International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization on TPE (IOTPE)

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

December 2010	Issue 5	Volume 2	Number 4	Pages 32-40

HYBRID MODELING OF POWER SYSTEMS FOR COORDINATED VOLTAGE CONTROL

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Abstract- Modeling and simulation of increasingly complex power systems is becoming more important for design, implementation and validation of power system on-line management. Current special-purpose tools are generally weak in the sense that they are mostly block-oriented and thus demand a huge amount of manual rewriting to get the equations into explicit input-output state-space form. Moreover, modification and examination of their encapsulated component models is very time-consuming and often practically impossible. Logical controllers as well as thresholds reached by discrete mechanisms introduce discrete events into continuous dynamics of power systems. This paper describes an efficient hybrid framework for modeling and simulation of power systems in the interest of coordinated voltage control and stability analysis using Modelica as a general-purpose object-oriented language. The proposed hybrid framework has been tested on a 12-bus power system. Simulation results show that the interaction between continuous dynamics of the power system and hybrid automata representing the discrete logical controllers and also nonlinear behavior of load dynamics can easily be studied in the proposed framework. On the other hand, the simulator is significantly fast allowing any coordinated control strategy to be effectively verified in real-time as countermeasure to arrest voltage collapse.

Keywords: Modeling, Hybrid Automata, Voltage Control, LTC, OXL, QSS, Modelica, Dymola.

I. INTRODUCTION

Nowadays, almost all aspect of modern life highly depends on reliable electricity. Maintaining an acceptable voltage profile across a power system in both normal and emergency situations is a very vital issue as system voltages vary continuously according to the electrical demand, control actions and emergency situations occurred in the system. Low voltages can cause damage to electrical motors and may lead to failures in electronic devices, or may initiate a voltage collapse, and high voltages can cause dangerous electric arcs (flashovers) by exceeding the insulation capabilities of electric devices [1]. Moreover, recent economical and ecological constraints and ever-increasing power consumption stresses the power system to operate closer and closer to its safety and stability limits. Under such a stressed condition, voltage instability results from the inability of reaching a sustainable operating point in a controllable way, following a major disturbance in the power system, so that the steady-state post-disturbance system bus voltages are no longer acceptable.

Voltage instability due to a cascade of events may lead to voltage collapse often resulting in blackouts or separation of the system into separate unsynchronized islands. Voltage collapse normally is not due to a single contingency but instead due to cascading failures. It is typically caused by an initiating disturbance, like transmission line outage or short circuits. The operation of protection relays to remove the faulted line/device may lead to overloading of the other transmission lines. Subsequent line tripping results in drastic voltage decay and as a result under-voltage relays may trip generation units. This in turn deteriorates the situation leading to partial or complete blackout [2]. The financial loss caused by voltage collapse is extremely high which obviously has a significant negative effect on the national economy. Hence, developing any design methodology to avoid voltage collapse, or at least to postpone it even in few cases, is very important. According to the literature, many voltage collapse incidents have been caused by uncoordinated interactions of local controllers following a major disturbance [1]. Therefore, this paper attempts to provide a hybrid modeling framework towards the ultimate goal of designing a well-performed system-wide feedback controller coordinating different actions taken by many different local controllers. This requires an accurate or estimated model of the power system incorporating all continuous and discrete dynamics to initiate a voltage collapse.

Beside the continuous dynamics of the power system which mostly arise from the physical laws at the system level, various discrete events may also occur in power system. Logical controllers like Load Tap Changing transformers (LTCs) or Capacitor Banks (CBs), as well as thresholds influencing continuous dynamics like Over Excitation Limiter (OXL), and faults and thus the operation of the protection devices such as relays and switchgears, introduce discrete events into continuous dynamics of power systems driving overall system to the new mode of operation. Hybrid nonlinear dynamic behavior of power systems involves an intrinsic strong coupling between continuous dynamics and these discrete events. This occurs for example during voltage collapse phenomena when several discrete devices switch on and off as a reaction to local measurements of currents and voltages that are influenced by local and global continuous dynamics of the system, and by the state of discrete components like LTCs and CBs.

In order to devise a truly model-based coordinated voltage control, this paper describes an efficient hybrid framework for modeling and simulation of power using Modelica as a general-purpose object-oriented language.

This paper is organized as follows. Section II compares in detail the block-oriented and object-oriented tools. Useful features of Modelica, an object-oriented language, for modeling and simulation of power systems will be discussed in this section. Hybrid automata representing discrete events will be explained in section III. The model of components used for coordinated voltage control will be presented in section IV using the proposed hybrid framework. These models are used, in section V, to capture the hybrid behavior of a 12-bus power system model and to investigate different (coordinated) countermeasures against voltage collapse following a major disturbance. Conclusions and directions for future works are provided in section VI.

