Development of Dynamic Test Cases in
OPAL-RT Real-time Power System Simulator

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Abstract— The paper describes the development of the
dynamic models of a number of commonly used test power
systems in OPAL-RT real-time simulator environment.
The process of building the dynamic test cases is described,
and the challenges faced during such development are
discussed. The performance of the dynamic test cases is
investigated under various disturbances such as single-
line-to-ground fault, line outages, step load change, and
tap changing of on-load tap changers.

Keywords— Dynamic simulation; OPAL-RT; SimPowerSystem

I. INTRODUCTION
To analyse the performance of the power systems under large
disturbances, it is important to consider the dynamic models of
the individual components[1]. Time-domain simulations,
involving numerical integration and solution of the differential
and algebraic equations describing the power system, predict
the trajectory of the system states following a disturbance. The
dynamic data for a number of test systems are available in the
literature[2]. However, very few of these references contain
the complete set of static and dynamic data that are required to
run dynamic simulations with the detailed dynamic models of
the components. The chosen platform for simulation is
eMegaSim real-time simulator from OPAL-RT Inc.,
Canada[3].

Dynamic simulation of power systems involves the
solution of a large number of differential and algebraic
equations (DAEs). The differential equations need to be
solved by using suitable numerical integration techniques. A
real-time simulator, such as the OPAL-RT eMegaSim, uses
parallel computing facilities to solve the DAEs in real-time.
This means that, a dynamic phenomenon, such as power
transients, is simulated, and the results are made available to
the user exactly as it happens in actual power systems. Off-
line PC-based simulators may perform the simulations as
accurately as the real-time simulator. However, the time-
response of the solutions, for large systems, may be slower
than the actual phenomenon. The operator can, therefore, gain
more confidence in the design of the hardware device or
software routine for controlling the power system, if they are
tested in close loop with the real-time simulator.

The eMegaSim real-time simulator from OPAL-RT
integrates Matlab Simulink and SimPowerSystem toolboxes,
and RT-LAB distributed processing software and hardware
platform for high speed and real-time simulation of
electromagnetic transients[3].The source codes for the block
diagram level models can be automatically generated and
uploaded into the target processor for real-time simulation.

The major issues in developing the complete dynamical
model of the system, such as building models of the individual
components, compilation, and initialization are discussed
briefly in this paper. The models of various components, such
as the synchronous machine, the governor/turbine, the
excitation system, the three-phase transformer, the
transmission line, the loads, the switches, and the various
measurement blocks used by the real-time simulator are also
briefly discussed. Some of the results from power flow
studies, dynamic simulation, fault studies, sudden changes in
load, and tap change in load tap changers (LTCS) are
presented. The complete dynamic models of two test systems,
viz., WSCC 9-bus system and New England 39-bus system are
developed, and used for the simulation studies.

This paper is organized as follows: The sections II
describes about various components used to build the system
model, Section III presents a brief description about OPAL-RT
simulator. The system description has been presented in section
IV. The test results and discussions are described in Section V
and, finally, the main conclusions are provided in Section VI.

II. MODEL DETAILS
Brief details regarding some of the important components
used in the building the dynamical models of power system
are discussed below:
A. Synchronous Machine

The generator model considered for the study is full detailed model present in SimPowerSystem toolbox. The input to the model are mechanical power input and outputs are machine speed in rad/sec. Various measurement signals can be used for various studies and control applications. The model takes into account the dynamics of the stator, the field, and the damper windings also.

B. Excitation System

The IEEE DC1A type[1] exciter which is used in this paper, is also present in SimPowerSystem toolbox. The basic elements that form the excitation system block are the voltage regulator and the exciter which provides direct current to the synchronous machine field winding. It also performs control and protective functions for satisfactory function of the power system [1].

C. Steam Turbine and Governor

A steam turbine converts stored energy of high pressure and high temperature steam into rotating energy, which is in turn converted into electrical energy by the generator. The kinetic energy of this high velocity steam is converted into shaft torque by the buckets. The model details can be found in [4].

D. Load Modelling

Accurate load modeling is an important issue, must be modeled to achieve an adequate match between actual and simulated behavior. The load models are traditionally classified as static loads and dynamic loads. For static loads the load impedance $Z$, is constant and determined from the nominal phase-to-phase voltage $V_n$ at the specified frequency. Hence, the active power $P$, and reactive power $(Q_L-Q_C)$ consumed are proportional to the square of the applied bus voltage.

