Adaptive Remedial Action Scheme based on Transient Energy Analysis

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***Abstract*-- Remedial action schemes are designed to avoid wide spread outages after a severe contingency. In practice, these schemes are primarily static. That is, the action is pre-determined for a particular situation based on extensive off-line studies. This paper presents a method for an adaptive scheme based on transient energy analysis suitable for on-line calculations. The approach assumes the system separates into two groups in the first swing after a severe contingency along a key path and that generation tripping and/or load shedding is needed to survive the swing. Based on off-line studies and simple on-line calculations of the ability of the system to absorb the excess kinetic energy, the amount and location of the generation tripping is determined. This method provides a way to implement an adaptive RAS for different faults and operating points in real-time operation. The IEEE 39-bus system is used to illustrate the proposed method.**

***Index Terms*-- Adaptive, Differential Potential Energy, Lyapunov Methods, Remedial Action Scheme, Residual Kinetic Energy, Transient Energy**

I. Introduction

TRANSIENT stability has become a greater concern with the possibility that, due to economic considerations, the system is operated close to the stability limit. Generally, there are two types of transient stability control in a power system: preventive and corrective. Preventive control reschedules generation, or takes other appropriate action, when there exists a potential instability in the power system. The problem with preventive control, of course, is that regardless of whether a contingency occurs, or is likely to occur, economic operation of the system is impacted. Under deregulation, preventive control may be a particularly expensive approach to avoid instability. Alternatively, corrective control acts to maintain system stability only after a contingency occurs. Corrective transient stability control is a difficult task given the extremely short time available for response. For severe contingencies, many utilities have implemented Remedial Action Schemes (RAS), also referred to as Special Protection Schemes. As defined in [1], a RAS is designed to detect abnormal system conditions and take predetermined corrective action to preserve system integrity and provide acceptable system performance. RAS tend to be system and situation specific and may involve extreme actions such as, generation tripping or load shedding, or less disruptive actions such as, capacitor insertion or transformer tap blocking.

Both preventive control and RAS must determine the possibility of system instability and the actions that can steer the system away from instability. In [2], the coherency index is used to measure stability and then rescheduling is calculated by a sensitivity of this index with respect to generation outputs. The Transient Energy Method (TEM) ([3-4]) can also be used for preventive control. For example, the condition of the PEBS (Potential Energy Boundary Surface) crossing is added to the constraint set in [5] where a nonlinear optimization model is used to reschedule the system. Similarly in [6], the sensitivity of energy margin is used in the constraint set of an optimization model. In [7], the SIME (Single Machine Equivalent) method is used to calculate the margin of instability and an iterative procedure is implemented between the SIME and an OPF model to reschedule the system.

Generally, the computational procedures for RAS require an iterative procedure for the given severe contingencies. The instability is determined by any of several methods but most commonly by extensive time domain simulations since computations are off-line. Still, the energy margin method [8] or the coherency index method [2] could also be employed. After screening for the severe contingencies, a database or lookup table can be established for on-line decision [9-10]. The determination of a RAS scheme can be combined with the computation of preventive control to provide comprehensive control for a pre-defined system disturbance [11].

There are two common assumptions for most of these studies of preventive control and RAS. First, they assume the control action does not change the mode of disturbance (MOD). Second, the control schemes are established based on predefined scenarios, i.e., a control action is computed and determined given an operating point and fault scenario. For those scenarios that are not predefined the closest neighborhood method can be used, but it may be inaccurate in practice. Furthermore for RAS to find a sufficient action, engineers need to repeat numerical simulations on many candidate actions. Although these computations are off-line,

This work was supported in part through the Consortium for Electric Reliability Technology Solutions (CERTS), funded by the Assistant Secretary of Energy Efficiency and Renewable Energy, Office of Distributed Energy and Electricity Reliability, Transmission Reliability Program of the U.S. Department of Energy under Interagency Agreement No. DE-AI-99EE35075 with the National Science Foundation, and in part through PSerc a National Science Foundation I/UCRC.

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frequent update for new operation conditions is still necessary and the computation burden and testing are key issues for implementation. In this paper, a new computation method of RAS is proposed based on the transient energy analysis assuming a fixed MOD. The new method reduces the needed numerical simulations and provides a quantitative relationship between transient energy, the operating point, fault scenario and the needed RAS actions. Hence, this enables an adaptive RAS assuming the required communications exist.

