EFFICIENT TRANSIENT STABILITY ASSESSMENT USING TRANSIENT ENERGY FUNCTION

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Abstract - *This paper presents an efficient transient stability assessment using the transient energy function approach. A robust algorithm for computation of controlling unstable equilibrium points is proposed. The importance of the computation of the controlling uep is further emphasised with a new methodology for improvement of stability margins based on the eigenvalue analysis of the controlling uep. A very fast screening tool is presented.*

Keywords - *Small-signal stability, transient energy function, transient stability, participation factors.*

1. INTRODUCTION

Dynamic Stability Assessment (DSA) typically requires great computational effort. As on-line DSA has to be performed with periodicity of a few minutes, every effort to speed up the evaluation process would allow more efficient and fast stability assessment. Although the processing speed available in modern computers and the use of advanced numerical solution of differential-algebraic system allow the use of time domain simulation for on-line DSA, the computational effort is still very high. Therefore, efficient screening tools are very useful in the stability assessment process. Considerable research in direct and hybrid methods has been performed during the last three decades [7,12,15,16,21] to find efficient solutions suitable for on-line Transient Stability Assessment (TSA). The hybrid methods, in particular, have shown very promising results. These methods combine step-by-step time simulation, which allows modelling flexibility, with the stability and sensitivity indexes given by Transient Energy Functions (TEF). These yield more insight in a reduced computation time. Direct methods, on the other hand, have shown great difficulty to deal with the modelling complexity required in practical stability studies. Nevertheless, they can efficiently be used for very fast contingencies screening, thus significantly reducing the overall computational effort.

This paper presents advances in TSA using a hybrid formulation. It is mainly concerned with the practical implementation issues of TEF in TSA. Therefore, the objective is focused on the robustness of the TSA and on the computation of sensitivity information, in addition to the usual stability margin. A new approach for the computation *of controlling unstable equilibrium points* (uep) is proposed to improve the robustness of two existing algorithms [2,9]. A simple and very fast contingency ranking method is described. It is also shown that the eigenanalysis of the uep is a powerful tool for assessing transient stability sensitivity indices.

Although the calculation of controlling unstable equilibrium points is not essential to assess stability margins, it can provide important sensitivity information regarding transient stability. Eigenanalysis of the uep is proposed as a means of obtaining the sensitivity information for power system operation. It is shown that the participation factor and mode shape can correctly identify the power plants that most affect a particular mode of instability. Alternative system rescheduling, to improve transient stability margins, can then be determined by appropriately changing generation at those power plants.

The main difficulty in the computation of uep has been to find an initial condition sufficiently close to the solution so that convergence is always ensured. The Exit Point method [2] uses a theoretically based approach to find this initial condition and has shown better results than other methods [5,17], although convergence failures may happen [3,4,10,11]. A new algorithm is proposed in this paper to improve the convergence problems inherent to this method. A particular post-fault unstable trajectory is used instead of the fault-on trajectory as a better approximation to the critically unstable trajectory. The exit point of this trajectory was found, in this work, to be a better initial condition to the computation of the controlling uep.

Additional computational effort is always required if the controlling uep is to be found. When computational speed is of main concern, it is preferred to have a faster though not necessarily so accurate method as a pre-screening tool and leave the computation of uep only for critical cases. The hybrid method of this paper provides an estimation of the critical clearing time prior to the computation of the controlling uep. The algorithm for estimation of critical clearing time is quite simple, fast and does not require additional computational time, as it is part of the process of computing the controlling uep.

The methods proposed in this paper are being implemented in a DSA project at Furnas Centrais Eletricas, a major power utility in Brazil.

2. ENERGY FUNCTIONS

The non-linear power system model comprises a set of differential and algebraic equations

$$\dot{x} = f(x, y) \quad (1)$$

$$0 = g(x, y) \quad (2)$$

where x and y are the vector of state variables and algebraic variables respectively.

The potential and kinetic energy are computed along system trajectories, which are the numerical solution of Equations (1,2).

