

# A New Approach to Constructing Seasonal Nomograms in Planning and Operations Environments at Idaho Power Co.

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**Abstract**—This paper addresses a novel approach to constructing seasonal nomograms for both planning and operations environments. The paper describes how the nomograms were automatically constructed for the Idaho Power Co. (IPC) power system network. The approach presented in this paper offers a unique capability to automatically determine the effect of various stressing factors on the studied interfaces (paths) in planning and operations environments. This approach also allows the operator to determine and visualize the secure operating region. The study was performed using the IPC loadflow data to validate the proof of concept and determine the effect of various stressing patterns on the monitored paths in the IPC power system. The approach proposed in this paper will allow operators to construct seasonal nomograms in operations environment.

**Index Terms**—Seasonal nomogram; secure operating region, stressing factor; transfer capability.

## I. INTRODUCTION

AS power utilities operate their grid closer to the technical limits, an efficient security assessment and transfer capability computation should be performed in order to maintain reliable operation of a power system network.

The transfer capability of a transmission system is the ability of the system to transfer power over the transmission network in a reliable manner from one point to another at any given time without compromising system security. In a number of utilities (in WECC) the transfer capability of the transmission system is measured in terms of the value of real power flow on a particular interface (e.g., path).

Significant research has been conducted on the various aspects of security and transfer capability calculations in transmission power systems [1].

Seasonal nomograms are often used to access the transfer

capability by identifying the stressing patterns for which system operation remains secure [2].

A seasonal nomogram is defined by several stressing patterns which are represented by different sets of stressing factors, such as power transfers, load/generation scaling, contingencies. The seasonal nomogram is shown on the plane of two paths.

Thus, the most important task in creating a seasonal nomogram is selection of the stressing factors for each stressing pattern, which have the highest impact on the paths under consideration.

Nomograms are usually not created in operations and real-time environments. Operators rely on the planning personnel to provide them with the results of transfer capability analysis.

In a planning environment, this can be a time-consuming and cumbersome task.

Existing utility practice includes creating a new power flow case for each stressing pattern. After that, the stressing pattern is being adjusted such that monitored limits are not violated. Then, a new power flow case is created to incorporate these adjustments.

After the case has been created, the real power flow on each branch comprising the path is computed, and then, the total path flow is manually calculated. This iterative process continues until a case is developed such that the maximum value of power flow on the monitored path is developed. Each stressing pattern is shown as a point on a nomogram, which is manually constructed.

The final step of this process is connecting all points by straight lines using extrapolation. This plot represents the boundary of secure operating region.

This paper addresses the development of a fast process for constructing seasonal nomograms and visualization of the secure operating region. Also, the paper describes how this process was applied to IPC power system network and the secure operating region was determined.

The program "Boundary of Operating Region" (BOR) was used as the basis for all computations in this project [3].

BOR is a part of the Physical and Operational Margins (POM) Suite. BOR calculates transfer capability limits and a boundary of the operating region within which the system operation is secure [4, 5].

A powerful AC analysis tool, BOR is a quick and

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convenient tool to determine and graphically display a region within which no violations of the monitored constraints occur.

The graphical output of BOR is a boundary of the operating region. Each point on the boundary corresponds to at least one of the constraints being violated. Operating within the boundary is secure; i.e., each point within the boundary corresponds to such operating conditions (for example, such flows on the interfaces) that no constraints are being violated.

The boundary is a multi-colored graph. Each color on a boundary corresponds to violation of one of the following constraints and limits:

- Voltage stability
- Voltage limit and/or pre-to post contingency voltage drop
- Reactive margin
- Thermal overload of lines and transformers
- Flowgate limit

When the approach is utilized during contingency analysis, the most critical outages for the specified path are automatically determined and ranked based on the size of the secure operating region.

BOR has the capability to automatically identify the secure operating region that satisfies the N-1 reliability criteria.

When used together with Optimal Mitigation Measures (OPM) application which is a part of the POM Suites, BOR illustrates the effect of remedial actions on the operating region and allows the user to determine the most effective mitigation measures.

