

# Implementation of Optimal Mitigation Measures for Transmission Planning Assessment

Jason Robison, *Southwest Power Pool*, Makarand “Mak” Nagle, *Southwest Power Pool*,  
Marianna Vaiman *V & R Energy Systems Research, Inc.*

**Abstract—** With the increasing comprehensiveness of the North American Electric Reliability Corporation standards, it is essential that software developments parallel the requirements of bulk power system owners, operators, and users that are applicable to approved reliability standards. In this paper, the authors present and discuss the results of a Transmission Planning compliance assessment conducted by Southwest Power Pool, a Regional Transmission Organization within the Eastern Interconnection of the North American Bulk Electric System. This assessment involves seven seasonal models and the analysis of more than 3.5 million contingencies.

**Index Terms—** NERC TPL Assessment Process, Massive AC Contingency Analysis, Optimal Mitigation Measures.

## I. INTRODUCTION

The North American Electric Reliability Corporation (NERC) Transmission Planning (TPL) standards TPL-001-0, TPL-002-0, TPL-003-0, and TPL-004-0 require Near-Term and/or Longer-Term assessments be conducted annually for the Bulk Electric System (BES). These assessments insure that the BES maintains its reliability to prevent potential blackouts and/or voltage collapse. As the registered Planning Authority and Transmission Planner for its portion of the BES, it is the responsibility of Southwest Power Pool (SPP) to conduct these studies [1] – [5].

Several methods for conducting these studies are being explored by transmission planners. These methods include Probabilistic Reliability Assessment, Deterministic Reliability Assessment, and Value Based Reliability Assessment [6] – [9]. This paper reports on SPP use of the deterministic approach with more focus on contingencies based on single transmission element outage.

In years 2005 – 2007, SPP included the requirements of these standards in its SPP Transmission Expansion Plan (STEP) development process. In 2008, SPP began using Physical Operational Margins (POM) software to assess its portion of the BES for the NERC TPL compliance assessment.

In 2009 SPP incorporated a POM add-on module, Optimal Mitigation Measures (OPM) to examine the mitigation techniques for the potential violations. This paper describes the incorporation and results from POM and from the OPM module.

## II. POM AND OPM OVERVIEW

### A. Physical Operational Margins (POM)

POM is a software tool developed by V&R Energy Systems Research, Inc. (V&R) which is a load flow, contingency analysis, voltage stability, and transfer analysis application. POM has been extensively benchmarked by both V&R and by program users [6], [7]. This tool is intended to perform massive contingency analysis based on user selected lists, or automatically selected N-1 and N-2 contingency lists based on user defined model element selection.

POM is an AC analysis application, which uses the full Newton-Raphson method to solve a nonlinear power flow model. The normal conditions (N-0) model and each (N-k) contingency are applied while simultaneously monitoring multiple constraints: voltage stability, thermal overload, voltage range, and voltage limit violations. These constraints can be monitored over the entire system model or any portion thereof.

Several modes of operation are offered by POM: interactive, automatic, and script-based operation. POM analyses include: single and high order contingency analysis, load scaling analysis, power transfer analysis, PV- and QV-curve analysis, etc. This paper deals exclusively with critical contingency identification which is the evaluation of automatically selected (N-k) contingency lists. A database is created, and any contingency which causes a model constraint violation of one or more constraints is recorded along with data about those violations. This database is later analyzed, providing information regarding the reliability of the existing or planned electric system as modeled.

### B. Optimal Mitigation Measures (OPM)

The OPM module is activated when POM finds a violation of one or more constraints [10]. This module employs multiple measures to mitigate the constraint violations based on the user defined priorities and re-evaluates the model solution after each of the attempted mitigations. Three separate sets of measures are available for N-0 (e.g., contingencies are not

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Jason R. Robison is with Southwest Power Pool, Little Rock, AR 72205 USA (e-mail: [jrobison@spp.org](mailto:jrobison@spp.org)).