The *kinetic energy* is given by

$$Vke(\varpi) = \sum_{i=1}^{n} \frac{1}{2} M_i . \varpi_i^2 \quad (3)$$

$$\varpi_i = \omega_i - \frac{1}{M_t} \sum_{j=1}^{n} M_j . \omega_j \ ,$$

$$M_t = \sum_{i=1}^{n} M_i \ ,$$

where M_i is the inertia constant of machine *i*; M_t is the total system inertia, ω_i the rotor speed of machine *i*, ϖ is the rotor speed referred to the Centre of Inertia (COI) and n is the number of machines. The kinetic energy has to be corrected to eliminate those components that are not related to system separation [6].

The *potential energy* is computed by

$$Vpe(\theta) = \sum_{i=1}^{n} \int f_i(\theta) d\theta_i \quad (4)$$

$$\theta_i = \delta_i - \frac{1}{M_t} \sum_{j=1}^{n} M_j . \delta_j$$

$$f_i(\theta) = Pm_i - Pe_i(\theta) - \frac{M_i}{M_t} Pcoi(\theta) \quad (5)$$

$$Pcoi(\theta) = \sum_{i=1}^{n} Pm_i - Pe_i(\theta) \quad (6)$$

where δ_i is the rotor angle of machine *i*, θ_i is the rotor angle of machine *i* referred to the centre of inertia - COI, Pm_i is the mechanical power of machine *i* and Pe_i is the electrical power of machine *i*. The integral (4) is approximated by the trapezoidal rule.

The potential energy, which is path dependent, can be interpreted as level surfaces on the angle subspace. The system associated with this subspace is referred to as the *reduced system* or the *gradient system* and is defined as

$$\dot{\theta} = -\frac{\partial Vpe(\theta)}{\partial \theta} = f(\theta) \quad (7)$$

The stability boundary of the gradient system is referred to as the Potential Energy Boundary Surface (PEBS). It is approximately identified in the angle subspace for every θ^* such that

$$Ft = \sum_{i=1}^{n} f_i(\theta^*) . \Delta\theta_i = 0 \quad (8)$$

where $\Delta\theta_i$ (the angular difference between two time steps) is computed along the system trajectory.

Equilibrium points for the dynamic system are solutions of the following non-linear vector function.

$$f(\theta) = 0 \quad (9)$$

The computation of system equilibrium points by the Newton Raphson method requires an initial guess within the region of attraction of the solution.

The power system transient stability is evaluated for a given disturbance. Three stages involving structural changes in the system can be defined. The system prior to the fault, which is simply an equilibrium point represented by an initial condition, and the system during the fault and post-fault. Equations (1) and (2) assume different forms during the fault-on and post-fault periods.

If (1) and (2) have a post-fault asymptotically stable equilibrium point (sep), the fundamental problem of transient stability is knowing whether the post-fault will eventually settle down on the sep.

3. TRANSIENT STABILITY ASSESSMENT

The proposed algorithm for TSA was developed from the Exit Point method [2], also referred to as the boundary of stability region controlling unstable equilibrium point method (BCU). The Exit Point method was initially tested on the IEEE 50 generators test system, which is the system proposed on [20], but difficulties to converge to controlling uep in some cases were found by the authors. While striving to solve these convergence problems, the authors developed the algorithm reported in this paper. Relevant characteristics of the Exit Point method are now described.

From the sustained fault-on trajectory, detect an exit point on the PEBS (stable manifold of the controlling uep). From the exit point, integrate the gradient equations (7) to find a point in the neighbourhood of the uep. This point is then used as the initial guess to compute the controlling uep.

