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Study on OPAL-RT Simulation System Hardware in Loop and Simulation on Microgrid Black Start

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Study on OPAL-RT Simulation System

Hardware in Loop and Simulation on Microgrid Black Start

By

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ABSTRACT

In power grid simulation able to provide real time simulation give us an advantage to see how to power grid work in real time and let the electrical power grid operator to make adjustment in a humane time scale much more easily. Before OPAL-RT simulator system been sold in the market in late 1990s, real time simulation of the Electrical Grid is much more difficult. The OPAL-RT simulation system use a dictated computer system and efficient coding to make the power grid simulation runs much faster and able to display the result of the simulation in real time. The OPAL-RT simulation system also has many digital and analog output and input port, which can be use to connect and control many external hardware, by using this feature we can make a hardware in loop simulation to control and read the output of power simulation hardware in real time. The scope of this project is to study how to program the OPAL-RT simulation system to do the hardware simulation. I will also simulate the microgrid during main electrical grid fault using OPAL-RT simulation system and study how to improve the stability of the microgrid during black start after disconnect with the main electrical grid. Finally I will create a hardware in loop simulation to find if the result of the computer simulation match with the hardware in loop simulation.
CHAPTER 1. OPAL-RT SIMULATION SYSTEM

1.1 INTRODUCTION

The OPAL-RT simulation system in my laboratory consist of a chassis called the OP5700 simulator with many connection ports on the output and computer and control hardware inside and, a interface software called RT-Lab that runs on the personal computer in my lab. The OP5700 simulator has a powerful and dictated CPU that use to run the simulation on the electrical grid and a FPGA that use to control the output and hardware. The random access memory of the system is 16GB. The RT-Lab works as the communication interface between the PC and OP5700 simulator, its job is to control the function of the OP5700 simulator and translate the Simulink model into an efficient code that can run on the OP5700’s CPU. The communication between PC and OP5700 is using the local area network or LAN via Ethernet cable. There the Redhat operating system installed on the OP5700 simulation system, it has a monitor output via VGN cable and accept the keyboard and mouse input, thus we can operate it locally without using PC.

1.2 THE APPEARANCE AND PORTS OF OP5700 SIMULATOR

Figure 1: APPEARANCE OF THE SIMULATOR
Figure 2: FRONTAL CONNECTION PORT

Figure 3: RJ-45 JACK FOR SINGLE MONITORING
As the image above shows the both front and rear connection port of the OP5700 simulator. The front end of the connection port is RJ-45 connector was mainly use to monitor the signal from the oscilloscope, which signal to monitor depend on the configuration of the Simulink file. The back side of the OP5700 simulator works as the signal control port to control the signal send into the hardware we later on used in the hardware in loop simulation.
1.3 SIMULATOR HARDWARE OVERVIEW

Study the hardware used inside OP5700 simulator can help us greatly understand how the system could be configured and how the system behaves.

Below is the diagram of the hardware connection inside the OP5700 simulator.

![Diagram of hardware connection inside OP5700 simulator](image)

As we can see from the image above, that CPU calculate how the simulation could have played out, and it will tell the FPGA board when to output or acquire a signal.

1.4 RT-LAB SOFTWARE OVERVIEW

The other important tool to run the simulation is the RT-Lab software. In this section I will only briefly talk about what kind of functionality do we expect from this software without going into much detail discussion on how to use this software.

The RT-Lab software is developed by the same corporation that make OP5700 simulator, it works mostly as the translator to translate the Simulink model that created on PC into an execution code that can be use to run on the simulator. It also can also
be use to control the parameter of the simulation and execution. Below is an image about of RT-Lab software main window.

![RT-Lab Main Window](image)

**Figure 7: RT-LAB MAIN WINDOW**

As you can see from the image above, it has a listed of the project that created that can be run the on the simulator. It also controls the simulator to load the project, execute the project or pause the running process. There are also other parameters that we can set for the simulation but I will not list it here.

### 1.5 SIMULINK MODEL SETUP

Unlike the way we normally run the Simulink on the PC, there are some requirements needed to setup the Simulink model in order for it to run on the simulator. Here I will briefly talk about what the requirements are, and overall what the structure of the Simulink model file looks like.
Basically when the Simulink model been run it will run in synchronize at the simulator and PC, thus a model need to specify which part will run on the simulator and which part will run on PC. The part run on the simulator will consist of the electrical grid configuration and the variety system that came with it. The part that runs on PC will consist of which signal from the electrical grid you wish to monitor in real time on PC. A special Simulink block that came with the RT-Lab is needed in order for these two part to communicate in real time. The naming of the two part is also need to follow a certain rule in order for the RT-Lab to identify during the translation process. The part runs on PC is called control subsystem, in Simulink model you need to name it to SC then follow a name you want to give. The part that run the the simulator is called master subsystem, in Simulink model you need to name it to SM then follow a name you want to give. Below is an image to show the overall view of the Simulink model.

