AEP Automatic Contingency Selector : Branch Outage Impacts on Load Bus Voltage Profile

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Abstract- This paper presents the details of a computationally efficient automatic voltage contingency selection algorithm developed for implementation at the AEP's new system control center in Columbus, Ohio. The methodology is based on the quantification of the real-time system-wide impacts of the transmission branch (line and transformer) outages on the load bus voltage profile via the fast computation of a quadratic system Performance Index (PI) for every branch, and subsequent sorting of the results according to the severity of effects. The algorithm enjoys superior computational complexity compared to the previously published work. An application of the algorithm to the AEP EHV real-time data base is presented as an illustration.

NOTATION

NBUS = Number of buses in the system

NLOAD = Number of load buses in the system

NL = Number of branches in the system

Q_i^{SP} = Scheduled reactive power at bus i

Q_i^{cal} = Calculated reactive power at bus i

V_i^{SP} = Scheduled voltage magnitude at bus i

V, δ = Base-case voltage magnitude and angle vectors, respectively

V^{ℓ}, δ^{ℓ} = Post-outage voltage magnitude and angle vectors corresponding to the outage of branch ℓ, respectively

ΔV_i^{max} = Permissible voltage deviation at bus i

ℓ = Post-outage quantity corresponding to outage of branch ℓ (superscript)

g_{ℓ} = Conductance of branch ℓ

b_{ℓ} = Susceptance of branch ℓ

$b_{\ell p}^{sh}$ = Shunt at p side of branch ℓ

$b_{\ell q}^{sh}$ = Shunt at q side of branch ℓ

R = Reference case quantity (superscript)

W_i^V = A real non-negative weight associated with bus i

m = Order of the voltage performance index

ΔV = Voltage magnitude correction

$\gamma(i)$ = Set of adjacent buses to bus i

B', B'' = Coefficient matrices of Fast Decoupled Load Flow (FDLF)

[.] = A vector quantity

diag{.} = A diagonal matrix

$||\ .\ ||$ = A vector norm

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O(.) = Algorithm computing time

INTRODUCTION

The traditional procedure for on-line steady-state security assessment at the current energy control centers is by evaluation of a large number of contingency cases. The computational burden that this task imposes on the present day computer installations has prompted the need for the development of systematic ways for the automatic selection of meaningful contingency cases. The objective is to reduce the number of potential cases under consideration and, at the same time, to determine the ranking of these cases according to their severity of effects for further analysis.

The current practice typically simulates the contingencies either:

- By selecting the outages to be studied from a pre-compiled list of meaningful contingencies, or
- By operator selection, depending on the power system state as given by a state estimator or any other on-line power system monitoring facility.

The former approach is an off-line planning practice applied to the on-line situation. Such a method fails to recognize the fact that system states assumed for the preparation of the contingency lists may differ from the real-time operation environment. In fact, what is understood to be a single contingency in a planning study may very well be a double, triple or even higher contingency in a real-time operation environment.

This analysis heavily draws on traditional Transfer Capability Curves and concentrates on the Key Facility Index provided by the system planners. Moreover, it has a local scope and not a global (i.e., system-wide) one.

The second method (i.e., operator selection) may prove to be burdensome even to experienced operators. As operating conditions in most systems become more stringent, the number of contingency choices increases and no amount of experience guarantees proper selection of troublesome contingency cases.

These considerations suggest the need for a systematic method for the automatic selection of contingencies that should be examined. The approach taken at AEP is to rank the outage events according to their severity so that only the higher ranked cases would then be studied in detail. The methods developed here to generate such rankings involve the use of system performance indices. A system performance index must be a single-valued function whose magnitude reflects the severity of out-of-limit bus voltages, reactive power injections or branch real and reactive flows resulting from a given contingency. Hence, in these studies, a system-wide performance index is defined as a penalty function type of index which penalizes any violations of the bus voltage profile, reactive power injection limit and transmission branch real and reactive flow capability constraints.

One such index is used to rank transmission branch and injection contingencies in terms of the severity of branch overloads. A different index is used for ranking transmission branch contingencies on the basis of their severity in terms of the out-of-limit voltage profile. A third index is used to analyze transmission branch contingencies in terms of their impacts on reactive power injections at the generation buses.

It is significant to notice that a single performance index encompassing a mixture of generically different variables such as bus voltage magnitude, branch real and reactive power flows, or real and reactive power injections, does not seem to be appropriate, since the effects of some limit violations may be masked in the process of aggregation.