The authors observed through numerous simulations [10] on the test systems that the initial guess for a solution of the equilibrium point is not always sufficiently close to ensure convergence. This is true even when a variable step algorithm with local truncation error control is used to integrate the stiff gradient equations. This possibly happens because either the fault-on trajectory does not lead to the desired manifold or the exit point is quite distant from the controlling uep and the integration of the gradient equations is unable to reach a close neighbourhood of the uep, so that convergence can be guaranteed. This problem was mainly verified on modes of instability that involved several machines. There are two basic patterns of the system energy and relative angular movements for system trajectories. Cases with a single machine mode of instability exhibit a smooth energy pattern as in Fig. 1, in which the PEBS is crossed (*Ft=0.0*), Equation (8), in a relatively short time after the critical clearing time (fast mode). The fault-on trajectory usually gives a good approximation to the controlling uep for these cases. Fig. 2 shows the pattern for multi-machine modes of instability in which the PEBS is crossed long after the critical clearing time (slow mode). In this case there are potential and kinetic energy interchanges related to inter-group angular oscillations not associated with the mode of instability. The fault-on trajectory and integration of the gradient equations, for the latter cases, either do not provide an exit point sufficiently close to the controlling uep, as required for convergence, or lead to an uep that is not the controlling one. Since it is difficult to determine analytically the reasons for such failures, the following hypothesis can be formulated:

- The fault-on trajectory may not lead to the stable manifold of the controlling uep because the transversality condition of the system is not verified [11]. This is particularly true if the system damping is small or zero. The Exit Point method was tested on the IEEE test system [20] for zero damping (original condition) and non-uniform small damping (artificially introduced). With the small damping introduced, the results were slightly improved.

- The inter-machine oscillations, which are not responsible for the system separation, may be significantly modified by the sustained fault-on trajectory. This would result in machine angular displacement at the exit point quite different from those on the controlling uep, additionally impairing the convergence process.

Whatever the reason for the convergence failures observed with the previous methods, the solution proposed is to use an alternative trajectory to detect an exit point closer to the uep than the one found by the sustained fault-on trajectory. The objective is to simulate a trajectory in which the fault is cleared some time (unstable clearing time - t_{ucl}) between the critical clearing time (t_{cr}) and the time an exit point is reached by the sustained fault-on trajectory (t_{ep}) i.e., $t_{cr}<t_{ucl}\leq t_{ep}$. Therefore, along the system trajectory, t_{ucl} is any fault clearing time greater than the time the stability boundary is crossed and smaller than the time the PEBS is crossed. The closer t_{ucl} is to t_{cr} the better as the critical cleared trajectory passes through the controlling uep. The time t_{ep} can be determined by (8), but t_{cr} is not previously known. Therefore, the critical clearing has to be estimated during the fault-on trajectory.

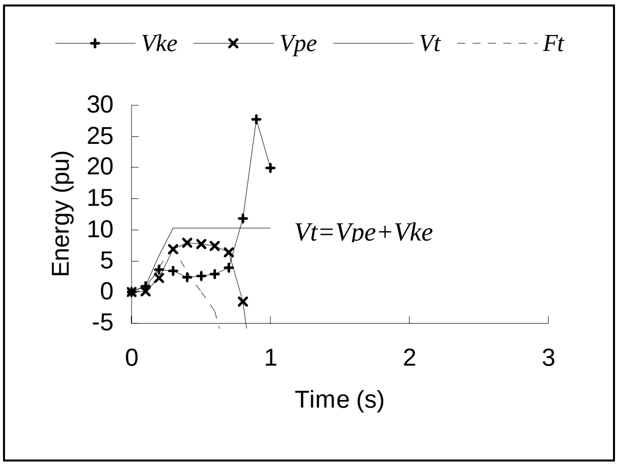


Figure 1. Energy plots for case 3 of Table I, $t_{cl} = 0.250s$.

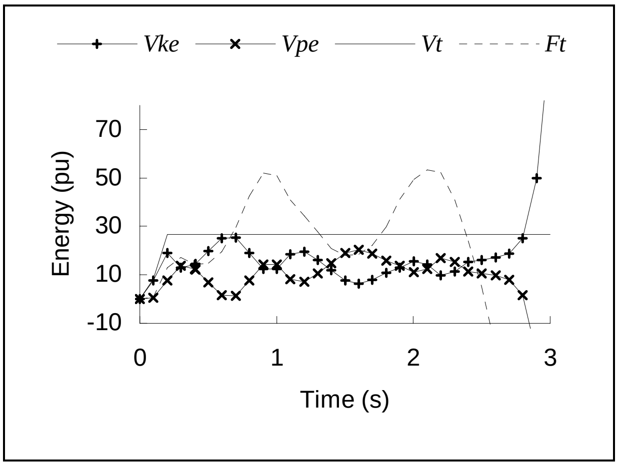


Figure 2. Energy plots for case 4 of Table I, $t_{cl} = 0.171s$.

