A Novel Non-Linear Security Based Approach to Assess Transfer Capability at Idaho Power Company

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***Abstract*— This paper presents a novel non-linear security-based approach for transfer capability assessment in Idaho Power Co. The objective of the study is to maximize a specific power transfer without violation of the monitored constraints. Contingency analysis is performed. Contingencies that have the most limiting effect on the transfers are determined and the most limiting facilities are identified. The smallest secure operating region is determined. The effect of mitigation measures on the transfer capability limit is analyzed. The study was performed using full AC analysis methodology for contingency screening and transfer studies. AC limits for transfer scenarios are computed based on thermal, voltage and voltage stability constraints.**

***Index Terms*—boundary of secure operating region, simultaneous power transfers, maximizing transfer capability, limiting contingencies.**

I. INTRODUCTION

POWER system security and transfer capability calculations are of the vital concerns in competitive utility business. They are new challenges facing deregulated electricity supply industry. Restructuring in the electric power industry has already resulted in system operation at higher transfer levels increasing the potential for security limit violations. Therefore, fast transfer capability assessment is of paramount importance in the open power market to provide reliable and secure transfer of power to the customers. The assessment of transfer capability limits on transfer paths/interfaces is more critical than ever before.

The transfer capability (TC) 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. Transfer capability, in general, is a nonlinear function of the system operating conditions and security constraints. TC depends on a number of factors such as system configuration, generation dispatch, load level, load distribution, power transfers between areas and the limits imposed on the transmission network due to thermal, voltage and stability considerations.

Over the last two decades considerable progress has been made in the areas of power system security and transfer capability calculations [1]. A number of methods have been presented in technical papers that specifically deal with computation of security and transfer capability limits [1] – [9]. Conventional studies on power system transfer capability are based on linear models such as distribution factors or transportation models [2]-[4], and very few are of non-linear nature [5]-[9]. The primary shortcomings of these tools are their accuracy; in most cases, they address only thermal constraints and do not deal with voltage constraints or instability (voltage, transient or oscillatory).

This paper presents a novel non-linear security-based approach for transfer capability assessment considering any type of security violations. The objective of the paper was to maximize a specific point-to-point power transfer without system constraint violation. The method identifies the most limiting facilities while determining the TC limit on a studied interface. In addition, the paper investigates the effect of different system operating measures on the transfer capability limits. Presented approach is utilized in a currently available commercial software Boundary of Operating Region (BOR) that can calculate TC limits and a boundary of the operating region within which the system operation is secure. Boundary of the secure operating region can be shown as a projection onto different planes such as: power transfers, load and generation, interface and/or tie line flows. Graphical results are available in 2-dimensional and 3-dimensional form. Each point within the boundary corresponds to such operating conditions (i.e. such combination of transfers) that no constraints are being violated. Operating within the boundary is secure. Each point on the boundary corresponds to at least one of the constraints being violated. BOR allows the user to automatically generate seasonal nomograms. The proposed approach is used in the paper to determine power transfer scenarios to achieve the maximum transfer capability. It can also be used to determine power transfer scenarios to achieve minimum cost. The proposed approach may be used for any number of simultaneous transfers.

BOR computes two types of indices for each run: an index corresponding to the area of each projection (S) and an index corresponding to the volume of the entire operating region (V). Contingencies are ranked based on the size of the area of the operating region.

The proposed method was applied to the Idaho Power system to determine TC for its transmission paths with

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neighboring systems. The implementation of the proposed method has demonstrated that it is very fast, robust, practical and suitable for actual system operation and planning studies. Additionally, the proposed methodology is used to carry out sensitivity studies to determine the impact of changes in system parameters and operating conditions on the TC limits. Under normal system conditions BOR can be used for cost saving strategies and post-contingent system security and under emergencies, it can be used for rapid alleviation of present violations.

The objectives of the study are:

- To maximize the existing transfer without any topology change and/or additional investments.
- To determine the most severe contingencies, i.e. the contingencies that have the most limiting effect on the transfers.

The paper is organized as follows. In Section II, a specific point-to-point transfer is studied. Section III deals with maximizing the initial transfer using the proposed approach. Section IV describes the results of contingency analysis while simulating two simultaneous transfers that comprise the initial transfer. Section V is devoted to using remedial actions in order to increase the size of secure operating region. Detailed security assessment is presented in Section VI. Section VII describes maximizing transfer capability during security analysis. Finally, in section VIII, some conclusions are presented.

II. Simulating the Initial Power Transfer

This section describes transfer simulation study in order to determine maximum transfer capability in Idaho Power Co. (IPC) system. IPC network consists of approximately 14000 buses and 17000 branches.