II. MODELICA AND DYMOLA

Traditional special purpose tools e.g. PSCAD/EMTDC as well as general-purpose block-oriented tools e.g. Matlab/Simulink, for modeling and simulation of power systems are computationally very efficient and reasonably user friendly, but their closed architecture makes them very time consuming and often practically impossible to examine or modify component models [3]. Component models should be as close as possible to the corresponding physical subsystems that build up the overall system, but due to causal modeling of these tools, the block diagram structure cannot always reflect the actual topology of the physical system in the sense that some components cannot be visible as an individual block and have to be combined into the model of other components and thus the proper understanding of the interaction between components becomes very difficult [4].

Causal modeling is a fundamental limitation of block-oriented tools at which the blocks have a unidirectional data flow from inputs to outputs. This is the reason why some components cannot be simulated easily because there will be a loop which only contains algebraic equations. This is a well-known drawback of Matlab/Simulink which is not always able to handle the algebraic loops [5].

In order to be able to overcome the above-mentioned drawbacks, general-purpose object-oriented tools have been proposed which are based on acausal modeling. Particularly, because of nonlinear hybrid behavior of power systems, the desired tool should also support the hybrid modeling.

Modelica is a free general-purpose object-oriented equation-based language and has been designed to allow tools to generate very efficient codes for modeling of complex physical system. The modeling effort and complexity is considerably reduced in Modelica since the model of components can be reused avoiding tedious and error-prone manual manipulations.

There exist several free as well as commercial tools based on the Modelica language e.g. OpenModelica from OSMC, MathModelica by MathCore, SimulationX by ITI, MapleSim by MapleSoft and Dymola by Dassault systems/Dynasim [6]. Dymola, Dynamic Modeling Laboratory, is a powerful commercial simulation environment with the ability of dealing with huge systems described by more than hundred thousand equations containing a symbolic translator for Modelica equations generating C code for simulation. Graph theory is used to identify the variables to be solved in each equation and to find the minimal set of equations. The generated C code can via its convenient interfaces be transformed into a Matlab/Simulink S-function C mex-file which can be simulated in Matlab/Simulink as an input/output block. Modelica has two very important features which make it very efficient for modeling of power systems. These features are discussed in detail below.

A. Acausal Modeling

In order to allow reuse of component models, the equations should be stated in a neutral form without consideration of computational order, meaning that a model's terminals do not necessarily have to be assigned an input or output role [3, 4, 13].

Causality is generally not assigned in power systems. Setting the causality of an element of the power system involves representing the model equations in an explicit input-output state-space form required by Matlab/ Simulink [7]. Often several manual steps including differentiation are required to transform the equations into this form. The need for manual transformations implies that it is cumbersome to build physics based model libraries in the block based tools. A general solution to this problem requires a paradigm shift. Acausal modeling tools relax this causality constraint and allow focusing on the individual components and on the way these components are connected to each other by the topology of the system [5, 7, 14]. Modelica effectively supports acausal modeling.

B. Hybrid Modeling

The behavior of power systems is characterized by the complex interactions between continuous dynamics of the power system and many hybrid automata representing the discrete logical controllers, i.e. power systems exhibit complex hybrid behavior and therefore their model is conveniently expressed in the following mixed discrete-event continuous differential algebraic equations form:

$$
\begin{aligned}
&0 = g\left(x(t), y(t), z(t)\right) \\
&\dot{x}(t) = f\left(x(t), y(t), z(t)\right) \\
&z(t_k^{+}) = h\left(x(t_k^{-}), y(t_k^{-}), z(t_k^{-})\right) \\
&z(t) = z(t_k^{+})\ ;\ t_k \le t < t_{k+1}
\end{aligned}
\tag{1}
$$

where t_k is an increasing sequence of event times, when some discrete state of the system changes (e.g. LTC tap changes, or OXL limit reached). The dynamic continuous state vector x relates to synchronous generator, Automatic Voltage Regulator (AVR), OXL and load dynamics. On the other hand, the algebraic state variables y relates to network voltages and currents via load flow equations with fast dynamics, and the discrete-event state variables $z(t_k)$ typically arise from discrete control logic such as thresholds reached by OXLs and logical controllers such LTC, CB and disturbances. Modelica provides ordinary differential equations (ODEs) and differential-algebraic equations (DAEs) to mathematically describe the continuous time components model. It also supports several formalisms e.g. hybrid automata for modeling the evolution of the times when events occur.

III. HYBRID AUTOMATA

A hybrid automaton (HA) is a dynamical system describing the evolution in time of a hybrid system involving the interaction of both discrete state and continuous state variables. As shown in Figure 1, a HA typically consists of several discrete states (modes) in which different continuous dynamics subject to specific algebraic constraints has to be followed as long as the related invariants are satisfied. As soon as the transition violates one of the guards, i.e. an invariant is no longer true, or fulfills some conditions on continuous state (enabling condition) an event occurs and the system switches to another mode (in general this transition may also involve a state reset in the continuous part of the states).