The algorithm to estimate t_{cr} is quite simple and it is explained using an analogy with the one-machine-infinite-bus system. The angle of the peak of the power transfer curve in the one-machine-infinite-bus system ($\approx 90^{\circ}$) corresponds to approximately half of the potential energy of the uep with respect to the post-fault stable equilibrium point. When the machine angle reaches 90 degrees, the potential energy at the uep - critical energy - can be approximately predicted. This peak corresponds in the multi-machine system to the *principal singular surface* [1,18]. The intersection of the fault trajectory with the principal singular surface is identified here using the following formula, which involve some approximations.

$$\frac{d^2Vpe(t)}{dt^2} = 0 \qquad (10)$$

Once a point in the principal singular surface is found the critical energy is extrapolated as being twice the potential energy at this point. If the total system energy is greater than the critical energy, then $t_{ucl} > t_{cr}$. Otherwise, $t_{ucl} \leq t_{cr}$.

The proposed algorithm to compute the controlling uep can be summarised as follows:

i - From the fault-on trajectory, detect the principal singular surface using (8);

ii - extrapolate the critical energy as twice the potential energy at the principal singular surface;

iii - clear the fault if the total energy is greater than the critical energy, otherwise sustain the fault until this condition is satisfied and only then clear the fault;

iv - from the post-fault trajectory, detect the maximum in the potential energy;

v - use the point at the maximum potential energy as an initial condition and integrate the post-fault gradient system to find the first local minimum $\sum_{i=1}^{n} f_i^2(\theta)$.

vi - use the point of this local minimum as the initial guess to solve (9) by the Newton-Raphson method. The solution obtained is the controlling uep.

Note that if the estimated t_{ucl} is close to but smaller than the t_{cr}, the post-fault trajectory will not cross the potential energy boundary surface. However, the trajectory shall pass close to the uep at the point of maximum potential energy. This point can be used as an initial guess to compute the uep. If the estimated t_{ucl} is greater than t_{cr}, the post-fault trajectory will cross the potential energy boundary surface at a point closer to the uep than the exit point computed by the sustained fault-on trajectory.

The correction of the kinetic energy is important to minimise estimation errors. If the mode of instability is not previously known by operator’s experience, it is required to estimate some candidate modes [7,16] and choose the one that yields the smaller kinetic energy to compute the total energy in step (iii).

4. UEP COMPUTATION

An efficient sparse algorithm to compute uep has been proposed in [9]. It is similar to a load flow computation. An important feature of this method is the allocation of the Power at the Centre of Inertia - *Pcoi* outside the Jacobian matrix. In the ordinary load-flow solution, the difference between the system load and generation is allocated to the slack bus. This is not adequate in the computation of the uep solution because it implies that the slack bus generator would not have the same acceleration as the other generators in the system. A necessary condition for the uep solution is the same absolute acceleration for all machines. This implies that the excess or deficit in generation (*Pcoi*) has to be allocated among the machines in proportion to their inertia constants. It is also proposed in [9] that the slack bus shall be allocated at a load bus.

This algorithm was tested and showed good results. However, two modifications were devised by the authors to improve further its convergence characteristics:

1. It was observed that the original algorithm may generate large values of the power at the slack bus (*Pslack*) at each iteration, converging to a pseudo-solution. A new solution considering this large value of *Pslack* reallocated may not converge. A better scheme is to include *Pslack* in the convergence check and allocate it at each step.

2. The allocation of *Pcoi* and *Pslack* as shunt conductance rather than mechanical powers has proved valuable to enhance convergence, as it improves significantly the conditioning of the Jacobian matrix by increasing the values of its diagonal elements. This definitely improved convergence.