Figure 8: SIMULINK SETUP
As you can see from the image above that the two subsystem are connected with each other with a control signal going out of the part that runs on PC to the part that runs on simulator, and monitor signal going the opposite way.

Another thing need to pay attention before running the simulation is that the simulator will only accept discrete step simulation and have a certain restriction on the sample time of the simulation. The sample time can’t go below $10^{-5}$ second for the simulation, or the simulator will not run.

After the Simulink model meet the requirement to run on the simulator, all you need to do is to create a project on the RT-Lab software and upload your Simulink model to the created project and let the RT-Lab translate and upload the code to the simulator and you can see the result in real time on your PC.
CHAPTER 2. THE SIMULATION OF MICROGRID BLACK START WITH DESCRETE GENERATOR

2.1 INTRODUCTION

The modern development of the wind and solar energy let smaller community at remote locations around the world, put more wind turbines and solar panels to their local electrical grid to get cheaper electrical energy [1]. By doing so these small communities formed a local microgrid, with its own electrical energy producer and consumer, but a recently hot research topic is on if the main electrical grid have a electrical fault, will the discrete and localized generator can black start their own local grid after disconnect with the main electrical grid [2] [3].

In this chapter we will experiment on the OPAL-RT simulator with main electrical grid fault and microgrid black start in real time to see, if it possible for the microgrid to return its original frequency and voltage by using the generator available locally connected the microgrid.

2.2 SIMULINK SETUP

As I have state in pervious chapter that the Simulink need two subsystems in order to run. The one that runs on the simulator is show below:
Figure 9: SIMULINK MASTER SUBSYSTEM OVER VIEW

Figure 10: FAULT CONTROL MODULE
Figure 11: MAIN GENERATOR MODULE

Figure 12: WIND TURBINE MODULE
Due to the close distance between the wind turbine and solar farm to the load and simplify the simulation, in this module I will not add the line inductance. The load is
pure resistive. The electrical fault generator will generate a electrical fault that short all generator in the microgrid, and after certain amount of time the main circuit breaker will break the microgrid from main electrical grid and microgrid will work as an island mode, I will then take the load voltage and frequency measurement to see if the load could back to its normal voltage and frequency.

The part that runs on PC will take the measurement in real time, below is overview of the subsystem that runs on PC.

*Figure 15: CONTROL SUBSYSTEM OVERVIEW*

The control subsystem that runs on PC, have a manual switch that control the electrical fault in the master subsystem. The scope in the control subsystem take the measurement from the microgrid load and display its voltage and frequency.
2.3 RENEWABLE ENERGY GENERATOR OUTPUT

As you can see from the module above, that we have wind turbine generator, and solar farm in our microgrid, both of these two type of generator’s power output depend on its local environment. Here I list the generator output plot of wind turbine respect to wind speed, and solar farm at 1000 W/M^2 solar irradiation and ambient temperature.

![Wind Turbine Power vs Wind Speed](image)

*Figure 16: WIND TRUBINE POWER VS WIND SPEED*
In my setup I will set the wind speed at constant 11 m/s and solar irradiation at 1000 W/m².

2.4 THE INTRODUCTION TO MICROGRID BLACK START TEST

With a relative simple microgrid to analysis and test, all we need to to came up a plan to do the black start test. Here down below is the different test that I will take:

1: Microgrid with only solar and wind generator, without load balance control.

2: Microgrid with only solar and wind generator, with load balance control.

3: Microgrid with only solar and wind generator, without load balance control, with synchronous condenser.
4: Microgrid with only solar and wind generator, with load balance control and synchronous condenser.

5: Microgrid with solar, wind and diesel generator, without synchronous condenser.

6: Microgrid with solar, wind and diesel generator, with synchronous condenser.

In order to say the simulation shows that the microgrid successfully black start the frequency must return to 60Hz after disconnect with main electrical grid and the voltage need to return to normal, which in this case is 1 per unit.

There are some parameters also need to concern in the simulation, the parameter can change accordingly but I will list below what the parameter are and what my setting was:

1: The amount of time that takes for the main power grid breaker to disconnect with the main power grid after the fault. In all the cases I choose the breaker responds time to 0.1 second.

2: The amount of load after main power grid disconnection. It can change when there is a load balance controller.

3: When to disconnect and reconnect with main power grid. I choose manual disconnect and reconnect in all cases.

In the following sections of this chapter, I will analysis case by case on each test result.