Note the communication and measurement infrastructure play an important role on the possible RAS and time available for reaching decisions. This work does not address the system problems instead the reader is referred to [12-13] detailed analysis.

II. Background On RAS Computations

Background on the TEM is given in the Appendix. This section discusses the application of TEM to determine a RAS criterion. Following the analysis of MOD in [3], it is known that the CUEP (Controlling Unstable Equilibrium Point) is determined by the MOD. That means for a given post-fault network topology and dispatch pattern, if different faults cause the same MOD, then the CUEP is known. So, the critical energy is independent of these faults.

A similar concept can be applied to RAS actions. Define the following:

- A RAS *analysis* case is one that requires a RAS to maintain stability after a severe contingency.
- A scenario will be called a RAS *reference* case if its dispatch pattern and topology are the same as those obtained from the analysis case *following* some RAS action.

Now suppose the RAS is generation rejection, then the amount of a RAS is the difference of generation between the analysis case and a reference case. Assuming the RAS does not change the MOD, the CUEP of each reference case is determined by the same MOD. Then for a given analysis case, the larger the critical energy a reference case has at its CUEP, the greater the possibility the corresponding RAS action can steer the system away from instability in this MOD. Thus, if the critical energy of a reference case is greater than the initial energy of the analysis case at the time the RAS is initiated, then the reference case will provide sufficient action.

One could compare the energy of an analysis case with a set of candidate RAS actions to find an adequate scheme. However, the assumption that RAS actions won't change the MOD tells us that for a given network topology and dispatch pattern, the critical energy of a reference case is fixed and independent of the analysis cases. This suggests that many computations in a repeated simulations approach to determining the RAS are not necessary.

To illustrate this further, consider Fig. 1, where the PEBS is used to approximate the stability boundary of the system. Suppose there are two reference cases and one analysis case. The two reference cases are notated by case cr and ca, respectively. If case cr is used to determine the RAS action for the analysis case, the system is still unstable. On the other hand, case ca is a sufficient. The points pcr and pca are the SEP (Stable Equilibrium Point) of the reference cases, while UEP_{cr} and UEP_{ca} are the corresponding CUEPs. The potential energy at UEP_{cr} and UEP_{ca} is V_f and V_e, respectively. The point $pras$ is a point on the trajectory of the analysis case when the RAS action is taken. At $pras$, the analysis case has kinetic energy V_0. If the RAS is determined by case cr, there will be a residual kinetic energy ΔV_1 when the trajectory arrives at the stability boundary of the pcr. Now suppose the potential energy at point $pras$ corresponds to pcr and pca are V_a and V_b, then the following equations hold:

$$V_a + V_0 = V_f + \Delta V_1 \quad (1)$$

$$V_b + V_0 = V_e \quad (2)$$

$$V_b = V_a + V_h \quad (3)$$

where V_h is the compensation for PE between the two reference cases. From (1)~(3), a new relationship among these three cases is found:

$$V_e = V_f + V_h + \Delta V_1 \quad (4)$$

After rearranging and allowing for an adequate stability margin, it can be used as a criterion for the needed RAS:

$$\Delta V_1 < V_e - V_f - V_h \quad (5)$$

By this criterion, the RAS computation is separated into two parts: 1) Using case cr as the reference of the RAS action and calculating the residual kinetic energy (RKE), which is ΔV_1 in (5); 2) Calculating the difference of potential energy (DPE) of case cr and some other reference case, e.g. case ca, which is the right hand side of (5). The final RAS action is determined by requiring:

$$RKE < DPE \quad (6)$$

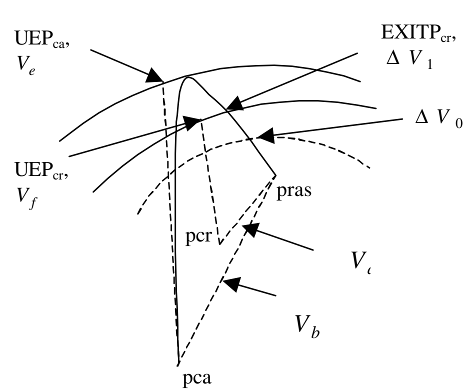

Fig. 1. Comparison of Energy

For a given system topology and operating point, if the MOD does not change for different faults or control actions, the potential energy V_f and V_e will not change. The compensation for PE V_h depends on the point $pras$, i.e., depends on the fault scenario, which causes DPE to be fault dependent. Still, in practice, V_h may be small for two reasons. First, the time to initiate a RAS action is short, say less than around 0.2 seconds after the fault. Second, the RAS reference cases cr and ca can be selected to be close to each other. Furthermore, using the approximated method of DPE given in the next section, the DPE can be used as a constant for a set of faults or operating points.