BOR, along with the POM scripting capability, was utilized during the present study as the basis for constructing seasonal nomograms and determining the secure operating region.

## II. SELECTING THE STRESSING FACTORS WITH THE HIGHEST IMPACT ON THE MONITORED PATHS

This Section describes how the stressing patterns that have the highest impact on the monitored path were identified.

The impact of a stressing pattern (SP) on a power system is measured as the value of real power transferred by a path (or paths) in a particular direction (e.g., system transfer capability). Selection of a set of stressing factors (SFs) comprising the SP affects power flow on a selected path:

$$SP_k = \bigcup_{i=1}^{m_k} SF_{k,i}$$

The scripting capability of POM-BOR was used for each set of SFs to identify such SP (or scenario) that the maximum transfer capability is reached.

The described capability allows for accessing power flow case parameters while varying the SFs within the same run. Thus, there is no need to create multiple new power flow cases in order to represent each change to the SP. Also, participation of each SF in the SP may be easily changed in order to identify the best set of SFs.

For each scenario ( $SP_k$ ), the values of SFs were proportionally changed from the base case values with a user-specified step. For each value of the SP, the total real flow on each of the two monitored paths was automatically computed. At the same time, graphical output was automatically plotted

on the plane of two monitored paths and tabular results were displayed.

Tabular output was saved for further analysis. In addition to the real flows on the paths for each value of the SP, any user-specified output may be selected.

The simulation stops if any of the monitored and enforced constraints (such as, voltage stability, voltage limit, thermal limit, flowgate limit) is violated or any of the monitored parameters reaches its limit.

Applying three different scenarios ( $k = 1, \dots, 3$ ) is shown in Fig. 1. The results are shown on the plane of the monitored paths (Path I, Path II). The set of  $SF_{k,i}$  is the same in different  $SP_k$ , but participation of each SF differs.

Each SP is changed from the base case values until the violation occurs.

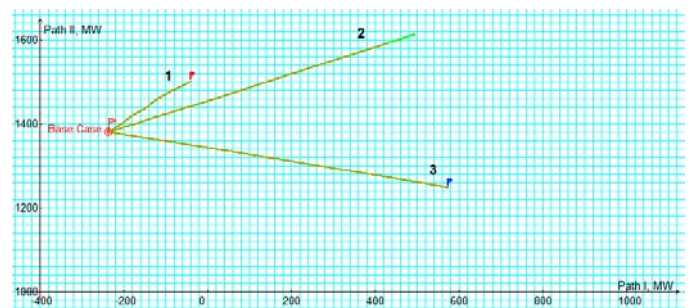


Fig. 1. Plotting Three Different Scenarios on the Plane of the Monitored Paths

Color-coding of the last point or segment on the plot corresponds to violation of one of the monitored constraints:

- Red - Voltage stability
- Light Green - Voltage limit
- Dark Green - Pre-to post contingency voltage drop
- Magenta - Thermal overload
- Tile - Flowgate limit
- Blue - Available resources reach limit values

The limiting constraint for  $SP_1$  is voltage stability violation (red point in Fig. 1). The limiting constraint for  $SP_2$  is voltage limit violation (green segment in Fig. 1). The limiting condition for  $SP_3$  is no available resources in the system (blue dot in Fig. 1).

Results of computing maximum transfer capability for three scenarios are summarized in Table I.

TABLE I  
MAXIMUM TRANSFER CAPABILITY OF THREE STRESSING PATTERNS

SP	Path I, MW		Path II, MW		Limiting Violation
	Value	Change	Value	Change	
Base Case	-240	n/a	1380	n/a	n/a
SP 1	-40	200	1500	120	Voltage Stability
SP 2	420	660	1600	220	Voltage Constraint
SP 3	580	820	1240	-140	Resources Have Been Used

The proposed approach allows an operator and planning engineer to easily select a stressing pattern with the highest impact on the monitored paths, Path I and Path II, see Fig. 1

and Table I. For example, SP<sub>3</sub> has the highest impact on Path I flow.

It takes 2-3 sec to determine the maximum transfer capability for each SP for an 8000-bus WECC load flow case.

