Ciencia y Tecnología, 30(1): 24-40, 2014
ISSN: 0378-0524

LONG-TERM VOLTAGE STABILITY ASSESSMENT USING QUASI-STEADY STATE SIMULATION IN MATLAB

Gustavo Valverde, Eddie A. Araya-Padilla.*

Escuela de Ingeniería Eléctrica, Universidad de Costa Rica, 11501-2060 San José, Costa Rica.

Recibido febrero 2013; aceptado junio 2014

Abstract

A Quasi Steady State Simulator (QSSS) for long term voltage stability assessment has been developed, tested and verified in Matlab. Theory and modelling assumptions behind QSSS are explained, including many elements present in long term voltage stability scenarios. The software was developed to perform large contingencies for *N*-bus systems with classical representation of generators and motors in stability studies, including simple control models of Automatic Voltage Regulators (AVR), Overexcitation Limiters (OEL) and Load Tap Changer (LTC). The simulator was finally compared to full time domain simulations in small power systems, showing good accuracy and low computational efforts. It was found that QSSS is able to follow the long term evolution of voltages when the system is still short term stable after each discrete change.

Resumen

Un simulador cuasi-estacionario se desarrolló (QSSS: Quasi Steady State Simulator, por sus siglas en Inglés), probó y verificó en Matlab. La teoría y las suposiciones del modelaje detrás del QSSS se explicaron incluyendo la mayoría de elementos presentes en los escenarios de estabilidad de tensión de largo alcance. El software desarrollado para evaluar grandes contingencias, para un sistema de *N*-barras con la representación clásica de generadores y motores en los estudios de estabilidad, incluyó modelos de control sencillos de reguladores automáticos de tensión (AVR: Automatic Voltage Regulators, por sus siglas en Inglés), limitadores de sobrexcitación (OEL: Overexcitation Limiters, por sus siglas en Inglés) e intercambiadores en derivación bajo carga (LTC: Load Tap Changer, por sus siglas en Inglés). El simulador se comparó con simulaciones detalladas, en pequeños sistemas de potencia, mostrando una buena exactitud y bajo esfuerzo computacional. Se encontró que el QSSS es capaz de seguir la evolución de las tensiones en el largo plazo, cuando el sistema todavía permanece estable en el corto plazo, después de cada cambio discreto.

Key words: Voltage Stability, long-term simulations, quasi-steady state simulations, power system modelling.

Palabras clave: Estabilidad de tensión, simulaciones de largo alcance, simulaciones cuasi-estacionarias, modelaje de sistemas de potencia.

* Autor para correspondencia: gvalverde@eie.ucr.ac.cr

I. INTRODUCTION

Incidents of power system blackouts have shown the vulnerability of economic societies to failures [1], [2], [3]. As a consequence, plenty research has been carried out to find ways to reduce major effects caused by power system disturbances.

Computer simulations are carried out to study how power systems behave under contingency conditions. They are used to make decisions during the planning and operating state [4], so they have to be accurate enough to describe the system, while maintaining computational efficiency and speed.

Different simulations require large memory space and computational time to perform their calculations, especially in long term dynamic studies. Because of this, many techniques have been used to reduce computational steps based on matrix sparsity techniques, and modeling simplifications [5].

This paper focuses on a simulation tool named Quasi Steady-State Simulation (QSSS) and it is used for long term voltage stability assessment [6]. The main benefit of QSSS is the substantial reduction of computational effort without compromising significant accuracy of long term simulations. This paper presents the methodology of QSSS and the required equations to develop the software in Matlab.

In the Quasi-Steady State approach, time domain simulations are simplified by replacing the short term dynamics by their equilibrium points. In fact, the method concentrates on long term instability mechanisms driven by long term equipment actions.

The first part of this paper provides an introduction to voltage stability including definition and classification stated in the open literature. Then, long term voltage stability assessment is briefly explained with an explanation of the quasi-steady state methodology. Assumptions and simplifications for equipment such as generators, motors and loads are then presented including control actions of Automatic Voltage Regulators (AVR), Overexcitation Limiters (OEL) and Load Tap Changer (LTC) Transformers. Finally, the validation of the software is carried out for two small power systems comparing the simulator results with full time simulations in IPSA+, a commercial software package.

II. LITERATURE REVIEW

Voltage Stability

Power systems stability concerns with the ability of a power system to remain in equilibrium operation when subjected to disturbances. To have a better understanding, system stability was classified into three categories according to physical nature: rotor angle, frequency or voltage stability [7]. This paper focuses on the latter one.

A. Definition and Classification

There are multiple and similar definitions for voltage stability, but they usually refer to the ability of a power system to maintain voltages within permissible values in all buses under normal operating conditions or after being subjected to a disturbance. In other words, a post-disturbance system is considered voltage stable if voltages near loads are similar to the initial conditions [1], [7].

Depending on the severity of the disturbance, voltage stability is classified into large-disturbance and small-disturbance voltage stability [2]. The first one corresponds to circuit outages, loss of generations or short circuits and the latter one is related to small perturbations in the system such as incremental changes in system loads.

The absence of voltage stability is known as voltage instability, which occurs when load restoration draws more power than the capability of the transmission and generation system [6]. It is characterized as an aperiodic and progressive decrease (or rise) of voltages in a portion of the system.

Several factors contribute to voltage instability including [1], [2]:

- Large loading conditions of transmission systems
- Low voltage profile
- Voltage sources far from load centres
- Insufficient reactive sources on load buses

Apart from these factors, extensive use of shunt capacitors to increase power transfer makes the system to operate closer to the maximum deliverable power. As a consequence, the stability margin is reduced in case of contingencies [1], [6].

Increase or loss of extensive loads, change of power transfers from/to other areas and element tripping by protective devices are typical causes of voltage instability. However, there is the possibility of having progressive voltage drops due to rotor angle instability.

The term voltage collapse is associated with voltage instability and is defined in [7] as the "*process by which the sequence of events accompanying voltage instability leads to a blackout or abnormally low voltages in a significant part of the system.*"

During a disturbance, the major problem faced by power system operators is the load recovery (motors, LTCs and thermostatic actions), which increases power consumption during emergency conditions, leading to reduced voltages in the transmission system. In fact, reference [1] describes voltage stability as load stability to point out how load characteristics dominate on system voltage behavior.

B. Time Frame Division

Voltage instability can last from few seconds to several minutes. Some devices respond faster than others according to their time constants. Hence, a time frame division was established for voltage stability assessment.

Different authors classified voltage stability into three scenarios short, mid and long term stability. However, the tendency is now to combine mid and long term stability into one single group.