In case of 3-phase dynamical load model the active power $P$ and reactive power $Q$ of the load vary as follows:

$$P(s) = P_0 \left( \frac{V}{V_0} \right)^{q_p} \frac{1+T_{p1}s}{1+T_{p2}s}$$

$$Q(s) = Q_0 \left( \frac{V}{V_0} \right)^{q_q} \frac{1+T_{q1}s}{1+T_{q2}s}$$

where $V_0$ is the initial positive sequence voltage, $P_0, Q_0$ are the initial active and reactive power, $V$ is positive sequence voltage, $n_p$ and $n_q$ are the exponents to control the load, $T_{p1}$ and $T_{q1}$ are time constants controlling the dynamics of the active power $P$, $T_{p2}$ and $T_{q2}$ are time constants controlling the dynamics of the reactive power $Q$. Hence the user has more flexibility to decide the type of load required. Both the type of load components are available in SimPowerSystem toolbox[4].

E. Transmission Line Modelling

A transmission line is characterized by four parameters: series resistance $R$ due to the conductor resistivity, shunt conductance $G$ due to leakage currents between the phases and ground, series inductance $L$ due to magnetic field surrounding the conductors, and shunt capacitance $C$ due to the electric field between conductors. There are two types of line models. The pi and distributed line models are widely used in model building of the transmission lines. The pi type model is generally used for short length lines with lumped parameter, whereas in distributed parameter line model, resistance, inductance, and capacitance are uniformly distributed along the line. These line models are available in the SimPowerSystem block-set. However, in hard real time simulation, numerical oscillations are observed that often affect the accuracy of the result. To avoid this type problem, Advanced Real time electro Mechanical Simulator (ARTEMiS) distributed transmission line model is used to make parallel simulation of an electric circuit that enables distributed simulation of power systems on several CPUs or cores. The ARTEMiS used the intrinsic delay of the line to split the circuit without affecting the dynamic property of the system.

III. OPAL-RT SIMULATOR

The eMEGASim® simulator used in this work contains a powerful real-time target computer equipped with 12 OP5600, 3.3 GHz processor cores, with 8 cores activated, running on Red Hat Linux real-time operating system. Two user-programmable FPGA-based I/O management options available, powered by the Xilinx OP5142 Spartan-3 FPGA boards. The 4A288a input/output package is composed of 80 Digital I/O points, and more than 64 analog I/O channels. The OPAL-RT simulator present in the lab is shown in Fig. 1. The software platform required is discussed below.

A. RT-LAB Overview

RT-LAB is a distributed real-time platform that allows users to test dynamical models built in MATLAB/Simulink environment, for Hardware in Loop (HIL) simulation at very high accuracy, low cost, and in real time. RT-LAB’s flexibility and scalability allows it to be used in virtually any simulation or control system application, and to add computing-power to simulations, where and when it is needed. To simulate very complex non-linear systems like power system in real time with high precision and high stability, the RT-LAB comes with special Simulink-based modelling tools, namely, ARTEMIS and RT-Events that allows real time simulation in multi-core processors. The brief description of these tools as follows.

ARTEMIS:

It is a power systems real-time solver that provides a high degree of stability for the discrete time state-space models. It also enables parallel computation of electric circuits on different CPU cores. It enables to simulate a very large number of switches in real-time.
RT-Events:

The RT-Events Block-set works with a fixed step size solver; hence it is compatible with the Real Time Workshop (RTW), and can be used for real-time applications.

OPAL-RT Structure:

To ensure real time simulation, a larger system model can be divided into a number of subsystems, and can run in multi core/processors in parallel without affecting the dynamics of the original system. In the RT-LAB model, there is always one master subsystem in each model; however, slave subsystem only needed when distribute the computational effort across multiple cores. The signal communication is done across two subsystems, with the help of Opcomm block. For connecting two subsystems one should use ARTEMiS transmission lines/distributed parameter lines.

Execute the Model under RT-LAB:

The steps to simulate the system in RT-LAB are depicted in the flowchart in the Fig.3.

IV. SYSTEM DESCRIPTION

Two test systems are considered: the IEEE-9 bus system and the New England 39 bus system. The brief descriptions about the two systems are as follows.

A. WSCC 9 Bus System

The WSCC 9 bus system consists of three generators and three loads. The load demand at bus 5 was \(125 + j520\) MVA, bus6 a load demand of \(90 + j30\) MVA and load bus 8 having demand of \(100 + j35\) MVA. The generator and line parameters considered are taken from[5]. The single line diagram of the system has given in Fig. 3.

B. New England 39 Bus System

The proposed methodology has been implemented on New England system[6], which consists of 10-machines and 39-buses as shown in Fig. 4. Each generator is assumed to be provided with governor, AVR and IEEE type-1 exciter. The loads in the system are assumed to be constant impedance type.