The final algorithm can be summarised as follows:

i - Use the augmented Jacobian system, including the internal generator buses;

ii - compute *Pcoi* (6) and *Pslack* and allocate them in the admittance matrix as shunt conductance, $G_i=M_i(Pcoi+Pslac)/M_tE_i^{\,2}$, where E_i is the machine voltage at the internal bus. This is only possible because the moduli of the internal voltages are considered constant for the uep computation;

iii - solve one iteration of the Newton-Raphson method for (9);

iv - check for convergence (*Pslack* is also checked for a small tolerance). Stop if converged; else go to step (ii).

5. TEST RESULTS

The proposed methods were evaluated using the same 33 cases analysed in [4]. System trajectories were computed through the implicit trapezoidal rule. Table I summarises the results for the computation of the critical clearing times. The error is computed by

$$Error = 100.\frac{tcr_{TEF} - tcr_{SBS}}{tcr_{SBS}}$$

Symbols SBS and TEF in Table I denote the step-by-step and the proposed transient energy function methods of this paper respectively.

Table I – Results of critical clearing time computation.

Case	t_{cr} (s)			Error (%)	Itera tions
No.	Fault Bus / Line Open	SBS	TEF		
1	59/59-72	0.224	0.220	1.79	4

2	73/73-74	0.215	0.200	-6.98	6
3	112/112-69	0.249	0.240	-3.61	4
4	66/66-69	0.170	0.172	1.18	20
5	115/115-116	0.292	0.290	-0.68	3
6	100/100-72	0.259	0.260	0.39	5
7	101/101-73	0.246	0.240	2,44	6
8	91/91-74	0.189	0.185	-2.12	2
9	7/7-6	0.108	0.110	1.85	8
10	7/7-6(interarea)	0.108	0.105	-2.78	2
11	6/6-1	0.168	0.168	0.00	5
12	12/13-14	0.172	0.176	2.33	5
13	6/6-10	0.176	0.175	-0.57	6
14	33/33-39	0.385	0.405	5.19	7
15	33/33-49	0.387	0.410	5.94	8
16	66/66-111	0.175	0.175	0.00	5
17	106/106-74	0.185	0.185	0.00	6
18	69/69-32	0.205	0.205	0.00	5
19	69/69-112	0.203	0.205	0.99	5
20	105/105-73	0.212	0.220	3.77	21
21	73/73-75	0.213	0.200	-6.10	6
22	67/67-65	0.234	0.240	2.56	5
23	59/59-103	0.224	0.225	0.45	6
24	12/12-14#1&,2	0.169	0.165	-2.37	20
25	105/105-73#1,#2	0.119	0.110	-7.56	9
26	66/66-8#1,#2	0.176	0.185	5.11	6
27	6/6-(1,2,7)	0.000	0.000	0.00	18
28	6/6-(9,10,12#1,#2)	0.075	0.070	-6.67	11
29	33/33-(37-40,49,50)	0.357	0.360	0.84	8
30	33/33-(37-40)	0.373	0.385	3.22	6
31	66/66-(111#1,#2,#3)	0.082	0.090	9.76	5
32	73/73-(26,72,82,101)	0.212	0.210	-0.94	6
33	73/73-(69,75,91,96)	0.212	0.205	-3.30	6

The errors found are within a reasonable margin. The algorithm has always converged to an equilibrium point, although for the cases 10, 24 and 25 it was necessary to introduce an artificial small damping to converge to the controlling uep. Except for a few cases, the algorithm required only a few iterations to converge.

6. FAST SCREENING

The objective of a fast screening method is to classify stability cases according to their severity and leave a rigorous detailed analysis only for the critical ones. The clearing time t_{ucl}, which is an upper boundary for an estimation of the t_{cr}, is already a rough estimation of case severity. However, it is possible to improve further this estimation using the PEBS method (i.e., the potential energy of the exit point is used as the critical energy) [15]. The PEBS method tends to give an underestimated t_{cr} [4]. Its error is usually within a 20% range. The proposed algorithm compares the t_{cr} determined by the PEBS with t_{ucl}. If it is less than t_{ucl} an average of these two values is taken as the estimation of the t_{cr}. If it is greater than t_{ucl}, t_{ucl} is taken as the estimated t_{cr}. Table II shows the t_{cr} estimated for the same 33 cases of Table I and Fig. 3 summarises the errors of the fast screening method with respect to the step-by-step calculations.