III. Computation and Implementation of RAS

A. Two-area system

Given the MOD assumption, a two-area system can be used to further simplify the RAS computation. A typical two-area system has the following characteristics:

- Given a topology and a fault scenario, there exists a transfer limit across the tie lines.
- When the operating point is greater than the transfer limit, faults on tie and key transmission lines always cause the same mode of disturbance.
- If a case is unstable after the disturbance, it may be insufficient to drop the transfer power down to the transfer limit. For most cases, more generation and load must be dropped in both areas. This means the case with the transfer limit does not provide an adequate estimate of the energy margin.
- The criterion of (6) can provide insight to the amount of generator dropping or load shedding needed.

For brevity, the procedure to find a MOD is not presented here. Some methods for MOD determination can be found in [2-3] and [7].

B. Computational Procedure of RKE and DPE

In (5), the original expression of DPE includes three variables of potential energy that all are difficult to calculate. By definition, DPE is the difference of the ability to absorb kinetic energy between two RAS reference cases. In [8] and [14], the hybrid method is used to calculate the energy for a system with a given topology and operating point, where the PEBS is used to approximate the stability boundary. In the hybrid method, the residual kinetic energy at the PEBS crossing point is used as the energy margin of an unstable case. For a stable case, the kinetic energy will return to zero before the trajectory achieves the PEBS. Then the energy margin is estimated by the potential energy between the PEBS and the point where the kinetic energy is zero. This computation is realized by adding a pseudo fault that causes the system to be unstable at the time when the kinetic energy is zero. The energy margin is the difference between the injected kinetic energy and the residual kinetic energy at the PEBS crossing point plus a compensation for the position change along the trajectory caused by the pseudo fault.

This idea is extended to the calculation of RKE and DPE in the RAS computation. Using the example of section II in which there are two reference cases cr and ca, and one analysis case. The procedure to calculate the RKE is to find the first local minimum corrected KE of an analysis case after the RAS action using the case cr as the reference. Similar to [8], a pseudo fault is added on the two selected reference cases, cr and ca. Then, the DPE can be approximated as the difference of the ability to absorb the kinetic energy injected by the pseudo fault between these two RAS reference cases. Fig. 2 gives a simple illustration of this idea.

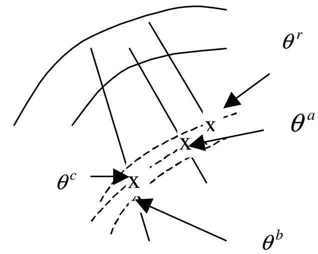

Fig. 2. Estimate the DPE

This figure is a modified version of Fig. 1 where θ^a and θ^b are points in the angle space at the clearing time of the two reference cases cr and ca, respectively. Then θ^c is the point on the trajectory of case ca that has the same potential energy as the point θ^a and θ^r is the point at the RAS time along the trajectory of the analysis case.

Given two reference cases with case cr the critical case (a case achieving the transfer limit or a case corresponding to the minimum required RAS action.) and a pseudo fault scenario (fault type, location and clearing time), the procedure to calculate the DPE for the reference cases is follows:

1. If a case is stable, then use the hybrid method to calculate the positive margin V_{EM}, and let $V_i = V_{EM} + V_{keclr}$, ($i = 1$ for case cr, $i = 2$ for case ca, V_{keclr} is the kinetic energy at the clearing point).
2. If a case is unstable, calculate $V_i = V_{keclr} - V_{ke\min}$, where $V_{ke\min}$ is the first local minimum kinetic energy, i.e., the kinetic energy at the point crossing the PEBS.
3. Calculate the compensation for PE between two cases DV_{pe} (discussed below).
4. Find the total different energy between two reference cases as: $DV = V_2 - V_1 - DV_{pe}$.