Various definitions for HA in different research communities have been so far proposed [2]. But, the basic idea explained above always stays the same. The following definition has been adapted from [8]. An HA H is a 9-pole:

$$H = \left[Q, X, f, g, Init, \mathrm{inv}(.), E, G, R\right] \tag{2}$$

where $Q = \{q_1, q_2, \ldots\}$ is the set of all admissible discrete states.

$X \subseteq R^n$ is the set of continuous states.

$f\ (\cdot, \cdot): Q \times X \to R^n$ defines the differential dynamics.

$g\ (\cdot, \cdot): Q \times X \to R^m$ defines the algebraic constraints.

$Init \subseteq Q \times X$ is the set of all admissible initial states.

$\mathrm{inv}(\cdot): Q \to P(X)$ is the invariant set in state $q \in Q$.

$E \subseteq Q \times Q$ is a set of events.

$G: E \to P(X)$ is the set of guard conditions.

$R(\cdot, \cdot): E \times X \to P(X)$ is a reset map.

where $P(X)$ denotes the set of all possible subsets of X.

The dynamic behaviour of a HA can be described as follows. Given an initial state $(q_0, x_0) \in Init$ of HA, the systems continuous state trajectory x evolves according to (3) as long as $x \in \mathrm{inv}(q_0)$.

$$
\begin{aligned}
&0 = g_0\left(x(t), y_0(t), q_0\right) \\
&\dot{x}(t) = f_0\left(x_0(t), y_0(t), q_0\right), x \in \mathrm{inv}(q_0)
\end{aligned}
\tag{3}
$$

As soon as the guard condition $G(q_0, q_1) \subseteq R^n$ of any event (q_0, x_0) is triggered, the discrete transition occurs resetting x according to the reset map $R(q_0, q_1, x)$. In this new state, the differential dynamics and algebraic constraints of this state will be followed until another event is triggered.

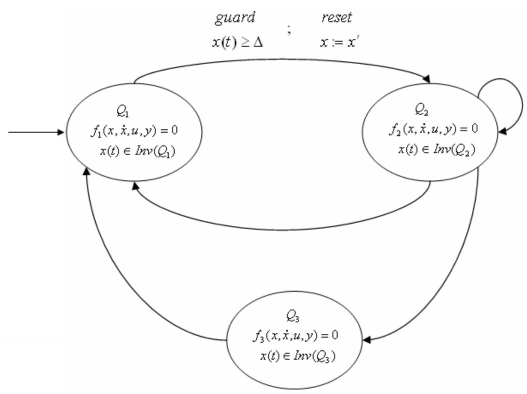


Figure 1. Hybrid automation

IV. MODELING OF BASIC COMPONENTS OF POWER SYSTEM FOR COORDINATED VOLTAGE CONTROL

For the purpose of coordinated voltage control, in the time scale of 0.1 second to several minutes, a power system is advantageously considered as hybrid dynamical system and its basic components are modeled using Modelica. Continuous dynamics are expressed by DAEs and discrete events are modeled as hybrid automata. All component models are transparent and can easily be modified or extended. Notice that we aim at modeling of power system components in the hybrid framework taking discrete-events into account, while a basic Modelica library ObjectStab for power system stability studies has been proposed in [9].

The system is assumed to successfully perform frequency regulation through a single slack bus. Since the dynamics of the power flow equations are infinitely fast at the time scale of the voltage control problem, we only model in this section the state evolution of the synchronous generators and the LTCs. Note that voltage collapse in power systems is often a relatively slow phenomenon from several seconds to a few minutes- and the long-term dynamics of interest thus can be advantageously captured by the well-known Quasi Steady State (QSS) approximation assuming that short term fast dynamics are infinitely fast and can be represented by their algebraic equilibrium equations instead of by their full dynamics [10]. QSS simulation allows obtaining very much faster-than-real time simulators for reasonably sized systems.

According to the well-known so-called *VQ* characteristic of a typical synchronous generator equipped with AVR, over excitation limit and armature limit specify different operating conditions for voltage control. In normal mode of operation, AVR controls the reactive power generation and maintains the terminal voltage (*PV* mode; constant terminal voltage). For heavy load condition, the maximum reactive power generation limit can be reached and from there on the generator terminal voltage is no longer controlled but the machine will operate under OXL control (*PQ* mode; constant reactive power generation). If the voltage degradation still persists, the armature limit may be reached and as a result the reactive power generation will be drastically reduced [10].

Under steady-state operation, and for constant active power P, equation (4) describes the possible combinations of values of V and Q achievable for a typical unsaturated round-rotor generator with the e.m.f proportional to the field current equation:

$$E_q = \frac{V^4 + V^2 Q X_d + V^2 Q X_q + Q^2 X_d X_q + V^2 Q X_d + P^2 X_d X_q}{V\sqrt{P^2 X_q{}^2 + V^4 + Q^2 X_q{}^2 + Q^2 X_q{}^2 + 2V^2 Q X_q}} \quad (4)$$

Different equations describing *VQ* characteristic in steady-state is given in Table 1.