### III. BENCHMARKING THE PROPOSED APPROACH AGAINST THE EXISTING TECHNIQUE

IPC provided a nomogram with six points. Each point on the nomogram corresponds to a different stressing pattern which is represented by a power flow case. These stressing patterns were inputted into POM as the maximum value of SP<sub>k</sub>.

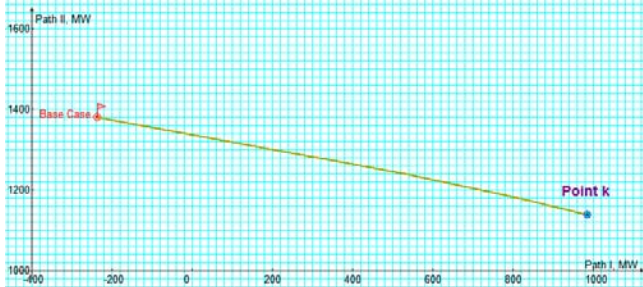


Fig. 2. Utilizing the SFs to Plot a Point on the Nomogram

The line drawn in Fig.2 starts from the base case values of real flows on each of the monitored paths. Each point on the line represents a system state that is stressed with the intermediate values of SFs. Point k represents a new power flow case.

A case study was performed using a base case and six stressing patterns (patterns 1 – 6) provided by IPC. Since conditions for stressing patterns 3 and 4 are very close, SP 3 was excluded from further analysis.

A nomogram was automatically plotted using the proposed approach, see Fig. 3.

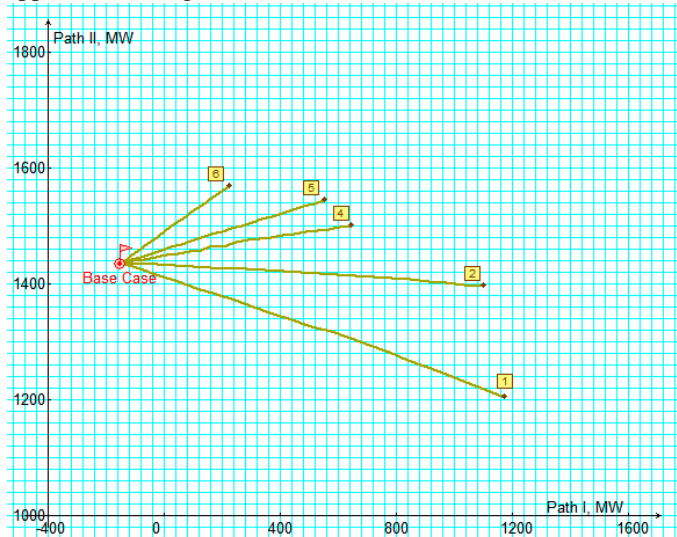


Fig. 3. Plotting a Seasonal Nomogram

The nomogram shows five points, which correspond to five different SPs.

Fig. 3 shows five SPs on the plane of the monitored paths

(Path I, Path II).

Each point on the nomogram is plotted using the technique which eliminates a time-consuming process of manually creating a new power flow case. POM-BOR was utilized to plot the points on the nomogram. Each point on the plotted line corresponds to the condition when system operation is secure.

Comparison of the values of power flows on Path I and Path II on the POM nomogram against that provided by IPC, shows that the results are very close.

### IV. THE CONCEPT OF THE SECURE OPERATING REGION

This Section addresses the issue of determining the secure operating region and its boundary.

In an n-dimensional space  $\Omega_n$  of all SPs the boundary of the secure operating region is an n -dimensional surface  $\Phi_n$ . The surface  $\Phi_n$  covers the n-dimensional body within which the point, that represents the base case values, is located:

$$SF_{k,0} = 0; k = 1, \dots, n.$$

This point is the origin of coordinates and the line drawn from this point while continuously changing a particular SP<sub>k</sub> (by changing i) is the coordinate axis in  $\Omega_n$ , and each point  $\theta_k$ , where violation of one of the monitored constraints occurs (see Section II) is the intersection of the corresponding coordinate axis with the  $\Phi_n$ .

