltage regulator. The model described above may be used to trace the system behavior during the transient post-fault period. Because this is not the focus of this paper, details associated with the integration of the equations will not be addressed in this work. The point of concern is the long term behavior, which assumes that the system may maintain the equilibrium during the transient process. This assumption drives one to the following consideration in equation (3):

$$0 = f(x, y, z, w) \tag{5}$$

Since transient dynamics are neglected, no numerical integration is necessary. Thus, an iterative method is used to calculate the state variables, just like in a load flow calculation. Hence, a Newton method suffices the analysis. The process above may be visualized by the following example:

Assume the set of equations:

$$\begin{aligned} f(x,y) &= \dot{x} = 1 - \sin(x) + \cos(y) \\ g(x,y) &= 0 = x - y^2 \\ x(0) &= .5 \end{aligned} \tag{6}$$

If the quasi-dynamic model is employed, the differential equation vanishes, and equations (1) become:

$$\begin{aligned} 0 &= 1 - \sin(x) + \cos(y) \\ 0 &= x - y^2 \end{aligned} \tag{7}$$

The solution may now be obtained according to the Newton-Raphson´s method. For this purpose, the Jacobian matrix, shown in equation (8), should be calculated.

$$J = \begin{bmatrix} \frac{\partial f}{\partial x} & \frac{\partial f}{\partial y} \\ \frac{\partial g}{\partial x} & \frac{\partial g}{\partial y} \end{bmatrix} = \begin{bmatrix} -\cos(x) & -\sin(y) \\ 1 & -2y \end{bmatrix} \tag{8}$$

Fig. 1 depicts the total solution (obtained when the homogeneous and particular solutions are calculated), and the solution for the quasi-dynamic model. Note that as the transient period is overcome, the transient and long term models provide the same results.

It is important to stress that, for the long-term period, the quasi-dynamic model brings no approximation, since it provides exactly the same solution as obtained by the classical procedure, as shown in Fig. 1. This leads one to conclude that tracing the transient period and jumping to the quasi-dynamic model may provide good results. This is discussed next.

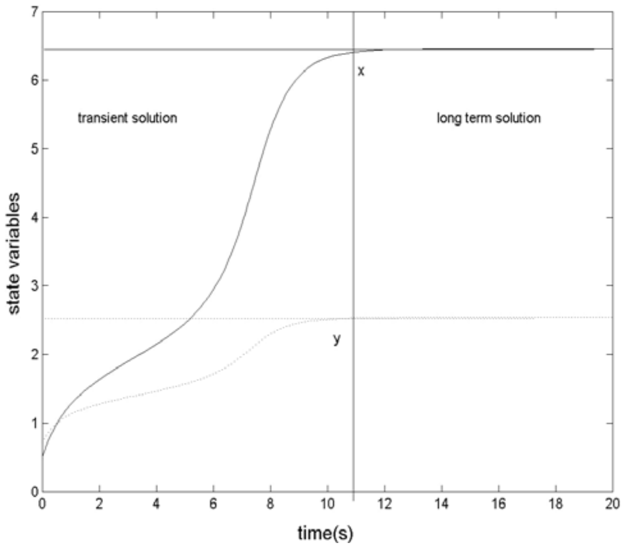

Fig. 1 – Transient and long term solutions

III. The Unified Computational Tool For Transient And Long Term Periods

From the results depicted in Fig. 1, if one is interested in the long term analysis, the quasi-dynamic model provides accurate results. If, however, the transient period is focused, the integration of the equations is needed. This is effectively carried out by the trapezoidal rule, given by:

$$x_{n+1} = x_n + \frac{h}{2}\left[f(x_n, y_n, t_n) + f(x_{n+1}, y_{n+1}, t_{n+1}) \right] \tag{9}$$

where h stands for the step size. The process is accelerated if a varying step size is assumed. Manipulating equation (9) helps to understand the method proposed in this paper. This equation may be written as:

$$0 = F(x,y) = -x_{n+1} + x_n + \frac{h}{2}[f(x_n, y_n, t_n) + f(x_{n+1}, y_{n+1}, t_{n+1})] \tag{10}$$