Following the above calculations, the compensation of PE then is separated into two parts, one is the difference between the two reference cases, i.e., the difference of PE between θ^a and θ^b called $PE(\theta^a, \theta^b)$, the other is the difference between $PE(\theta^r, \theta^a)$ and $PE(\theta^r, \theta^b)$.

The trapezoidal method can be used to approximate the potential energy between two points if they are close to each other by:

$$V_{pe} = -\frac{1}{2}\sum_{i=1}^{n}\{[P_{acci}(t_1) + P_{acci}(t_2)] \times [\theta_i(t_2) - \theta_i(t_1)]\} \qquad (7)$$

To compute the compensation of PE, two further approximations are used: one, using the acceleration power at θ^b, i.e. $P_{acc}(\theta^b)$, to approximate the acceleration power at θ^c, and two, using θ^a to approximate θ^c. Then from (7), the $PE(\theta^a, \theta^b)$ will be:

$$PE(\theta^a, \theta^b) = -\frac{1}{2}\sum_{i=1}^{n}\{[P_{acci}(\theta^b) + P_{acci}(\theta^b)] \times [\theta_i^a - \theta_i^b]\} \qquad (8)$$

As for the second part of the compensation of PE, it can be ignored if the point θ^r is not far apart from or lower than the clearing point of the pseudo fault of the reference case cr. This assumption will hold if the clearing time for the pseudo fault is chosen carefully. Hence, the procedure to calculate the compensation for potential energy DV_{pe} is:

1. Record the angle vector (in the COA frame) in the calculation of DPE for the two reference cases cr and ca at the clearing time.
2. Calculate the acceleration power of case ca at the clearing time (A.7). Note that the value of the post-fault system is used.
3. Calculate the $PE(\theta^a, \theta^b)$ from (8).
4. Use the absolute value of $PE(\theta^a, \theta^b)$ to approximate DV_{pe}, which ensures a conservative estimate.

C. *Computation Procedure of Adaptive RAS*

Using the two-area system model and the computation method in the previous subsection, an adaptive RAS can be implemented for faults along key transmission paths. The computation can be separated into two parts: off-line and on-line computation. The procedures are as follows.

Off-line computation:

1. Select a critical reference case, which may be the case with the transfer limit or one corresponding to the minimum RAS action.
2. Set the pseudo fault close to the end of the transmission line near the supply area. The clearing time is chosen to be slightly longer than the normal clearing time in a practical system to ensure some margin.
3. Apply the method of section III to find the DPE.
4. Use linear regression method (or other data fitting method) to find a relationship between the DPE and the RAS actions. If a reference case is far from the critical case, the result may be very conservative but one can select one or more intermediate cases. The DPE can then be calculated in parts.
5. Given an analysis case (with a given operating point and fault location), calculate the RKE with respect to the critical case.
6. Repeat step 5 for different RAS analysis cases and apply a regression method to find a relationship between the RKE and fault location as well as operating point.

On-line computation:

1. Monitor the operating point and estimate the fault location.
2. From the relationship obtained in step 6 above find a value of RKE and compare with the corresponding DPE obtained in step 4 above.
3. Determined a qualifying reference case using the criterion (6): $RKE < DPE$.
4. A sufficient RAS action can then be determined by the difference between the RAS analysis case and the qualifying RAS reference case.

Finally, the communication and measurement infrastructure have a significant influence on the possible RAS and time available for computations. Time delay needs to be considered in the off-line and on-line calculations. If detailed information for estimating a fault location is not available, the most conservative estimate has to be used for on-line decision.

IV. EXAMPLE

A. *Study system: Modified IEEE 39-bus system*

The IEEE 39-bus system, illustrated in Fig. 3, is modified to be a two-area system such that the outlined area is the primary supply area and exports power to the rest of the system. The tie lines between the areas are lines 16-17 and 16-15. Faults on these lines will create a severe disturbance in this system and require remedial action. (Note, a power system should survive all *N-1* contingencies with the RAS only triggered for severe contingencies that may be *N-2* or greater, here a single three-phase fault on these transmission lines leads to instability.) Only first swing instability is considered in the examples.