A power transfer is simulated by increasing the import from Northwest to IPC. Generation is increased in the source area (Northwest) and decreased in the sink area (IPC).

The following three constraints were simultaneously monitored during power transfer analysis:

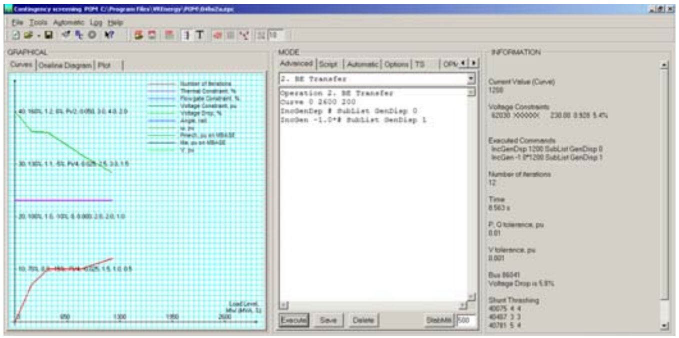
- Voltage stability constraint
- Thermal constraint

  115% of Rating B is monitored as the thermal constraint.
- Voltage constraint

  Pre-to post contingency voltage drop of 5% is monitored for N-1 contingencies.

  Pre-to post contingency voltage drop of 10% is monitored for N-2 and higher order contingencies.

The maximum value of power transfer was determined while monitoring voltage, thermal and voltage stability constraints. The power transfer was simulated starting from the base case values with a 200 MW transfer step. Power transfer that can be simulated in addition to the transfers present in the base case is determined. The maximum value of power transfer is 1000 MW (see Fig. 1). The limiting condition for this transfer is voltage constraint.



```
2. BE Transfer
Operation 2. BE Transfer
Curve 0 2600 200
IncGenDsp # SubList GenDisp 0
IncGen -1.0*# SubList GenDisp 1
```

```
Current Value (Curve)
1200
Voltage Constraints
 62030 XXXXXX    230.00 0.926 5.4%
Executed Commands
 IncGenDsp 1200 SubList GenDisp 0
 IncGen -1.0*1200 SubList GenDisp 1
Number of iterations
12
Time
8.563 s
P, Q tolerance, pu
0.01
V tolerance, pu
0.001
Bus 86041
Voltage Drop is 5.8%
Shunt Thrashing
40075 4 4
40487 3 3
40781 5 4
```

Fig. 1. Maximum Value of the Power Transfer

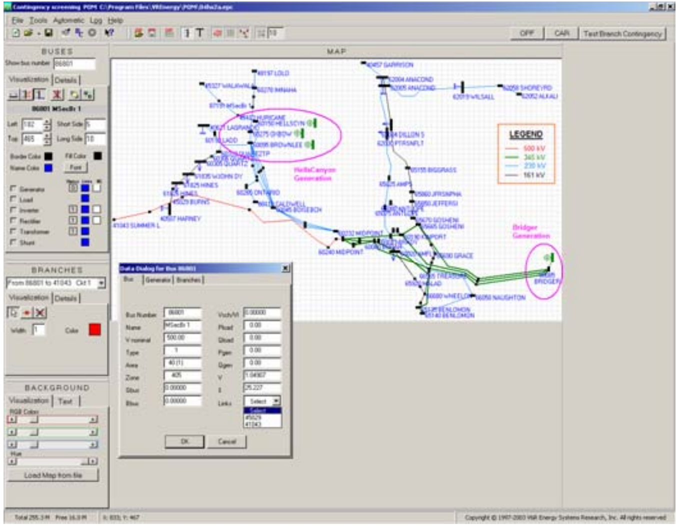
III. Maximizing the Initial Power Transfer

This Section describes the use of the proposed approach to increase the transfer capability.

The following approach is used to maximize the existing transfer without any topology change:

1. The initial power transfer is divided into two simultaneous transfers.
2. Boundary of the operating region is constructed.
3. A graph representing the sum of two transfers is drawn.
4. At the point where the sum of two transfers reaches its maximum, the values of each transfer are determined. Based on these values, participation factors of both transfers are computed. These participation factors are used to re-compute the initial power transfer.