Short term covers scenarios up to few seconds after a disturbance. At this stage, short term dynamic load components restore their power in few seconds [6]. Here, modeling requirements are similar to rotor angle stability since the time scale is the same for both of them. In fact, many times instability mechanisms are combined between voltage and rotor angle phenomena [1], [7]. The set of equations which models this period can be grouped as [6], [8]:

$$\mathbf{0} = \mathbf{g}(\mathbf{x}, \mathbf{y}, \mathbf{z}_{\mathrm{c}}, \mathbf{z}_{\mathrm{d}}) \tag{1}$$

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{y}, \mathbf{z}_{\mathrm{c}}, \mathbf{z}_{\mathrm{d}}) \tag{2}$$

where (1) represents the network relationships (i.e. power flow equations) and (2) represents the short term dynamics of AVRs, generators, SVCs, motors, HVDC components, etc.

Algebraic variables are grouped in vector $\mathbf{y}$ and state variables in vector $\mathbf{x}$. In addition, $\mathbf{z}_{\mathrm{c}}$ and $\mathbf{z}_{\mathrm{d}}$ correspond to state vectors of discrete and continuous long term dynamics, respectively.

Long term scenarios involve slower acting equipment actions such as LTCs, thermostatically controlled loads and generator over-current limiters. This kind of controllers and protective devices are designed to act when short-term actions have passed out. This is to avoid unnecessary actions or interaction of many controllers that may lead to unstable operation of the system [6].

In some cases, static analysis is enough to predict system stability. Other times, when timing of equipment actions is a concern, time domain simulations have to be carried out.

Long term dynamics are represented by [6], [8]:

$$\dot{\mathbf{z}}_{\mathrm{c}} = \mathbf{h}_{\mathrm{c}}(\mathbf{x}, \mathbf{y}, \mathbf{z}_{\mathrm{c}}, \mathbf{z}_{\mathrm{d}}) \quad (3)$$

$$\mathbf{z}_{\mathrm{d}}(k+1) = \mathbf{h}_{\mathrm{d}}(\mathbf{x}, \mathbf{y}, \mathbf{z}_{\mathrm{c}}, \mathbf{z}_{\mathrm{d}}(k)) \quad (4)$$

where the set of equations in (3) represent the behavior of equipment such as thermostatic and recovery of aggregated load and (4) represent discrete transitions due to control, protecting and limiting devices.

Long Term Voltage Stability Assessment

Long term voltage stability concerns with outages of equipment and not by the severity of the initial disturbance [7]. This is, post-contingency analysis becomes critical to judge whether an equilibrium condition is reached or not. The most common methods used for contingency analysis are post-contingency load flow, P-V & V-Q curves, and time domain simulations.

A. Post-Contingency Load Flow

Post-contingency load flow is the simplest and well known methodology to evaluate the impact of contingencies in power systems [6], [9]. The method consists on performing power flow simulations under certain outages due to a given disturbance. The goal is to find the post-disturbance equilibrium points.

In the case that long term equilibrium condition is not reached, the numerical solver will diverge implying the system is not stable for such outages. However, divergence can be reached with the numerical method if the system is close to maximum power transfer (even when a stable equilibrium point exists). Nowadays power flow programs are able to converge close to this maximum operating point using "non divergence" techniques [10]. However, these methods do not provide enough information about the nature and location of the problem. In fact, some assumptions may not reflect the real conditions of the system.

B. P-V and V-Q Curves

These curves are based on power flow techniques and they are widely used because of their simplicity and the relevant information they may provide.

The methodology to build P-V curves consists of increasing the power transfer from one area to another while sensing the voltage at critical buses. The main information provided by this approach is the maximum transferable power before system collapses. However, the disadvantage of P-V curves is the problem of divergence when maximum power transfer is close to occur. This problem could be solved applying *continuation power flow* techniques.

In the case of V-Q curves, they are fast when processed automatically without problems of convergence [10]. The method consists of installing a fictitious synchronous condenser at the critical bus recording the reactive power produced as voltage changes. It means, voltage magnitude at the new PV bus is the independent variable and the reactive power injection at the same bus is the dependent variable.

V-Q curves provide information of the amount of shunt compensation needed at a specific bus [6]. However, the allowable power loading is not directly given with V-Q curves and they do not give information of the global optimal compensation needs. In addition, timing actions of protective and control devices are not considered [10].

The disadvantages described before leads to the necessity of better techniques to assess post-disturbance system behaviour.

C. Full Time Domain Simulations

The most accurate method to assess longer term voltage stability is full time domain simulations. In fact, it is considered the benchmark to verify post contingency power flow based simulations [10]. Here exists the possibility of studying other instability mechanisms not captured by steady state methods.

Time domain simulations have the posibility to predict the time available for operator actions. In addition, it is able to simulate LTC transformers, dynamic loads, over-excitation/armature limiters and capacitor switching based on time delay settings. These simulations require higher computational efforts due to more accurate model requirements and the application of numerical integration for large set of differential-algebraic equations.

D. Quasi-Steady State Simulations

Since full time domain simulations are difficult to process, it is possible to simplify long term instability analysis by replacing short term dynamics by their equilibrium points [6].

Quasi-steady state approach is based on the latter technique in which short term dynamics are considered infinitely fast that can be represented by their equilibrium equations [3], [6], [11], [12].

It means that the set of equations in (2), representing dynamics of generators, motors and AVRs, are now equalized to zero. The new set of equations for QSSS is given by equations (1), (3), (4) and now equation (5):

$$\mathbf{0} = \mathbf{f}(\mathbf{x}, \mathbf{y}, \mathbf{z}_{\mathrm{c}}, \mathbf{z}_{\mathrm{d}}) \qquad (5)$$

This technique has the advantage of having fast and good convergence performance. In addition, it maintains the accuracy of full time domain simulation because it takes into account limiters and control actions [11]. In fact, it has been used for security limit determination, real time applications and training simulations [12].

A QSSS sketch is presented in Figure 1. After a disturbance, the new equilibrium point is calculated based on the pre-disturbance condition. Transitions from A to A` (B to B`) corresponds to discrete equipment actions such as LTC or over-excitation limiters in generators.