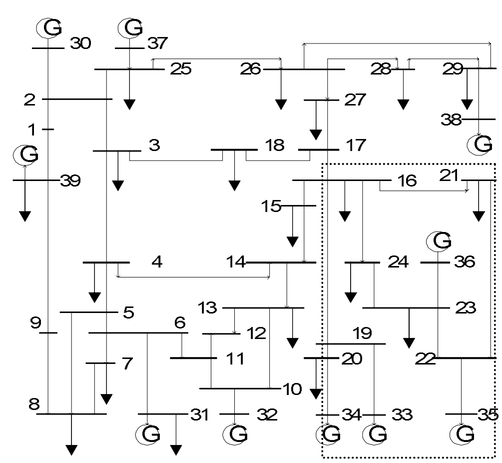

Fig. 3. IEEE 39-bus system

The two examples in this subsection illustrate the adaptive RAS for different fault locations and operating points. The first example shows the actions for different operating points. The RAS will trip generation at a plant that is in the supply area and this plant will pick up all changes in the transfer power. The second example is similar but corresponds to different fault locations along the tie line. Specifically, assume the RAS implements generator rejection at bus 35 that is balanced by load shedding at bus 18. For simplicity in this small system, it is assumed that either generation dropping or load shedding can be done in blocks of 20 MW. In a larger practical system, the amount would be determined by unit sizes and interruptible load. The maximum amount of a RAS action is the minimum of the generation at bus 35 and the load at bus 18.

Example 1 – adaptive RAS for operating points

Suppose in the demand area, the load at bus 18 is varied to create different operating points. The line fault is a three phase fault to ground on the transmission line from bus 16 to 17 located very close to bus 16. The fault is cleared in 0.1s and the RAS actions occur at 0.2s after the fault (0.1s after the fault clears). The generation pattern of the supply area is listed in Table I. The generation at bus 35, G_{35}, varies to balance the load at bus 18. When G_{35} is 460 MW, the transfer power achieves its transient limit for the given fault scenario.

The case at the transfer limit is referred to as the critical case. All cases with higher transfer power than the critical case will require RAS actions since they are unstable for the given fault scenario. The RKE of the RAS analysis cases with respect to the critical case are listed in the Table II. The DPE is calculated using a pseudo fault with 0.18s clearing time. DPE are calculated for seven reference cases and a 2nd order regression model is used to estimate the DPE for the other cases. The regression curves of the DPE and RKE are plotted in the Fig. 4 and Fig. 5. For a new case, the RAS action can be determined by comparing the DPE and RKE. For example, given an operating point with G_{35} = 600MW, the RKE is 0.8, the RAS reference case whose DPE is greater than 0.8, is the case with G_{35} = 330MW. Then the RAS action is to shed load and drop generation equal to the difference or 270 MW. Complete results are given in the Table IV

TABLE I GENERATION OF THE SUPPLY AREA

Bus	G_{33}	G_{34}	G_{35}	G_{36}
MW	502	508	Varying	500

TABLE II RKE OF RAS ANALYSIS CASES

G_{35}	740	720	700	680	660	640	620
RKE	1.567	1.452	1.354	1.246	1.135	1.033	0.921
G_{35}	600	580	560	540	520	500	480
RKE	0.803	0.685	0.571	0.447	0.322	0.185	0.029

TABLE III DPE OF RAS REFERENCE CASES

G_{35}	440	420	400	380	360	340	320
DPE	0.112	0.219	0.341	0.478	0.613	0.739	0.870

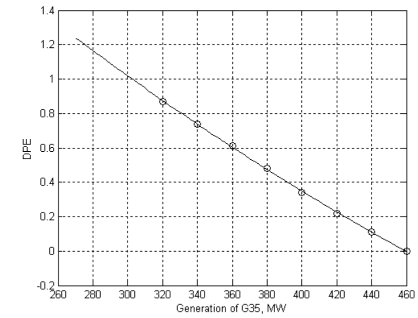

Fig. 4. DPE of RAS reference cases

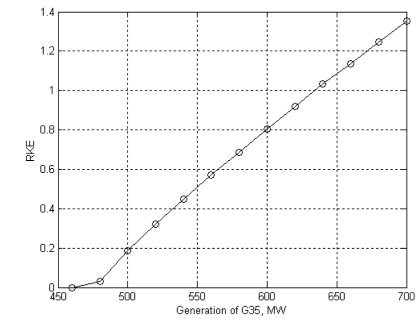

Fig. 5. RKE of RAS analysis cases

TABLE IV RAS DETERMINATION

G_{35} (MW)	L_{18} (MW)	RAS from proposed method		RAS from numerical simulation
		Fig. 4 & 5	Rounded to 20 MW block	
700	430	>430	>430	420
680	410	>410	>410	380
660	390	377	380	340
640	370	343	360	305
620	350	307	320	270
600	330	270	280	235
580	310	233	240	217
560	290	195	200	185
540	270	156	160	130
520	250	116	120	95
500	230	73	80	60
480	210	26	40	30[a]

