Benchmark Model for Hybrid Systems Design based on a Small-scale Power System Model

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Abstract

This paper has been inspired with the newly developed wide-area monitoring and control platform for power systems productised by ABB Switzerland Ltd. A benchmark problem for hybrid systems analysis and controller synthesis is reviewed here. All required signals can be obtained in practice from global phasor measurements available in real-time through the wide-area monitoring system. The aim of this paper is to illustrate voltage instability problems in power systems to support studies on synthesis of new emergency control strategies, which are necessary to avoid a collapse followed by the subsequent blackout.

Keywords: Power system dynamic stability, Voltage control, Hybrid systems.

1 Introduction

ABB has developed a new wide-area measurement and control system (WAMC) which utilizes phasor measurement units. The time synchronized phasor measurements can capture very effectively the power system dynamics. The WAMC platform is based on collecting and evaluating these measurements in real-time. Hence, this platform enables to implement a number of new applications; from monitoring of stability limits and critical system states to remedial actions against instabilities and control actions for network controllers (Rehtanz et al., 2002).

In parallel, within the frame of the European Union sponsored project Control & Computation (EU CC), a number of test cases (Larsson, 2002a,b) focused on voltage stability in power systems has been defined. This paper summarizes one of these test cases, which due to its nature, suits well especially to hybrid

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system approaches. The full description of the test case can be found at the project website (Larsson, 2004).

Even though the reduced power system considered here is rather small, it contains some features which make it interesting for this kind of study. Firstly, there is hybrid behaviour that arises from discrete control logic in the generator and voltage controllers which are embedded in these components. Secondly, there is a non-linearity in the continuous time dynamics of the system. In a separate study (Larsson et al., 2002), it has been shown that small equivalents can accurately be used to make stability assessment of a complex power system. Thus, control design based on these testcases can well be applicable also to practical power system, and later implemented on the platform described earlier in the introduction.

The goal is to design an appropriate emergency control law such that a system collapse – followed by the subsequent blackout in the power system – can be avoided. It is assumed here that only the phasor measurements provided by the WAMC platform are available for the controller as an input information.

2 ABB Test Case

This note provides additional documentation about the ABB test case. The models have been implemented in Modelica (Tiller, 2001). See the source code and its HTML documentation for a detailed information about the implementation of the various component models.

The basic power system contains two generators and three lines as shown in Fig. 1. Additionally there is a transformer that can regulate the (customer) voltage at Bus 4 and a capacitor bank that can support the voltage at Bus 3. The generator Ginf is a model of the surrounding network which is assumed to be strong, and generator G1 is equipped with a voltage regulator with a field voltage limit at 2.2 p.u. The transformer T1 is equipped with a voltage regulator modelled by a state-machine. These controllers constitute a primary control layer which should preferably be not be modified. The task of the the test case is to design a secondary control layer which has access to the following input signals:

- CapStep—an integer variable that can take the values [0,1,2,3]. Each step corresponds to 0.1 p.u. of reactive compensation. Increase of this control will increase the voltage at Bus 3, however the effectiveness of the control is highly dependent on the operating point.
- LoadStep—an integer variable that can take the values [0,1,2,3]. Each step corresponds to disconnection of 5 % of the load at Bus 4. This action will
always effectively increase the voltage at Bus 4. However, the use of load
disconnection must be limited to extreme cases where it not possible to
stabilize the voltage using a combination of the other two control.
• TapVref–a continuous variable that can take values in the interval [0.9..1.1]
and corresponds to the setpoint of the voltage regulator of transformer T1
that regulates the voltage at Bus 4.

In addition there is a disturbance input (which can be assumed measured):

• Faulted–a boolean input indicating whether or not there has been a fault
on line L3. The disconnection of the line is modelled by a change of its
impedance from 0.5 to 1.5 p.u. and corresponds to the disconnected of two
out of three parallel lines.

Three outputs have been assigned:

• V2–the voltage at bus 2, close to the generator voltage. This voltage is reg-
ulated by generator G1 so it it kept constant. However, when the generator
becomes overloaded (that is, Ef≤Efmax) the generator loses its voltage
control capability and the voltage V2 may drop.
• V3–the voltage at bus 3 can be controlled using the capacitor at Bus 3.
• V4–the voltage at Bus 4 can be controlled by the tap changer on the trans-
former T1. However, after the fault has been applied the system becomes
heavily stressed and V3 decreases as V4 is increased. When there is no
longer support of the voltage at bus 2 and 3 from the generator G1, this
effect becomes dominant and each (upwards) tap step made on transformer
actually decreases the voltage of Bus 4.
2.1 Control Objectives

The aim of the emergency control is to stabilize all voltages at values above 0.9 p.u following the fault. A secondary aim to to minimize the amount of load shedding applied. The tertiary objective is to keep the voltage at bus 4 close to 1 p.u, and to minimize the amount of capacitor control required to do so. That is, load shedding can be used to fulfil the primary objective but not the the tertiary.

Computational delay times of up to 30 s are acceptable, however all controls are more effective when applied as soon as possible following the fault.

2.2 Example Simulations

This sections presents some example simulations and demonstrates the application of emergency controls.

Fig. 2 shows the system response to the fault applied at 100 s. The voltage drop following directly from the fault is not severe, however the load dynamics and tap changer control drives generator G1 towards its capability limit. When this is reached at 224 s, the generator voltage drops and the system collapse follows at about 390 s.