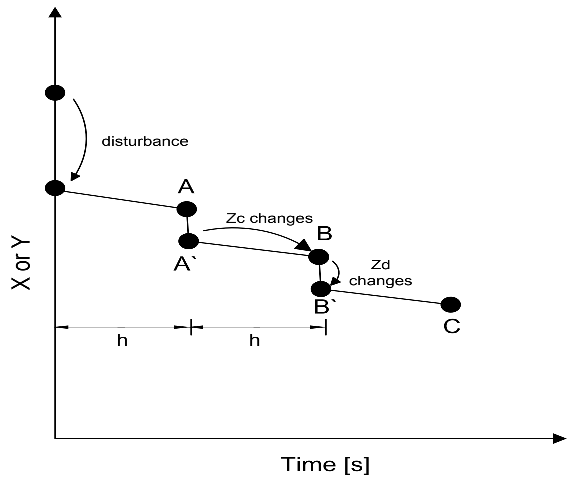

FIGURE 1. Steps involved in QSS method [6]

Evolution from A` to B (B` to C) is obtained integrating the long term dynamics equations of loads. In case that loads are 100% static, transitions from A` to B are straight lines parallel to axis x. The time step h is usually specified constant. The various discrete devices are checked on each time step and then switched when their internal delays are reached [6].

Equilibrium points A`, B`, C` at time $n+1$ are calculated from initial guess of A, B, C at time n. The solution is reached by applying the Newton method.

Mathematically,

$$\begin{bmatrix} \mathbf{x}_{n+1}^{(0)} \\ \mathbf{y}_{n+1}^{(0)} \end{bmatrix} = \begin{bmatrix} \mathbf{x}_n \\ \mathbf{y}_n \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} \Delta\mathbf{x}_{n+1}^{(k+1)} \\ \Delta\mathbf{y}_{n+1}^{(k+1)} \end{bmatrix} = -\begin{bmatrix} \frac{\partial \mathbf{f}}{\partial \mathbf{x}} & \frac{\partial \mathbf{f}}{\partial \mathbf{y}} \\ \frac{\partial \mathbf{g}}{\partial \mathbf{x}} & \frac{\partial \mathbf{g}}{\partial \mathbf{y}} \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{f}(\mathbf{x}_{n+1}^{(k)}, \mathbf{y}_{n+1}^{(k)}) \\ \mathbf{g}(\mathbf{x}_{n+1}^{(k)}, \mathbf{y}_{n+1}^{(k)}) \end{bmatrix} \tag{7}$$

The superscript denotes the k-th iterative step and the subscript indicates the variable value at time $n+1$. It is important to note that the Jacobian matrix in (7) is different from the Jacobian used in the power flow calculation due to the addition of the short term equilibrium equations [13].

In order to reduce computational effort, the "very dishonest" Newton method can be deployed. Here, the Jacobian matrix is updated only for equipment outages, limiter actions or in cases where slow convergence is detected. However, smooth changes of long term dynamic equations, changes in transformer ratios or variations in susceptances do not trigger Jacobian updates [14].

Since short term dynamics are assumed to be stable, the QSS methodology is not able to follow the system evolution as soon as system loses stability. At this point there is no convergence and the equilibrium condition is not found anymore. This becomes the main limitation of the method. However, as soon as convergence is lost, it is concluded that an instability mechanism has occurred.

Figure 2 summarizes the QSSS procedure involving the disturbance, equilibrium points, integration (if any) and discrete transitions.

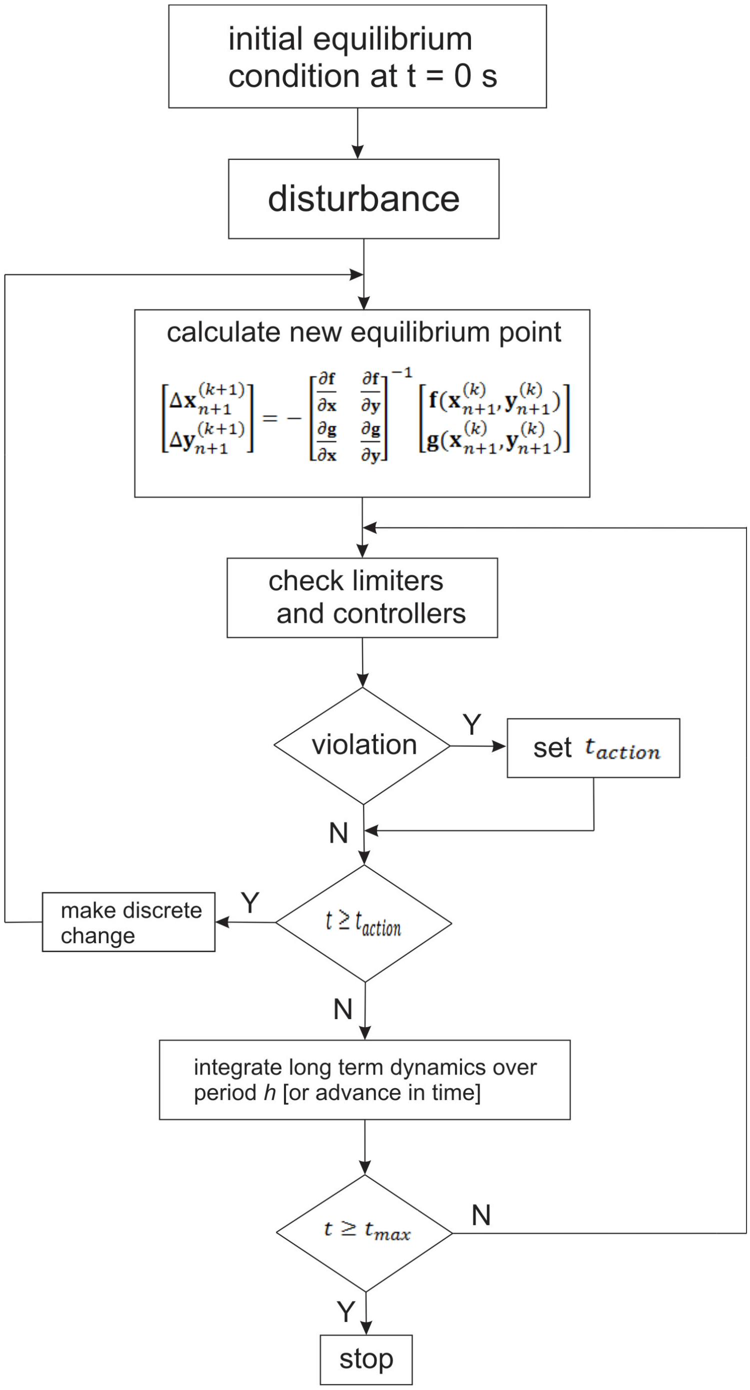

FIGURE 2. Flow Chart for QSS Simulation

The simulator will not converge if no equilibrium point exists. Hence, an instability condition is detected.

III. MODELLING REQUIREMENS FOR QSSS

Adequate modelling becomes essential for power flow, full time simulations and simplifications such as QSSS. The following sections describe characteristics and modelling of system equipment and some control devices that participate on long term voltage stability.