Applying such a formulation to equation (7) yields:

$$\begin{aligned} 0 &= F(x) = -x_{n+1} + x_n + \frac{h}{2}\begin{bmatrix} 1 - \sin(x_n) + \cos(y_n) + ... \\ ...1 - \sin(x_{n+1}) + \cos(y_{n+1}) \end{bmatrix} \\ 0 &= G(x) = x_{n+1} - y_{n+1}^2 \end{aligned} \tag{11}$$

The above set is now algebraic, and its Jacobian is given by equation (12) (recall that x_{n+1} is procured, whereas x_n is known). In equation (12), the subscript dyn refers to dynamic. This formulation enables one to solve this equation by the Newton-Raphson´s method.

$$J_{dyn}=\begin{bmatrix}-1+\frac{h}{2}\frac{\partial f}{\partial x} & \frac{h}{2}\frac{\partial f}{\partial y}\\ \frac{\partial G}{\partial x} & \frac{\partial G}{\partial y}\end{bmatrix} \tag{12}$$

Applying equation (12) for the set of equations (7) yields:

$$J_{dyn}=\begin{bmatrix}-1-\frac{h}{2}\cos(x) & -\frac{h}{2}\sin(y)\\ 1 & -2y\end{bmatrix} \tag{13}$$

Note the similarity between equations (8) and (13). Equation (13) considers directly the integration step, enabling one to solve the set of equations iteratively. Therefore, the length of the integration step is considered into the linearized set of equations, but no integration is explicitly carried out. Note that the partial derivatives with respect to the static variables remain the same. This is the main difference in relation to the work presented in [9], since that work focuses on taking bigger integration steps as the long-term process is triggered. In this paper, the Newton-Raphson´s method is directly employed for both formulations, reducing the computational load involved in the calculation. The step size control follows the same methodology of the numerical integration process as presented by the authors in [10]. The difference arises when the step size increases (for example three or four times the previous step), and the formulation migrates from the transient to the quasi-dynamic approach. On the other hand, the method proposed in this work migrates directly to the quasi-dynamic approach as its period is identified [11].

In this paper, a function based on the rate of successive integration points is performed. Depending on the monitored conditions for the last three steps, the quasi-dynamic process may be triggered. The methodology provides very satisfactory results in various configurations, such as load ramp, simulation faults and eigenvalues analysis. Note, however, that the eigenvalues analysis is carried out for the system Jacobian as shown in equation (3), easily obtained from equation (12). This avoids the eigenvalues to be sensitive with respect to the step size h. Such a consideration enables one to obtain the same results as the ones described in [12], when tracking the eigenvalues along the time evolution is the focus.

The time scales along with the system is decomposed is presented in [13] so the long-term behavior (consequence of load evolution), discrete dynamics (associated with LTC (Load Tap Changer) or discrete OXL (Over eXcitation Limiter)), transient dynamics (associated with synchronous machines), voltage regulators and topological conditions (given by the network equations) are clearly detailed [14-15].

The IEEE (1.1) machine model is used. It consists of 4 differential equations for each generator. The simple IEEE Type 1 model represents the voltage regulator.

IV. TANGENT VECTOR AS THE BLOCKING TIME IDENTIFICATION

When the power flow model is used, the system of equations may be represented as follows:

$$g(y,\lambda)=0 \tag{14}$$

where λ is the system parameter. In a continuation method, where the system load margin is the point of concern, λ is the load/generation increase factor. This assumes that the system may become unstable as a function of successive load increases. It may be possible, however, that a stable equilibrium point is associated with a low voltage magnitude. In such a situation, it may be desirable to increase the voltage level. The parameter that takes the system to a new operating point, in this case, is a tap change. The partial derivatives of Equation (14) with respect to the system parameter λ at an equilibrium point j, yield:

$$\frac{\partial g}{\partial y}|_j \frac{dy}{d\lambda}|_j + \frac{\partial g}{\partial \lambda}|_j = 0 \tag{15}$$

Hence, the tangent vector is given by :

$$\frac{dy}{d\lambda}|_j = -\left(\frac{\partial g}{\partial y}|_j\right)^{-1}\frac{\partial g}{\partial \lambda}|_j \tag{16}$$

Where: $\frac{\partial g}{\partial y}|_j$ = Jacobian matrix at the point j;

$\frac{\partial g}{\partial \lambda}|_j$ = Partial derivative with respect to the system parameter (in this case, tap). Except the entries associated with the buses connected to LTC´s, all components of $\partial g/\partial \lambda$ are zero.