2.5 MICROGRID WITH ONLY SOLAR AND WIND GENERATOR, WITHOUT LOAD BALANCE CONTROL

In this Simulink model configuration, it will be the same configuration as shown in figure 9. Below is the simulation result.
Figure 18: LOAD FREQUENCY

Figure 19: LOAD VOLTAGE IN PER UNIT
In the simulation the load consumes more power than the generator can provide. As you can see from the simulation result above that the load frequency increase uncontrollably and the voltage drop to almost none. We can not say the microgrid black start in this case.

2.6: MICROGRID WITH ONLY SOLAR AND WIND GENERATOR, WITH LOAD BALANCE CONTROL BUT NO SYNCHRONOUS CONDENSER.

In this simulation, I going to add a control system that can adjust the amount of load to control the frequency back to normal. Below is the load control schematic.

As you can see there is a read out of the voltage from the bus that feed into the load and that information was send to the frequency regulator to control the amount of load needed make the frequency back to 60Hz. Below are the results of the simulation.
Figure 21: LOAD FREQUENCY

Figure 22: LOAD VOLTAGE IN PER UNIT
As we can see from simulation above that like the simulation without the load control, the load frequency rises uncontrollably, and load voltage decrease to almost none, thus a large amount of power is needed to provide right after the fault is cleared to kick start the microgrid.

2.7: MICROGRID WITH ONLY SOLAR AND WIND GENERATOR, WITHOUT LOAD BALANCE CONTROL, WITH SYNCHRONOUS CONDENSER.

In this simulation, we are going to try using the synchronous condenser to provide some initial stability to provide power to drive the load and see if it works out better. The synchronous condenser models like below.

*Figure 23: SYNCHRONOUS CONDENSER MODEL*
The synchronous can store large amount of kinetic energy to convert to electrical energy and it can provide 300kVA of complex power. Below is the simulation result.

*Figure 24: LOAD FREQUENCY*

*Figure 25: LOAD VOLTAGE IN PER UNIT*
The simulation result show that the synchronous condenser does stabilize the voltage but the load frequency still rises uncontrollably, add the load frequency control is needed.

2.8: MICROGRID WITH ONLY SOLAR AND WIND GENERATOR, WITH LOAD BALANCE CONTROL AND SYNCHRONOUS CONDENSER.

Since in the simulation above, shows that by adding the synchronous condenser the load voltage does recover, but the frequency rises uncontrollably, thus in this simulation we add the frequency controller to control the amount of load that applied to the generator and see if the frequency can be controlled. Below is the simulation result.

![Figure 26: LOAD FREQUENCY](image)
The simulation result show after certain amount to time after the main electrical grid disconnection, the load frequency control did manage to drive back the frequency back to 60Hz and the voltage like the previous simulation return back to normal. This control scheme did work as we expect, but it going to expensive to add both synchronous condenser and load frequency control into the microgrid, thus in next simulation we going to add a diesel generator into the micro grid to see if it works better without load frequency control and synchronous condenser.
2.9: MICROGRID WITH SOLAR, WIND AND DIESEL GENERATOR, WITHOUT SYNCHRONOUS CONDENSER.

In this simulation, we are going to add a diesel generator that has a rating of 3.125MVA, which is enough to drive the load after the main electrical grid disconnection.

The diesel generator is modeled as follows.

![Diagram of Diesel Generator Model](image)

**Figure 28: DIESEL GENERATOR MODEL**

As you can see from the control scheme of the diesel generator, it will try to find the amount of power available to control the amount of torque available to drive the generator and make the load frequency to 60Hz. Below are the simulation results.
Figure 29: LOAD FREQUENCY

Figure 30: LOAD VOLTAGE IN PER UNIT
The simulation result out preformed the simulation without diesel generator and, the frequency is most stable. The assumption of the simulation was to operation the diesel generator during the entire period of time, even before the main electrical grid disconnection which is not a good idea. In next simulation we want to add a synchronous condenser to stabilize the grid first after the main electrical grid disconnection and then start up the diesel generator to provide the addition power, which going to save some money since we only use diesel generator when the microgrid is in island mode.

2.10: MICROGRID WITH SOLAR, WIND AND DIESEL GENERATOR, WITH SYNCHRONOUS CONDENSER.

In this simulation we are going to add the synchronous condenser into the pervious microgrid schematic and the simulation result is shown below.

![Figure 31: THE LOAD FREQUENCY](image)
As you can see from the result shown above, the load frequency changed rapidly after the main electrical grid disconnection, this is due to the time that need to take for the diesel generator to start, after the diesel generator start and it was able to drive the load into stability in both voltage and frequency.