Each point inside this n-dimensional body represents the secure operating state with the particular values of real power flows on two monitored paths ( $\Theta_1$  and  $\Theta_2$ ).

With the increase of any SP<sub>k</sub> the flows on  $\Theta_1$  and  $\Theta_2$  change, and the change in the SP<sub>k</sub> is represented by an almost straight line on the coordinate plane ( $\Theta_1 ; \Theta_2$ ). Therefore, the curve on  $\Phi_n$  between two points  $\theta_i$  and  $\theta_j$  will bound the secure operating region as a circular sector.

The arc of this circular sector is the boundary of secure operating region drawn between each pair of points on the nomogram:

$$F_{ij} = f(\theta_i, \theta_j); F_{ij} \in \Phi_n$$

This boundary may be determined using POM-BOR.

Two different displays of the boundary are presented in this paper. The first display, described in Section V, is on the plane of different SPs. The second display, described in Section VI, is on the plane of flows on the monitored paths.

### V. DETERMINING THE SECURE OPERATING REGION

The boundary of the secure operating region was determined for each pair of points on the nomogram (see Fig. 3) using POM-BOR.

First, the boundary is constructed on the plane of SPs.

The secure operating regions for each pair of neighboring points (e.g., SPs) on the nomogram are shown in Fig. 4. The boundary is shown on the plane of SPs. The point

corresponding to the base conditions is point (0, 0). Operating within the region corresponds to such combination of SPs that no violation of monitored and enforced constraints occurs.

Operating outside this region corresponds to at least one of the monitored and enforced constraints being violated.

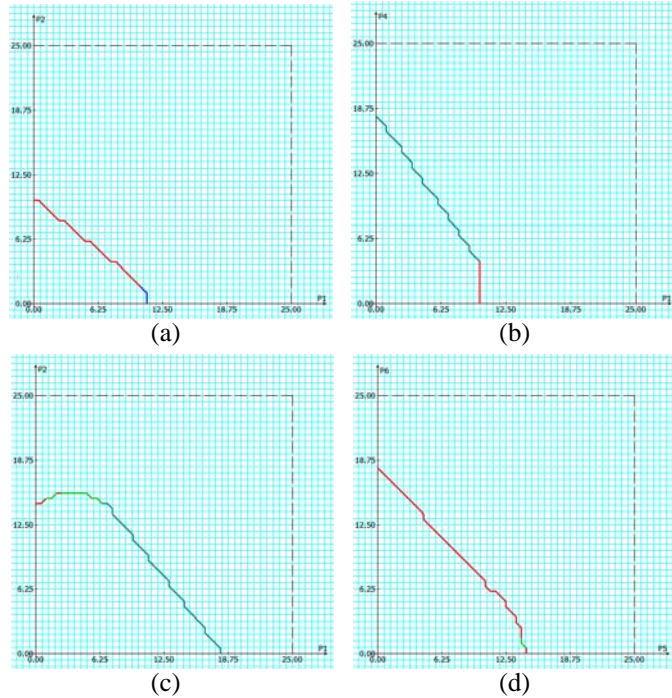


Fig. 4. Secure Operating Regions for Neighboring Points on the Plane (SP<sub>i</sub> ; SP<sub>j</sub>)

Fig. 4(a) shows the boundary of the secure operating region between points 1 and 2 on the nomogram. The boundary is shown on the plane (SP1, SP2). Color-coding of the boundary corresponds to violation of one of the monitored and enforced constraints. Two limits are violated on the boundary:

- Red - Voltage stability
- Blue - Available resources reach limit values

Fig. 4(b) shows the boundary of the secure operating region between points 2 and 4 on the nomogram. The region is shown on the plane (SP2, SP4). Two limits are violated on the boundary:

- Red - Voltage stability
- Tile - Flowgate limit

Fig. 4(c) shows the boundary of the secure operating region between points 4 and 5 on the nomogram. It is shown on the plane (SP4, SF5). Three limits are violated on the boundary:

- Red - Voltage stability
- Green - Voltage limit
- Tile - Flowgate limit

Fig. 4(d) shows the boundary of the secure operating region between points 5 and 6 on the nomogram. It is shown on the plane (SP5, SP6). Two limits are violated on the boundary:

- Red - Voltage stability
- Green - Voltage limit

The boundary of the secure operating region was also determined for all other pairs of points on the nomogram

shown in Fig. 3.

