5.12 Automated Integration of Condition Monitoring with an Optimized Maintenance Scheduler for Circuit Breakers and Power Transformers (T-19)

Summary	Cost-effective transmission equipment maintenance requires on-going integration of information from multiple sources. This project will develop a real-time software solution that performs this information integration automatically.
Research Need	Equipment maintenance is costly but essential to ensuring transmission system reliability. Its effectiveness can vary dramatically depending on the target and timing of the maintenance activities.
Research Stem	T&D Technologies
Academic Team Members	Jim McCalley (Iowa State, EE-lead: jdm@iastate.edu, 515-294-4844) Mladen Kezunovic (Texas A&M, EE), Chanan Singh (Texas A&M, EE), Vasant Honavar (Iowa State, Computer Science)
Industry Team Members	Mid American Energy (Andrew Geest), Omaha Public Power District (Jim Foley), Reliant Energy HL&P (Don Sevcik), TXU (Jim Bell), Mitsubishi (David Wong)
Funding Period	June 1, 2002 to June 30, 2005
Budget	$21,250 per year for each researcher. Total: $85,000 per year for three years (2002-2004).

Project Description: Equipment maintenance is costly but essential to ensuring transmission system reliability. Its effectiveness can vary dramatically depending on the target and timing of the maintenance activities. The existing state-of-the-art offers at least three basic approaches for making the decisions associated with identifying maintenance activities: condition-based maintenance (CBM) initiates a maintenance activity when data from monitoring the equipment indicates a need, reliability centered maintenance (RCM) prioritizes maintenance activities based on quantification of likelihood and consequence of equipment failures, and optimization techniques offer methods of maximizing effectiveness of the maintenance activities subject to constraints on economic resources, available maintenance crews, and restricted time intervals. These three approaches are illustrated in the circled part of Fig. 1 [ieee01]. *Our objective is to develop a system wide maintenance allocation & scheduling system based on integration of condition-monitoring with an RCM-based optimized scheduler for transformers and circuit breakers.* In order to limit the project objective to one that can be accomplished within the designated budget and duration, we will focus on circuit breakers and transformers for the following reasons: expenditures for the associated maintenance of this equipment represents a large percentage of maintenance budgets; their failure can have significant system reliability impact; and monitoring technologies for each of these equipment types presently exist within substations of PSERC member utilities. There are two subgoals associated with accomplishing the project objective. The first is to develop the analytic models and procedures for using conditions of the monitored equipment in decision making related to a maintenance allocation and scheduling function. The second is to create the software infrastructure necessary for performing automated and continuous integration of the various data sources when updating the maintenance schedules.

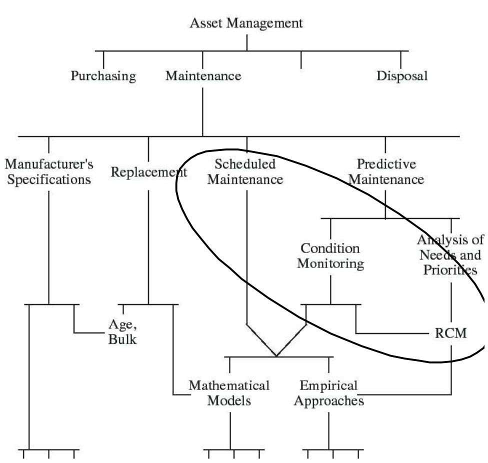

Fig. 1: Maintenance approach overview

Potential Industry Benefits: This project will benefit the PSERC member companies in two specific ways: (1) Improved reliability: By using the software solution, companies will experience a significant increase in transmission system reliability per dollar spent on maintenance activities. This reliability improvement will come about as a result of focusing the maintenance resources on reducing the risk of failure of the most critical and expensive equipment.
(2) Reduced cost of human labor: A multiagent software (MAS) will provide autonomous oversight and coordination of the software tasks, relieving humans from tedious and labor-intensive data manipulation associated with integration of the various information resources. We expect that MAS, because of its effectiveness in facilitating task coordination for distributed information systems, will prove to be a very cost effective solution.

Expected Outcomes: There are 5 specific deliverables associated with this project, as described below:

- Report 1, Condition monitoring and failure probabilities: This report will identify and describe the monitoring technologies, the data collected, and the failure modes. It will provide models relating these issues to equipment failure probabilities.
- Report 2, Maintenance and failure probabilities: This report will identify and describe the maintenance strategies that mitigate the failure modes described in report 1.It will provide models relating these maintenance strategies to equipment failure probabilities.
- Report 3, Integration of condition monitoring with maintenance scheduling: This report will describe the implementation of the optimization method for identification and scheduling of the maintenance activities based on the condition-based monitoring information.
- Report 4, Use of multiagent system for data integration: This report will describe the software agent design requirements and the multiagent software (MAS) infrastructure including the agent platform, communication protocols, inter-agent messaging, coordination mechanisms, and data access methods.
- Report 5, Software solution: The solution will consist of four individual software agents, developed in Java, corresponding to the functionalities described in reports 1-4, together with the MAS infrastructure necessary to support the agents.
- Report 6, Project summary and prototype: This report will summarize project results and provide specifications regarding how to illustrate application of the software system on a prototype mock-up of a large-scale power system.