In order to maximize the initial power transfer, two subsystems are selected in the sink area: Hells Canyon generation and Bridger generation, see Fig. 2. The sink area is divided into two separate subsystems based on geographical location of generators and transmission line flows.



```
Bus Number  86001        Vsch/Vi  0.00000
Name        MSecBr 1     Pload    0.00
V nominal   500.00       Qload    0.00
Type        1            Pgen     0.00
Area        40 (1)       Qgen     0.00
Zone        405          V        1.04907
Gbus        0.00000      δ        25.227
Bbus        0.00000      Links    Select
                                  45029
                                  41043
```

Fig. 2. Geographical Map of IPC: Two Subsystems in the Sink Area

Thus, the initial transfer is divided into two simultaneous transfers. The two transfers are simulated as follows:

- Transfer 1: From Northwest to Hells Canyon generation
- Transfer 2: From Northwest to Bridger generation

Transfers 1 and 2 comprise the initial transfer (see Fig. 1).

Fig. 3 shows the boundary of the operating region for two simultaneous transfers (no contingencies are applied).

Transfer 1 is shown on the *x*-axis; Transfer 2 is shown on the *y*-axis.

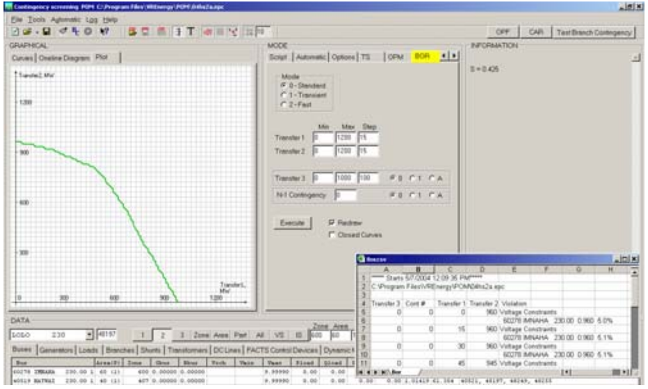


Fig. 3. Boundary of Operating Region for Two Simultaneous Transfers

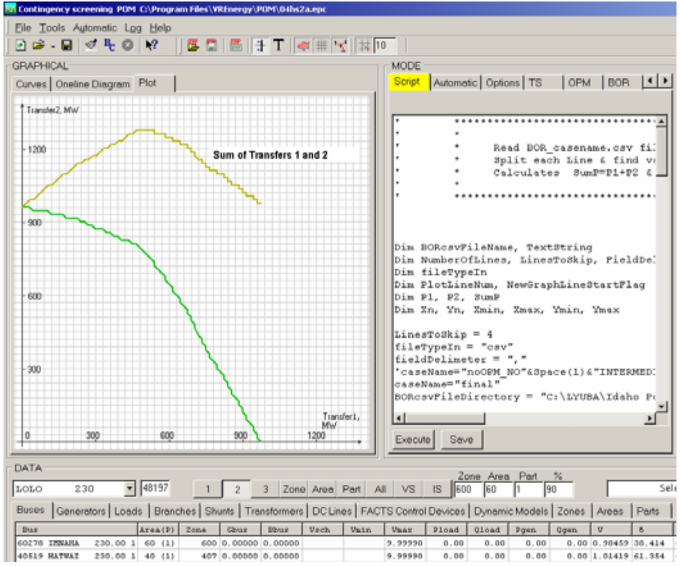
Each color on the boundary corresponds to violation of one of the following constraints and limits:

- Pink - Thermal violation;
- Green - Voltage range violation;
- Dark green - Pre- to post-contingency voltage drop violation;
- Tile - Flowgate violation;
- Red - Voltage stability violation;
- Black - User-specified transfer limit is reached but no violations are identified;
- Gray - Available generation (load) in source/sink subsystems has been used.

Fig. 3 shows that the limiting condition for these two simultaneous transfers is voltage constraint (dark green color). The area of the secure operating region is 0.425 p.u. The size of the operating region area is normalized by x-and y-axes maximum values.

The region within the boundary is secure operating region for Transfers 1 and 2. Operating beyond the boundary is insecure since it causes violation of monitored constraints.

The sum of Transfers 1 and 2 is shown in Fig. 4. It is shown as a golden curve.



```
'          ******************************
'          *
'          *      Read BOR_casename.csv fi
'          *      Split each Line & find v
'          *      Calculates  SumP=P1+P2 &
'          *
'          ******************************



Dim BORcsvFileName, TextString
Dim NumberOfLines, LinesToSkip, FieldDe
Dim fileTypeIn
Dim PlotLineNum, NewGraphLineStartFlag
Dim P1, P2, SumP
Dim Xn, Yn, Xmin, Xmax, Ymin, Ymax

LinesToSkip = 4
fileTypeIn = "csv"
fieldDelimeter = ","
'caseName="noOPM_NO"&Space(1)&"INTERMED
caseName="final"
BORcsvFileDirectory = "C:\LYUBA\Idaho P
```