## VI. PLOTTING THE SECURE OPERATING REGION ON THE PLANE OF TWO PATHS

The boundaries of the operating region shown in Fig. 4 were then plotted on the plane of power flows on monitored paths (Path I, Path II). The boundary is shown between each pair of neighboring points on the nomogram, see Fig. 5.

The boundary of the secure operating region was drawn for each pair of SPs on the nomogram (see Fig. 3). In order to compare the results, all points shown in Fig. 3 are also shown in Fig. 5.

Color-coding of the boundary is the same as described in Section V.

The boundary given in Fig. 5 includes the boundaries plotted in Fig. 4(a) – 4(d) which are shown on the plane (Path I, Path II).

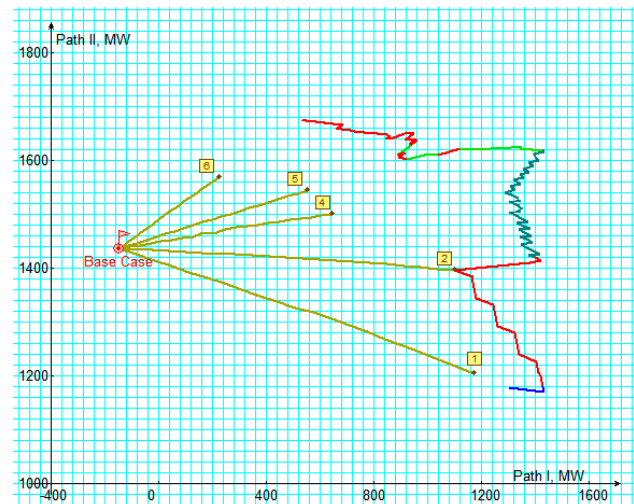


Fig. 5. The Boundary of the Secure Operating Region on the Plane (Path I, Path II)

Fig.5 shows that there are gaps between the points obtained using the conventional technique and the boundary of secure operating region. The maximum transfer capability for each SP can be considerably increased by closing the gaps on the plot. This is one of the main advantages of the proposed approach.

In order to close the gap, each SP was increased beyond the values identified in the base cases which were provided by IPC. The SPs were increased until violation of at least one of the monitored and enforced constraints occurs. These are points 1', 2', 4', 5', and 6' which were positioned on the boundary.

The coordinates of the point where each line that represents the change in the SP intersects with the boundary (see Fig. 6) is the maximum value of real flow on the monitored paths for each SP. Increase of the SPs beyond this value causes a violation of at least one of the monitored constraints.

Thus, points 1', 2', 4', 5', and 6' on the boundary are the maximum values of SP1, SP2, SP4, SP5 and SP6, respectively.

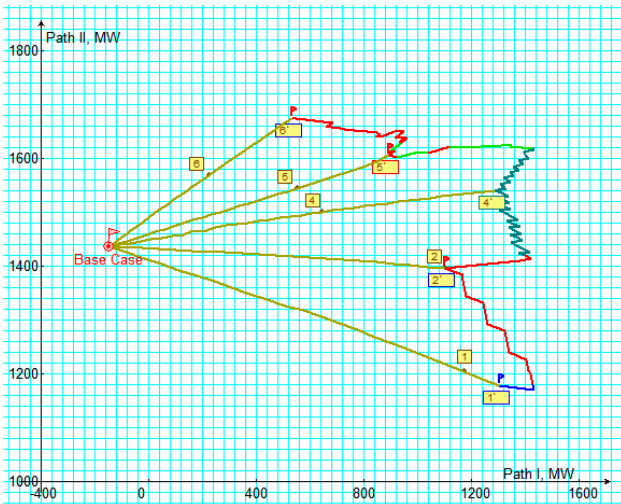


Fig. 6. Maximum Transfer Capability for Each SP and the Boundary of the Secure Operating Region

In order to obtain an accurate representation of the secure operating region, the boundary should be also plotted for all other pairs of points on the nomogram and superimposed on the plot shown in Fig. 6.