The model above is derived from the static model. In this sense, only the load flow equations are considered, which enables one to determine a set of control actions associated with a known equilibrium point.

As the LTC tends to recover the voltage level, its action is reflected in a new operating point. This action tends to produce a better voltage profile, and a stable operating point could be achieved [16]. It is possible, however, that from a certain operating point, and such an action produces a deteriorating condition, which could, eventually, drive the system to voltage collapse. Because Equation (16) shows how the state variables change as a function of the system parameter, it will be used as an index. The LTC action is meant to enhance the voltage level in a bus of interest. For normal operating conditions, there is a correspondence between the tap position and the voltage variation at the bus controlled. This is directly provided by the entry dVint/dλ, where int refers to the bus monitored. As long as dVint/dλ has the same coherent sign, the voltage level at bus *int* is correctly controlled, and when this sign changes, this action provides an opposite effect. This is enough to propose this index to monitor the instant of tap blocking. Although the index adopted here assumes the tap changer as a continous variable, in practice it is considered as a discrete control.

Because of this, the tap is blocked at the instant closest to the one calculated by the methodology. Note also that the post fault equilibrium point obtained is stable. In this sense one could argue that such a system is not susceptible to reach voltage instability, and the problem focused here regards only voltage control. The next section discusses how voltage control actions may drive the system to instability.

Note that it could be argued that a local control would be enough to trigger (or stall) tap changing. This is true, and that is the reason why the methodology proposed here for blocking the tap variation is very simple. Discussing the implications associated with this blocking instant, however, may be important [11]. Because of that, such a discussion is carried out in the next section.

V. LOAD SHEDDING STRATEGY

If all the measures discussed before are not enough to drive the system to a good operating condition, two options may arise: a) the system may work temporarily in a non satisfactory situation, and b) the system cannot work under the imposed conditions. If option (b) is the issue and no control action is available, load shedding may occur.

In general, load shedding is analyzed in power systems as a consequence of a frequency problem or a low voltage profile. If frequency is the issue, several options for load shedding may be adopted. Voltage collapse and under voltage problems may also take load shedding into consideration as a corrective measure.

In this paper, a novel approach to determine the amount of load shedding is proposed. The under voltage magnitude in a bus of interest is the flag. The idea is similar to the remote voltage control, widely employed in the literature. In that kind of control, a generator monitors the voltage level in a remote load bus. The voltage level at the load bus is known, whereas the voltage level at the generator is a state variable. The practical effect in the implementation is the replacement of a column, since the partial derivatives calculated in relation to the voltage level at the generator must be incorporated into the set of equations. In this paper, the idea is to shed load in order to maintain the voltage level in a value pre specified. Because the voltage level is known, it is removed from the set of the state variables. However, such a value is only reached as a function of a load shedding, which is considered as a state variable, according to Equation (17).

In Equation (17), H, $\tilde{N}$, M and $\tilde{L}$ are the partial derivatives of the active and reactive power equations (ΔP and ΔQ) in relation to the phase angles (Δθ) and voltage level (ΔV). $\tilde{N}$ and $\tilde{L}$ differ from the ordinary Jacobian because it does not contain the partial derivatives with respect to the voltage level at the bus controlled. The last column comes from Pk = Pko (V, θ) – ΔC and Qk = Qko (V,θ) – ΔC, where k is the bus likely to experiment load shedding (ΔC).

$$\begin{bmatrix} \Delta P \\ \Delta P_k \\ \Delta Q \\ \Delta Q_k \end{bmatrix} = \left[\begin{array}{c|c|c} H & \tilde{N} & \begin{matrix} 0 \\ \vdots \\ 0 \\ -1 \end{matrix} \\ \hline M & \tilde{L} & \begin{matrix} 0 \\ \vdots \\ 0 \\ -1 \end{matrix} \end{array}\right] \begin{bmatrix} \Delta \theta \\ \Delta V \\ \Delta C \end{bmatrix} \qquad (17)$$

Few observations about Equation (17) should be addressed: The convergence is obtained normally according to the Newton-Raphson process. No numerical problems are expected, since the set of equations is not singular.

Only the power flow equations are considered. Hence, at this stage, the quasi dynamic model is not required, even though its use causes no problem.