M. Nagle is with Southwest Power Pool, Little Rock, AR 72205 USA (e-mail: [mnagle@spp.org](mailto:mnagle@spp.org)).

Marianna M. Vaiman is with V&R Energy Systems Research, Inc., Los Angeles, CA 90049 USA (e-mail: [marvaiman@vrenegy.com](mailto:marvaiman@vrenegy.com)).

applied), N-1 and N-2 contingencies.

The mitigation measures employed by OPM include: MW re-dispatch, Mvar re-dispatch, line switching in and out, emergency load curtailment, forced phase-shifter adjustment, forced capacitor and reactor switching, forced transformer tap change, capacitor placement, and user-defined operating procedures. These measures are employed iteratively according to a priority set and a number of attempts set for each measure. Priorities, number of attempts, and other options are defined by the user, as shown in Figure 1.

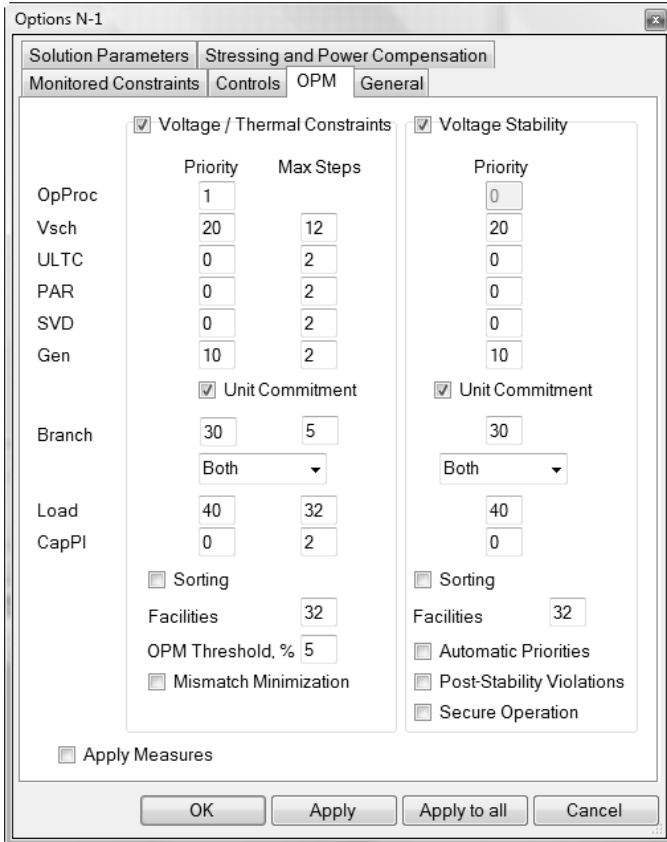


Fig. 1. A Sample OPM Interface for Mitigating Post-Contingency Violations

The execution of a mitigation measure involves several steps. OPM first selects a mitigation measure with the highest priority. It then evaluates if a given measure would provide relief for any or all of the violated constraints. The module then finds the amount of adjustment where the measure provides the most relief.

If the model constraint violations are fully relieved, the constraint violations existing before the mitigation measures and the mitigation measures are recorded. If a given OPM measure cannot completely mitigate post-contingency violations, or there are no available mitigation measures, values are recorded in the database for violations before and after the mitigation measures selected by OPM.

The uniqueness of OPM is that it has the capability to automatically alleviate post-contingency violations during massive contingency analysis.

### III. SPP NERC TPL ASSESSMENT PROCESSES

The most recent SPP Model Development Working Group

(MDWG) load flow models are used as base cases for these assessments. The Near-Term TPL Compliance Assessment uses load flow models for the current year including: summer peak, fall peak, and winter peak, as well as models for the subsequent year including: spring peak and summer peak. The Longer-Term Assessment uses only two MDWG load flow models: winter peak of year-six, and summer peak of year-seven.