Table II - Fast screening results.

Case	t_{cr}	Case	t_{cr}	Case	T_{cr}
1	0.220	12	0.182	23	0.218
2	0.203	13	0.185	24	0.183
3	0.245	14	0.340	25	0.123
4	0.174	15	0.340	26	0.175
5	0.290	16	0.173	27	0.063
6	0.265	17	0.203	28	0.060
7	0.245	18	0.198	29	0.305
8	0.185	19	0.198	30	0.325
9	0.105	20	0.204	31	0.090
10	0.093	21	0.203	32	0.203
11	0.181	22	0.255	33	0.203

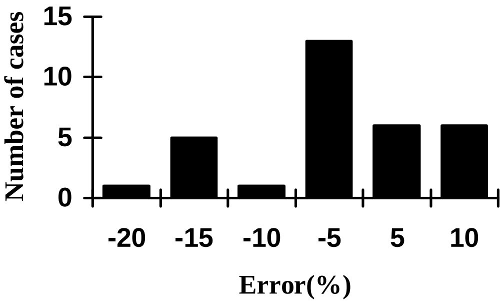
The errors in Table I are in the range $\pm$7% (except for the case 31) while the fast screening errors are in the range –20% to 10%. Assuming that a +20% range is reasonable for screening purposes, those results clearly show that the computational effort to locate the controlling uep is not necessary for fast screening purposes.

If one decides to classify only the cases with t_{cr} smaller than 0.12s, for example, the pre-screening algorithm could be set to select every case with estimated t_{cr} smaller than 0.145s (20% margin). It would then correctly classify 6 cases (cases 9, 10, 25, 27, 28 and 31). Great computational time would be saved. The case of fault on bus 6 with opening of lines 6-1, 6-2 and 6-7 (case 27) is not included in Fig. 3. The algorithm gives an estimated t_{cr} =0.063s for this case. The calculated error would be infinite. However, the case would be correctly classified.

Figure 3 – Errors incurred when used the fast screening algorithm.

7. EIGENANALYSIS ON THE UEP

The following question usually arises in transient stability assessment. Given an initial condition and a set of disturbances, how much can the generation in a power plant or in a group of power plants be increased without violation of a given stability margin? This problem is usually answered, in traditional TSA, by conducting a series of step-by-step simulations while



increasing generation at the desired power plant(s) until the prescribed stability margin is reached. In TEF methods, this effort can be significantly minimised using sensitivity analysis [7,19]. Nevertheless, another important question has not yet been properly addressed by the TEF methods. The question is as following: given an initial operating condition, how this condition can be changed to increase the stability margin for a set of critical disturbances? To answer this question, it is proposed a new approach based on the computation of the eigenvalues and participation factors [8,13,14] of the system on the uep.

Linearisation of (1) and (2) results in

$$\begin{bmatrix} \Delta \dot{x} \\ 0 \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} . \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix}, \qquad (11)$$

where J_1, J_2, J_3 and J_4 are sub-matrices of the Jacobian matrix. (11) can be reduced as

$$\Delta \dot{x} = \left(J_1 - J_2 J_4^{-1} J_3 \right) \Delta x = A \Delta x \qquad (12)$$

The *eigenvalues* of matrix A are defined as the values of λ satisfying

$$\det(A - \lambda I) = 0 \qquad (13)$$

For each eigenvalue, λ_i, there exist vectors p_i and q_i which satisfy the equations

$$\begin{aligned} A p_i &= \lambda_i p_i, \\ q_i^t A &= \lambda_i q_i^t \end{aligned}, \qquad (14)$$

where p_i and q_i are the *right* and *left eigenvectors* of A associated with λ_i.