In this paper, load shedding is executed at the bus whose voltage level is monitored. The program, however, may handle other combinations of voltage control/load shedding with no problem.

VI. METHODOLOGY

The analysis is carried out in such a way to explore the features of the proposed methodology. In this sense, from a stable operating point, a ramp load increase is considered. Following this load increase direction, the proposed model captures the system dynamic response along the time evolution. After the ramp load increase is considered, the system long term response and load margin are calculated, so a comparison with the base case is carried out.

Along the process, some control actions, like tap blocking, shunt capacitor switch and load shedding are considered.

VII. TEST RESULTS

The system used to assess the computational tool consists of 36 buses (28 load buses and 8 generators) and 46 transmission lines. The total system load stands for 680.0 + j181.70 MVA. Such a system represents a real Brazilian system with all the machines fully detailed.

The study is carried out in two ways: first, a sequence of two steps is applied. The critical Bus 1354 is then monitored. The first part of the test is executed with no tap blocker neither load shedding considered. Fig. 2 presents the result obtained. The dotted line is associated with the full simulation, whereas the full line represents the quasi dynamic approach. Because the tap changer is still working, the solutions do not emerge into a single one, which occurs when a steady state condition is reached.

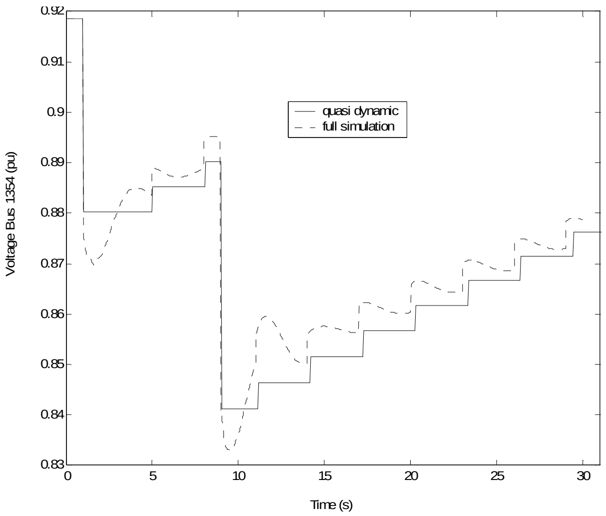

Fig. 2 – Voltage Level at Bus 1354 (step and no control)

As one can see, the voltage level obtained is not satisfactory. Even worse, this is not true even neglecting the tap limits. Now, both the tap blocker methodology presented in Section IV and load shedding in Section V are carried out. The results are displayed in Fig. 3.

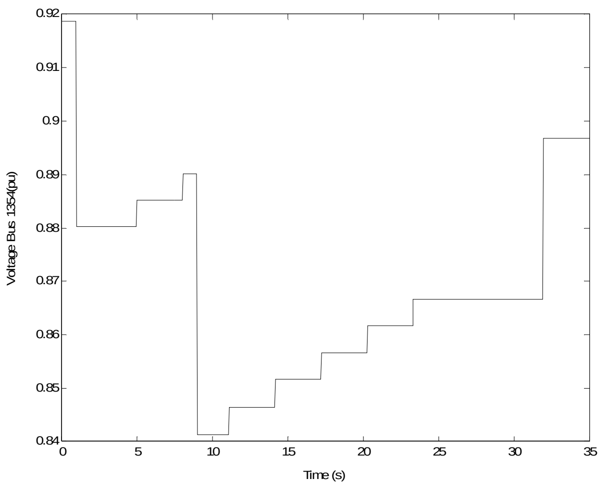

Fig. 3 – Voltage Bus 1354 -tap blocking and load shedding

From Fig. 3 one can see that the load shedding meant to bring the voltage level above 0.89 p.u. works properly for this purpose.

Now, a ramp load increase is considered. As done before, the test is executed without load shedding. However, tap blocker is scheduled to work when necessary, yielding the results of Fig. 4. Note the tap blocker working during the ramp load increase, which lasts from 1 to 10 seconds. After the ramp is over, the tap blocker works in order to restore the voltage level.