Technical Approach:

A. Condition Monitoring and Failure Probabilities:
We will focus on two types of equipment in regards to condition monitoring: power transformers and circuit breakers [web01].

1. Power transformers: One industry partner indicates that they will in the near future begin monitoring 345/161KV transformer banks using GE hydran units monitoring hydrogen, CO, acetylene, and ethylene.gas, with an alarm tied to the SCADA system, downloading every 15 days. A vendor at http://www.servon.com/products/TG-gmb-sub.asp reports significant sales of a commercial product that performs on-line monitoring of all eight fault gases, temperature, and loading to predict transformer integrity using Web-displays. The Doble Insite Intelligent Diagnostic Device, http://www.doble.com/pdf/idd.pdf, provides on-line diagnostics of bushings and current transformers. Sensors, mounted directly on the bushing test tap or CT tap of any manufacturer, measure and store measurements associated with capacitance and power factor in order to detect insulation deterioration in condenser core, core surface, or the porcelain inner surface. Another easily monitored device on a transformer would be the radiator fan using a simple CT current monitor to identify failed fan motors.
2. Circuit breakers: Available commercial systems are capable of measuring number of operations, contact travel time, static contact resistance, phase currents, coil currents, heater and pump currents, and oil pressure and temperature, and ambient temperature. Some can also measure mechanism vibration and dynamic contact resistance (measured during breaker operation). We will focus on

monitoring technologies related to the following three approaches: a.) Determining IsquareT (duty cycle) using protective relay measurements such as provided with SEL relays; b.) Capturing changes in CB contacts and currents using standard test equipment such as Hathaway RTR; c.) Monitoring of additional contacts from auxiliary equipment and measurements of non-electrical quantities based on solutions such as the Doble Insite system.

The approach will be to identify specific failure modes characterized by each individual measurement, for specific device types and manufacturers. Most measurements taken by the above-described monitoring systems are not precise single-numbered values for a pass-fail maintenance decision, but rather are *signature data* that must be interpreted relative to reference data. We will develop procedures for using such data to enhance the accuracy of failure probability estimates. Our focus will be on circuit breakers and power transformers, but the basic concepts should be applicable to other types of device as well, e.g., load tap changers, substation batteries, etc. One very simple method would be to estimate a failure probability for a piece of equipment, and then, for each measurement, identify the "normal" value and a conservatively estimated value that would indicate failure. A relation could then be obtained based on these two conditions that provides the failure probability as a linear function of the measurement. More rigorous methods will be developed based on modeled physics of the failure mode; for example, we have correlated power transformer failure probabilities to ambient temperature in reference [mcc01].

<u>B. Maintenance Activities and Failure Rate Reductions</u>: Some typical maintenance activities for power transformers include: visual inspections, operational checks, thermography, oil and gas component analysis, oil conditioning, insulation resistance tests of pump and fan motors, device lubrication, vibration testing, torquing of connectors/supports, earthing integrity checks, insulation testing, and oil topping. Typical maintenance activities for circuit breakers include: visual inspections, thermography, device lubrication, contact visual inspections, contact timing, resistance and gap and wipe measurements, contact replacements, contact repairs, insulation measurements, tightening oil/gas pressure seals, gas addition, oil conditioning and painting. Some companies identify maintenance levels for each piece of equipment, with each successive level consisting of an increasingly more rigorous combination of maintenance activities. We will develop models relating each of the maintenance activities to the component failure probability [can86, end88, end89]. Probabilistic models will be developed providing a quantitative connection between maintenance actions and reliability. These models will be based on the concept that for maintenance or inspection to affect reliability, there needs to be an underlying process of deterioration because if no deterioration is present then maintenance is not needed. The deterioration process will first be conceptualized; one way of doing this is to divide the process into stages. Maintenance actions will be linked with the deterioration process and parameters characterizing the models will be identified. These parameters can then be estimated and updated using the data. Once the models are developed, the interplay between the level and frequency of maintenance and reliability can be studied.