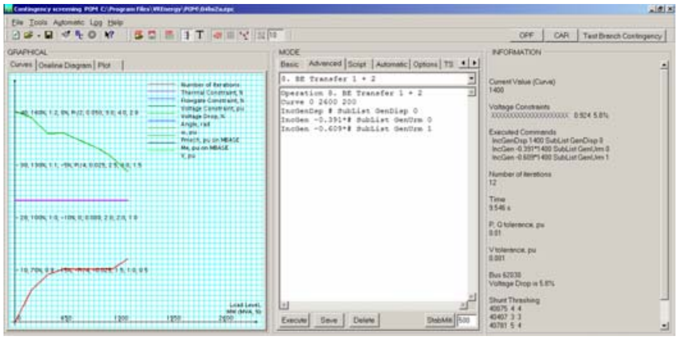
Bus	Area(P)	Zone	Gbus	Bbus	Vsch	Vmin	Vmax	Pload	Qload	Pgen	Qgen	V	δ
60278 IMNAHA 230.00 1	60 (1)	600	0.00000	0.00000			9.99990	0.00	0.00	0.00	0.00	0.98459	38.414
40519 HATWAI 230.00 1	40 (1)	407	0.00000	0.00000			9.99990	0.00	0.00	0.00	0.00	1.01419	61.354

Fig. 4. Graph of the Sum of Transfers 1 and 2

The sum of two transfers is shown in Fig. 4 as a function of Transfer 1. The curve representing the sum of two transfers reaches its maximum of approximately 1280 MW when power transfer 1 is 500 MW, and power transfer 2 is 780 MW. Thus, the maximum transfer capability determined by BOR for the in initial transfer (from Northwest to IPC) is 1280 MW. The participation factors for each power transfer (for each sink location) are:

- 0.391 for Transfer 1
- 0.609 for Transfer 2

Then, simulation of the initial power transfer shown in Fig. 1 is repeated using the participation factors determined from Fig. 4. Source and sink subsystems used for simulation of the transfer are the same subsystems as those used for simulation of the initial power transfer. However, in Fig. 5 sink area is divided into two separate subsystems based on geographical location of generators and transmission line flows. For each of the two sink subsystems, participation factors determined by BOR are used.



```
0. BE Transfer 1 + 2
Operation 0. BE Transfer 1 + 2
Curve 0 2400 200
IncGenDsp # SubList GenDisp 0
IncGen -0.391*# SubList GenUrm 0
IncGen -0.609*# SubList GenUrm 1
```

Current Value (Curve)
1400

Voltage Constraints
XXXXXXXXXXXXXXXXXXXX 0.924 5.8%

Executed Commands
IncGenDsp 1400 SubList GenDisp 0
IncGen -0.391*1400 SubList GenUrm 0
IncGen -0.609*1400 SubList GenUrm 1

Number of iterations
12

Time
9.546 s

P, Q tolerance, pu
0.01

V tolerance, pu
0.001

Bus 62038
Voltage Drop is 5.8%

Shunt Thrashing
40075 4 4
40407 3 3
40781 5 4

Fig. 5. Maximum Transfer Capability

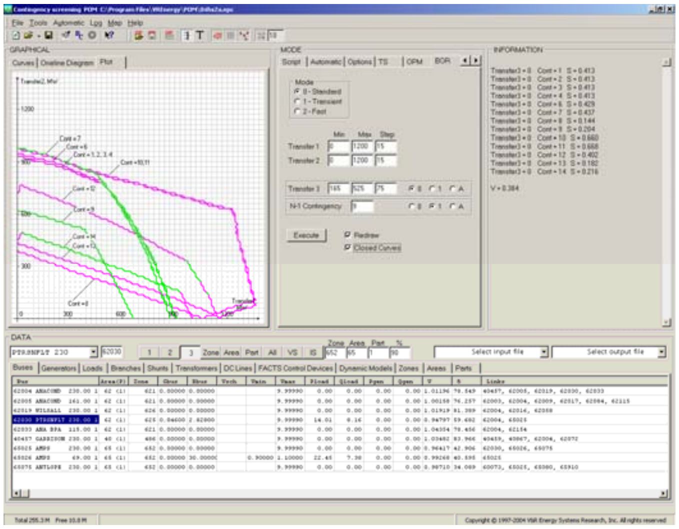
Power transfer shown in Fig. 5 is limited by violation of voltage constraint at transfer level 1400 MW. Since the power transfer is simulated with a 200 MW step, the maximum transfer level at which no constraints are violated is 1200 MW. This result corresponds to the maximum transfer value of 1280 MW identified by BOR (see Fig. 4).