The right eigenvector determines how each system mode is observed among the components of the state vector (mode shape). The left eigenvector is related to modal controllability. The contributions of the individual generators to the mode of instability are correctly evaluated by using *participation factors* (P_{ki}):

$$P_{ki} = p_{ki} q_{ki} ,$$

where p_{ki} and q_{ki} are the *kth* elements of p_i and q_i, respectively. The participation factors are dimensionless measures of state x_k in mode i.

The controlling uep is known to be of type one [7,15], therefore the linear equation (11) for this point has only one unstable real eigenvalue. Then an interactive procedure to compute just one eigenvalue is recommended, e.g., inverse iteration method. A reasonable initial guess for this method can be a positive real value such as 5.0.

The objective of computing participation factors on TSA is to identify the power plants that affect most a particular mode of disturbance. Then, an efficient system rescheduling can be performed by decreasing generation at machines with highest participation in the mode under consideration. This generation can be reallocated among those power plants with the lowest participation.

This method was successfully applied to the IEEE test system [20]. Four cases (10, 27, 28 and 31) of Table I are here analysed to show the effectiveness of the proposed eigenanalysis.

The following procedure was adopted to show the usefulness of the proposed method:

- Classify the power plants into two or three groups according to the magnitude of their participation factors;
- From the base case, shift 10% of the generated power from the group with largest participation factor to those generators having the smallest participation factors (third machine group) and evaluate the new t_{cr};
- From the base case reduce the same amount of power from the second machine group and evaluate the t_{cr}.
- Reschedule power only among generators belonging to the third group.
- Identify the generator group where power reduction brings a higher increase in the t_{cr}.

Tables III to VI show the effect of power rescheduling of machine groups (classified according to their participation factors) on the critical clearing time.

These tables clearly show that the best improvement in the stability margin is achieved when reducing generation at the machines with highest participation factors (first group). These results completely validate the proposed methodology.

Table III - Case 10 - original t_{cr} =0.105s (unstable λ = +2.14, at uep).

Generator Group (bus numbers)	Particip. factor (pf) range	Original Condition (MW)	Modified Condition (MW)	New t_{cr} (s)
93,104, 110,111	0.8<pf	6700	6030	0.175
105,106, 124	0.3<pf<0.8	5705	5035	0.135
All others	pf<0.3	11248*	10578*	0.105

* - Total of machines 130 and 135.

Table IV - Case 27 - original t_{cr} =0.0s
(unstable λ = +2.43, at uep).

Generator Group (bus numbers)	Particip. Factor (pf)	Original Condition (MW)	Modified Condition (MW)	New t_{cr} (s)
104,111	0.7<pf	4000	3600	0.105
93,110	0.1<pf<0.2	1400	1000	0.080
All others	pf<0.1	5705*	5305*	0.005

* - Total of machines 105, 106 and 124.

Table V - Case 28 - original t_{cr} =0.075s
(unstable λ = +2.21, at uep).

Generator Group (bus numbers)	Particip. Factor (pf)	Original Condition (MW)	Modified Condition (MW)	New t_{cr} (s)
93,104, 110,111	0.0<pf	5400	4960	0.130
105,106, 124	0.2<pf<0.4	5705	5165	0.095
All others	pf<0.1	11248*	10708*	0.075

•- Total of machines 130 and 135.

Table VI - Case 31 - original t_{cr} =0.082s
(unstable λ = +5.61, at uep).

Generator Group (bus numbers)	Particip. Factor (pf)	Original Condition (MW)	Modified Condition (MW)	New t_{cr} (s)
111	pf=1.	2000	1800	0.125
All others	pf<0.1	2000*	1800*	0.085

* - Total of machine 104.

8. CONCLUSIONS

Improvements in two existing methods are proposed in this paper. They make the computation of controlling unstable equilibrium points more reliable and TEF transient stability assessment more efficient.

It is shown that the eigenanalysis of the uep can provide important sensitivity information to system operation and planning. Other information, such as the best location for FACTS devices or transmission reinforcement to improve transient stability, can also be obtained with eigenanalysis of uep, this being object of current investigation.

Another contribution of this paper is a fast method to compute the critical clearing time to be used as a screening tool.

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