<u>C. Integration of Condition Monitoring with Scheduling</u>: We will utilize a maintenance scheduling software application to optimize the selection and scheduling of the maintenance activities. We generically refer to this application as the Integrated Maintenance Selector and Scheduler (IMSS). The IMSS requires failure probabilities for each component (line, transformer, generator) in the system. It uses a long-term (e.g., year-long) hour by hour risk assessment to compute the failure impact for each component. The risk is computed as a product of contingency probability and contingency impact, where impact is quantified in terms of reliability criteria violations associated with overload, low voltage, and voltage instability. This contingency analysis, in combination with the component failure probabilities, gives the hour-by-hour year-long risk variation for each component. Cumulative risk reduction associated with each maintenance activity is computed. This computation results in candidate maintenance activities and start times designated by triplets consisting of {maintenance activity, start time, cumulative risk reduction}. The selection and scheduling function then choses those triplets that maximize the total risk reduction subject to any desired constraints that are specified. These results provide the selected

maintenance activities and a corresponding schedule to maximize the system risk reduction over the year. The actions of the IMSS are illustrated in Fig. 2.

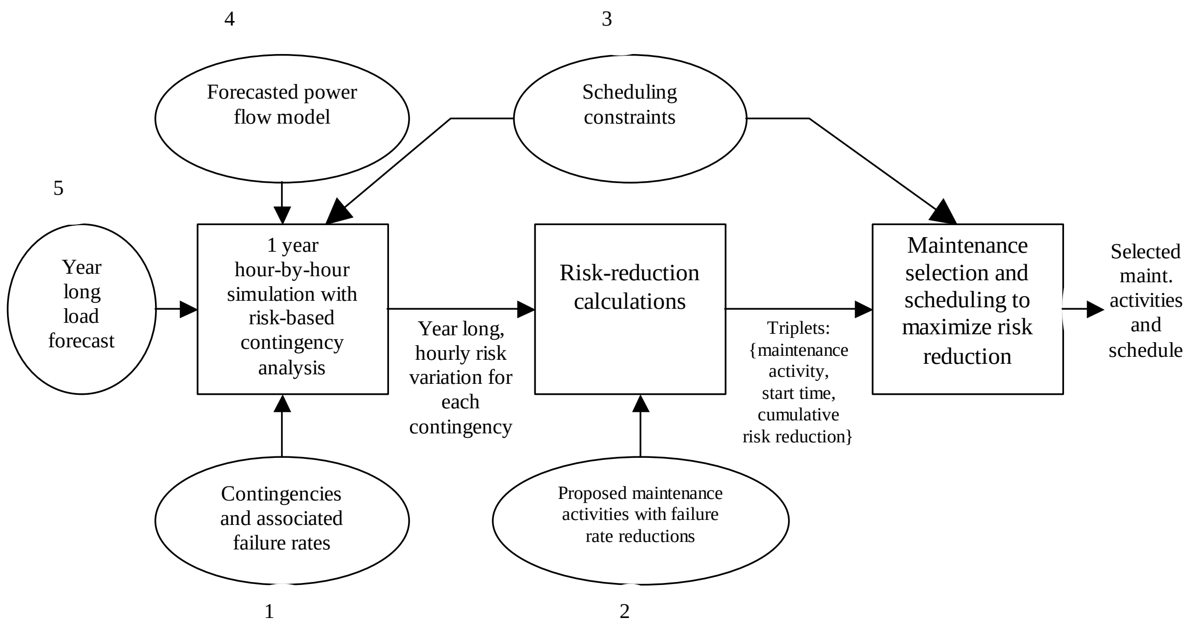

Fig. 2: Integrated Maintenance Selector and Scheduler (IMSS)

D. Software Infrastructure: Referring to Fig. 2, if all input data (represented by the ovals) were static, then we need only to perform the above process once per year. However, these data are quite dynamic, continuously changing throughout the year, particularly the contingencies and associated failure rates, as the failure rates are influenced by both the condition monitoring and previous maintenance activities. Therefore, we envision that the IMSS would process on a periodic basis, with process frequency specified by the user, to continuously update the next year's (month's, week's) maintenance schedule. Normal human coordination of the IMSS would require significant time to obtain/update the various input data, particularly under frequent iterations. It is for this reason that we implement a multiagent system, thus satisfying the need for automating the information gathering, processing, and decision making within the IMSS. Multiagent software have proven to be an attractive approach to coordinated decision making using multiple, heterogeneous, distributed, and in many cases, autonomous information sources. Agent infrastructures provide basic support for creation and deployment of agents (including support for transportation of procedures) across heterogeneous distributed computing platforms; naming and directory services; messaging and message forwarding services that enable communication among agents; agent authentication and related security functions. Such agent infrastructures make it possible for clients or users to supply specific procedures as needed at run time to be executed where the data and computing resources are located and receive the analysis results instead of raw data. We will perform a requirements analysis and specification of agent infrastructures for IMSS. This will include several aspects including the agent platform, interagent messaging, conversation and coordination protocols, multi-agent system architecture, and individual agent designs. As part of this work, we will demonstrate the features of alternative agent platforms including the Voyager platform from Objectspace, Inc. and the Concordia platform from Mitsubishi Electric. We will specify, design, and implement the agent infrastructure including software agents for data extraction, data integration, and coordinated decision making in IMSS using these agent platforms.