Five areas of application for the Automatic Contingency Selection (ACS) techniques have been envisioned at AEP as follows:

1. Selection of transmission branch contingencies adversely affecting the real power flow (MW) at the transmission facilities (algorithm PSEL).
2. Selection of transmission branch contingencies adversely affecting the voltage profile at the load buses (algorithm VSEL).
3. Selection of transmission branch contingencies adversely affecting the reactive power injections (MVAR) at the generation buses (algorithm QSEL).
4. Selection of real power (MW) injection contingencies adversely affecting the real power (MW) flow at the transmission facilities (algorithm IPSEL).
5. Selection of reactive power (MVAR) injection contingencies adversely affecting the reactive power flows at the transmission facilities or bus voltage profile (algorithm IQSEL).

Computationally efficient algorithms for the implementation of the automatic contingency selectors in the aforementioned areas have been under development at AEP during the past few years [1]. Algorithm PSEL is fully described in [2]. The present paper illustrates algorithm VSEL, whereas QSEL, IPSEL and IQSEL algorithms will be the subjects of future papers.

The essence of the algorithms is to quickly rank contingency events in such a manner that sequential contingency testing could be carried out (with an on-line full

AC load flow function, for example), starting with the most severe contingency (in terms of causing transmission branch overloads, abnormal voltage profile or reactive power problems) and terminating when the sequence of contingencies no longer poses problems.

VOLTAGE PERFORMANCE INDEX

The voltage Performance Index (PI) chosen to quantify the system abnormalities due to the out-of-limit bus voltage profile is defined as:

$$J(V) = \sum_{i=1}^{NLOAD} \frac{W_i^V}{m} \left(\frac{V_i - V_i^{SP}}{\Delta V_i^{max}}\right)^m \qquad (1)$$

This performance index takes into account the voltage magnitude constraints at all the load buses in the system. The permissible voltage deviation ΔV_i^{max} represents the threshold beyond (above and below) which bus voltage magnitudes are outside their limits, thus yielding a large value of the index J(V). Note that when all deviations from the specified bus voltage magnitudes are within their corresponding ΔV_i^{max}, the performance index J(V) is small. The upper and lower bounds on the voltage magnitudes at bus i are, hence, implicitly specified as ($V_i + \Delta V_i^{max}$), and ($V_i - \Delta V_i^{max}$), respectively.

In the context of real power contingency selection of [2], it has been observed that situations may develop where the limit violations may not be recognized (masking effect). There are two ways to deal with this phenomenon. One approach is to increase the order of the performance index, m. Although this approach is quite effective in mitigating the effects of masking, it introduces computational complications in the implementation of automatic contingency selectors. The second approach for reducing masking effect is by partitioning the monitored network into smaller subsets and perform multiple rankings.

The system can conceptually be broken up into local areas and rankings can be performed on an area-wide basis as opposed to a system-wide one. A local area is a logical subset of the monitored facilities which may, or may not, correspond to a geographically or electrically contiguous area. A local area might be the set of all 765-345 KV transformers, for example.

Nevertheless, the underlying automatic contingency selection algorithm is identical regardless of the mode of implementation. Network partitioning achieves masking effect reduction by breaking up the summation of (1) into several smaller summations to reduce (or, ideally eliminate) the adverse effects of aggregation.

AN OVERVIEW

At AEP, the first function to be developed within the automatic contingency selection area was the real power problem of [2]. An efficient DC load flow-based formulation was successfully implemented (algorithm PSEL). The authors made an attempt to pursue a similar course of action, namely, a DC load flow approach to automatic voltage contingency selection (i.e., a pure Q-V formulation). The rankings thus obtained were unreliable when checked against the results generated by the full AC load flow simulation of each branch outage and explicit substitution of the post-contingency voltage magnitudes into the performance index of (1). The first impression was that the well-known decoupling principle of the real and reactive power related variables would not apply in this context.

It was concluded that a better procedure would be to first update the bus phase angles due to the branch outage, before correcting the voltage magnitudes. This essentially implies one full iteration of the fast decoupled load flow of [3]. The authors of [4] apparently reached the same conclusion concurrently. This procedure can be summarized as follows.

ALGORITHM 1P-1Q

begin

(1) form and factor the coefficient matrices B′ and B";

(2) for all the transmission branches in the network do begin

(3) update the nodal admittance matrix to reflect the branch outage;

(4) solve for the bus angles using the real power portion of FDLF equations and network compensation;

(5) solve for the voltage magnitudes using the reactive power portion of FDLF and network compensation;

(6) compute the performance index value;

end

(7) sort the performance index values in descending order;

end

The computational complexity of this algorithm will be analyzed as follows. For sparse matrices, the worst case computation time for step (1) is proportional to NBUS. Step (3) takes constant time. Step (4), on the other hand, is at least proportional to NL, since its time is proportional to the number of the entries in the adjacency list of the factored B′ matrix. Step (5) is also O(NL). Step (6) requires CPU time proportional to NBUS, and finally step (7) can be executed in O(NL log NL). Since steps (4) and (5) are O(NL) and these steps are executed NL times, the worst case computational burden of this algorithm is $O(NL^2)$ which is quite intensive. It will be shown that a substantially more efficient formulation is feasible and its performance for the AEP EHV real-time data base will be compared with the algorithm 1P-1Q for the same base-case.