#### A. Near-Term TPL Compliance Assessment

This Process addresses the need for the Near-Term studies required by the NERC TPL standards: TPL-001-0, TPL-002-0, TPL-003-0, and TPL-004-0. These assessments, when coupled with the Longer-Term TPL Compliance Assessment and the Stability Study, provide the required assessments which allow the TPL Compliance Statement for each TPL standard to be generated. The Near-Term TPL Compliance Assessment, Longer-Term TPL Compliance Assessment, and the four TPL Compliance Statements are submitted to SPP-Regional Entity (RE), SPP-Regional Transmission Organization (RTO) Compliance, SPP Members, and NERC as documentation of compliance for SPP-RE Members and SPP-RTO.

This process assesses a Complex Contingencies List (CCL) for each category. The CCLs are compiled and updated by SPP staff and members to represent occurrences which are considered for special analysis. These CCLs are the most accurate study of (N-k) contingencies. These contingencies include load throw-over and shared breakers for multiple element events, but are not as exhaustive as the Automatically Selected Lists (ASL). These lists are then assessed to help fulfill requirements for TPL-002-0, TPL-003-0, and TPL-004-0.

This process generates and assesses lists of contingencies based on model element base voltage. Elements are automatically selected for N-1 ASLs according to Table 1.

TABLE 1  
AUTOMATICALLY SELECTED ELEMENTS FOR N-1 ASSESSMENT

Element	Base KV	Source
Complex Elements (Cat. B, C, D)	---	SPP & Members
Branch	69 KV+	Software Selection
Generator	All	Software Selection
Transformer	100 KV+	Software Selection

These element outages were also automatically paired for N-2 ASLs according to Table 2. These lists are assessed to help fulfill requirements for TPL-002-0 and TPL-003-0.

TABLE 2  
AUTOMATICALLY PAIRED ELEMENTS FOR N-2 ASSESSMENT

N-2 Category	Combination Rule
Branch-Branch	Same Zone
Branch-Generator	Same Area
Generator-Generator	All Combinations

A lists of potential voltage violations and thermal overloads found by POM is sent to SPP member entities along with a list of the triggering contingencies and remedial actions found by OPM. SPP member entities then develop mitigation plans for those contingencies triggering constraint violations which could not be mitigated by OPM and validate the measures suggested by OPM. The mitigations developed by SPP member entities are matched with the constraint violations and reviewed by SPP staff. When all constraint violations have been addressed by SPP member entities or OPM, a report is generated by SPP staff [11], and approved by the SPP Transmission Working Group (TWG). This process generally runs annually from January to April [12].

### B. Longer-Term TPL Compliance Assessment

This Process addresses the need for the Longer-Term studies required by the NERC TPL standards: TPL-001-0, TPL-002-0, and TPL-003-0. This process is quite similar to the Near-Term assessment.

A few of the differences in the Longer-Term Assessment are given. This assessment does not include Category D contingencies from the CCL. The load models used in the Longer Term assessment include all the reliability projects with in-service dates before the modeled season and approved under SPP Transmission Expansion Plan (STEP) [13].

### C. Stability Study

SPP members provide SPP staff with a list of NERC Table 1, Category B, C and D reliability type contingencies and tower outages (events) to analyze for powerflow and stability performance. The selected events are analyzed against the most recent SPP MDWG light load stability model. The analyses are conducted using the Power Systems Simulator for Engineering (PSS/E) – Dynamic Simulation software provided by Siemens Power Technologies, Inc. This process also uses a sub-set of voltage stability violations found in both the Near-Term and Longer-Term assessments.

All events are tested for a five-cycle duration in order to assess system performance. In addition, some events are tested for faster clearing times and different generation dispatches. A quarter cycle time step is generally used in these simulations. Events requiring clearing times faster than five cycles are reported along with any generation re-dispatch needed to maintain reliability [14].