The transfer was increased 200 MW (or approximately 17%) as compared to the transfer simulated in Fig. 1. Thus, using BOR a power transfer may be increased without any network changes and/or additional investments. As a result of using BOR, the transfer was increased from 1000 MW to 1200 MW.

IV. CONTINGENCY ANALYSIS RESULTS FOR TWO SIMULTANEOUS POWER TRANSFERS

Contingency analysis was performed while simulating Transfer 1 and Transfer 2. Eight N-1, four N-2, and two N-3 contingencies were applied during the study.

Boundary of the operating region was constructed for each contingency. Boundaries are displayed in Fig. 6.



Mode
● 0 - Standard
○ 1 - Transient
○ 2 - Fast

	Min	Max	Step
Transfer 1	0	1200	15
Transfer 2	0	1200	15
Transfer 3	165	525	75

Transfer 3: ● 0 ○ 1 ○ A
N-1 Contingency: 9 ○ 0 ● 1 ○ A

☑ Redraw
☑ Closed Curves

Transfer3 = 0 Cont = 1 S = 0.413
Transfer3 = 0 Cont = 2 S = 0.413
Transfer3 = 0 Cont = 3 S = 0.413
Transfer3 = 0 Cont = 4 S = 0.413
Transfer3 = 0 Cont = 6 S = 0.429
Transfer3 = 0 Cont = 7 S = 0.437
Transfer3 = 0 Cont = 8 S = 0.144
Transfer3 = 0 Cont = 9 S = 0.204
Transfer3 = 0 Cont = 10 S = 0.660
Transfer3 = 0 Cont = 11 S = 0.668
Transfer3 = 0 Cont = 12 S = 0.402
Transfer3 = 0 Cont = 13 S = 0.182
Transfer3 = 0 Cont = 14 S = 0.216

V = 0.384

PTRSNFLT 230 | 62030 | Zone 652 | Area 65 | Part 1 | % 90

Total 255.3 M Free 10.8 M

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Fig. 6. Boundaries of Operating Region during Contingency Analysis

Based on the size of the area of the operating region, the most severe contingencies are contingencies 5, 8 and 9.

Contingency 5 causes violation of monitored constraints on the base case and all transfer levels. Thus, boundary of the secure operating region is not drawn. Contingencies 8 and 9 have the smallest size of the operating region area (0.144 p.u. and 0.204 p.u., respectively).

Fig. 6 shows that the smallest size of the secure region of operation is formed by boundaries for contingencies 8 and 9. These boundaries are closest to the initial point (0, 0). The smallest region is bound by Operation 8 on the top and by Operation 9 on the right (see Fig. 7).

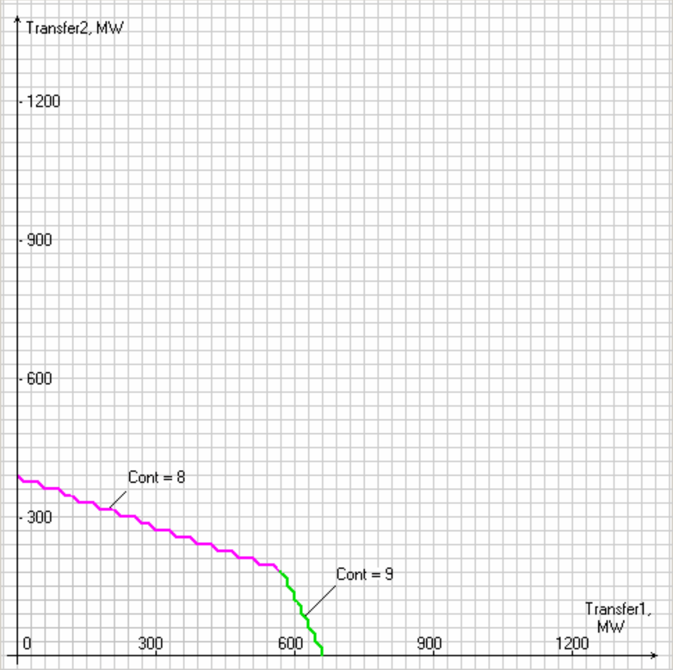


Fig. 7. The Smallest Area for All Contingencies

V. USING REMEDIAL ACTIONS TO INCREASE THE SIZE OF THE SMALLEST SECURE OPERATING REGION

This Section describes the use of load curtailment in order to increase the smallest secure operating region.

