Real-Time Hardware-in-the-loop Simulation for Protection Applications
- from a smart-grid perspective

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29th October, 2019
Motivation

A smart-grid requires an ICT support system
- Protection applications and algorithms developed need to consider this.
What is digital substation?

IEC 61850 – "COMMUNICATION NETWORKS AND SYSTEMS IN SUBSTATIONS"

Pros and cons of IEC 61850 based digital substation:

- Standard Ethernet-based communications systems
- No "spaghetti" mess behind
- Easy system expansion
- Increased system reliability
- Interoperability
- Increased safety for personnel

- More expensive implementation
- Training required
- Modifications from traditional automation system
- Cyber security
Role of Communication in smart-grid protection

Challenges:
- Deploying power system protection applications with communication technology e.g. wide area networks
- Capture network parameters that affect performance of protection traffic in intra/inter substation i.e. delay, packet loss, jitter
- OPAL-RT simulator limited in the ability to simulate communication network impairments

Need to factor communication effects in power system protection applications
Role of Communication in smart-grid protection

Proposed Approach

Communication network emulation; a solution to reflect the characteristics of the ICT system and its interface with the physical power process.

Click Router as a Network Emulator Design Tool
Outline

- Network emulator design
- Architecture & Features
- Integration of emulator and HIL Test bed
- Composing new elements
- Case Studies, Results & Evaluations
Network Emulator Design & Applications

Design

• Emulator enable us to change delay, jitter and packet corruption as a function of time.
• Control communication properties between multiple source relays and destination relays
• Impairing specific subsets of the network traffic
• Vary the properties of communication parameters in real time using - using handlers
• Bandwidth restriction
• Emulate different queueing schemes and traffic priorities
Motivation for choice of tool: Click Modular Router

Click Router is a software framework for building flexible and configurable routers

- **Flexibility**
  - Adding new features to enable experimentation
- **Openness**
  - Allow users to build and extend
- **Modularity**
  - Simplify the composition of existing features & addition of new features
Router as a Graph of Elements & Push and Pull Connections

- **Push connection**
  - Source pushes packets downstream
  - Triggered by event, such as packet arrival
  - Denoted by filled square or triangle

- **Pull connection**
  - Destination pulls packets from upstream
  - Packet transmission or scheduling
  - Denoted by empty square or triangle

- **Agnostic connection**
  - Becomes push or pull depending on peer
  - Denoted by double outline
Test power system network with CC in Opal RT-Lab/Matlab

Network Emulator

OPAL simulator OP5600

Practical protective relays

SV, GOOSE
-status of CBs and SGs to CC
-SG switch order from CC

SV, GOOSE
-status of CBs and SGs from relay
-SG switch order to relay

Integration of Emulator and HIL: Setup
Real time Hardware in the loop (HIL) protection lab at NTNU

1. Opal-RT simulator
2. ABB Relion 670 relays
3. OMICRON CMC 356
4. IEC61850 based communication network

5. Host PC and HMI for Opal simulator and network analyzer
6. Communication switch emulator-Click and Network analyzer-Wireshark
7. Host PC and HMI for PCM 600 and ABB relays
Composing new elements: Emulator with IEC 61850 Capabilities

- Classifying IEC 61850 GOOSE & SMV packets

```
require(clicklocal);

FromDevice(eth1) -> ic :: IECClassifier(GOOSE, SMV, -)
ic[0] -> Queue(10000) ->ToDevice(eth0);
ic[1] -> Discard;
ic[2] -> Discard;
ClickyInfo(STYLE @import test-clicky.css);
```
Composing new elements: GOOSE Classifier

require(clicklocal);

FromDevice(eth0)
   -> ic :: IECClassifier(GOOSE, SMV, -)

ic[0]-> Strip(14)
  -> CheckGOOSEHeader()

  -> gc :: GOOSEClassifier(GOOSE_TRIP1, GOOSE_OV2PTOV, -)

gc[0]->ToDevice(eth1);

gc[1]->ToDevice(eth2);


tc[1]->Discard;

tc[2]->Discard;
Composing new elements : Random Delay Element

• An element that applies random delay time on packets passing the router
• Assumes uniform distribution

```
require(clicklocal);

FromDump(/home/charles/Documents/tracedumps/udpsample1.pcap, STOP true)
   -> Strip(14)-> CheckIPHeader()
   -> ip :: IPClassifier(udp,tcp,icmp,-)
   tp[0] -> tp :: Tee(2)
   tp[0] -> q1::Queue(1000);

   tp[1] -> Queue(1000) -> RandomDelay(1,5) -> q1;
   |
   q1 -> Unstrip(14) -> ToDump(/home/charles/Documents/tracedumps/drop.pcap);
   ip[1] -> Discard;
   ip[2] -> Discard;
   ip[3] -> Discard;

ClickyInfo(STYLE @import test-clicky.ccss);
```
• **Case Study : HIL POTT application**
  • Emulator introduces delay of 0.35 seconds on GOOSE packets
  • ABB Relion 670 relay GOOSE publisher
  • Relay in OPAL-RT GOOSE subscriber

• **Zone 2 backup protection to clear fault, 0.3 seconds**

• Normal operation: detected fault cleared by the permissive trip signal
• Abnormal operation (delay introduced); POTT failed to clear fault in time
  • Backup protection was triggered at 0.3s to clear fault
Sample Values in Wide Area – VLAN Architecture for state estimation

- VLAN; a distinct Ethernet LAN sharing the same physical medium with other VLANs
- Method involves assigning a unique VLAN tag to SV data to routed outside the substation
- Enables connecting process busses from different substation
- Investigating the performance of the process bus network, i.e. **characterizing latency and jitter for situations such as heavily loaded networks.**
- Feasible in a dedicated and isolated network for the utility - limitations
Routable SV in Wide Area for State Estimation; Laboratory Set up
Conclusion

- Emulator can be used to change communication properties of delay, jitter, packet loss, packet corruption and bandwidth for WAN power system applications.

- Smart-grid HIL simulation approach can be used to estimate communication network constraints to be considered in protection application settings to allow for transient communication QoS parameters.
  - Investigate effects of network congestion and packet loss on different protection algorithms.
  - Model time delays and data loss to study effects of relay performance compromised by distributed generation and non-zero fault impedances.
References;


Thanks for the attention