### D. TPL Compliance Statements

This process uses Near-Term and Longer-Term Assessments as well as the Stability Study to evaluate the adequacy of the electrical transmission system within the SPP footprint and report these findings to: SPP Compliance Department, SPP-RE, and NERC. Figure 2 shows the mapping of the assessments made to the TPL Compliance Statements issued by SPP. Compliance Statements are issued by SPP-RTO for TPL-001-0, TPL-002-0, TPL-003-0, and TPL-004-0.

Each of these Compliance Statements provides a detailed description of how every requirement or sub-requirement is fulfilled by SPP processes. Each of these documents also

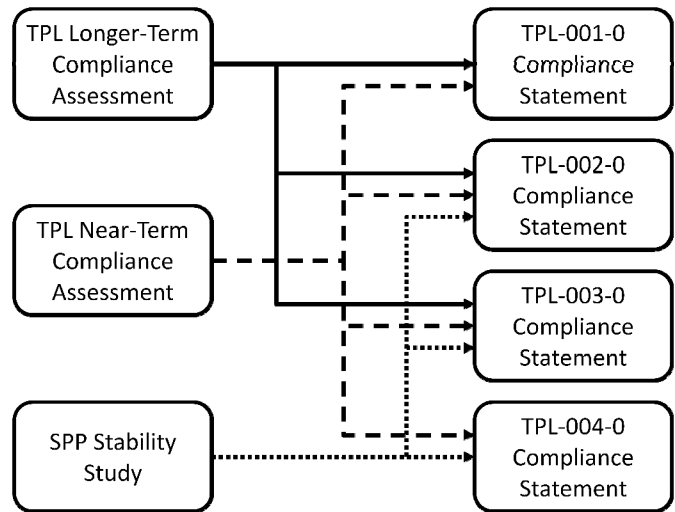


Fig. 2. Longer-Term Assessment, Near-Term Assessment, and Stability Study are shown mapped to the particular TPL standards they help fulfill

contains a detailed list of references pointing to process documentation supporting the studies and a description of how each requirement is fulfilled

## IV. SPP USE OF POM/OPM

### A. POM use for TPL Compliance Assessment

For the 2008 and 2009 annual Near-Term and Longer-Term TPL Compliance Assessments, SPP chose POM for its analysis tool. POM program was developed by V&R and tested through an effort with EPRI and other utilities while introducing Probabilistic Reliability Assessment (PRA) concept in Transmission Planning [15]. One of the key advantages of POM is its computing speed being 5 to 10 times faster than other similar load flow programs.

### B. Large-Scale use of POM

The MDWG models used for the Near-Term and Longer-Term TPL Compliance Assessments were 30k and 50k bus PSS/E Load flow models. Each contingency list assessed with POM was on the order of 500K-700K contingencies per season. Between the Near-Term and Longer-Term Assessments, seven seasons were assessed. The total number of contingency assessments performed by POM was over 3.5 million. According to V&R, this is the largest number of contingencies per one run processed through OPM, and the overall largest workload POM-OPM has endured.

The truly massive number of contingencies screened in this analysis provided valuable feedback concerning the robustness of POM. Earlier versions of POM were designed for running up to 200K contingencies per run. As NERC standards are becoming more stringent and more exhaustive contingency analysis is being performed by utilities, ISOs and RTOs, the most recent version of POM is designed such that millions of contingencies may be applied during one simulation run. The most recent version used by SPP has shown no difficulties while assessing lists of more than 700K contingencies.

A seasonal assessment with 500K contingencies while applying mitigation measures requires a run time of approximately 48 hours using a 3.4GHz Intel™ Core 2 Duo

processor with 2x2GB DDR2 800 MHz RAM. Initially assessments had to be conducted using lists which were divided into smaller sub-lists containing around 150K contingencies. Later, it was discovered that the Windows XP Operating System (OS) requires a special 3GB flag which allowed the system to access 3GB of RAM instead of the 2GB accessible without this flag. Using a newer OS would allow even more RAM to be used.

