Cyber-Physical Systems Distributed Control: The Advanced Electric Power Grid¹

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Advanced power electronics and energy storage, when combined with embedded networked computation, allow SCADA systems to move beyond centralized monitoring to active, distributed, control of the power grid. The power grid, power electronics, energy storage and embedded control software form a Cyber-Physical-System, whose design is heavily influenced by fault tolerance, security, decentralized control, and economic aspects. The envisioned advanced electric power grid provides a rich environment for the study of several inherent problems. These systems form one of the largest and most complexly inter-connected networks ever built, and their scale makes controlling them extremely difficult. Recent federal mandates for deregulation further increase the difficulty of control. Heavier power transfers resulting from independent ownership and potentially widespread use of distributed energy generation will make power systems increasingly vulnerable to cascading failures in which a small series of events can lead to a major blackout. The envisioned advanced electric power grid must include support for decentralized generation, energy storage, and transmission controllers, whose local actions can be coordinated across multiple time scales including long term (minutes to hours), dynamic (milliseconds to seconds), and local control (microseconds) for integrated and efficient control of the power grid as a whole.

The family of Flexible AC Transmission System (FACTS) devices holds considerable promise as future advanced power system controllers [1]. Unified power flow controllers (UPFCs) are hybrid FACTS devices that can control both active and reactive power flow on the line and bus voltage. Power system control has traditionally been accomplished through generator control action. Controllers, such as FACTS, that are embedded throughout the network can potentially provide better performance since, unlike generator control, their actions directly affect the local dynamics in the network. UPFCs are good candidates for distributed power grid control methodologies. Before UPFCs can be implemented on a wide-scale basis, they must coordinate their actions with each other dynamically and rapidly in the event of a contingency; therefore, extensive verification of operation should be carried out.

Traditional software-based simulation has the disadvantage of being unable to exactly replicate real operational conditions. On the other side, a small laboratory power system is not capable of fully capturing the depth and breadth of large-scale power system dynamics. One way to bridge the gap between simulation and real conditions is to combine real-time simulation (RTS) and hardware-in-the-loop (HIL).

FACTS Interaction Laboratory (FIL)

The FACTS Interaction Laboratory (FIL) based on HIL-RTS has been developed at the University of Missouri-Rolla for advanced FACTS/UPFC research. A conceptualization of the FIL is shown in Fig. 1. A realistically sized power system is modeled in the real-time simulation engine using a commercial iHawk Xeon multiprocessor system from Concurrent Computer Corp. The simulation engine is interfaced via a “hardware-in-the-loop” mechanism to provide voltage and power flow information to the UPFC devices at their interconnection points. This approach allows the UPFCs to be easily relocated within the simulated system and different controls to be tested.

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To date, three UPFC devices have been constructed. These devices are interconnected via the simulation engine that mimics the dynamic response of a power system. The simulation engine sends frequency, voltage, and current flow measurements to an external synchronous machine in the lab and a programmable load. The synchronous machine and programmable load generate the physical conditions that an actual UPFC device would encounter. The UPFC responds to these physical changes. The UPFC responses are fed back into the simulation as inputs. This setup is shown in Fig.2.

Fig. 2. Conceptual layout of hardware and simulation engine

The left portion of Fig.2 represents the simulation engine whereas the right portion shows the actual hardware. The synchronous machines are not part of the simulation but are used to produce the necessary active power flow on the lines in which the UPFC devices are placed. The programmable loads represent the load of the system “seen” by each of the UPFC devices. These loads change depending on the placement of the UPFC devices in the simulated power system.
The FIL can be used to test various placements and control strategies for the UPFCs in a large power system. The UPFCs can be easily “moved” from one place to another to validate their impact on cascading failures and to test whether or not there are any unforeseen control interactions. Fig. 3. shows the results from a typical FIL experiments. The actual UPFC power flows are filtered and then fed through an A/D converter into the simulation. The simulated system then reacts to the changes in the power flow and voltage settings of the UPFC. Conversely, short circuits and line outages can be simulated in the program and then the UPFC can be tested on how it reacts. This is especially useful for testing whether or not the UPFCs can mitigate cascading failures by selecting the correct power flow settings for the particular scenario.