A. Network Representation

For simplicity reasons, the equivalent π circuit represents passive elements such as transmission lines, cables, power transformers and some other series elements.

By using the polar form of voltages and the corresponding conductance G and susceptance B from the admittance matrix, it is possible to obtain the voltage (V) - currents (I_P, I_Q) relationships for bus i as:

$$I_{P_i} = \sum_{j=1}^{N}(G_{ij}V_j\cos(\theta_i - \theta_j) + B_{ij}V_j\sin(\theta_i - \theta_j)) \tag{8}$$

$$I_{Q_i} = \sum_{j=1}^{N}(G_{ij}V_j\sin(\theta_i - \theta_j) - B_{ij}V_j\cos(\theta_i - \theta_j)) \tag{9}$$

where V_i and θ_i are the voltage magnitude and angle at bus i. Equations (8) and (9) are classified as algebraic equations represented by the generic expression in equation (1).

B. Synchronous Generator

The synchronous machine is represented by three reactances (x_q , x_d , x'_d) and the open-circuit transient time constant T'_{d0}. In this simplified representation, only two differential equations are used to model the dynamics of the synchronous machine:

$$\dot{E}'_q = \frac{1}{T'_{do}}(v_{fd} - (x_d - x'_d)i_d - E'_q) \tag{10}$$

$$\dot{\omega} = \frac{\omega_0}{2H}(P_m - P_e) \tag{11}$$

Equation (10) corresponds to the dynamics of the field flux, expressed in terms of the emf behind transient reactance E'_q. Here, v_{fd} is the applied voltage in the field winding and i_d is the d-axis current, in p.u.

Equation (11) corresponds to the dynamics of the rotor speed ω, expressed in terms of the mechanical power P_m and the electrical power P_e, both in p.u. In addition, ω_0 is the nominal angular speed in rad/s and H is the inertial constant in s.

In this paper, a linear AVR model is used, represented by:

$$\dot{v}_{fd} = \frac{1}{T}(-v_{fd} + K(V_{ref} - V - x_{oel})) \tag{12}$$

The field voltage is changed to maintain the machine terminal voltage V close to the set point V_{ref}, according to the gain value K. Signal x_{oel} corresponds to the over excitation limiter output that will be explained in the following sections.

Equations (10)-(12) correspond to the short term differential equations of the synchronous machine that are going to be equalized to zero in QSSS [6], [12]. If saturation is considered, it is necessary to include another algebraic equation to model its effect.

If saturation is included, each generator will have three equilibrium equations in the form of equation (5) with three state variables: E_q the machine internal voltage, E_q^s the saturated internal voltage and the power angle δ . Thus, for a given generator with terminal voltage V under no OEL action, the corresponding equilibrium equations are:

$$0 = E_q - K(V_{ref} - V) \tag{13}$$

$$0 = P_m - P_e \Rightarrow P_m - VI_{P_g} = 0 \tag{14}$$

Note that v_{fd} has been replaced by E_q (this is true in p.u. in exciter base [6]). Hence, equation (13) corresponds to the AVR equilibrium and equation (14) corresponds to the equilibrium of the rotor speed.

The remaining equation must provide a relationship of saturation between E_q and E_q^s. Using modelling assumptions provided in [6], it is possible to obtain:

$$0 = E_q - (1 + m[\left(V + x_l I_{Q_g}\right)^2 + \left(x_l I_{P_g}\right)^2)]^{n/2})E_q^s \tag{15}$$

where x_l is the stator leakage reactance and constants m and n are used to model the machine saturation.

Generator currents I_{P_g} and I_{Q_g} in equations (14) and (15) must be in terms of algebraic and state variables:

$$I_{P_g} = \frac{E_q^s E_q}{x_l E_q + (x_d - x_l) E_q^s} \sin(\delta - \theta) + \frac{VE_q}{2}\left(\frac{1}{x_l E_q + (x_q - x_l) E_q^s} - \frac{1}{x_l E_q + (x_d - x_l) E_q^s}\right) \sin 2(\delta - \theta) \tag{16}$$

$$I_{Q_g} = \frac{E_q^s E_q}{x_l E_q + (x_d - x_l) E_q^s} \cos(\delta - \theta) - VE_q\left(\frac{\sin^2(\delta - \theta)}{x_l E_q + (x_q - x_l) E_q^s} + \frac{\cos^2(\delta - \theta)}{x_l E_q + (x_d - x_l) E_q^s}\right) \tag{17}$$

where θ is the terminal voltage angle with respect to the system reference.

C. *Static Loads*

Aggregated loads are classified as static loads when their response to changes in voltage or frequency is so fast that a new steady state is reached very quickly [2]. In fact, most aggregated loads are considered static loads.

The most common model for static loads as a function of voltage is the *exponential model.* Another widely used representation of loads is the *ZIP* or *polynomial model* where loads are represented by a composition of constant power, impedance and current loads.

In terms of network representation, static loads are handled as negative injected currents in equations (8) and (9), using the exponential modelling:

$$I_{P_L} = -P_0 \frac{V^{\alpha-1}}{V_0^{\alpha}} \tag{18}$$

$$I_{Q_L} = -Q_0 \frac{V^{\beta-1}}{V_0^{\beta}} \tag{19}$$

where P_0 and Q_0 are the pre-disturbance active and reactive power demand. In addition, parameters α and β characterize the voltage dependency of loads. More detailed static load models integrate the effect of frequency but in this QSSS these models are not considered since frequency is assumed constant during the simulation period.

D. Induction Motors

The main assumption for motor modelling is that stator and rotor transients are neglected. In fact, the rotor acceleration equation is the only dynamic representation of the machine:

$$\dot{s} = \frac{1}{2H}\left(T_e(V, s) - T_m(s)\right) \tag{20}$$

where s is the rotor slip, T_e and T_m are the electrical and mechanical torque respectively, whereas H is the machine inertia in seconds. The mechanical torque could be represented with a constant, quadratic or higher order model.

Induction motors are considered short-term dynamic loads and they are replaced by their equilibrium equations in QSSS. So, the equilibrium equation for an induction motor is:

$$0 = T_m(s) - \frac{V^2 x_m^2 \frac{r_r}{s}}{\left(\left(r_1 + \frac{r_r}{s}\right)^2 + (x_1 + x_r)^2\right)\left(r_s^2 + (x_s + x_m)^2\right)} \tag{21}$$

where x_s, x_m and x_r are the stator, magnetizing and rotor reactance referred to the stator. In addition, r_s and r_r are the stator and rotor resistance referred to the stator. If core losses are neglected:

$$r_1 + jx_1 = \frac{jx_m(r_s + jx_s)}{r_s + j(x_s + x_m)} \tag{22}$$

Equation (21) belongs to the group of equations of the form equation (5). Here the short term state variable in equations (1) – (5) is the rotor slip s.