### C. OPM use for modeling Real-Time Operations

OPM was used by SPP to simulate the procedures of real-time operations on the BES in response to outages. SPP Technical Studies and Modeling (TS&M) group worked with the SPP Operations department to develop and validate the simulated actions modeled by OPM with the actual measures carried out by real-time operations.

Several of the mitigation measures which OPM could suggest were discussed. The top candidates among OPM activities were MW re-dispatch, Mvar re-dispatch, and line switching. The activities with the least viability for this type of study were load-curtailment, and capacitor placement.

- 1) **MW re-dispatch** is carried out by the SPP Energy Imbalance Service (EIS) Market, but can be re-dispatched by real-time operations if required by transmission constraint. SPP chose this as its first priority for OPM since it is usually handled automatically and because of its effectiveness for relieving thermal overloads.
- 2) **Mvar re-dispatch** can be handled by real-time operations by requesting re-dispatch from individual generation operators or balancing authorities. SPP chose this as its second priority for OPM because it can be handled simply by operations, and because of its effectiveness for relieving voltage violations.
- 3) **Line switching** can be accomplished by real-time operations via Supervisory Control And Data Acquisition (SCADA) enabled breakers. This was chosen as the third priority for OPM for line switching out only since it can be accomplished with SCADA enabled breakers.
- 4) **Forced phase-shifter adjustment** can be handled through SCADA, but was not used since SPP has only one automatic phase-shifter.
- 5) **Forced capacitor and reactor switching** can be accomplished for some SCADA enabled capacitors and reactors, but model information is not available as to which ones are enabled. This measure was not chosen.
- 6) **Forced transformer tap change** can be accomplished for some SCADA enabled Under-Load Tap Changers (ULTC), but model information is not available as to which ULTCs are SCADA enabled. This measure was not chosen.
- 7) **User-defined operating procedures** can be defined in POM format. SPP is currently investigating the benefit of defining these operating procedures and incorporating them as the first priority for OPM, but this measure was not chosen for this study.
- 8) **Capacitor placement** was not chosen because it cannot be done in real-time.

- 9) **Emergency load curtailment** was chosen as the last priority for Category C and Category D events only.

After running a set of N-1 and N-2 contingencies, TS&M presented a sample of the resulting violations and the suggested measures obtained from OPM. SPP Operations agreed that these mitigations were viable solutions if such an operating condition occurred in real-time.

Further, SPP submitted a comprehensive list of all mitigations suggested by OPM to SPP members along with the list of contingencies which caused model constraint violations. These mitigations were reviewed by members and were largely supported. Most SPP members agreed that the OPM measures provided adequate mitigation, and that the measures based on the priorities that were selected by SPP were generally successful. Due to the large volume of available output, additional reporting capabilities might be added through queries or scripting programs to present the results to SPP members in an easy-to-interpret form. SPP has changed its process to present only results of contingencies which could not be fully mitigated by OPM, and only results for those contingencies before OPM relief.

### D. OPM Results as a Contingency Severity Measurement

TPL-002-0, TPL-003-0, and TPL-004-0 state under R1.3.1, “[To be valid, assessments shall] be performed and evaluated only for those Category B [or C, or D] contingencies that would produce the more severe System results or impacts. The rationale for the contingencies selected for evaluation shall be available as supporting information. An explanation of why the remaining simulations would produce less severe system results shall be available as supporting information,” [2], [3], [4]. By limiting the measures available to OPM, SPP has adapted this tool to the evaluation of the severity of an event. The process for determining the contingencies which produce the most severe impacts is handled differently for a CCL and an ASL.

With CCL, SPP members and staff use judgment, past experience, and outage documentation to evaluate which contingencies would cause more severe impact. With an ASL, POM selects the elements to be faulted dependent on base voltage. Additionally, SPP uses OPM to evaluate which outages real-time operations could mitigate without problem.

