RELIABILITY ASSURANCE OF EMERGING CYBER-PHYSICAL POWER SYSTEMS

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Outline

- Introduction – importance of reliability evaluation
- Power system reliability modeling:
  - Dimensions of development
  - Solution approaches
  - Observations
- Emerging power systems
- Suitability of current techniques
- Reliability techniques for emerging power systems
- Concluding remarks
Introduction

- Power systems: integration of current carrying components, protection systems, computing and communication
- Human interface – contrary to public perception, power systems are not fully automated
- Complexity is increasing in the emerging power systems - more monitoring, control and communications added.
- Sources of failure:
  - physical components,
  - software failures,
  - failures in cyber network,
  - human failures
Modeling and evaluation of these complex systems is important for assuring the reliability of these emerging power systems.

Considerable research and development work has been done over the past several decades to develop methodologies for reliability evaluation of the power systems.

Contemporary power system reliability methods focused almost entirely on the failure of physical components – current carrying part.
Current techniques: dimensions of development

- **System coverage:** What part of the system is modeled.

- **Solution approaches:**
  - models are used
  - the mathematical methods employed for solution.
Level of system coverage

- Generating capacity reliability evaluation (HL1): basic objective is to determine adequacy of generation to meet demand with a given probability.
  - Single area: Transmission assumed capable of transporting power from generation to load. Conceptually all generation and load in an area assumed connected to one bus.
  - Multi-area: Inter-area tie line constraints are considered. Intra-area constraints considered only indirectly.
Single area & multi-area models

Generation

Load

Area 1
Area 2
Area 3
Area 4
Level of system coverage - continued

- Composite system reliability evaluation (HL2): joint treatment of generation and bulk transmission.
  - Constraints imposed by the capacity and impedance of transmission lines are considered.
  - Voltage constraints may also be considered

- Distribution system reliability (HL3): given the reliability at distribution substation, determine the reliability at customer level.

- Special topics: reliability of protection systems and their impact on system reliability.
Composite system & Distribution system
Solution approaches

- **Analytical methods**: mostly used in single, multi-area and distribution system models.
- **Monte Carlo simulation**: mostly used in multi-area and composite system models.
- **Intelligent search techniques**: still in development stage for either increasing the efficiency of analytical or simulation or providing an alternative to Monte Carlo simulation.
- **Hybrid**: mixing for increased strength.
A general schematic
System Models

- System models differ depending upon the intended application.
- For single area studies the model is fairly simple unless operating considerations are included.
- For multi-area studies the system model is more complex.
- Presently composite level represents the highest level of complexity.
  - Even at this level, complicating issues like the impact of malfunction of protective relays or impact of post fault events are generally excluded.
  - Load is assumed forecast and its responsiveness to market conditions and type of generation available is not modeled in detail.
State identification and selection

- Impossible to consider all possible system states – so called curse of dimensionality
- Analytical methods try to meet challenge of dimensionality by state merging, truncation and implicit enumeration.
- Monte Carlo simulation meets this challenge by sampling
- Recently emerging intelligent search techniques, focus is on identifying dominant failure states.
State Evaluation

- In any method, the selected state needs to be evaluated to determine if the objectives of the system are satisfied.
- This may be simple addition or subtraction
- This may be a network flow model:
  - transportation type model
  - Or more time consuming DC or AC power flow model.
Observations

- Three parts of a power system: Current carrying part, protection system and cyber part.
- To this day, power system reliability methods have focused primarily on current carrying part.
- Some work on protection and cyber part has been reported but analysis on the whole CPS is lacking.
- Dimensionality and complexity are two major challenges in power system reliability analysis.
- Dimensionality arises from a large number of components and combination of possible states.
Observations - continued

- Complexity arises from complex interrelationship between components and modification of system behavior by operating strategies.
- Capacity and admittance of components distinguishes power system from some other systems and make the reliability analysis more difficult and computation intensive.
- Demarcation of power system into hierarchical levels has been beneficial for guiding the development of reliability methods but has also narrowed its focus leading to ignoring interfaces outside this framework.
Emerging Power Systems

- The power systems of the future will be different from this decade.
- Two major factors contributing to this change:
  - Large scale penetration of renewable energy sources of variable output – wind and solar
  - Smart grid initiative backed by federal government in USA and similar efforts in other countries.
Emerging Power Systems—continued

As an example, according to 2009 NERC report, approximately 260 GW of new ‘nameplate renewable capacity’ is projected to be installed in USA over the coming 10 years.
Emerging Power Systems - continued