Some preliminary equation manipulations are presented in Appendix I which serve as the basis for further algorithmic derivation.

POST-OUTAGE VOLTAGE DERIVATION

Consider equation (A1.8) of Appendix I:

$$[\frac{\Delta Q}{V}] = K_o + K_1 \delta \quad (2)$$

This equation is the cornerstone in the derivation of the algorithm VSEL. Upon the occurrence of a breaker switching operation (a forced or scheduled branch outage), the network topology is modified and a new ranking needs to be determined. Suppose the switching operation resulted in the outage of branch ℓ interconnecting buses p and q. Then,

$$[\frac{\Delta Q}{V}]^{\ell} = K_o^{\ell} + K_1^{\ell}\delta^{\ell} \quad (3)$$

Assuming that transmission branch ℓ is represented by an equivalent π model, the compensation to K_o due to the branch outage would consist of three terms corresponding to the series element and two shunts. K_1, on the other hand, only depends on the series elements. Equation (2) thus becomes:

$$[\frac{\Delta Q}{V}]^{\ell} = (K_o + \hat{b}_\ell N_\ell + X_{\ell 1}U_{\ell 1} + X_{\ell 2}U_{\ell 2}) + (K_1 + A_\ell \hat{M}_\ell^t)\delta^{\ell} \quad (4)$$

where,

$$\hat{b}_\ell = b_\ell (V_q - V_p)$$

$$X_{\ell 1} = -V_p^R b_{\ell p}^{sh}$$

$$X_{\ell 2} = -V_q^R b_{\ell q}^{sh}$$

N_ℓ = A sparse NLOAD-vector of at most two non-zero entries corresponding to buses p and q with values +1 and -1, respectively.

$U_{\ell 1}$ = A sparse NLOAD-vector of at most one non-zero entry corresponding to bus p with value +1.

$U_{\ell 2}$ = A sparse NLOAD-vector of at most one non-zero entry corresponding to bus q with value +1.

A_ℓ = A sparse NLOAD-vector of at most two non-zero entries corresponding to buses p and q with values $-V_q^R(g_\ell + \alpha b_{\ell\ell})$ and $V_p^R(g_\ell - \alpha b_{\ell\ell})$

$\hat{M}_\ell$ = A sparse NBUS-vector with values +1 and -1 at entries p and q, respectively

The post-outage phase angle vector δ^{ℓ}, can efficiently be computed by applying the Sherman-Morrison-Woodbury inverse matrix modification of [5] to the DC load flow equation as follows [2]:

$$\delta^{\ell} = \delta - C_\ell \theta_\ell (B')^{-1} M_\ell \quad (5)$$

where,

$$\theta_\ell = \delta_p - \delta_q$$

$$C_\ell = \{ b_\ell^{-1} + M_\ell^t (B')^{-1} M_\ell \}^{-1}$$

M_ℓ = A sparse (NBUS-1)-vector with values +1 and -1 at (non-slack) entries p and q, respectively

Substitute (5) in (4) to obtain:

$$[\frac{\Delta Q}{V}]^{\ell} = (K_o + \hat{b}_\ell N_\ell + X_{\ell 1}U_{\ell 1} + X_{\ell 2}U_{\ell 2}) + \{(K_1 + A_\ell \hat{M}_\ell^t)(\delta - C_\ell \theta_\ell (B')^{-1} M_\ell)\} \quad (6)$$

The FDLF formulation, on the other hand, implies:

$$[\frac{\Delta Q}{V}]^{\ell} = B''^{\ell} [\Delta V]^{\ell} \quad (7)$$

or,

$$[\Delta V]^{\ell} = (B''^{\ell})^{-1} [\frac{\Delta Q}{V}]^{\ell} \quad (8)$$

and in terms of the base-case B" matrix,

$$[\Delta V]^{\ell} = \{B'' + b_\ell N_\ell N_\ell^t\}^{-1} [\frac{\Delta Q}{V}]^{\ell} \quad (9)$$

and

$$[\Delta V]^{\ell} = \{(B'')^{-1} - \hat{C}_\ell (B'')^{-1} N_\ell N_\ell^t (B'')^{-1}\} [\frac{\Delta Q}{V}]^{\ell} \quad (10)$$

where,

$$\hat{C}_\ell = \{b_\ell^{-1} + N_\ell^t (B'')^{-1} N_\ell\}^{-1} \quad (11)$$

The voltage profile update due to the outage of branch ℓ can thus be generated by substituting (6) into (10). The post-outage voltage magnitude then would be:

$$V^{\ell} = V + [\Delta V]^{\ell} \quad (12)$$

or,

$$\begin{aligned} V^{\ell} = {} & V + (B'')^{-1}K_0 + \hat{b}_{\ell}(B'')^{-1}N_{\ell} + X_{\ell_1}(B'')^{-1}U_{\ell_1} + \\ & X_{\ell_2}(B'')^{-1}U_{\ell_2} + (B'')^{-1}K_1\delta \\ & - C_{\ell}\theta_{\ell}(B'')^{-1}K_1(B')^{-1}M_{\ell} + \hat{\theta}_{\ell}(B'')^{-1}A_{\ell} \\ & - C_{\ell}\theta_{\ell}(B'')^{-1}A_{\ell}\hat{M}_{\ell}^{t}(B')^{-1}M_{\ell} \\ & - \hat{C}_{\ell}(B'')^{-1}N_{\ell}N_{\ell}^{t}(B'')^{-1}K_0 - \hat{C}_{\ell}\hat{b}_{\ell}(B'')^{-1}N_{\ell}N_{\ell}^{t}(B'')^{-1}N_{\ell} \\ & - \hat{C}_{\ell}X_{\ell_1}(B'')^{-1}N_{\ell}N_{\ell}^{t}(B'')^{-1}U_{\ell_1} - \hat{C}_{\ell}X_{\ell_2}(B'')^{-1}N_{\ell}N_{\ell}^{t}(B'')^{-1}U_{\ell_2} \\ & - \hat{C}_{\ell}(B'')^{-1}N_{\ell}N_{\ell}^{t}(B'')^{-1}K_1\delta + \\ & C_{\ell}\hat{C}_{\ell}\theta_{\ell}(B'')^{-1}N_{\ell}N_{\ell}^{t}(B'')^{-1}K_1(B')^{-1}M_{\ell} \\ & - \hat{C}_{\ell}\hat{\theta}_{\ell}(B'')^{-1}N_{\ell}N_{\ell}^{t}(B'')^{-1}A_{\ell} + \\ & C_{\ell}\hat{C}_{\ell}\theta_{\ell}(B'')^{-1}N_{\ell}N_{\ell}^{t}(B'')^{-1}A_{\ell}\hat{M}_{\ell}^{t}(B')^{-1}M_{\ell} \end{aligned} \quad (13)$$

where,

$$\hat{\theta}_{\ell} = \hat{M}_{\ell}^{t}\delta$$

FINAL FORM OF PI

To analyze the voltage performance index of (1), note that for the special case of $W_i^V = 1$; $i = 1,2...,NLOAD$, and $m = 2$ and for the post-outage state, (1) becomes:

$$J(V^{\ell}) = \frac{1}{2}\sum_{i=1}^{NLOAD}\left(\frac{V_i^{\ell} - V_i^{SP}}{\Delta V_i^{max}}\right)^2$$

$$= \tfrac{1}{2}\sum_{i=1}^{NLOAD}\left(\frac{V_i^{\ell}}{\Delta V_i^{max}} - \frac{V_i^{SP}}{\Delta V_i^{max}}\right)^2 \quad (14)$$

In vector form, (14) would appear as:

$$J(V^{\ell}) = \tfrac{1}{2}(D_oV^{\ell} - D_oV^{SP})^t(D_oV^{\ell} - D_oV^{SP}) \quad (15)$$

where,

$$D_o = \text{diag}\ \{(\Delta V_1^{max})^{-1},\ldots,(\Delta V_{NLOAD}^{max})^{-1}\} \quad (16)$$

Expansion of (15) yields,

$$J(V^{\ell}) = \tfrac{1}{2}\ \{(V^{\ell})^tDV^{\ell} - 2(V^{\ell})^tDV^{SP} + (V^{SP})^tDV^{SP}\} \quad (17)$$

where,

$$D = \text{diag}\ \{(\Delta V_1^{max})^{-2},\ldots,(\Delta V_{NLOAD}^{max})^{-2}\} \quad (18)$$

Substituting (13) into (17), would generate the expanded version of $J(V^{\ell})$. The performance index value for the current base-case condition, $J(V)$, can easily be extracted in the expansion of (17), i.e., given

$$J(V) = \tfrac{1}{2}\ \{V^tDV - 2V^tDV^{SP} + (V^{SP})^tDV^{SP}\} \quad (19)$$

then,

$$J(V^{\ell}) = J(V) + \{\text{correction sum}\} \quad (20)$$

Equation (20) implies that the performance index values for different branch outages can efficiently be calculated by simply updating the base-case PI. The {Correction Sum} of (20) includes many scalar quantities generated as the result of several matrix multiplications. Some of these terms are common to all the branches in the branch list and hence, need to be computed only once per execution of the ACS. On the other hand, a number of scalar quantities appear repeatedly in {Correction Sum} which are scalar functions of the branch under study, the FDLF coefficient matrices (i.e., B′ and B″), the performance index parameters and the "Reference" case data (i.e., K_0 and K_1). Hence, they can be generated off-line for every branch in the branch list and subsequently stored. They need to be updated only upon the introduction of a new reference case or a permanent topological change (breaker status change) or on operator request. The off-line scalars are listed in Table I. Each entry in Table I is a scalar quantity corresponding to branch ℓ and since there are NL branches in the monitored system, twenty-eight vectors of size NL are required for storage. Notice that only physical branches corresponding to lines and transformers are processed by ACS. Fictitious branches introduced by the external equivalent function (REI in this case) are exempted from ACS for obvious reasons.