During the 2009 Near-Term Assessment, SPP undertook a benchmarking effort for OPM, SPP members were asked to evaluate measures suggested by OPM for all contingencies for Category B, C, and D CCLs. The measures were overwhelmingly accepted by member entities. Most member entities considered the model violations mitigated by OPM using this set of available measures to be less severe than those which could not be relieved. SPP members were asked to provide mitigation strategies for those events which OPM could not mitigate [11].

The benchmarking of OPM included the N-1 contingencies from seasonal ASLs. These evaluations were documented in the 2009 TPL Near-Term Compliance Mitigation Reports [16], and almost all measures were found acceptable. SPP members were also asked to evaluate the measures proposed

by OPM for fully mitigated contingencies, and provide mitigation for those which OPM could not relieve with the available measures. SPP members generally found the contingencies which OPM relieved to be less severe, while more severe contingencies required member developed mitigation strategies.

N-2 contingencies from ASLs were not included in the benchmarking due to the excessive work which would be required from SPP members in evaluating the many thousand N-2 contingencies. Many members remarked that the N-2 events from ASLs which could not be relieved by the priorities used for OPM were among the most severe.

In all, the member comments regarding the measures suggested by using these priorities for OPM indicate that it is an effective tool for lessening the workload by mitigating many of the thousands of N-1 and N-2 events which caused model constraint violations. Additionally, these comments indicate that OPM, when used as a simulation of real-time operations, is a good measure of the severity of a particular outage depending on its success in relieving the model constraint violations from that outage.

V. RESULTS

The following tables provide some results from the 2009 Near-Term TPL Compliance Assessment [11]. The numbers shown in each table represent the number of potential violations occurring as a result of events, not the number of events with potential to cause violations. It is important to note that all potential violations were mitigated either by OPM measures which were approved by SPP members, or by measures developed by SPP members.

Shown on Table 3 are the numbers of model constraint violations for ASLs N-1 events shown by season.

TABLE 3  
CRITICAL EVENTS FOR AUTOMATICALLY SELECTED N-1 ASSESSMENT

Season	Branch		Transformer		Total	Mitigated
	Vmax	Vmin	Overload	Overload		
Summer 09	54	47	366	24	491	491
Fall 09	67	36	25	4	132	132
Winter 09/10	53	42	46	9	149	149
Spring 10	27	34	32	-	93	93
Summer 10	35	106	143	4	288	288

Table 4 provides numbers of potential violations resulting from N-2 events in ASLs.

TABLE 4  
CRITICAL EVENTS FOR AUTOMATICALLY SELECTED N-2 ASSESSMENT

Season	Branch		Transformer		Total	Mitigated
	Vmax	Vmin	Overload	Overload		
Summer 09	188	790	2547	268	3793	3793
Fall 09	272	560	1208	181	2221	2221
Winter 09/10	268	579	1926	149	2922	2922
Spring 10	147	587	722	158	1614	1614
Summer 10	101	515	1111	87	1814	1814

Potential violations resulting from Category B CCL events are shown in Table 5, and Category C/D events in Table 6.

TABLE 5  
CRITICAL EVENTS FOR COMPLEX CONTINGENCY CATEGORY B

Season	Branch		Transformer		Total	Mitigated
	Vmax	Vmin	Overload	Overload		
Summer 09	5	14	17	2	38	38
Fall 09	11	13	2	-	26	26
Winter 09/10	6	13	8	1	28	28
Spring 10	-	14	3	4	21	21
Summer 10	2	13	18	4	37	37

TABLE 6  
CRITICAL EVENTS FOR COMPLEX CONTINGENCY CATEGORY B

Season	Branch		Transformer		Total	Mitigated
	Vmax	Vmin	Overload	Overload		
Summer 09	3	123	96	24	246	246
Fall 09	1	48	11	8	68	68
Winter 09/10	15	58	16	13	102	102
Spring 10	8	118	22	15	163	163
Summer 10	2	67	87	21	177	177

Table 7 shows the totals of potential violations by list type for each SPP member. Substitute names were used to preserve member privacy. It must be noted that some violations may have affected two or more member areas, and were counted once for each effected area.