Work Plan: Table 1 below provides project milestones by year.

Table 1: Project Milestones by Year

Deliverable and researchers responsible	Work schedule						
	6/1/02	1/1/03	7/1/03	1/1/04	7/1/04	1/1/05	6/1/05
Report 1, Condition monitoring and failure probabilities - **Circuit breakers** (Kezunovic and Singh) - **Power transformers** (McCalley and Singh)	■	■					
Report 2, Maintenance and failure probabilities - **Circuit breakers** (Singh and Kezunovic) - **Power transformers** (Singh and McCalley)	■	■	■	■			
Report 3, Integration of condition monitoring with scheduling (McCalley, Singh, and Honavar)		■	■	■	■	■	
Report 4, Use of multiagent system for data integration (Kezunovic, Honavar, and McCalley)	■	■	■	■	■		
Report 5, Software solution (Honavar and Kezunovic)			■	■	■	■	
Report 6, Project summary and prototype specification (McCalley and Kezunovic)				■	■	■	■

Related Work: There are 3 areas of ongoing work that has particular bearing on this project, as described in the following.

- The optimization program solution procedure, called the IMSS in Fig. 2, is under development within another PSERC-funded project led by J. McCalley together with T. Van Voorhis, an optimization expert in the Iowa State University department of Industrial and Systems Engineering, and A. P. Meliopoulos of Georgia Tech. This project began in June, 2001. It is expected that this software will be completed by June, 2003.
- M. Kezunovic is currently working on an on-going PSERC-funded project with developers at Mitsubishi to use software agents in scheduling of maintenance activities applied to circuit breakers and generators [xua01]. The project will be completed in 2002.
- J. McCalley and V. Honavar have been working together for two years now applying multiagent systems to security-related decision-making in control centers [vis00, vis01].

We expect to draw heavily from these three related areas of work.

How this Work Differs from Related Work: There has been a great deal of work reported in the literature on transmission equipment maintenance, but we are not aware of any work that is integrating CBM, scheduled maintenance, and RCM as described here. Further, we are not aware of on-going work that utilizes multiagent system technology in automating the transmission system maintenance-related decision-making.

References:

[ieee01] "The Present Status of Maintenance Strategies and the Impact of Maintenance on Reliability," an IEEE Task Force paper chaired by J. Endrenyi, members J. McCalley, C. Singh, et al., to appear in IEEE Trans. on Pwr Sys.

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[xua01] X. Xu, M. Kezunovic, "Mobile agent software applied to maintenance scheduling," to appear in the Proc. Of 2001 North American Power Symposium, Oct. 2001, College Station, Texas.
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[vis01] V. Vishwanathan, J. McCalley, and V. Honavar, "A multiagent system infrastructure and negotiation framework for electric power systems," Proc. of the IEEE Porto PowerTech Conference, Sept., 2001, Porto, Portugal.

5.12.1 Project Status

Status as Reported for the May 2002 IAB Meeting

Work progress since the report for the December 2001 IAB meeting
This is a new PSERC project. Work is just beginning.

Description of work activities and anticipated project outcomes/deliverables by each project team member during next reporting period

- McCalley: Contribute to preliminary draft of Report 1, on "Condition monitoring and failure probabilities for power transformers," and identify possible methods of establishing link between maintenance activities and failure probabilities for power transformers, with C. Singh. Contribute to the preliminary design of the multiagent system for data integration (to be included in Report 4), with M. Kezunovic and V. Honavar.
- Honavar: Contribute to the preliminary design of the multiagent system for data integration (to be included in Report 4), with M. Kezunovic and J. McCalley.
- Kezunovic: Contribute to preliminary draft of Report 1, on "Condition monitoring and failure probabilities for circuit breakers," and identify possible methods of establishing link between maintenance activities and failure probabilities for circuit breakers, with C. Singh. Create preliminary design of the multiagent system for data integration (to be included in Report 4), with J. McCalley and V. Honavar.
- Singh: Create preliminary draft of Report 1, on "Condition monitoring and failure probabilities for power transformers and circuit breakers," and identify possible methods of establishing link between maintenance activities and failure probabilities for power transformers and circuit breakers, with J. McCalley and M. Kezunovic.

Description of and reasons for any revisions to the workplan that was reported for the December 2001 IAB Meeting
No revisions.

Students working on the project during the next reporting period
There will be a total of 4 students supported under this project. At this time, only one of them has been identified, but the other 3 will be identified shortly.

Zhong Zhang, zzkerry@iastate.edu

5.12.2 Project-Related Documents

Work is just beginning on the project.

Click here to return to the Project Overviews