Fig 6 indicates that voltage stability is the limiting constraint in the vicinity of points 2' and 6'. Voltage stability and voltage constraint violations are the limiting constraints in the vicinity of point 5'. Flowgate violation is the limiting constraint in the vicinity of point 4'. All available resources have been used in the vicinity of point 1'.

After the boundaries between all points on the nomogram were determined, the secure operating region for all SPs can be determined.

This is the region within which operation is secure for all SPs under consideration. Operating within this region corresponds to such combinations of flows on Path I and Path II that no violation of enforced constraints occurs.

There are several ways to construct the secure operating region for all SPs. The existing practice [2] is: points without constraint violation and points where constraint violation occurs are being separated with the minimum number of straight lines (usually two or three) as shown in Fig. 7.

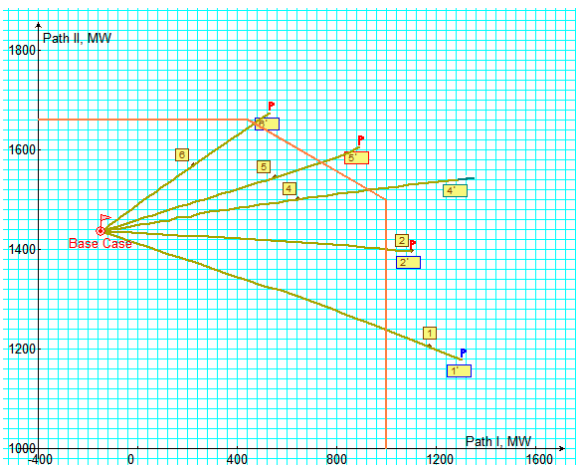


Fig. 7. Existing Approach to Plotting the Secure Operating Region Boundary

There is another approach that suggests connecting the neighboring points with straight lines, as shown in Fig. 8.

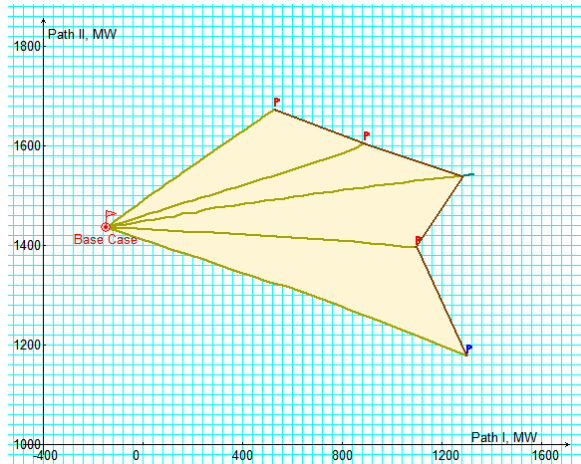


Fig. 8. Connecting Neighboring Points on a Nomogram to Represent the Boundary of the Secure Operating Region

The proposed approach to plot the boundary for all SPs is based on the capability of BOR to determine the maximal common operating region (COR) for all SPs under consideration.

As a result of utilizing this approach, the exact boundary of the secure operating region is determined, as shown in Fig. 9.

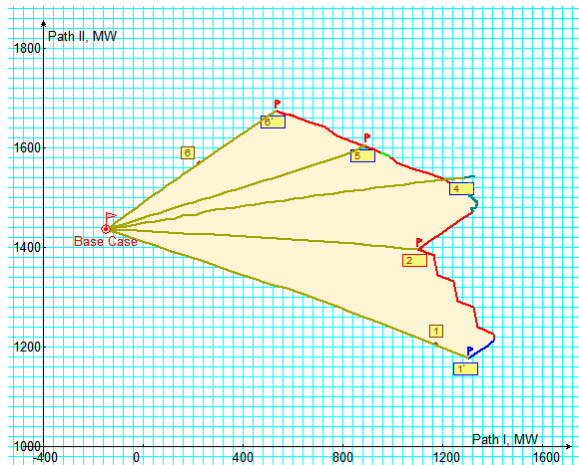


Fig. 9. Automatically Plotting the Boundary of the Secure Operating Region on the Nomogram Using BOR

Comparison of Fig. 7 and Fig. 9 shows that utilizing BOR increases the size of the secure operating region.