Optimal Mitigation Measures (OPM) software was used along with BOR for this part of the study.

Prior to applying mitigation measures, secure operating region for Operation 5 does not exist. After applying mitigation measures, the operating region exists, and its area is increases to 0.555 p.u.

Areas of secure operating regions for contingencies 8 and 9 increase from 0.144 p.u. to 0.598 p.u. and from 0.204 p.u. to 0.433 p.u, respectively.

The most severe contingency after mitigation measures are applied is Operation 9.

The smallest size of the secure region of operation is formed by boundaries for contingencies 8 and 9. These boundaries are closest to the initial point (0, 0). The smallest region is bound by Operation 8 on the top and by Operation 9 on the right (see Fig. 8).

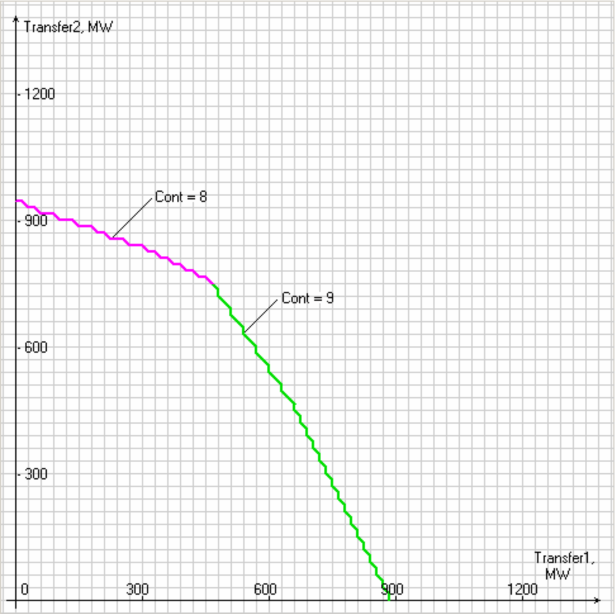


Fig. 8. The Smallest Area after Load Curtailment is Applied

VI. DEPENDENCE OF THE SMALLEST SIZE OF THE OPERATING REGION ON THE AMOUNT OF LOAD CURTAILMENT

This Section analyzes the dependence of the operating regions on the amount of load curtailment for Operations 5, 8 and 9. Operating region boundaries for this analysis were constructed while using the amount of load curtailment as a parameter for a set of projections on the plane (Transfer 1, Transfer 2).

Boundaries for Operations 5, 8 and 9 for different amounts of load curtailment are given in Fig. 9. The amount of load curtailment varies from 0 MW to 525 MW (maximum available load at buses identified by OPM).

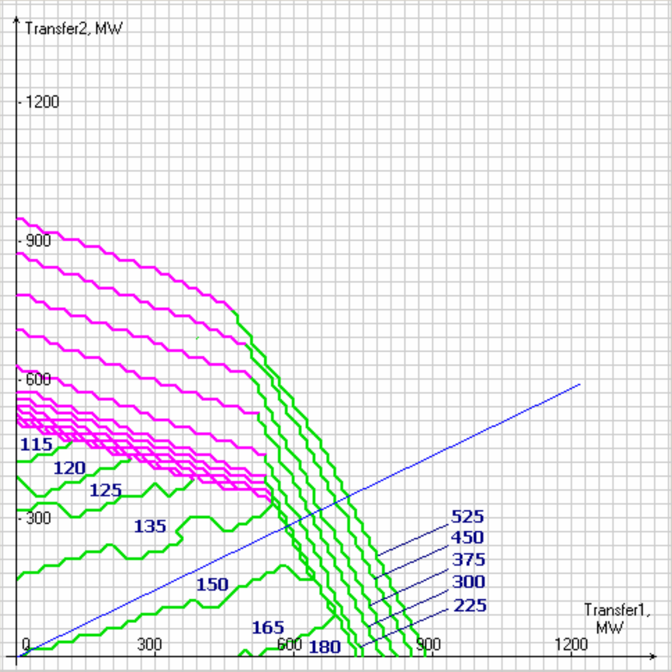


Fig. 9. Operations 5, 8 and 9: Dependence of the Size of the Operating Region on the Amount of Load Curtailment

The blue line represents the initial power transfer shown in Fig. 1.

From Fig. 9 it follows that the smallest operating region is formed by boundaries for several contingencies. Dependence of load curtailment on the boundaries forming the smallest region is summarized in Table 1.