Finally, the expressions of injected currents to be included in (8) and (9) are:

$$I_{P_m} = -\frac{(r_s + r_e)\mathrm{V}}{(r_s + r_e)^2 + (x_s + x_e)^2} \tag{23}$$

$$I_{Q_m} = -\frac{(x_s + x_e)\mathrm{V}}{(r_s + r_e)^2 + (x_s + x_e)^2} \tag{24}$$

$$r_e + jx_e = \frac{jx_m\left(\frac{r_r}{s} + jx_r\right)}{\frac{r_r}{s} + j(x_r + x_m)} \tag{25}$$

E. Over-Excitation Limiters

Under normal conditions, the OEL is not activated. However, when the field current i_{fd} exceeds i_{fd}^{lim} after some delay, the output x_{oel} will introduce a signal in the AVR to reduce the field voltage (and the field current), as shown in equation (12).

Dynamics of OEL are actually not seen in QSSS but its effect is considered in the simulation as a discrete event. However, the timer must be included in the QSS formulation to know the moment at which the OEL will operate. If the OEL is considered to have an integral control:

$$0 = E_q - i_{fd}^{lim} \tag{26}$$

At this point, expression in equation (13) no longer holds and it has to be replaced by equation (26).

F. *Armature Current Limiters*

The armature current limiter is used to protect the stator windings. It commonly operates when the OEL actions lead to high armature currents in generators under large loading conditions [13]. As a result, the reactive power support of the generator is reduced even more. After some time delay, the armature current limiter ensures that:

$$I_{Q_g} \leq \sqrt{I_{max}^2 - I_{P_g}^2} \tag{27}$$

Under armature current limiter actions, equation (17) representing the generator reactive current is thus replaced by equation (27). This action is considered again as a discrete event for QSSS purposes.

G. *Load Tap Changer Transformers*

Transformers with the ability of voltage regulation dominate long term voltage instability. An LTC is a slowly acting device that controls the distribution side voltage of the transformer. The LTC performs a tap change if the controlled voltage remains outside of a dead-band for longer than a predefined delay.

In terms of modelling, the equivalent π representation of Figure 3 is used.

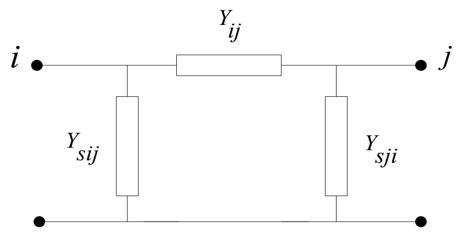

FIGURE 3. π representation for transformer modelling

For a turn ratio r and equivalent impedance Z_T [2]:

$$Y_{ij} = \frac{1}{rZ_T} \tag{28}$$

$$Y_{sij} = \left(\frac{1}{r} - 1\right)\frac{1}{rZ_T} \tag{29}$$

$$Y_{sji} = \left(1 - \frac{1}{r}\right)\frac{1}{Z_T} \tag{30}$$

Under large disturbances, LTC transformers start to change the tap positions to maintain load voltages. An important effect of LTC actions is the inclusion of an indirect load recovery mechanism, which reduces the possibility of long term equilibrium.

IV. RESULTS AND DISCUSSION

The QSS simulator developed in Matlab is now used to assess the long term stability of two small power systems. The first system studied was introduced in [6] and the second system is described in [1] and [2]. These small systems are suitable for the validation of the simulator since they provide most components involved in long term voltage stability.

Even when some load and control models were changed according to the interest of this paper, the topology of the systems remain the same.

Full time domain simulations (FTDS) were carried out with the software IPSA+ to compare the results of the QSSS in Matlab.

A. Test System 1

The system presented in Figure 4 is assessed for the outage of one line between buses 1 and 4. The equivalent system is modelled as an infinite bus and it is used as the system reference. The generator at bus 2 is controlled with an AVR and its field current winding is limited by an OEL.

The system parameters and all other data necessary to perform the studies are presented in [6]. The only difference is that load at bus 3 is composed by an equivalent induction motor drawing 550 MW (constant torque model) and an aggregated static load consuming 900 MW and 450 MVar with a constant impedance characteristic. Additionally, the capacitor connected at bus 3 is rated at 6.586 p.u.

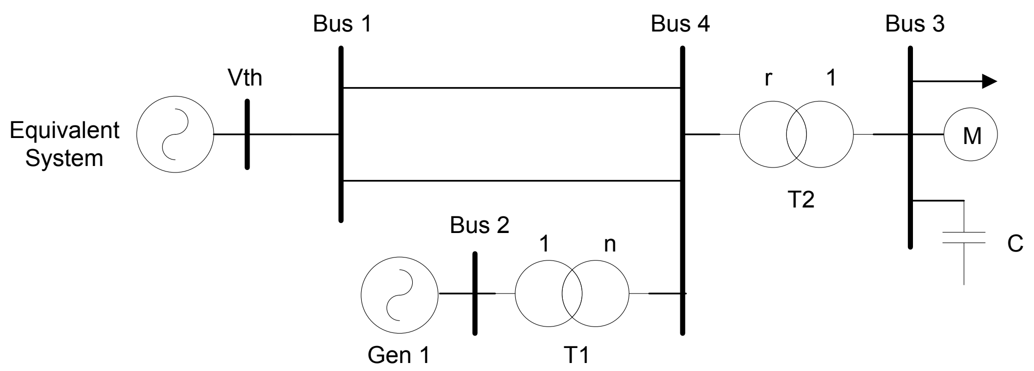

FIGURE 4. Test System 1

When the contingency is applied (outage of line 1-4), the voltage in the system drops instantaneously. Then, after some time delay the LTC tries to recover the voltage at bus 3. By doing so, there is a load recovery and a reduction in the transmission side voltage, as more reactive power is needed at bus 4. Figures 5 and 6 show the effect of the LTC in the distribution and transmission side during the first seconds of simulation.