The discrete-event transition among different operating modes of synchronous generator and the resulting interaction with continuous nonlinear dynamic of the system is being captured using the hybrid framework.

For the voltage control in the power transmission network under study in this paper, several control actions against voltage collapse such as switching of CBs, adjustment of terminal voltage setpoint of synchronous generators, LTC control and undervoltage load shedding are available.

Among these, LTC controls, as the most likely driving mechanism for voltage control but also a possible cause of voltage collapse in the long-term, is of special interest.

Table 1. Different operating conditions for synchronous generator

Under the control of AVR with a simple first-order transfer function model $G(V_0 - V) = \frac{V^4 + V^2 Q X_d + V^2 Q X_q + Q^2 X_d X_q + V^2 Q X_d + P^2 X_d X_q}{V\sqrt{P^2 X_q{}^2 + V^4 + Q^2 X_q{}^2 + Q^2 X_q{}^2 + 2V^2 Q X_q}}$ (5)
Under the control of OXL with an inverse-time characteristic and integral- type action model $E_{q\lim} = \frac{V^4 + V^2 Q X_d + V^2 Q X_q + Q^2 X_d X_q + V^2 Q X_d + P^2 X_d X_q}{V\sqrt{P^2 X_q{}^2 + V^4 + Q^2 X_q{}^2 + Q^2 X_q{}^2 + 2V^2 Q X_q}}$ (6)
Under the control of armature current limiter $Q = \sqrt{(VI_{\max})^2 - P^2}$ (7)

where,
G: steady-state open-loop gain of the AVR;
V_0: voltage setpoint;
Eq_{lim}: field current limit, slightly larger than the permanent admissible field current;
$I_{\max}$: maximum armature current;
X_d resp. X_q: direct resp. quadratic synchronous reactance of the synchronous generator.

A. ∞-Bus

By definition, an infinite bus refers to an infinitely strong rigid network with voltage and frequency unchanged under any load condition. Here it will be modeled as an ideal voltage source.

B. Transmission Line

Transmission lines can easily be modeled as π-equivalent circuits but here for simplicity they will be modeled as series impedances. They will be considered more inductive in transmission systems but more resistive in distribution systems.

C. LTC

LTCs are slowly acting discrete devices. Under traditional deadband control of LTC, the transformer ratio is changed by one step at a time if the voltage error at the designated side of the transformer (usually the distribution side) remains outside a deadband around a reference voltage v_{ref} longer than a specified time delays [11]. The LTC thus controls the voltage of the connected bus. Currently used LTC control strategies are implemented in several ways:

- Blocking: fixing tap positions at their current positions
- Locking: moving to a specific tap position, and then blocking at this tap position
- Reversing: changing the control logic to control the transmission side voltage instead of the distribution side
- Voltage setpoint reduction: lowering the reference voltage

However, those heuristic rules may not suffice to face all possible scenarios in such a large and complex system and up to now there has been relatively little attention paid to devising a truly model based coordinated voltage control of LTCs. The application of distributed Model Predictive Control (MPC) theory to coordinate control actions taken by different LTCs throughout control system has recently received an increasing attention.

Here LTC for simplicity is modeled as a hybrid automaton shown in Figure 2, using an ideal transformer with variable 1: n tap ratio in series with a pure leakage reactance X.

The system remains in the state *idle* as long as the voltage deviation Δv is less than the chosen deadband. When the limit is exceeded, a transition to the state *count* occurs initializing a timer. This timer is kept running until either it reaches the detection delay time T_d, causing a transition to the state *action*, or until the voltage deviation becomes less than the deadband, causing a transition back to the state *idle*. When entering the state *action*, tap changer operation starts and after the mechanical delay time T_m, the tap position change is completed and the control system then returns to state *idle* [11].

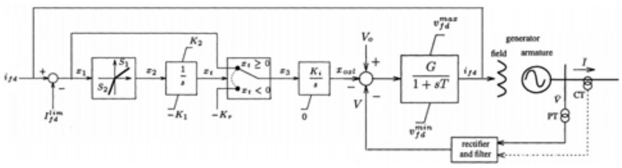


Figure 2. Hybrid automation model for LTC

D. Synchronous Generator Equipped with AVR and OXL

Synchronous generators are the primary source of active power and one of the main sources/sinks of reactive power in electrical power systems; therefore, they are to a great extent responsible for maintaining a good voltage profile across a power system. A general block diagram representation of a synchronous generator equipped with first order AVR and integral type OXL is shown in Figure 3 [10].