Table 1. Dependence of Load Curtailment on the Boundaries that Form the Smallest Secure Region

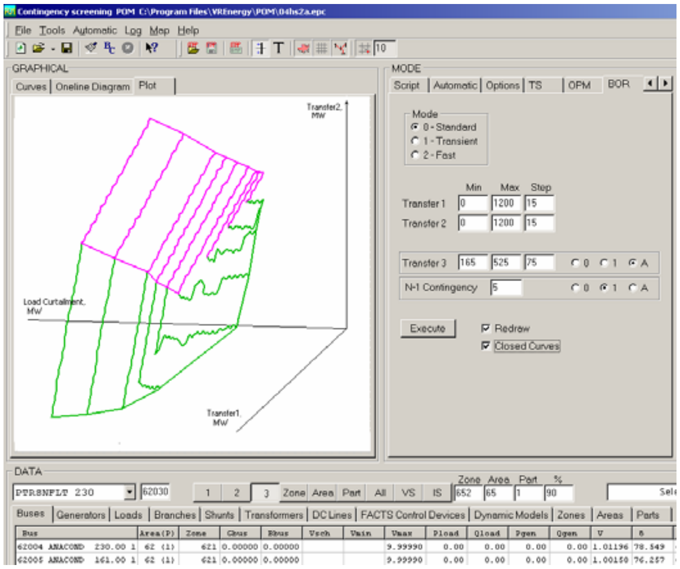
Load Curtailment, MW	Intersection of Boundaries
105 - 135	Operation 8 (top) Operation 5 (bottom)
150 - 165	Operation 8 (top) Operation 9 (right) Operation 5 (bottom)
180 - 525	Operation 8 (top) Operation 9 (bottom)

In Fig. 9, results are shown in 2-dimensional form as a set of projections on the on the plane (Transfer 1, Transfer 2) with the amount of load curtailment used as the parameter. The same results may be shown in 3-dimensional form.

Fig. 10 gives the same results as shown Fig. 9 but in 3-dimensional form.

The axes in Fig. 10 are:

- The *x*-axis represents transfer 1
- The *y*-axis represents transfer 2
- The *z*-axis represents the amount of load curtailment



Contingency screening POM C:\Program Files\VREnergy\POM\04hs2a.epc

10

Mode
● 0 - Standard
○ 1 - Transient
○ 2 - Fast

	Min	Max	Step
Transfer 1	0	1200	15
Transfer 2	0	1200	15
Transfer 3	165	525	75

Transfer 3: ○ 0 ○ 1 ● A

N-1 Contingency: 5 ○ 0 ● 1 ○ A

☑ Redraw

☑ Closed Curves

PTRSNFLT 230 62030

Zone 652 Area 65 Part 1 % 90

Bus	Area(P)	Zone	Gbus	Bbus	Vsch	Vmin	Vmax	Pload	Qload	Pgen	Qgen	V	δ
62004 ANACOND 230.00 1	62 (1)	621	0.00000	0.00000			9.99990	0.00	0.00	0.00	0.00	1.01196	78.549
62005 ANACOND 161.00 1	62 (1)	621	0.00000	0.00000			9.99990	0.00	0.00	0.00	0.00	1.00150	76.257

Fig. 10. Operations 5, 8 and 9: Dependence of the Size of the Operating Region on the Amount of Load Curtailment in 3-Dimensional Form

VII. MAXIMIZING THE TRANSFER CAPABILITY DURING SECURITY ANALYSIS

This section uses the approach described in Section III. The approach is based on the sum of power transfers 1 and 2.

The sum of two transfers is computed for each projection shown in Fig. 9. The sum of two transfers is shown as a function of Transfer 1 in Fig. 11.