Fig. 3 shows the response when the transformer voltage setpoint is reduced to 0.92 p.u. at time 110 s. The response is similar to that without emergency control, however the collapse occurs slightly later, at 410 s. Thus, we can conclude that the setpoint change alone is not sufficient to arrest the collapse, but it appears to have a positive influence since the collapse is delayed.

Fig. 4 shows the response when additional reactive support is provided by stepping up the capacitor bank C1 at 110 s. This relieves generator G1 of some reactive load and it is kept slightly below its field voltage limit. Therefore, the voltages eventually stabilize but the voltage of Bus 3 is still unacceptably low.

Fig. 5 shows the response when load is shed at time 110 s. This relieves generator G1 of both active and reactive load and it is kept well below its field voltage limit and the scenario is therefore stable. Also, the voltage drop over the remaining lines is reduced and also the voltage of Bus 3 is acceptable.

Fig. 6 shows the response when a combination of additional capacitor and tap setpoint change at time 110 s. The voltages are stabilized without load shedding at acceptable levels. According to the control objectives, these are the correct controls to apply.
Fig. 2. Response to the fault without emergency control.

Fig. 3. Response to the fault with adjustment of transformer voltage regulator set-point.

2.3 Simulink Model Files

The following files related to the full version of the test case can be downloaded from the EUCC webpage (Larsson, 2004):

- primarycontrolled.dll – the binary for the SimStruc model
- abbvars.mat – .mat file containing parameter data and other variables nec-
Fig. 4. Response to the fault with connection of additional capacitor bank.

Fig. 5. Response to the fault with load shedding.

ecessary for simulation
- testsim.mdl – Simulink shell model to simulate the test case
- primarycontrolled.mdl – Simulink model with external inputs/outputs that for example can be used to programmatically access the model
- scenSim.m – Example Matlab script that generates Figures 2–6.
- test.mod.m – Example Matlab script that shows how to properly initialize discrete and continuous state variables when the simulation is started programmatically.
- test.mod.x0.mdl Simulink shell model used by test.mod.m.
Capacitor Switching and Tap Reference Change

![Graph showing bus voltages over time](image)

![Graph showing G1 field voltage over time](image)

Fig. 6. Response to the fault with a combination of additional capacitor bank and adjustment of transformer voltage regulator setpoint.

- **testsim2.mdl, scensim.m** – Simulink version of the test case split into continuous and discrete parts. Since Simulink has trouble handling algebraic loops, a number of spikes occur during simulation. The use of this model is not recommended, and was used only to verify that the individual continuous and discrete submodels are working correctly.

Note that since the Simulink interface of Dymola (Elmqvist et al., 2000), that has been used to produce the Modelica model, does not yet fully support state-event handling, the Simulink model must be simulated with state-event detection disabled as has been done in the files testsim.mdl and openloop.mdl. In this version, both continuous and discrete behavior have been aggregated in the same model.

Note that the discrete states in the model are initialized with the values given in the parameter vectors when a Simulink simulation is started. To define the initial values of the continuous and discrete states at the start of a simulation, the correct updates must be made in the parameter vector primarycontrolled.p. This version of the testcase also provides many auxiliary variables that can be used for debug purposes.

3 Decomposition of Models into Continuous and Discrete Parts

As shown in Fig. 7, the hybrid system in Fig. 1 can be decomposed into one non-linear continuous part (without any hybrid dynamics) and one hybrid
Fig. 7. Decomposition of the hybrid system into its’ continuous and discrete parts. The continuous part essentially corresponds to an uncontrolled (open-loop) model of the power system and the hybrid part to the primary control systems that are applied.

3.1 Model of Continuous Open-loop Part

3.1.1 Simulink Model Files

The open loop power system can be represented on the form

\[ \dot{x} = f(x, u) \]
\[ y = g(x, u) \]

where \( x = [\text{Load}.xp, \text{Load}.xq] \) is the continuous state vector, \( y = [V2, V3, V4] \) is the output vector and \( u = [\text{CapStep}, \text{LoadStep}, \text{TrStep}, G1Efd, \text{faulted}] \) is the input vector.

Once it has been initialized by a call to the MATLAB m-file \texttt{cont.init.m}, the openloop part can be programmatically accessed through the m-files \texttt{cont.f.m} and \texttt{cont.g.m}. The Matlab script \texttt{testopenloop.m} which generators Fig. 8 shows how to call these functions. These functions also needs the SIMULINK models openloop.mdl and openloop2.mdl which acts as wrappers for the mex S-functions that have been generated from the Modelica model. Additionally to the signals in \( y \), also the state vector \( x \) has been included as outputs of the mex S-function.

Fig. 8 illustrates the nonlinearity in the continuous which is only slight, and occurs only at very low voltages.
3.2 Model of Discrete Part

The hybrid part essentially consists of a state machine that controls the position of the tap changer at transformer T1 from a voltage measurements on the secondary side of the transformer, and a proportional controller with a limiter, that controls the field voltage of generator G1. The best documentation of the discrete part is so far the Modelica code itself.

3.3 Future Work

In a later version, also a power system of realistic size will be modelled. Optimal control of such a system has previously studied by e.g. (Larsson, 2000).

4 Acknowledgement

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References