Example 2 – adaptive RAS for fault locations

In this test, the RAS actions for different fault locations along the transmission line from bus 16 to 17 are determined by the proposed method. Again, the faults are three phase to ground faults. The clearing time (neglecting that clearing times will change with the fault in order to simplify the comparison) and RAS action times remain the same. The generation output in the supply area of the analysis case is listed in Table V.

The analysis case itself is selected as the critical case. The RKE for different fault locations are given in Table VI The DPE is calculated similarly to example 1, but the clearing time for the pseudo fault is 0.13s. DPE are calculated only for the 11 RAS reference cases (in Table VII) and a 2nd order

[a] If RAS < 30MW, the system has negative damping.

regression model is used to estimate the DPE of other RAS reference cases. Then for different fault locations, the RAS action can be determined by comparing the DPE and RKE. These results are given in the Table VIII.

TABLE V GENERATION OF THE SUPPLY AREA

Bus	G_{33}	G_{34}	G_{35}	G_{36}
MW	650	500	600	400

TABLE VI RKE FOR FAULT LOCATIONS

% to bus 16	1	10	20	30	40	50
RKE	2.091	1.586	1.208	0.963	0.765	0.615
% to bus 16	60	70	80	90	99	
RKE	0.477	0.347	0.218	0.086	0.005	

TABLE VII DPE OF RAS REFERENCE CASES

G_{35}	580	560	540	520	500	480
DPE	0.057	0.135	0.199	0.274	0.373	0.463
G_{35}	460	440	420	400	380	
DPE	0.591	0.740	0.847	1.02	1.17	

TABLE VIII RAS DETERMINATION

Fault location (% to bus 16)	RAS from proposed method (Rounded to 20 MW block)	RAS from simulation (MW)
1	320	320
10	280	225
20	240	175
30	200	145
40	180	125
50	160	115
60	120	100
70	100	90
80	80	80[b]
90	40	70[b]
99	20	65[b]

TABLE IX EFFECT OF DPE CALCULATION

Fault location (% to bus 16)	RAS by pseudo fault with 0.13s clearing time	RAS by pseudo fault with 0.15s clearing time
1	320	380
10	280	340
20	240	280
30	200	260
40	180	220
50	160	200
60	120	160
70	100	140
80	80	100
90	40	60
99	20	20

B. Discussion

From the above two examples, it can be seen that the proposed method provides a good estimate, and always conservative, if the system is first swing unstable. The errors are considered acceptable since these actions will only take place for extreme events, and in any case, would be less disruptive than the fixed schemes currently in use. For those operating points or faults that are not predefined, we can also find a RAS action by using the regression curves of RKE and DPE. Still, there are some cases that lose stability due to negative damping when using the proposed method to determine the RAS. For these cases, small signal analysis is necessary.

In Example 2, the result obtained from regression for the fault location very close to bus 16 is almost the same as the result of the time domain simulation. If the DPE is calculated in detail for each case, we can obtain the RAS for this fault is 360MW that is conservative. Using the proposed method of DPE calculation in section III, the selection of the clearing time of the pseudo fault has a significant effect on the result. Generally, a rough range for this clearing time is between the normal clearing time and the RAS time. Simulation results show DPE will be more conservative as the clearing time is larger, hence the result of RAS will be very conservative if a large clearing time is used. Several trials might be needed to select an appropriate clearing time. Table IX shows the effects of the clearing time on the results of Example 2.

Finally, communication delays can be included in the computation procedure of RKE. In Fig. 5, the curve will move up if the RAS time is delayed by communication or any other reason. Typically, a delayed RAS action requires a greater amount of generation rejection.