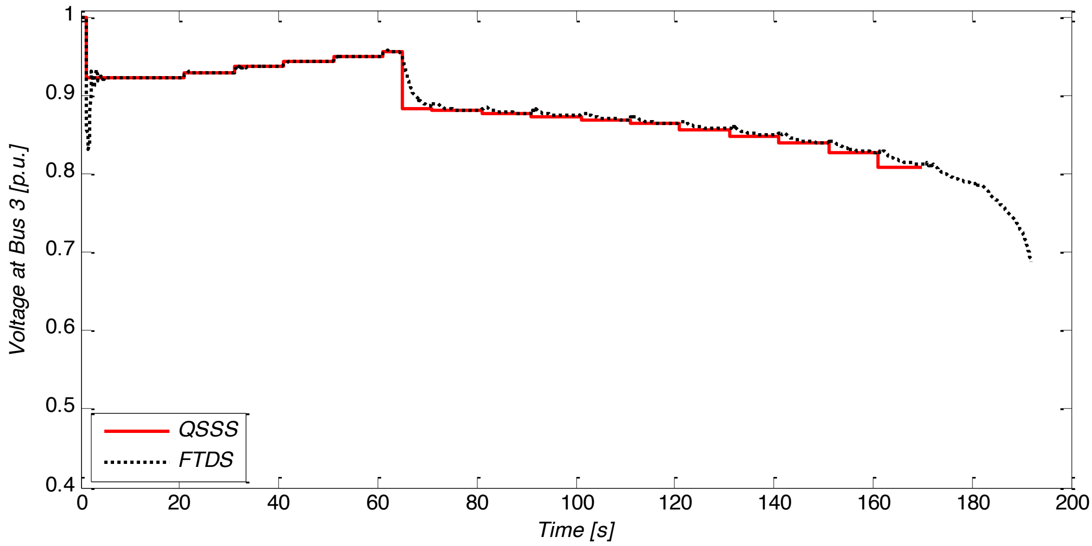

FIGURE 5. Voltage at bus 3.

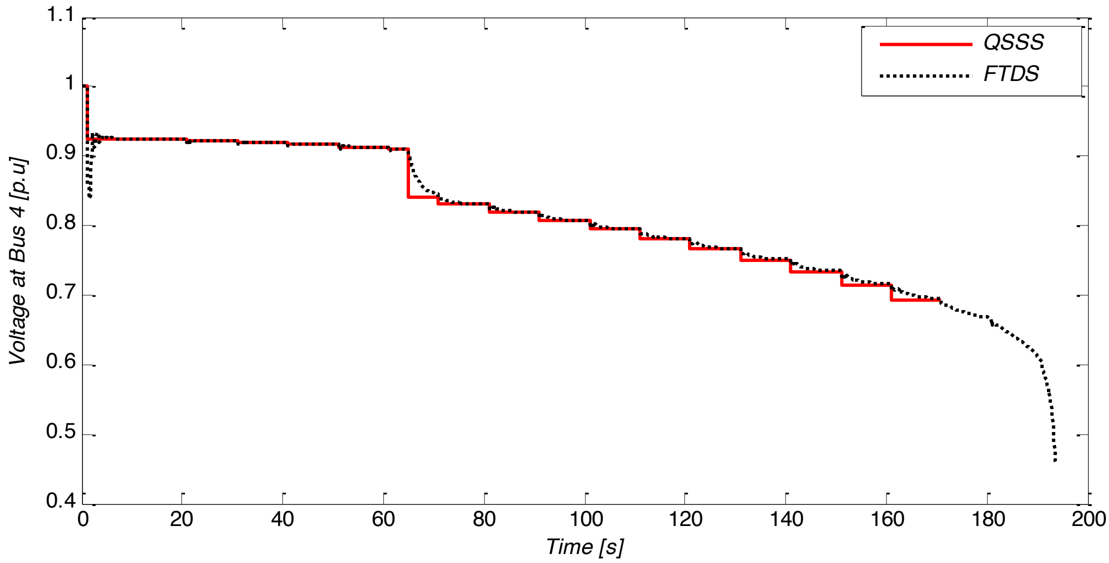

FIGURE 6. Voltage at bus 4.

Generator 1 mainly gives the reactive power needed at bus 4. However, as soon as the OEL is activated at about 61 seconds, the system loses reactive power support and all voltages start to decrease at each tap change. This behaviour continues until equilibrium is lost and the system finally collapses.

A short term instability condition is presented in the long term as the reduction of voltages makes the motor to lose equilibrium. In fact, the motor ends standstill as the system collapse. This is presented in Figure 7. Here, the QSSS shows a good approximation of the motor slip as long as the system remains in equilibrium.

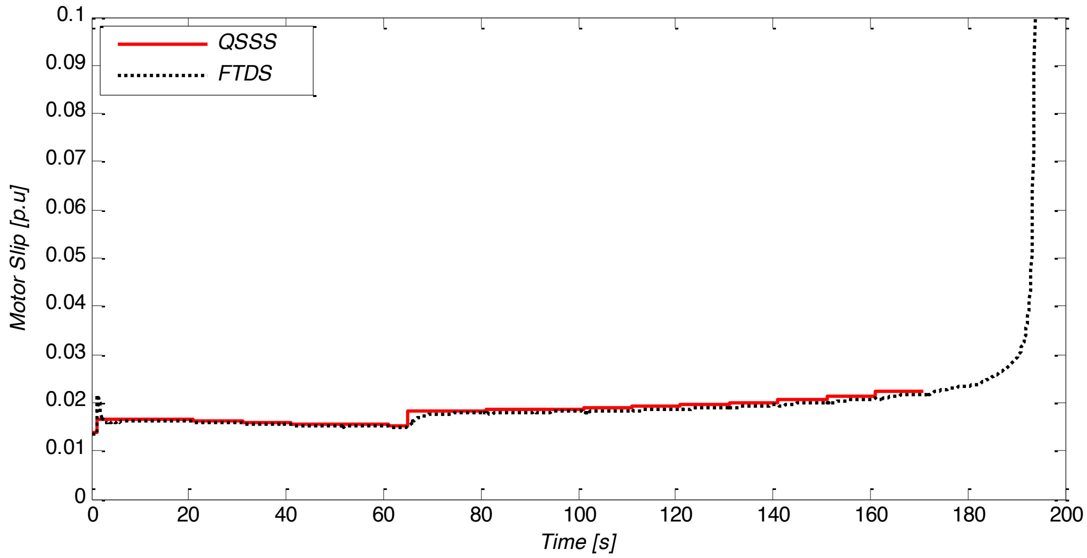

FIGURE 7. Motor Slip evolution.

In terms of QSSS, the method is not able to follow the instability condition. Instead of that, the QSS method detects a singularity in the Jacobian matrix confirming that the system is no longer stable.

As a consequence, the QSSS stops at 170 seconds of simulations and can not continue any longer. It is important to note that the QSSS loses some accuracy, as the instability condition is about to happen.

However up to this point, the QSSS already predicted the unstable condition and provided some information that a short term instability mechanism occurred. In addition, considering the fact that the time step used in QSSS was one second, and the computational time to obtain such plots was significantly lower compared to FTDS, it is concluded that QSSS is an accurate approximation even when dynamic loads are included in the study.