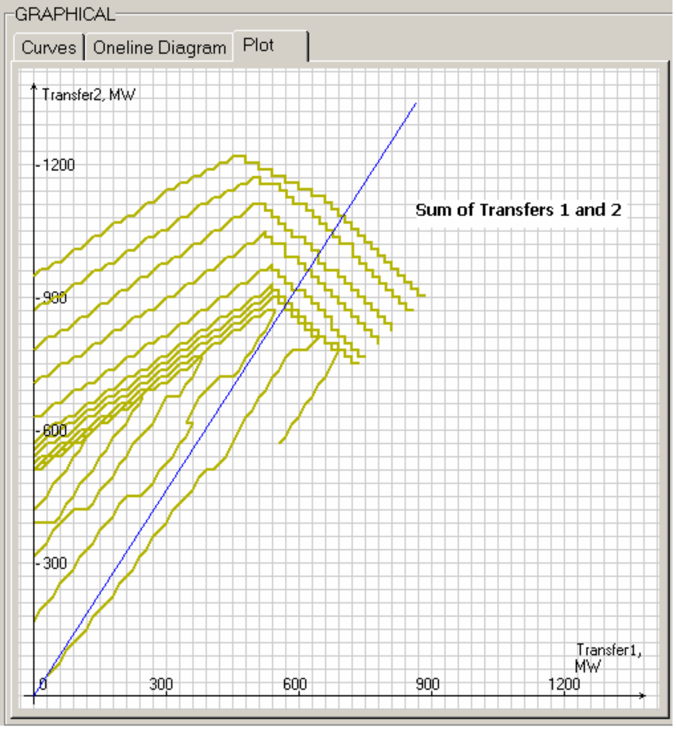


Fig. 11. Graph of the Sum of Transfers 1 and 2 for Different Values of Load Curtailment

The blue line represents the initial power transfer shown in Fig. 1.

Based on the results shown in Fig. 11, the transfer capability may be maximized. The approach is demonstrated in Fig. 12.

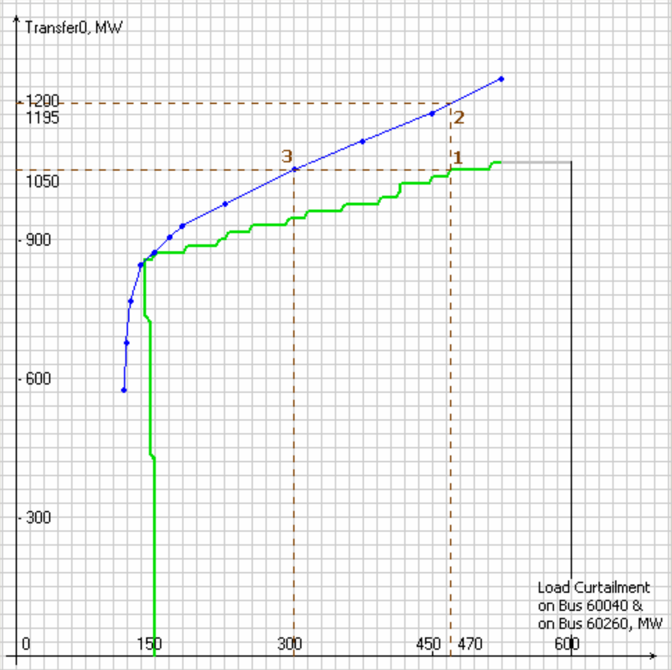


Fig. 12. Maximizing Transfer Capability Using BOR and OPM

The axes in Fig. 12 are:

- The *x*-axis represents the amount of load curtailment (at load buses selected by OPM).
- The *y*-axis represents the initial power transfer while applying Operation 5.

The green curve is obtained from Fig. 11. The curve is drawn using the points of intersection of the projections of the sum of transfers 1 and 2 (obtained for different amounts of load curtailment) and the projection of the initial transfer. It is constructed automatically by BOR. Green color corresponds to voltage constraint being violated in the intersection points.

The blue curve is also obtained from Fig. 11. The curve is drawn using the points where the sum of Transfers 1 and 2 reaches its maximum (obtained for different amounts of load curtailment).

Two conclusions are derived from Fig. 12:

1. The transfer capability may be increased for the same amount of load curtailment.
   For example, for the initial transfer the amount of load curtailment equal to 470 MW will increase the transfer to 1050 MW during security (i.e., contingency) analysis (see point 1 in Fig. 12). After the transfer has been maximized, the same value of load curtailment (470 MW) will increase the transfer to ≈1200 MW (see point 2 in Fig. 12).
2. The amount of load curtailment may be reduced to achieve the same value of transfer.
   For example, for the initial transfer, the amount of load curtailment equal to 470 MW will increase the transfer to 1050 MW during security analysis (see point 1 in Fig. 12). After the transfer has been maximized, the same value of power transfer may be achieved using only 300 MW of load curtailment (see point 3 in Fig. 12).

VIII. CONCLUSION

This paper describes an approach for maximizing transfer capability while performing contingency analysis in Idaho Power Co. Voltage, thermal and voltage stability limits are monitored during transfer and contingency analysis. The smallest secure operating region is determined. It is bound by boundaries formed by several contingencies. The effect of load curtailment on the smallest secure operating region is analyzed. As a result of utilizing the proposed approach, transfer capability is increased for the same amount of load curtailment. Also, the approach allows the user to reduce the amount of load curtailment to achieve the same value of transfer.

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X. BIOGRAPHIES

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