The AVR controls the field current I_{fd} to keep the terminal voltage of the synchronous generator close to the desired setpoint V_0. The OXL protects the field winding from overheating due to excessive current by keeping I_{fd} as close as possible to $I_{fd,lim}$ which is slightly larger than the permanent admissible field current. OXL activation has a direct effect on the voltage support provided by the generator and it must be included in the model of AVR for voltage instability studies.

Subtransient time constants which are a fraction of a second are negligible compared to the typical time interval of interest in voltage control and stability scenarios, and a 3rd order generator model accounting for the field winding only can effectively be used. Magnetic saturation is neglected for simplicity which is probably the most questionable simplification [10]. Assuming that the frequency and mechanical power are held constant, no governor will be considered.

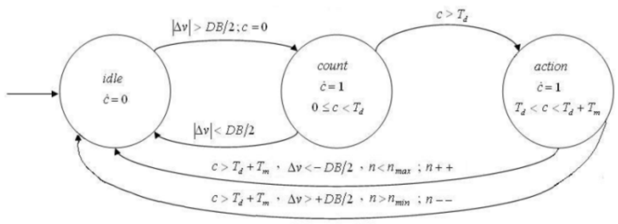
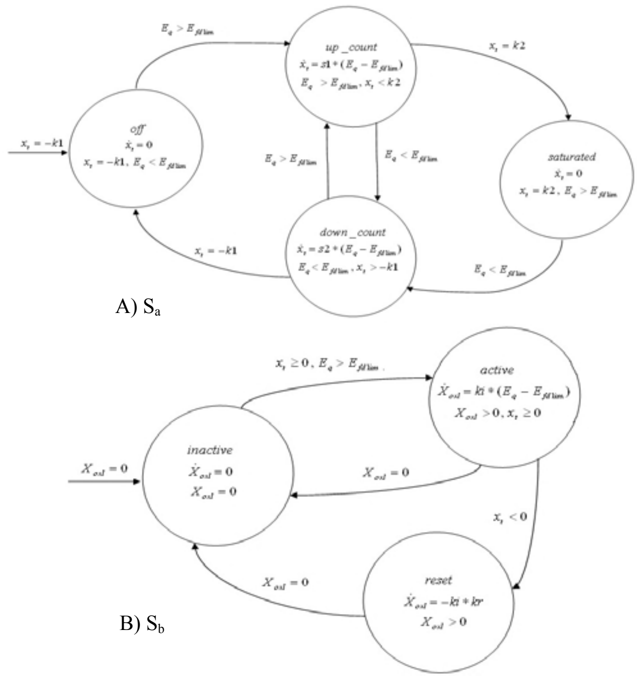


Figure 3. Block diagram model of synchronous generator with overall AVR and OXL

The AVR is represented by the simple first-order transfer function with anti-windup limits on the field voltage. G resp. T is the steady-state open-loop gain of the AVR resp. its related time constant. The translation of the OXL block diagram implementation with inverse-time characteristic and integral action, shown in Figure 3, into a hybrid automaton model is shown in Figure 4. The hybrid automata describing the OXL operation is decomposed into two smaller synchronously executing machines S_a and S_b which respectively implement inverse-time delay and limit enforcement by integral action. If I_{fd} exceeds $I_{fd,lim}$, the OXL intermediate state variable X_t starts increasing and as soon as it becomes positive, the error integration initializes and produces an X_{oxl} signal that is subtracted from the AVR inputs causing I_{fd} to decrease.



A) S_a

B) S_b

Figure 4. Hybrid automaton model for OXL
A) inverse-time delay B) limit enforcement by integral action

By way of summary, the continuous part of the synchronous generator model considered above as part of equation (8) can be written down in explicit matrix form as below.

$$f\left(x(t), y(t), z(t)\right) = \begin{bmatrix} \Delta\omega \\ \dfrac{1}{2H}(P_m - P_e - D\,\Delta\omega) \\ \dfrac{-E'_q + v_{fd} - (X_d - X'_d)i_d}{T'_{d0}} \\ k_i\,(E'_q + (X_d - X'_d)i_d - E_{q\lim}) \\ \dfrac{-v_{fd} + G(V_0 - V - x_{oxl})}{T} \end{bmatrix} \tag{8}$$

where $x = [\delta\ \Delta\omega\ E'_q\ x_{oxl}\ v_{fd}]^{\mathrm{T}}$. The discrete-event part of the synchronous generator model was already represented in Figure 4.

E. Dynamic Exponential Recovery Load

The voltage dependence of loads is a key mechanism and driving force of voltage instability and for this reason voltage instability has also been called load instability. Load restoration is a process during which the dynamics of various load components (induction motors, thermostatic loads) and control mechanisms (including

LTCs) tend to restore load power at least to a certain extent. Voltage instability results from the attempt of loads to draw more power than that can be delivered by the overall transmission and generation system.