2.11 CONCLUSION

From the simulation study above, we find that it is possible to black start the microgrid on it own with only solar and wind but there are other things needed to add into the microgrid. By adding the synchronous condenser and load frequency control we can let the microgrid to stabilize after a certain period of disturbance, but add load frequency control is very hard due to most demand is most likely wasted, and quick adjustment of the load is very hard thing to do. When we later added the diesel
generator that can generate enough the power the microgrid, the performance is most stable in both frequency and voltage, but realistically it will cost more to run due to we need to run the diesel generate all the time, and electrical grid fault is rare event. The better way of doing it is to add a synchronous condenser into the microgrid to make sure it can provide enough power to let the diesel generate to start which will take some time. The later method prove that it will cost some frequency instability as a trade off, but it will be more economic to run.
CHAPTER 3: HARDWARE IN LOOP SIMULATION

3.1 INTRODUCTION

The main idea of doing hardware in loop simulation is to test the physical response of the system as close to reality as possible. The simulator need to connect and control the physical power source and generator in order to run the simulation. In my lab we do have the hardware that we need to do the hardware simulation. In order to do the simulation that we need, we first need to have a controllable power source and a load simulator, then I need to find a way to connect them with my simulator and use a proper signal from the simulator to control the system. The OP5700 simulator did have a FPGA that can generate signal and control the power source, thus work out how to program FPGA is the first step toward doing hardware in loop.

3.2 PROGRAM VC707 FPGA

As what we have shown in the section 1.3, we do have an FPGA system code name VC707, installed on the simulator, and we can use it control the signal for the DB37 connector at the rear of the simulator.

In order to program the VC707 FPGA, a bitsteam file that can be used to program the FPGA was needed. Fortunately, during the initial system setup, we did get a copy of the bitsteam file, that can be use later on to program the FPGA. Below is the Simulink file that used to program the FPGA for the hardware in loop simulation.
Figure 33: SYSTEM OVERVIEW

Figure 34: CONTROL SUBSYSTEM

Figure 35: MASTER SUBSYSTEM
As you can see from system overview, the hardware initialization block is reference to the bitstream file that will be used to configure the FPGA. The control subsystem was like before to switch the electrical fault, and there is a monitor signal from master subsystem to read the data from the hardware and send it to the control subsystem for display.

3.3 HARDWARE USED IN THE SIMULATION

There are two hardware used in the simulation, one is power source, the other is the programmable load. Both of them have input and output terminal, by utilize these terminal available, we can control the hardware for the simulation.

The power source is called Chroma 61511 programmable AC source; it can read an analog signal from the DB37 connector and output a corresponding voltage. The ratio between the input and output voltage is shown below.

**Amplifier**: The output voltage \( V_{out} \) is the composition of the voltage set in MAIN PAGE and the suplemental programmed voltage inputted externally. The external V reference voltage range is from -10 V to 10V. When \( V_{ac}=0 \) and \( V_{dc}=0 \) in MAIN PAGE, the following formula can be used to calculate \( V_{out} \).

\[
\begin{align*}
V_{out\ (dc)} &= V_{ref\ (dc)} / 10 \times V_{dc} \times 424.2 \ Vdc \quad (range\ 300V) \\
V_{out\ (dc)} &= V_{ref\ (dc)} / 10 \times V_{dc} \times 212.1 \ Vdc \quad (range\ 150V) \\
or
V_{out\ (ac)} &= V_{ref\ (ac)} / 7.072 \ V_{ac} \times 300 \ Vac \quad (range\ 300V) \\
V_{out\ (ac)} &= V_{ref\ (ac)} / 7.072 \ V_{ac} \times 150 \ Vac \quad (range\ 150V)
\end{align*}
\]

**Figure 36: VOLTAGE OUTPUT CONVERSION**

The load used in the simulation was Chroma 63804 programmable load, it has terminals to read out the voltage and current, thus we can make the connection between the terminal and DB37 connector analog read in port to gather the voltage and frequency information during the fault. With everything we need, now we can do hardware in loop test.
3.4 TEST RESULT AND DISCUSSION

In this hardware in loop simulation, I going to simulate a simple electrical system fault and black start, and see the result of the simulation. The simulation result is shown below.

![Figure 37: NORMAL VOLTAGE FROM THE LOAD](image1)

![Figure 38: MICROGRID BLACK START RESULT](image2)
As you can see from the simulation result, as we can expect, that there is a voltage overshoot during the initial start up, the power source has enough power to quickly start the load, thus there is not too much voltage or frequency change right after black start.

3.5 CONCLUSION

The initial microgrid black start simulation did show some promising result, but due to currently I did not use digital signal to control the load, thus there are more work can be done, due to the short period of this project don’t have enough time to do the digital signal control. Doing the hardware in loop by use digital control signal will give you more control authority to the power source and read much more information from the load.

Both power source and load have parallel communication channel GPIB or serial communication channel RS-232. OP5700 simulation do not came with these communication channel directly.

More work need to study the digital communication protocol and use it to program the digital output from the DB-37 connector and make a connection cable to convert the DB-37 digital terminal to the digital communication terminal listed above. It will take some time to study, program and make connection cable by yourself, due to no such cable exist on the market.
REFERENCE