Equation (20), then, can be rewritten as:

$$J(V^{\ell}) = J(V) + \{\text{sum } 1\} + \{\text{sum } 2\} + \{\text{sum } 3\} \quad (21)$$

where, {Sum 1} includes branch independent, base-case dependent terms, {Sum 2} consists of branch independent, reference-case dependent terms, and {Sum 3} contains the terms involving the off-line scalars of

Table I.

The ingredients for generation of the terms in {Sum 2} and {Sum 3} are known before the next execution of the ACS and can be computed off-line and stored. The only terms that need on-line computing are confined to {Sum 1}.

TABLE I

OFF-LINE SCALARS

$K_o^t (B'')^{-1} D (B'')^{-1} A_\ell$	$U_{\ell 1}^t (B'')^{-1} D (B'')^{-1} U_{\ell 2}$
$K_o^t (B'')^{-1} D (B'')^{-1} U_{\ell 2}$	$U_{\ell 1}^t (B'')^{-1} D (B'')^{-1} U_{\ell 1}$
$K_o^t (B'')^{-1} D (B'')^{-1} U_{\ell 1}$	$N_\ell^t (B'')^{-1} D (B'')^{-1} K_1 (B')^{-1} M_\ell$
$K_o^t (B'')^{-1} D (B'')^{-1} N_\ell$	$N_\ell^t (B'')^{-1} D (B'')^{-1} A_\ell$
$K_o^t (B'')^{-1} D (B'')^{-1} K_1 B_1 M_\ell$	$N_\ell^t (B'')^{-1} D (B'')^{-1} U_{\ell 2}$
$M_\ell^t (B')^{-1} K_1^t (B'')^{-1} D (B'')^{-1} K_1 (B')^{-1} M_\ell$	$N_\ell^t (B'')^{-1} D (B'')^{-1} U_{\ell 1}$
$N_\ell^t (B'')^{-1} K_1 (B')^{-1} M_\ell$	$N_\ell^t (B'')^{-1} D (B'')^{-1} N_\ell$
$A_\ell^t (B'')^{-1} D (B'')^{-1} K_1 B_1 M_\ell$	$N_\ell^t (B'')^{-1} A_\ell$
$A_\ell^t (B'')^{-1} D (B'')^{-1} A_\ell$	$N_\ell^t (B'')^{-1} U_{\ell 2}$
$U_{\ell 2}^t (B'')^{-1} D (B'')^{-1} K_1 (B')^{-1} M_\ell$	$N_\ell^t (B'')^{-1} U_{\ell 1}$
$U_{\ell 2}^t (B'')^{-1} D (B'')^{-1} A_\ell$	$N_\ell^t (B'')^{-1} N_\ell$
$U_{\ell 2}^t (B'')^{-1} D (B'')^{-1} U_{\ell 2}$	$\hat{M}_\ell^t (B')^{-1} M_\ell$
$U_{\ell 1}^t (B'')^{-1} D (B'')^{-1} K_1 (B')^{-1} M_\ell$	C_ℓ
$U_{\ell 1}^t (B'')^{-1} D (B'')^{-1} A_\ell$	$\hat{C}_\ell$

IMPLEMENTATION CONSIDERATIONS

The real-time environment in which the ACS functions operate is envisioned as follows:

The state estimator provides a model for the AEP monitored system. The outside areas and the unobserved portion of the AEP system would be represented by the external equivalent function. A pre-processor would combine these two models to generate a real-time base-case which would be accessed by ACS. At the present time, only branches residing in the AEP monitored area would be processed. This, however, is a data limitation issue and not one caused by the function itself. Future inter-utility data exchange between neighboring power systems would resolve this problem. That is, ACS would be enabled to extend its domain to include some key external facilities which are critical to the security of the AEP system.

The K_1 matrix represents the network structure and is consequently sparse. Some small entries in K_1 represent "loose" couplings between buses and are essentially noise effects. One can, then, introduce a threshold, h, below which K_1 matrix entries could be considered negligible and hence, replaceable by zero. The introduction of this approximation is justified by the fact that the proposed algorithm itself employs some approximations and, therefore, only significant entries of K_1 should be retained.