According to [10, 12] a so called additive generic self-restoring load in which the load state variable is added to the transient characteristic will be modeled with an exponential type of voltage characteristic. The load dynamics of the additive generic model are given by the following differential equations.

$$\begin{aligned}
\dot{x}_p &= -\frac{x_p}{T_p} + P_0\left(\left(\frac{v}{v_0}\right)^{\alpha_s} - \left(\frac{v}{v_0}\right)^{\alpha_t}\right) \\
P &= (1-k)\left(\frac{x_p}{T_p} + P_0\left(\frac{v}{v_0}\right)^{\alpha_t}\right) \\
\dot{x}_q &= -\frac{x_q}{T_q} + Q_0\left(\left(\frac{v}{v_0}\right)^{\beta_s} - \left(\frac{v}{v_0}\right)^{\beta_t}\right) \\
Q &= (1-k)\left(\frac{x_q}{T_q} + Q_0\left(\frac{v}{v_0}\right)^{\beta_t}\right)
\end{aligned} \quad (9)$$

where,

P, Q: actual active resp. reactive power consumed by the load;

P_0, Q_0: nominal load powers consumption;

v_0: reference voltage;

T_p, T_q: active resp. reactive power recovery time constants;

x_p, x_q: continuous state variable of load dynamics;

α_s, β_s: steady-state active resp. reactive power voltage dependency;

α_t, β_t: transient active resp. reactive power voltage dependency.

The scale factor of (1-k) on the load power has been introduced to model load shedding. No load shedding (full load) corresponds to k=0, while complete load shedding is given by k=1. In the case of any voltage drop on the load bus following a disturbance in power system, the load restoration process will initially start responding with its transient characteristics and the actual power consumed will drop instantaneously. Following this the load state variables x_p and x_q will start to increase causing both actual real and reactive power to recover to their steady-state characteristics. This process will end when either the steady-state characteristics are achieved or when the state variables reach their bounds.

F. CB

Switched capacitor banks can locally support the voltage in connected bus. Each switching step of a CB corresponds to the injection of some reactive compensation which is quadratically dependent on the voltage, so it will provide less support at low voltages.

V. SIMULATION RESULTS

The effectiveness of the proposed hybrid framework has been tested via some interesting experiments relating to coordinated voltage control on a realistic size 12-bus power system. This case study is taken from [11] and sets a control problem with around 20 control inputs, many measured disturbance inputs and up to 30 controlled outputs and many auxiliary outputs.

As shown in Figure 5, the considered power system is composed of three topologically almost identical areas connected together via three double tie lines as transmission system. The generators in Areas 2 and 3 are equipped with OXL modeled as in [10], while area 1 is fed by an ∞-bus. The distribution substation in each area is equipped with an LTC and a CB.

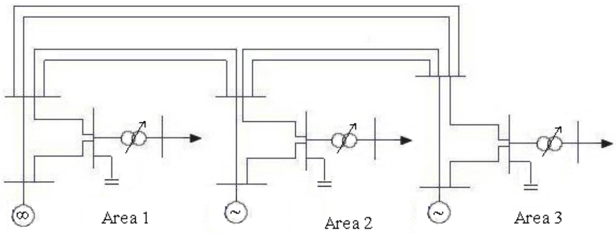


Figure 5. One-line diagram of a 12-bus power system

LTC and OXL constitute a primary control layer and our control objective is to design a secondary control layer to stabilize all bus voltages at values in the interval of [0.9, 1.1] p.u. by applying different (coordinated) counter- measures against voltage instability following the tripping of some transmission lines. The interaction between continuous dynamics of the power system and hybrid automata representing OXL and LTC and also the nonlinear behavior of load dynamics will be presented. Furthermore, it will be shown that in order to stabilize the bus voltages, switching of manipulated variables, i.e. the amount of loads to be shed and CB switching, can be minimized by a properly coordinated voltage control. Currently this strategy is determined by trial and error, but systematic search strategies, using the fast simulation tool, will be presented in a paper under preparation.

To have an idea about time scale values involved in this simulation, note that T'_{d0}=8 s for synchronous generators, T=0.1 s for AVRs, x_t= (20-100) s for OXLs, T_d+T_m=30 s for LTCs and T_p=T_q=60 s for loads have been considered.

A. No Secondary Control

The load voltages, and the behavior of LTCs and OXLs are shown in Figure 6 following the tripping of the double tie line between areas 1 and 3 at t=100 s where a standard uncoordinated primary control strategy is used. Instability occurs and the solver fails to solve the non-linear equations of the system at t=652.3 s when simulation stops. Directly following the fault, load voltages in each area drop, slightly in area 1 compared to others, but soon after a short term equilibrium, with all load voltages apparently settling down close to 1 p.u., is established. After this point the mechanism driving the system response is LTC and OXL together with load dynamics.