- To accommodate large scale penetration of variable energy sources, storage will also need to be added.
- Installation of hardware for interactive relationship between the supplier and consumer will add to complexity and interdependency between the cyber and physical parts.
- Complexity and interdependency will introduce more sources of problems and make reliability analysis more challenging.
The current techniques have focused primarily on the current carrying part of the power system. Work has been done on the cyber part but the interrelationship between the cyber and physical has not been tackled adequately. Limited work done in including the SCADA system. Some work also done in the modeling of protection systems and their impact on the current carrying part.
Suitability of Current Techniques—continued

- The approach to modeling of the impact of protection systems may have relevance to modeling of CPS.
- There is a recognition that it is impractical to model details of protection and current carrying part simultaneously.
- General approach:
  - analyze the protection separately
  - model the interface of the protection system through their effect on the ability to isolate the faulted part or unnecessary isolation of healthy parts at the point of circuit breakers.
Cyber part needs to be included as its availability determines the implementation of intended remedial actions.

For example, in composite system reliability analysis, if there is loss of load, we try to re-dispatch generation or curtail load to see if the abnormal conditions can be alleviated.

This is usually accomplished by performing a power flow calculation. If an optimal power flow solution can be found to solve this imbalance, we assume that the condition can be alleviated.
Need to Include Cyber Part – continued?

- To orchestrate the solution, however, we not only need the generators and transmission lines but we also need the availability of the cyber part, i.e., control and communication system.

- In the current reliability analysis it is, however, assumed that such a solution can be implemented with probability one, assuming implicitly that the control and communication system never fails.

- Another example is the efficient utilization of wind energy using the cyber links. What will happen if the cyber part fails what impact will it have on reliability.
So to get realistic evaluation of reliability, inclusion of cyber part is important as is the inclusion of protection failures.

To develop a comprehensive approach, we need to categorize the effect of cyber link failures.

The next slide lists these categories in the decreasing order of severity of impact.
Impact of Cyber Link Failures

- **Catastrophic effects**: Monitoring and control failures leading to reduced capacity for handling contingencies.

- **Degrading effects**: Degrading effects leading to inefficient utilization of resources.

- **Local effects**: Effects limited in duration and impact.
Current Techniques for Future Objectives

- Protection system that interacts with the current carrying part has been included by doing a separate analysis of the protection system and then modifying the circuit breaker model using the parameters derived.

- The parameters derived:
  - Unreadiness probability: probability of not acting when the protection system needs to act.
  - Probability of undesired tripping.

- Generally there is a defined relationship between a set of protective devices, the part of the circuit they are protecting, and the circuit breakers that they are supposed to activate.
Possible Approaches to Reliability Techniques for Future Power Systems

- Complexity and dimensionality complicate the reliability analysis of the whole system in a single step.
- Even for the current carrying part alone, it is not computationally efficient or even possible to model all the components distinctly and simultaneously.
- Some consolidation at the subsystem level is generally necessary.
- Also it is necessary to move sequentially in analysis.
Modeling Local Effects

- More interested in continuity of signals rather than capacity of links
- Analytical methods like cut-sets or Monte Carlo could be used.
Degradation Effects

- Degrade the ability of system to optimal use of current carrying part.
- More serious than the local effects
- Perhaps still could use continuity criterion making state evaluation less time consuming.
Catastrophic Effects

- More interaction between cyber and physical part and analysis will be more complex.
- In some situations the problem could be simplified by analyzing the cyber part and representing this through the unreadiness probability and the probability of undesired activity or some similar parameter.
- The models of current carrying part would need to be modified to incorporate these effects.
Concluding remarks

- The current techniques for power system reliability are focused mainly on the current carrying part of the power grid with some work done in the inclusion of protection systems.
- However, the cyber and physical part of power delivery will continue to grow more complex.
- Interaction between cyber and physical part and analysis can lead to more complex failures.
Concluding remarks - continued

- The literature on the reliability of the cyber part is practically non-existent.
- The analysis of the power system as a cyber-physical system appears to be a challenging task because of the dimensionality and complexity issues.
This presentation has classified this analysis into three categories: local, degrading and catastrophic type failures.

It appears that it may be possible to solve this problem using an approach similar to one employed for protection systems where the interaction of cyber part may be modeled as unreadiness probability or probability.

This presentation has provided only an overall vision of the problem and possible solution approaches.

Considerable research effort is needed to study this problem in detail and formalize these classes and approaches for solution.
Acknowledgement

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