TABLE II

REAL-TIME RESULTS

AC RANK	BRANCH p	BRANCH q	AC-LOAD FLOW	1P-1Q	1P-1Q RANK	ACS	ACS RANK
1	9	45	.57865E+02	.58093E+02	1	.57042E+02	1
2	5	2	.56160E+02	.56020E+02	2	.54712E+02	2
3	38	37	.55363E+02	.55375E+02	3	.53599E+02	3
4	11	22	.54880E+02	.54706E+02	4	.53415E+02	4
5	48	61	.54700E+02	.54626E+02	5	.52748E+02	6
6	6	13	.54573E+02	.54027E+02	10	.52075E+02	12
7	14	4	.54552E+02	.54367E+02	7	.52098E+02	11
8	35	66	.54505E+02	.54423E+02	6	.52600E+02	7
9	8	14	.54414E+02	.54175E+02	9	.53131E+02	5
10	15	16	.54219E+02	.54268E+02	8	.51781E+02	22
11	4	15	.54189E+02	.53866E+02	15	.52170E+02	10
12	9	8	.54124E+02	.53986E+02	12	.52547E+02	8
13	4	48	.54064E+02	.54001E+02	11	.51976E+02	14
14	54	31	.53991E+02	.53974E+02	13	.52321E+02	9
15	13	61	.53938E+02	.53858E+02	16	.51971E+02	15
16	61	65	.53933E+02	.53933E+02	14	.51861E+02	20
17	34	32	.53912E+02	.53832E+02	17	.51753E+02	23
18	27	11	.53883E+02	.53786E+02	18	.51936E+02	17
19	27	11	.53851E+02	.53756E+02	20	.51906E+02	19
20	44	21	.53772E+02	.53671E+02	22	.51679E+02	24
21	12	16	.53770E+02	.53679E+02	21	.51651E+02	26
22	43	62	.53719E+02	.53771E+02	19	.51982E+02	13
23	32	64	.53603E+02	.53478E+02	25	.51790E+02	21
24	5	60	.53601E+02	.53508E+02	23	.51662E+02	25
25	11	17	.53586E+02	.53502E+02	24	.51498E+02	42
26	5	3	.53557E+02	.53476E+02	26	.51614E+02	28
27	5	14	.53518E+02	.53440E+02	27	.51583E+02	31
28	19	11	.53514E+02	.53434E+02	28	.51603E+02	29
29	68	70	.53512E+02	.53431E+02	29	.51564E+02	33
30	20	68	.53504E+02	.53424E+02	30	.51557E+02	35
31	20	70	.53501E+02	.53421E+02	31	.51558E+02	34
32	15	67	.53488E+02	.53408E+02	32	.51597E+02	30
33	59	16	.53479E+02	.53400E+02	33	.51498E+02	43
34	59	16	.53479E+02	.53399E+02	34	.51497E+02	44
35	17	12	.53455E+02	.53341E+02	39	.51505E+02	40
36	1	13	.53436E+02	.53356E+02	37	.51472E+02	47
37	34	35	.53429E+02	.53373E+02	36	.51509E+02	39
38	10	65	.53428E+02	.53349E+02	38	.51464E+02	51
39	52	20	.53412E+02	.53333E+02	40	.51483E+02	45
40	30	31	.53410E+02	.53330E+02	41	.51465E+02	50
41	34	42	.53381E+02	.53375E+02	35	.51555E+02	36
42	51	22	.53377E+02	.53281E+02	42	.51417E+02	53
43	17	18	.53355E+02	.53163E+02	51	.51500E+02	41
44	10	65	.53348E+02	.53270E+02	43	.51384E+02	54
45	19	18	.53340E+02	.53214E+02	47	.51466E+02	48
46	55	42	.53324E+02	.53245E+02	45	.51476E+02	46
47	30	32	.53316E+02	.53227E+02	46	.51343E+02	57
48	12	47	.53298E+02	.53266E+02	44	.51465E+02	49
49	68	71	.53273E+02	.53151E+02	52	.51569E+02	32
50	30	35	.53268E+02	.53207E+02	48	.51374E+02	55
51	30	35	.53268E+02	.53207E+02	49	.51374E+02	56
52	32	31	.53143E+02	.53068E+02	53	.51236E+02	60
53	50	47	.53102E+02	.53035E+02	54	.51935E+02	18
54	3	1	.53093E+02	.53026E+02	55	.51154E+02	63
55	4	13	.53078E+02	.52961E+02	59	.50977E+02	68
56	25	24	.53072E+02	.52994E+02	57	.51262E+02	59
57	29	28	.53067E+02	.53010E+02	56	.51230E+02	61
58	7	45	.53063E+02	.52884E+02	61	.51966E+02	16
59	36	37	.53030E+02	.53186E+02	50	.51635E+02	27
60	41	42	.53005E+02	.52969E+02	58	.51311E+02	58
61	58	48	.52909E+02	.52821E+02	63	.50845E+02	76
62	49	45	.52893E+02	.52837E+02	62	.51536E+02	37
63	36	33	.52862E+02	.52734E+02	66	.50921E+02	74
64	32	33	.52843E+02	.52935E+02	60	.51450E+02	52
65	43	44	.52825E+02	.52762E+02	65	.50973E+02	69
66	40	39	.52820E+02	.52702E+02	69	.51085E+02	64
67	24	23	.52777E+02	.52807E+02	64	.51213E+02	62
68	20	19	.52770E+02	.52649E+02	72	.50933E+02	72
69	29	43	.52737E+02	.52729E+02	67	.51034E+02	65
70	29	43	.52725E+02	.52721E+02	68	.51029E+02	66
71	68	69	.52716E+02	.52666E+02	71	.50813E+02	78
72	34	41	.52679E+02	.52687E+02	70	.50950E+02	70
73	28	64	.52650E+02	.52569E+02	75	.50825E+02	77
74	41	40	.52641E+02	.52644E+02	73	.50948E+02	71
75	62	46	.52603E+02	.52591E+02	74	.50921E+02	73
76	43	44	.52587E+02	.52530E+02	76	.50747E+02	80
77	29	30	.52532E+02	.52482E+02	78	.50651E+02	82
78	63	62	.52532E+02	.52497E+02	77	.51015E+02	67
79	57	32	.52500E+02	.52464E+02	79	.50913E+02	75
80	36	16	.52375E+02	.52464E+02	80	.50441E+02	87
81	29	66	.52331E+02	.52281E+02	81	.50468E+02	85
82	21	46	.52227E+02	.52154E+02	83	.50549E+02	83
83	25	26	.52156E+02	.52049E+02	85	.50761E+02	79
84	30	56	.52154E+02	.52169E+02	82	.50747E+02	81
85	26	59	.52001E+02	.52050E+02	84	.50365E+02	88
86	41	39	.51979E+02	.51947E+02	88	.50464E+02	86
87	23	22	.51979E+02	.52003E+02	86	.50533E+02	84
88	28	56	.51944E+02	.51980E+02	87	.50220E+02	89
89	28	59	.51793E+02	.51829E+02	89	.50056E+02	90
90	47	67	.51500E+02	.51718E+02	90	.51533E+02	38
91	53	37	.50031E+02	.49711E+02	91	.48414E+02	91