B. Test System 2

The 10-bus system in Figure 8 is also considered to validate the program. The outage of two transmission lines is going to be simulated by using QSSS and FTDS.

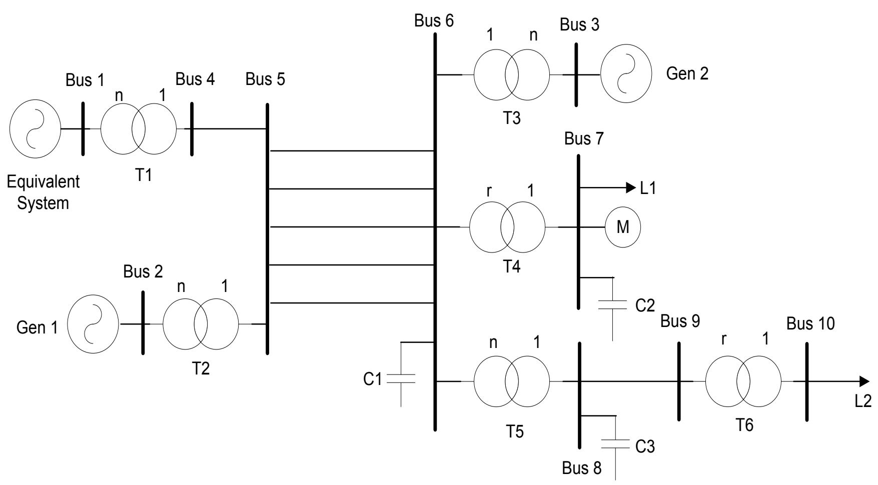

FIGURE 8. Test System 2

As the previous system, there is an equivalent system modelled as an infinite bus, which is used as the system reference. In addition, there are 2 generators, controlled by AVR and OEL, supplying part of the loads.

The system parameters and all other data necessary to perform the studies are presented in [2]. The main difference deals on the model of the AVR and OEL. These models were the same as system 1, detailed in [6].

There is an equivalent induction motor drawing 771 MW at bus 7. This motor is connected with a constant impedance load of 2500 MW and 544 MVAr. Transformers T4 and T6 are able to control the load voltage by changing their tap positions with different time delays.

The outage of a double circuit between buses 5 and 6 makes the LTC at T4 and T6 to operate after some time delay. However, the disturbance is so severe that T6 reaches its minimum limit in less than 100 seconds without recovering the voltage at bus 10, as shown in Figure 9.

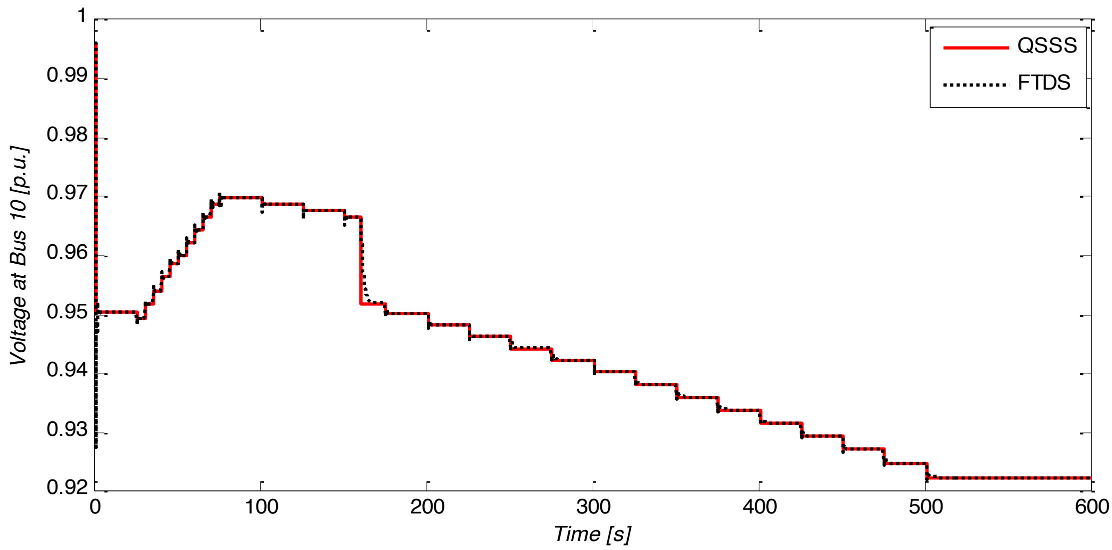

FIGURE 9. Voltage at bus 10.

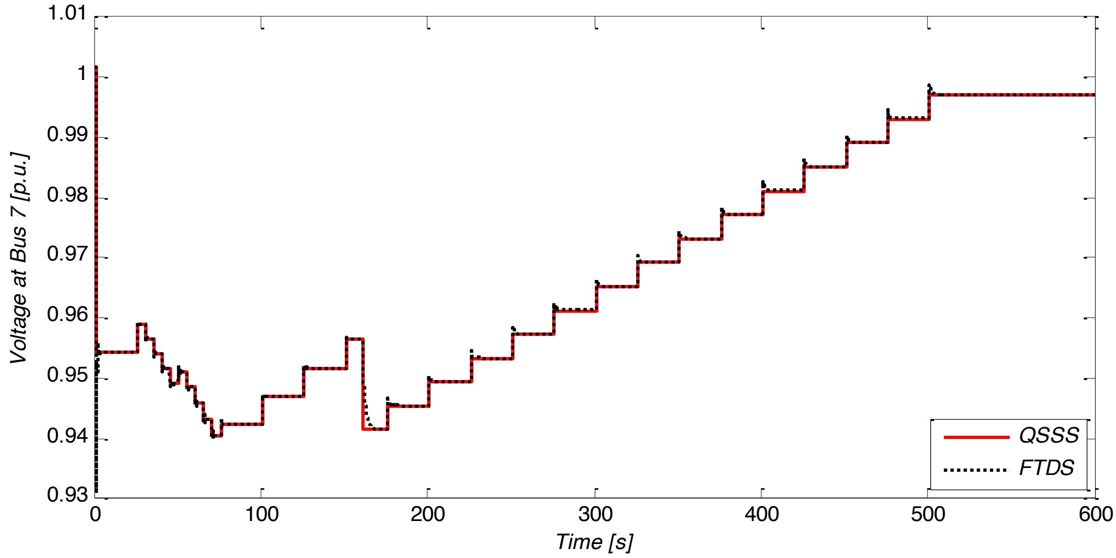

FIGURE 10. Voltage at bus 7.