TABLE 7  
CRITICAL EVENTS FOR 2009 TPL COMPLIANCE ASSESSMENT

Member	ASL	CCL		Total	Mitigated
		Cat B	Cat C, D		
Member A	388	-	-	388	388
Member B	99	-	-	99	99
Member C	236	-	72	308	308
Member D	2234	168	708	3110	3110
Member E	1712	18	19	1749	1749
Member F	40	3	11	54	54
Member G	810	1	-	811	811
Member H	171	-	-	171	171
Member I	2169	14	72	2255	2255
Member J	79	4	67	150	150
Member K	139	2	236	377	377
Member L	954	-	8	962	962
Member M	2601	-	48	2649	2649
Member N	401	-	4	405	405
Member O	1550	11	63	1624	1624
Member P	1416	-	31	1447	1447
Member Q	-	-	-	0	0
Member R	3	1	-	405	405
Member S	125	21	8	1624	1624
Member T	1	81	176	1447	1447

## VI. CONCLUSION

In this paper, the authors described SPP use of POM/OPM software for annual NERC TPL assessments. A brief overview was given for the POM/OPM algorithm and the operation of the software. Following this, the SPP processes for its NERC TPL assessments were described. An overview of SPP use of POM/OPM was then given. Finally, a summary of results was given from the SPP Near-Term TPL Assessment.

This paper shows the utility of POM/OPM software as used for NERC standards assessments. This software is especially effective when dealing with the millions of contingencies involved in an assessment for a large footprint such as SPP's. Further, this paper describes the approach used by SPP in using OPM to mitigate most of the model constraint violations discovered in this process. The results and experience from this study indicate that POM/OPM is an exceptionally good tool for this type of large-scale assessment.

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## VIII. BIOGRAPHIES



**Jason R. Robison** received his Bachelor's of Science in Systems Engineering, Electrical Systems from the University of Arkansas at Little Rock, Little Rock, AR, USA in 2008.

He is currently on his second rotation as part of an early-career engineer training and rotation program at Southwest Power Pool. His previous experience includes work on several NASA, NSF, and DOE grants as a Research Assistant on computer simulation for electro-dynamic screens, solar photo-chemical hydrogen production, and electronic single-particle aerodynamic relaxation technology. He received the 2008 Arkansas Space Grant Consortium, Workforce Development Grant to work at Jet Propulsion Laboratory on solid CO<sub>2</sub> cleaning and geothermal measurement for extraterrestrial applications.



**Mak Nagle** (M'1999) is working at Southwest Power Pool as Manager of Technical Studies and Modeling. His main role in SPP is to lead a group of engineers to develop various power flow models for the SPP footprint and conduct various technical analyses to maintain reliability of the electric grid.

His previous employment experience included Entergy Services where he was involved in Bulk Power and Operational planning. Mr. Nagle also worked in Siemens and Chemtex as a Project Engineer and Electric Design engineer respectively. Overall, he has 15 years of experience in Planning, Operations, Design and Project Execution in electrical field. Mr. Nagle completed his Bachelors in Electrical Engineering from University of Bombay in 1993 and Masters in Electric Power Engineering from Rensselaer Polytechnic Institute, Troy, NY in 1998.



**Marianna Vaiman** (M' 1997) received her BSEE and MSEE degrees from Moscow University of Transportation Engineering, Russia. She has 17 years of experience in power system studies. In 1992 she joined V&R Energy Systems Research, Inc. (V&R), where she is currently Principal Engineer and Executive Vice President. She leads the work in the following areas at V&R: Software Development, Consulting Activities, Research & Development Activities. She has over 15

publications devoted to the issues of power system stability and control.