The automatic contingency selection report is interpreted as follows:

The transmission coordinator or operations engineer in the control center examines the ACS branch ranking and would further analyze the "top" ranking contingencies by the study mode of the on-line load flow function. The question that naturally arises is "at what point the examination of the sorted branch list would terminate?." In other words, a Stopping Time (ST) resembling a similar concept in stochastic processes is needed [6].

A natural stopping time in the ACS report for further analysis would be the base-case value of the performance index, J(V). Such heuristic ST is only one of several feasible stopping time criteria and further real-time tests may suggest an alternative.

A systematic way of determining the "goodness" of the current "Reference" case (i.e., an earlier base case typically preceding real-time by several hours depending on the time of day) used to generate the coefficient matrices K_0 and K_1, is by the following procedure:

begin,

IF $(||\delta^R - \delta|| < e)$ THEN

Retain the current reference case;

ELSE

Generate an alarm/log;

Replace the reference case by the current base-case;

Re-generate K_0 and K_1 matrices;

END IF

end

where e is a system dependent threshold to be determined experimentally. The justification for the above validation test is that the bus phase angles closely track the daily load curve and do vary after each Economic Dispatch calculation (EDC), in contrast to the voltage magnitudes which remain fairly constant over a long period of time in normal state. If the validation test fails, an alarm and/or a log would be generated to inform the operator to dispose of the given reference case and re-form the corresponding coefficient matrices from the current real-time data to be used for some period of time depending on the location on the daily load curve.

REAL-TIME RESULTS

The algorithms VSEL and 1P-1Q were tested for the AEP EHV real-time data base. The exact AC solution for all the transmission branch outages were obtained and the corresponding voltage performance indices were computed and subsequently, sorted in descending order. The corresponding PIs for 1P-1Q and VSEL algorithms were also computed and listed according to the AC solution ranking, as well as their own "stand-alone" ranking as a measure of their capture rate. The results for h= .05 are compiled in Table II.

The AC solution demands approximately 22 minutes of CPU time on an IBM 3033 machine running under OS-MVS operating system. The solution to 1P-1Q requires 96 seconds on a VAX-11/780 machine running under VAX/VMS operating system. The on-line portion of VSEL requires only 5.6 seconds on the same machine with results almost identical to 1P-1Q but at considerable savings in CPU time. The base-case performance index value for this run is 53.53819. Using the performance index value corresponding to the base-case as the stopping time results in capturing seven out of the top nine contingencies with the remaining two contingencies being close runner ups.