After the fault the generator field current in area 2 jumps to 2.13 p.u. which exceeds $I_{fd,lim}$ =1.88 p.u. for this generator. This initiates the inverse time characteristic of the OXL and eventually the OXL is activated at t=140.7 s meaning that the voltage support provided by this generator is withdrawn. This results in a further reduction of the load voltage causing the LTC to increase the tap position until the maximum tap limit is reached. Note that the integral type OXL forces the field current to $I_{fd,lim}$ and subsequent tap changes result in a transient field current rise, which is quickly sensed and corrected by the OXL.

B. LTC Setpoint Reduction

As the former experiment showed the LTC tap movements in areas 2 and 3 aggravated further the load voltages profile and finally the load voltages collapsed dropping below 0.9 p.u. So, if the LTC tap movements can be somehow blocked or at least be slowed down, it seems that the voltage collapse possibly could be avoided or at least be delayed. Here, the load restoration process will be disabled by the reduction of the LTC setpoint voltage from 1 p.u. to 0.95 p.u. at t=150 s in both areas 2 and 3. As shown in Figure 7, this results in two downward tap movements for LTCs in both areas which relieves generator in area 3 of saturation and its field current is kept slightly below the limit $I_{fd,lim}$ =1.75 p.u. meaning that the related OXL will be inactivated in the long-term and as a result all load voltages are stabilized above 0.95 p.u.

C. A Coordinated Application of One Step CB Switching, LTC Setpoint Reduction and One Step Load Shedding

In case the fault considered earlier is followed by another line tripping, one of the lines between areas 2 and 3 at t=110 s, which is often the case due to a cascade of events in voltage collapse, simulation results, not shown here, show that single strategies such as LTC setpoint reduction, one step CB switching (corresponding to 0.1 p.u. of reactive compensation), one step load shedding (corresponding to disconnection of 10% of load) and even a mixture of the LTC setpoint reduction and CB switching individually fail to arrest the voltage collapse.

However, it is possible to stabilize all the load voltages by a coordinated application of (one step) CB switching, LTC setpoint reduction and (one step) load shedding in areas 1, 2 and 3 at the right moment. As shown in Figure 8, switching of CB in area 2 relieves the generator in this area of some reactive power, on the other hand, load shedding in both areas 2 and 3 relieves the generators in these areas of both active and reactive power and as a result keeps the generator field currents well below their limit ($I_{fd,lim}$ =1.88 p.u. for area 2 and $I_{fd,lim}$ =1.75 p.u. for area 3). Notice that both OXLs are inactive in the long-term.

VI. CONCLUSIONS AND FUTURE WORK

Logical controllers e.g. LTCs and CBs as well as discrete control logics such as thresholds reached by OXLs introduce discrete events into power system continuous dynamics. The resulting dynamic behavior often involves intrinsic interactions between continuous dynamics and discrete events, particularly during voltage collapse phenomena when many discrete devices (either controllers or thresholds) switch on and off. The ordering of these events is very important for the stabilization and is modeled using concurrent execution of hybrid automata.