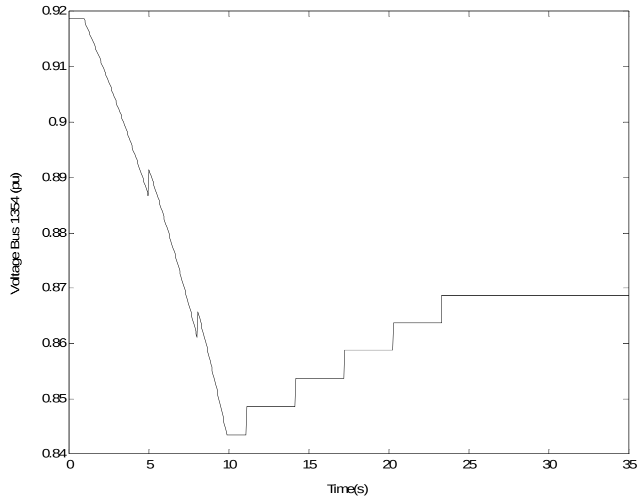

Fig. 4 – Voltage at Bus 1354 for a ramp and no controls

Once again, the tap changer is not enough to restore the voltage level. Note that at around 25s. the tap changer is blocked, keeping the voltage level close to 0.86 p.u.. In order to restore the voltage level, load shedding is now considered, generating Fig. 5.

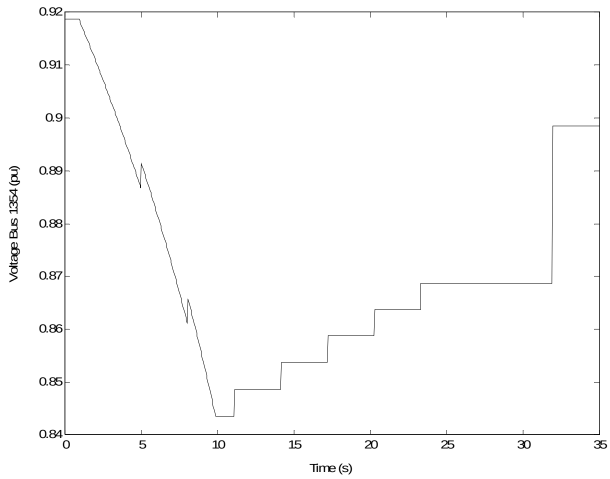

Fig. 5 – Voltage at Bus 1354 with load shedding

Note that the proposed methodology works well, keeping the system stable in an emergency condition of operation. Further controls may be incorporated into the methodology.

ACKNOWLEDGMENTS

The authors thank CNPq, Fapemig and Capes for the financial support.

VIII. References

[1] R. Deksnys and R. Staniulis, "Pricing Of Reactive Power Service", 2007 Estonian Academy Publishers, Oil Shale, 2007, Vol. 24, No. 2 Special, pp. 363-376.

[2] Federal Energy Regulatory Commission, "Principles for Efficient and Reliable Reactive Power Supply and Consumption", Staff Report, Docket No. AD05-1-000, February 4, 2005.

[3] Ismael El-Samahy, Kankar Bhattacharya, Claudio Cañizares, Miguel F. Anjos, and Jiuping Pan, "A Procurement Market Model for Reactive Power Services Considering System Security", IEEE Transactions On Power Systems, Vol. 23, No. 1, February 2008, pp. 137-149.

[4] H. D. Chiang, A. Fluak, K. S. Shah, N. Balu, "A Practical Tool for Tracing Power System Steady-State Stationary Behavior Due To Load And Generation Variations", IEEE Trans. Power Systems, vol. 10, no. 2, May 1995, pp. 623-634.

[5] R. Seydel, "From Equilibrium to Chaos-Practical Bifurcation and Stability Analysis," Elsevier Science, North-Holland, 1988.

[6] K. L. Lo, Y. A. Alturki, "Towards Reactive Power Markets. Part1: Reactive Power Allocation", IET Pro.-Generation, Transmission and Distribution, Vol. 153, No. 1, January 2006.

[7] K. L. Lo, Y. A. Alturki, "Towards Reactive Power Markets. Part2: Differentiated Market Reactive Power Requirements", IET Pro.-Generation, Transmission and Distribution, Vol. 2, No. 4, July 2008, pp. 516-521.

[8] Mevludin Glavic, Fernando L. Alvarado, "An extension of Newton–Raphson power flow problem", Applied Mathematics and Computation 186 (2007) 1192–1204.