The numerical results correspond to a 5:00 p.m. base-case and a 2:00 p.m. reference case which is an extreme case for illustration. In an actual production environment, the reference case validation test would be performed on an hourly basis and the results of the ACS would more closely track the AC load flow-based results.

CONCLUSIONS

Automatic Voltage contingency selection is an algorithmic procedure aimed at reducing the number of branch contingency cases necessary for the assessment of the steady state voltage security level of a power system. The objective of the procedure is the determination of a ranking of branch contingencies according to their expected severity. From this sorting, the branch contingencies may be studied until a stopping time is reached. Branches ranked below stopping time would not warrant further analysis. An application of the algorithm to the AEP real-time data base is presented. An extreme case is deliberately chosen to push the function to its limit.

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APPENDIX I

REACTIVE POWER MISMATCH IN MATRIX FORM

The reactive power mismatch at the load bus i in the Fast Decoupled Load Flow (FDLF) algorithm of [3] is expressed as:

$$\frac{\Delta Q_i}{V_i} = \frac{Q_i^{SP}}{V_i} - \frac{Q_i^{Cal}}{V_i} \qquad \text{(A1.1)}$$

The second term of (A1.1), in turn, equals:

$$\frac{Q_i^{Cal}}{V_i} = \sum_{j\varepsilon\gamma(i)} V_j(G_{ij}\, Sin\theta_{ij} - B_{ij}\, Cos\theta_{ij}) \qquad (A1.2)$$

Using a truncated Taylor series expansion for $Sin\Theta_{ij}$ and $Cos\Theta_{ij}$, one would obtain:

$$Sin\ \theta_{ij} \approx \theta_{ij} = \delta_i - \delta_j$$

$$Cos\ \theta_{ij} \approx 1 - \tfrac{1}{2}\theta_{ij}^2 = 1 - \tfrac{1}{2}(\delta_i - \delta_j)^2$$

$$\approx 1 - \tfrac{1}{2}(\delta_i - \delta_j)(\delta_i - \delta_j) \qquad (A1.3)$$

or,

$$Cos\ \theta_{ij} = 1 - \alpha_{ij}\ (\delta_i - \delta_j) \qquad (A1.4)$$

where,

$$\alpha_{ij} = \tfrac{1}{2}(\delta_i - \delta_j) \qquad (A1.5)$$

Substituting (A1.3) and (A1.4) into (A1.2) yields:

$$\frac{\Delta Q_i}{V_i} = \frac{Q_i^{SP}}{V_i} + \sum_{j\varepsilon\gamma(i)} V_jB_{ij} - \sum_{j\varepsilon\gamma(i)} V_j(G_{ij} + \alpha_{ij}B_{ij})(\delta_i - \delta_j) \qquad (A1.6)$$

By appropriate regrouping of terms in (A1.6), one obtains:

$$\frac{\Delta Q_i}{V_i} = \frac{Q_i^{SP}}{V_i} + \sum_{j\varepsilon\gamma(i)} V_jB_{ij} + \sum_{j\varepsilon\gamma(i)} V_j(G_{ij} + \alpha_{ij}B_{ij})\delta_j$$

$$- \{\sum_{j\varepsilon\gamma(i)} V_j(G_{ij} + \alpha_{ij}B_{ij})\}\delta_i \qquad (A1.7)$$

Transformation (A1.4) is significant, since by an intelligent choice of a topologically equivalent base-case, hereafter referred to as the "Reference Case", one can make the reactive power mismatch a linear function of the bus phase angles (and not a quadratic one) as shown in (A1.7). The reference case should precisely have the same configuration as the current base-case (i.e., the same nodal admittance matrix). It might have been given by a state estimation solution at some time T, earlier than the current time t, and would be used to compute (A1.7) in a closed form matrix notation as follows:

$$[\frac{\Delta Q}{V}] = K_0 + K_1\ \delta \qquad (A1.8)$$

Where,

K_0 = A non-sparse NLOAD-vector whose ith entry is:

$$(k_0)_i = \frac{Q_i^{SP}}{V_i^R} + \sum_{j\varepsilon\gamma(i)} V_j^R B_{ij}^R \qquad (A1.9)$$

K_1 = A sparse NLOAD X NBUS matrix such that for load bus i,

$$K_1(i,j) = V_j^R\ (G_{ij}^R + \alpha_{ij}^R B_{ij}^R) \qquad j \neq i$$

$$K_1(i,j) = -\sum_{j\varepsilon\gamma(i)} V_j^R(G_{ij}^R + \alpha_{ij}^R B_{ij}^R) \qquad j = i \qquad (A1.10)$$

Notice that with the introduction of the Reference Case, (A1.5) would become:

$$\alpha_{ij}^R = \tfrac{1}{2}(\delta_i^R - \delta_j^R) \qquad (A1.11)$$

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