The process described in Sections V and VI is automated, and the secure operating region is obtained in several execution runs.

## VII. CONCLUSION

The present paper describes a unique process for automatically constructing seasonal nomograms and identifying maximum transfer capability along critical paths in the Idaho Power Co. (IPC).

The objectives of the current study are:

- Analyze the effect of a stressing pattern (SP) on the monitored paths and determine those that have the largest impact on the monitored paths (e.g., interfaces).
- Compute and graphically represent the secure operating region for the SPs under investigation.

The study showed that the technique, introduced in this paper, is an easy and fast approach for constructing seasonal nomograms. This capability can be used to identify maximum transfer capability on major paths in both planning and on-line environments.

The effect of various SPs is analyzed in this paper, and the SPs that have the largest effect on the real flows on the monitored paths are selected.

The paper describes construction of the boundary of the secure operating region for IPC. Operating within this boundary is secure for all values of real flows on the monitored paths provided that these SPs are implemented. The boundary corresponds to violation of at least one of the enforced constraints.

A study was performed using the IPC loadflow data to validate the approach.

It took substantially less time to construct seasonal nomograms than conventional techniques. The benefits of the proposed approach include:

- A very time-efficient technique.
- No need to create a new base case for each SP and each change in the SP scenario.
- Automatically identifies the maximum value of each SP; i.e., the maximum transfer capability along monitored paths for each SP.
- Automatically determines the secure operating region and constructs its boundary

The results of the study were verified using the results that were obtained using the existing technique for constructing seasonal nomograms.

As this approach looks very promising, IPC will continue to implement this approach during contingency analysis.

The proposed approach will be also used to determine the most effective mitigation measures to increase transfer capability on the specified paths.

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## IX. BIOGRAPHIES

**Milorad Papic** (SM' 06) is presently working for the Idaho Power Company in the System Planning Department. He obtained his M.Sc. degree from Zagreb University in 1977 and his Dr. Tech. degree from Sarajevo University in 1980. Prior to his arrival at IPC, Dr. Papic held the Associate Professor position at Sarajevo University and was a consultant for Energoinvest and Electric Power Company of B&H. His principal interests include reliability modeling and evaluation of power systems, transfer capability, transmission planning and economics in power systems. He is a Senior Member of IEEE and a member of the Reliability, Risk and Probability Applications Subcommittee. Dr. Papic has published more than 50 research and professional papers and was principal investigator on several international research projects.

**Michael Vaiman** (M' 91) has over 40 years of power industry experience. He received his MSEE degree from Kaunas Polytechnic University, Lithuania in 1961, Ph.D. degree from Moscow University of Transportation Engineering, Russia in 1969, and D.Sc. degree from St. Petersburg Polytechnic University, Russia in 1986. He was a full professor, Department of Automatic Control and Telecommunications at Moscow University of Transportation Engineering, Russia until 1991. Since 1992 Dr. Vaiman is a President and Principal Engineer at V&R Energy Systems Research, Inc. His main areas of interest are power system stability and control, power flow and optimal power flow analysis, computer modeling of power system networks, selection of remedial actions for stability preservation; dynamic stability analysis.

**Marianna Vaiman** (M' 97) received her BSEE and MSEE degrees from Moscow University of Transportation Engineering, Russia. She has 15 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.

**Mark Povolotskiy** received his MS degree in Mathematics & Physics degree from Nezhin State University, Ukraine in 1978 and Ph.D. degree in Physics & Mathematics from Institute for Geophysics, Ukrainian Academy of Science, Ukraine in 1990. Dr. Povolotskiy has over 25 years of R&D experience. His main areas of interest include mathematical modeling of the power system networks, and deterministic and probabilistic approaches to the analysis of the power system. He joined V&R Energy Systems Research, Inc. in 2001, where he is currently Senior Support Engineer working in the areas of Software Support and Consulting Services. He has over 30 published works, including 1 patent.