[9] M. Stubbe, A. Bihain, J. Deuse, J. C. Baader, "STAG – A New Unified Software Program for the Study of the Dynamic Behaviour of Electrical Power Systems", IEEE Transactions on Power Systems, vol. 4, n.1, pp. 129-138, Feb. 1989.

[10] Manzoni A., Taranto G. N., Falcão D. M.: "A Comparison of Power Flow, Full and Fast Dynamic Simulations", Power Systems Computation Conference, 2002, Sevilha. Proceedings of the 14th Power Systems Computation Conference, 2002.

[11] C. Zambroni de Souza, B. Isaias Lima Lopes : "Unified Computational Tool for Transient and Long-Term Stability Studies", IET, Generation, Transmission and Distribution, Vol. 3, No. 2, pp. 173-181, Feb. 2009.

[12] Rajagopalan, C., Lesiuetre, B., Sauer, P. W., Pai, M. A.: "Dynamic Aspects of Voltage/Power Characteristics", IEEE Transactions on Power Systems, Vol. 7, pp. 990-1000, Aug. 1992.

[13] H. L. Fuller, P. M. Hirsch and M. B. Lambie : "Variable integration step transient analysis: VISTA", IEEE PICA Conf., pp. 277-284, 1973.

[14] Van Cutsem T., Vournas C. D.: "Voltage Stability Analysis In Transient And Mid-Term Time Scales", IEEE Trans. Power Syst., 1992, 11, (1), pp. 146–154.

[15] Van Cutsem T., Vournas C. D.: "Voltage Stability of Electric Power Systems", Kluwer Academic Publishers, 1998.

[16] T. Van Cutsem: "An Approach to Corrective Control of Voltage Instability Using Simulation and Sensitivity", IEEE Trans. on Power Systems, Vol. 10, No. 2, pp. 616-622, 1995.

Biographies

Valerio Oscar Albuquerque obtained his B. Eng from the Catholic University of Belo Horizonte in 1989 and his M.Sc. degree from the Federal University of Itajubá in 2002. He joined Cemig in 1986, where he works for the Planning Department. Currently he is a Ph.D. student at the Federeal University at Itajubá.

Rafael Coradi Leme received the B. Eng (2002), M.Sc. (2004) and D.Sc (2008) degrees, all in Electrical Engineering, from the Federal University of Itajubá. His area of interest lies on voltage stability analysis, dynamic systems and neural networks.

B. Isaias Lima Lopes received the B. Eng (1999), M.Sc. (2001) and D.Sc (2004) degrees, all in Electrical Engineering, from the Federal University of Itajubá. He is currently working at the Federal University of Itajuba, Brazil, as a Professor. His area of interest lies on voltage stability analysis, dynamic systems and neural networks.

Antonio Carlos Zambroni de Souza received the B.Eng. (1987), M.Sc. (1990) and Ph.D. (1995) degrees, all in Electrical Engineering, from the State University of Rio de Janeiro (UERJ), the Catholic University of Rio de Janeiro (PUC-Rio), both in Brazil, and the University of Waterloo, Canada, respectively. He is currently working at the Federal University of Itajuba, Brazil. His area of interest lies on voltage stability analysis and dynamic systems.

Rodnei Dias dos Anjos obtained his B. Eng from the Catholic University of Belo Horizonte in 1994. In 1986 he joined Cemig, where he is a Senior Engineer. He is currently a M.Sc student at the Federal University of Itajubá.

Otavio A. Salgado Carpinteiro received his Bachelor degreed in Mathematics and Music from the Federal University of Rio de Janeiro in 1980 and 1985, respectively. In 1988 he concluded his M.Sc. in Computer Engineering and his PhD in Cognitive Sciences in 1996. He is now at the Federal University of Itajubá and his areas of interest are neural network and operational systems.

Pedro P. Balestrassi received the D.Sc. degree in Industrial Engineering from the Federal University of Santa Catarina, Brazil, in 2000. Since 1994, he has been with the Federal University of Itajuba, Brazil, as Professor of Industrial Engineering. In 1998/1999, he was visitor at Texas A&M University (TX, USA) and in 2005/2006 he was visiting the University of Texas at Austin. His areas of interest lie in times series forecasting, ANN and statistics.

APPENDIX A – www.isaias.unifei.edu.br/BrazilianSystem36