V. SIMULATION RESULTS

This paper presents non-linear time-domain simulation results with various disturbances in both the WSCC 9-bus system and New England 39-bus system on OPAL-RT platform. The time-domain simulation carried out in opal-RT hardware has been presented in this section. Power systems experience a wide variety of disturbances. It is impractical and uneconomical to design controllers to maintain the systems stability for every possible contingency. To test the system behavior at various changes in operating conditions, large and small types of disturbances are considered that guide the operating engineer to take corrective action at the time of severity. The study of system stability, time to reach steady state, line power flows, on-load automatic tap changing transformer dynamics has been tested after being subjected to large and small disturbances in the system are presented below.

A. WSCC 9 Bus System

a) Single line to ground fault

Single line to ground fault applied in phase-A at bus 7 for 70 milliseconds. The response of active generation by the generator and the power flow in various transmission lines are shown in Figs. 5 and 6, respectively. It can be observed that the system has been stable and achieved steady state in 5 sec followed by the disturbance.
Another major disturbance applied to the system to test the stability with variation in operating condition temporally by taking out the line connecting buses 5 and 7 for 70 milliseconds. The response of line outage has been shown in Fig. 7 and 8.

c) Load Change
The load at bus-6 has been increased by 10% after 50 seconds start of simulation. Figs. 9, 10, and 11 show the responses of active generation by the generator, the generator speed deviation and the power flow in various transmission lines, respectively. It can be observed that steady state has been achieved and the active power flows in all the lines have increased from its nominal value and generator speed has been decreased.

d) On load tap changing
Most of the transformers are provided with taps on windings for voltage regulation by adjusting the taps position in discrete manner. The taps are electrical contacts that are designed to carry the rated current of the transformer. Here an automatic on-line tap changing transformer has been simulated. The input to the regulator is the magnitude of bus voltage. The tap position is automatically adjusted in discrete manner while achieving the desired voltage level. Fig. 12 shows the reference and tracking voltage with time and Fig.13 shows the tap position variation with time.
B. NE 39-Bus System

a) Single Line to Ground Fault
A self-clearing line to ground fault is applied in phase–A in the line joining bus 4 and bus 14 for 70ms. The active power generation and active power flow in transmission lines have been shown in Figs. 14 and 15, respectively. The result clearly shows the stability of the system, and steady state achieved with in 20 sec.

b) Line Outage
The line connecting buses 4 and 14 has taken out after 70 sec start of simulation to test the dynamic performance of the system. The response of line outage has been shown in Figs. 16 and 17. The system is found to be stable and there is small variation of steady state power flow in lines from its pre-fault operating condition.

c) Step Load Change
To test the system performance at different operating conditions a step load increase of 10% in load-4, load-8, load-18, and load-21 has been created simultaneously after 80 sec start of simulation. The result for active power generated by Gen-1,3,4, and 8 are depicted in Fig.18.

d) On Load Tap Changing
An On-Line Tap Changing Transformer (OLTC) has been placed in between bus 24 and load at that bus. The input to the regulator is the magnitude of bus voltage. The tap position is automatically adjusted in discrete manner to achieve the desired voltage level as depicted in Figs. 19 and 20.
VI. CHALLENGES FACED

In Matlab Simulink, the synchronous machine model is found to have some limitations. The model may give rise to numerical instability in discrete time step simulation, particularly in multi-machine inter-connected system. This can be overcome by ARTEMIS solver and placing a snubber resistance connecting a small-resistive load at generator terminals. In New England 39-bus system, as per the system data at bus-39, the generator is connected directly to bus without transformer. Marginal topological modification is created in the study to avoid simulation problems. An additional bus is added as bus-40, and a transformer is connected between bus-39 and bus-40. This modification has also been shown in Fig.4. Addition of additional transformer might affect the load flow results. Hence, the parameters values are carefully chosen so that the load flow results do not deviate much from the nominal values. New England 39-bus system also has been divided into multiple subsystems to distribute the computational load in various processing units for parallel processing operation, which helps in running the simulation in hard real time; otherwise, simulation overrun errors can be observed.

VII. CONCLUSION

In this paper, the development of power system dynamic models in OPAL-RT real-time simulator environment has been discussed. The performance of the dynamic test cases is investigated under various disturbances such as single line to ground fault, line outage, step load change, and tap changing of on load tap changers. The challenges faced during such development are also been discussed. The stability of the IEEE 9-bus system and New England 39-bus system has been studied.

VIII. ACKNOWLEDGEMENT

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