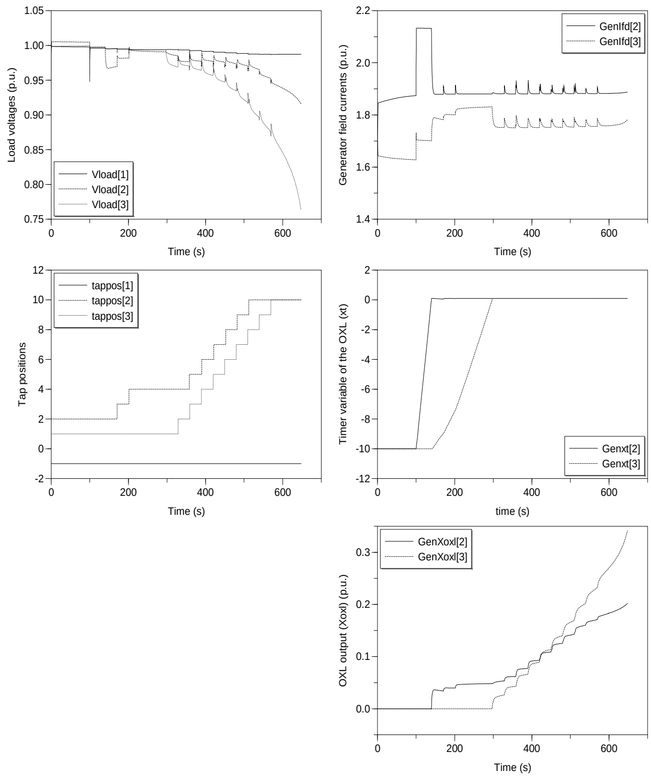


Figure 6. Response to the fault without secondary controller

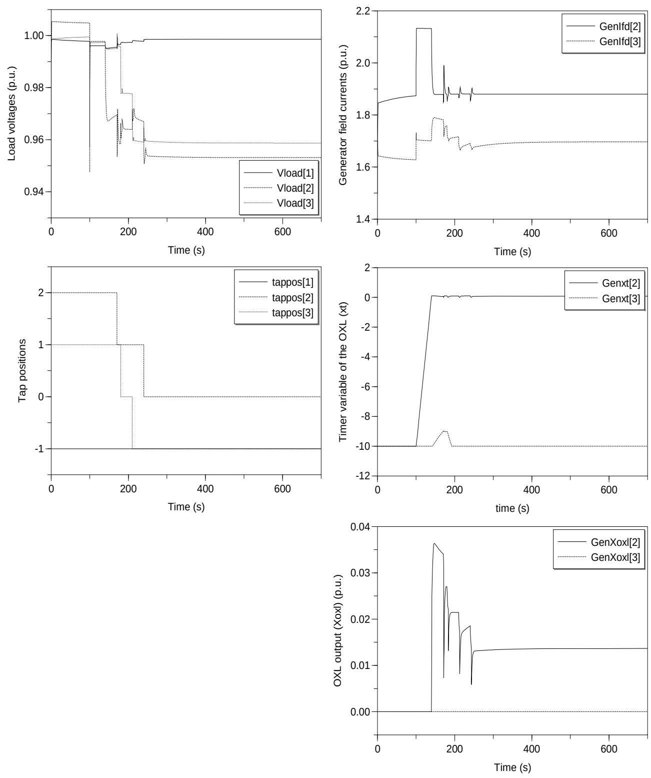


Figure 7. Response to the fault with LTC setpoint reduction

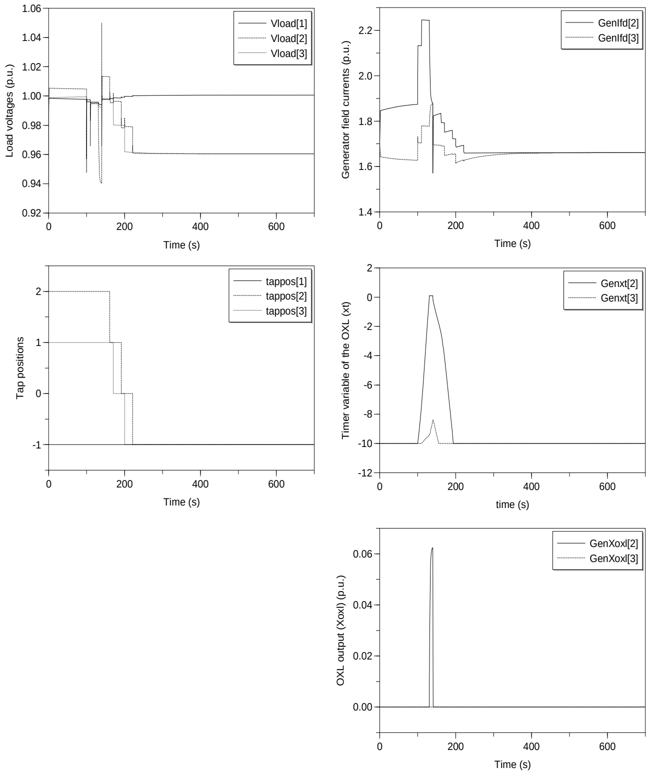


Figure 8. Response to the fault with a coordinated application of CB switching, LTC setpoint reduction and load shedding

This paper presented an efficient framework to capture the hybrid behavior of a large power system using Modelica as an object-oriented equation-based language. For the purpose of coordinated voltage control the Modelica model for transmission lines, LTCs, OXLs, CBs and dynamic exponential recovery loads has been presented in the hybrid framework. All component models are transparent and can easily be modified or extended.

Simulation results showed that the interaction between local controllers and continuous dynamics of power system as well as nonlinear behavior of load dynamics can easily be studied in the proposed hybrid framework and thus any appropriate coordinated voltage control action to arrest voltage collapse can effectively be analyzed. For the case study considered in this paper, the simulator integration time when running on a 3.15 GHz Intel Core 2 Duo CPU with 4 GB of RAM takes less than 1 s, i.e. about 700 times faster than real time, resulting in a flexible environment for modeling and simulation of large power systems at which any control strategy can easily be tested or verified.

In the current study the timing of the control actions was obtained by carrying out many simulations. In future work this timing of events will be obtained automatically by an MPC selecting the best scenarios among a small number of possible scenarios. The fact that these scenarios can be simulated over a long time window allows efficient and automatic comparison of their performance.

ACKNOWLEDGEMENT

This work was supported by the Special Research Fund at Ghent University (BOF) B/06484/01. This paper presents research results of the Belgian Network DYSCO (Dynamical Systems, Control, and Optimization), funded by the Interuniversity Attraction Poles Program, initiated by the Belgian State, Science Policy Office and EUFP7 project CON4COORD. The scientific responsibility rests with its authors.

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