**Experimental Verification of Cascading Failures**

The FIL can also be used to study the impact of FACTS devices on cascading failures. In this paper, we will highlight one particular cascading scenario of the 118 bus system shown in Fig. 4. In this scenario, a three-phase high impedance fault occurs on bus 37 and is cleared by removing line 37-39. This initiates a cascading failure as successive lines become overloaded and trip offline. Subsequently, line 37-40 overloads and trips, followed by line 40-42 after which the system becomes unstable. The time domain simulation of this cascade is shown below in Fig. 5.
Note that the fault is applied at time $t=0$ and line 37-39 is tripped shortly afterward. The power flow on line 37-40 immediately exceeds the line rating (shown by the blue dashed line). Corrective relay action trips the line after nearly four seconds. At this point, power on line 40-42 exceeds its rating (shown by the red dashed line). Note that negative indicates that power is flowing from bus 42 to bus 40. At 5.5 seconds, line 40-42 is tripped and the system goes unstable shortly before 6 seconds.
An analysis of this system indicated that if a UPFC were placed on line 37-40 with an active power setting of 0.55 pu, that the cascaded could be avoided. The simulation of the fault and 37-39 line trip is shown in Fig. 6. Note that both the active power flows on line 37-40 and 40-42 are maintained below their ratings. This scenario is then validated via the HIL with the actual UPFC on line 37-40. The results of the experimental hybrid simulation are shown in Fig. 7.

Fig. 5: time domain simulation of cascading failure

Fig. 6:  Simulation of a UPFC on 37-40

Fig. 7:  HIL simulation of fault and line-outage
This scenario is very similar to the simulation of Fig. 6. There are small, but significant differences however. First the control of the actual UPFC is slower than the simulated UPFC, therefore it takes slightly longer for the active powers to settle around their steady-state values. The waveforms of the HIL simulation also indicate a much larger impact of high frequency modal content. However, a frequency scan of both waveforms indicate that the dominant modal content is roughly the same for both waveforms. A frequency scan fits the waveforms to the series of summations where

\[ x(t) = \sum A_i e^{B_i} \cos (\omega(i)t + \theta(i)) \]

and

- \( A(i) \) is the magnitude or amount of the modal content
- \( B(i) \) is the damping factor (negative indicates damped response)
- \( \omega(i) \) is the frequency (in radians/second) of the modal response
- \( \theta(t) \) is the offset angle (will differ between responses since they do not start at the same instant in time)

Only the terms with significant modal content \( (A(i)>0.01) \) are given in Table I. Note that the largest modal content is at roughly 6.55 radians/sec, which corresponds to a frequency of 6.55/2\( \pi \) = 1.04 Hz, or roughly one cycle per second. This is consistent with the results in Figs. 6 and 7. The second largest modal content is at 13.05 radians/second, which is nearly twice the frequency of the first modal content. This too can be seen in the dynamic responses (especially the experiment/HIL response).

Table I: Summary of modal content

<table>
<thead>
<tr>
<th>Experimental/HIL</th>
<th>Simulation</th>
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<tbody>
<tr>
<td>mode</td>
<td>( A(i) )</td>
</tr>
<tr>
<td>1</td>
<td>0.02</td>
</tr>
<tr>
<td>2</td>
<td>0.05</td>
</tr>
<tr>
<td>3</td>
<td>0.02</td>
</tr>
<tr>
<td>4</td>
<td>0.04</td>
</tr>
</tbody>
</table>

It can be argued that modes 2 of the simulation is really an aggregate of modes 2-4 of the experimental response.

These results indicate that the FACTS laboratory is working as originally planned and can be used to validate a variety of experiments including control development, FACTS placement, and device interactions.

**CONCLUSIONS**

The FIL provides an excellent testbed for analyzing the interplay of power electronic controllers within the bulk power system. Numerous scenarios, control strategies, and topologies can be tested with ease and efficiency.

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**References**