Figure 10 shows the voltage recovery at bus 7. The voltage is recovered even after the OEL of generator 2 limited the field current (at about 160 seconds). Moreover, the actions performed by the LTC of T4 affected negatively the voltage at the distribution branch feeding load L2 as presented in Figure 9.

This case is a typical long term phenomenon where the actions of tap changers and generators limiters lead to unacceptable voltages in parts of the network. Figure 11 presents the voltage evolution in the transmission side.

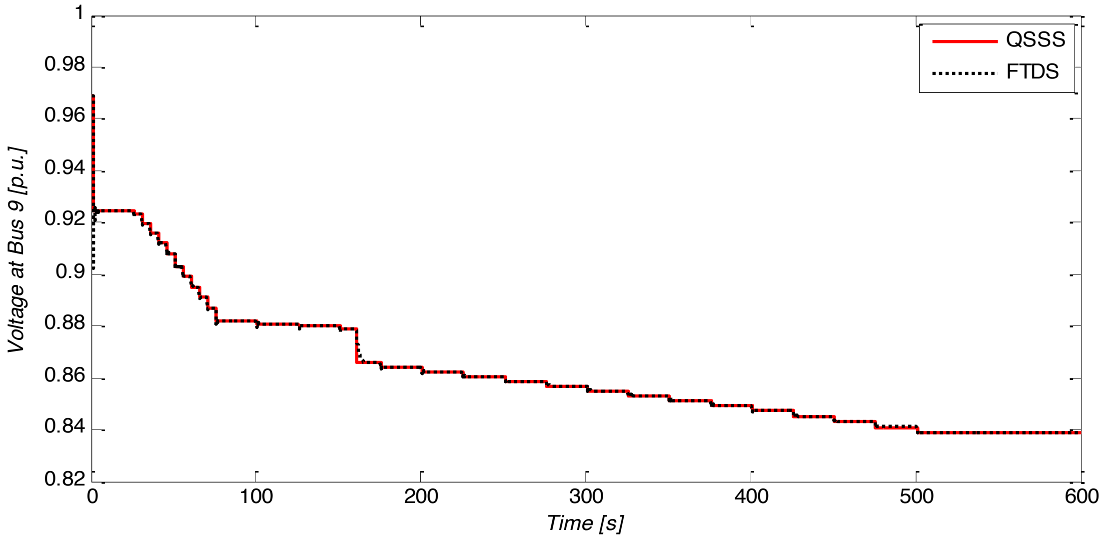

FIGURE 11. Voltage at bus 9. Transmission side.

After the entire tap changes and the OEL actions, the system ends up in unacceptable conditions (unstable) as transmission system operates at voltages below 0.9 p.u. In real cases, this situation could lead to outages of further elements due to under voltage limiters. As a consequence, a total black out may occur.

It is confirmed that the QSS simulator is able to represent the interaction of LTC actions with an excellent accuracy and low computational time.

Another factor to be considered is the computational time required on each simulator. For about 600 seconds of simulation in the 10-bus system, FTDS takes more than 20 seconds whereas the QSSS takes less than one second.

V. CONCLUSION

Quasi-Steady State simulation resulted in a good balance between simplification, efficiency and accuracy. Different comparisons verified the excellent approximation of the method. The full time domain and the QSS simulation results were almost the same.

QSSS was found to have a great performance to analyse long term voltage stability scenarios. In fact, at scenarios considering 500 seconds or more, the simulator kept the accuracy even when the time step was one second (or larger). However, when the system was close to become unstable, the method was not able to follow the full time domain simulation as convergence problems were faced at this point.

The accuracy and fast performance of this methodology can be successfully applied in real-time simulations or during planning stages for large power systems.

VI. REFERENCES

[1] Taylor, C.W., *Power System Voltage Stability*, McGraw-Hill: USA, 1994, pp. 18-40.

[2] Kundur, P., *Power System Stability and Control*, McGraw-Hill: USA, 1994, pp. 959-1022.

[3] Ajjarapu, V., *Computational Techniques for Voltage Stability Assessment and Control*, Springer: USA, 2006, pp. 15-25.

[4] Soman, S.A.; Khaparde, S.A.; Pandit, S., *Computational Methods for Large Sparse Power System Analysis*, Kluwer Academic Publishers: USA, 2002, pp. 22-45.

[5] Roytelman, I.; Shahidehpour, S.M. "A comprehensive long term dynamic simulation for power system recovery," *IEEE Trans. on Power Systems*. **1994,** 9, 1427-1433.

[6] Van Cutsem, T.; Vournas, C., *Voltage Stability of Electric Power Systems*, Kluwer Academic Publishers: USA, 1998 pp. 47-298.

[7] IEEE/CIGRE Joint Task Force on Stability Terms and Conditions, "Definition and Classification of Power System Stability," *IEEE Trans. on Power Systems*. **2004**, 19, pp. 1387-1401.

[8] Loud, D.; Rousseaux, P.; Lefebvre, D; Van Cutsem, T., "Time Scale Decomposition-Based Simulation Tool for Voltage Stability Analysis," *in Proc. IEEE Power Tech Conf.* ***2001***, pp. 1-6.

[9] Van Cutsem, T., Moisse, C. Mailhot, R., "Determination of Secure Operating Limits with Respect to Voltage Collapse": *IEEE Trans. on Power Systems.* **1999**, 14, pp. 327-335.

[10] Chowdhory, B.; Taylor, C.W, "Voltage Stability Analysis: V-Q Power Flow Simulation versus Dynamic Simulation" *IEEE Trans. on Power Systems*. **2000**, 15, pp. 1354-1359.

[11] Ning, A.; Shuangsi, Z.; Lingzhi, Z., "Power System Voltage Stability Limits Estimation Based on Quasi-Steady State Simulation" *IEEE International Conf on Power System Technology*. **2006**, pp. 1-7.

[12] Rousseaux, P., Van Cutsem, T., "Quasi-Steady State Simulation Diagnosis Using Newton Method with Optimal Multiplier" *IEEE Power Engineering Society General Meeting*. **2006,** pp. 1-7.

[13] Dong, F; Crow, M; Chowdhory, B.; Acar, L., "Mid-Term Voltage Stability Study Using the Quasi-Steady State Analysis Method" *on IEEE Power Engineering Society General Meeting*. **2003**, pp.1-6.

[14] Van Cutsem, T. ; Jacquemart, Y ; Marquet, J-N.; Pruvot, P. "A Comprehensive Analysis of Mid-Term Voltage Stability," *IEEE Trans. on Power Systems*. **1995,** 10, pp. 1173-1182.