V. CONCLUSION

This paper presents a new method for an adaptive RAS. This method calculates the DPE, the ability of each RAS action to increase the stability of the system, based on the transient energy analysis. A RAS action can be determined directly by comparing the DPE and RKE, the energy margin of an unstable case, instead of by repeated numerical simulations. This enables us to establish an adaptive RAS using fast on-line computations. A computation procedure for an adaptive RAS is proposed in Section III. A simple two-area system is used to test the method and illustrate the performance for different fault locations and operating points. Communication delay also can be included in the computation procedure.

The concept of hybrid transient stability analysis is used in the proposed computations to calculate all transient energy. It uses time domain simulation to calculate the kinetic energy and then uses the change of the kinetic energy to estimate the potential energy, so the method is flexible with respect to system modeling. There are still some issues, as indicated in the text, that will impact the result. If the clearing time of the pseudo fault in energy computation is too large, the result may be overly conservative. On the other hand, a simple regression method for DPE may be insufficient to guarantee a conservative result. More detailed consideration about these issues is underway, including applications on a larger more practical system.

VI. APPENDIX: SYSTEM MODEL AND TRANSIENT ENERGY METHOD

RAS computation in this paper is based on the TEM of which details can be found in [3]. This appendix gives a brief

[b] The system has negative damping if the RAS is less than the given value.

description of TEM and some concepts used in RAS computation. The power system can be modeled by the differential algebraic equations

$$\dot{x} = f(x, y) \qquad 0 = g(x, y) \tag{A.1}$$

Among the differential equations, the equations for rotor angle and speed in the COA frame are:

$$M_i \frac{d\omega_i}{dt} = P_i - P_{ei} - \frac{M_i}{M_T} P_{COA} \tag{A.2}$$

$$\frac{d\theta_i}{dt} = \omega_i , i = 1, \cdots, N \tag{A.3}$$

where M_i is the inertia constant for generator i and $M_T = \sum_{i=1}^{N} M_i$. $\theta_i = \delta_i - \delta_0$ is the rotor angle in the COA frame with $\delta_0 = \frac{1}{M_T} \sum_{i=1}^{n} M_i \delta_i$, while δ_i is the angle in the synchronous frame. The definitions for rotor speed ω_i in the COA frame are similar. The acceleration power is $P_{COA} = \sum_{i=1}^{N} (P_{mi} - P_{ei})$. Note, the angle and speed in COA frame have the property $\sum_{i=1}^{N} M_i \theta_i = \sum_{i=1}^{N} M_i \omega_i = 0$.

The transient energy defined for the post-fault system is:

$$V = V_{KE} + V_{PE} \tag{A.4}$$

where

$$V_{KE} = \frac{1}{2} \sum_{i=1}^{N} M_i \omega_i^2 \tag{A.5}$$

$$V_{PE} = -\sum_{i=1}^{N} \int_{\theta_i^s}^{\theta_i} P_{acc\,i}(\theta) d\theta \tag{A.6}$$

$$P_{acci}(\theta) = P_{mi} - P_{ei} - \frac{M_i}{M_T} P_{COA} \tag{A.7}$$

Suppose a system always separates into two groups after a disturbance, the corrected KE that contributes to the system separation is:

$$V_{KEcorr} = \frac{1}{2} M_{eq} \omega_{eq}^2 \tag{A.8}$$

where $M_{eq} = \frac{M_{cr} M_{sys}}{M_{cr} + M_{sys}}$, $\omega_{eq} = (\omega_{cr} - \omega_{sys})$, $M_{cr} = \sum_{i=1}^{N_c} M_i$, $M_{sys} = \sum_{i=1}^{N_{sys}} M_i$, $\omega_{cr} = \frac{\sum_{i=1}^{N_c} M_i \omega_i}{M_{cr}}$, $\omega_{sys} = \frac{\sum_{i=1}^{Nsys} M_i \omega_i}{M_{sys}}$, N_c is the number of advanced machines (or critical machines), and N_{sys} is the number of remaining machines. The so-called advanced machine is the one that tends to lose synchronism. Therefore, the corrected kinetic energy is the kinetic energy of the advanced machines relative to the remaining system.

Stability is assessed by checking the sign of the energy margin:

$$\Delta V = V_{cr} - V_{cl} \tag{A.9}$$

where V_{cr} is the critical energy at CUEP and V_{cl} is the energy at the clearing point. The criterion of energy method is:

- If $\Delta V > 0$ then system is stable.
- If $\Delta V < 0$ then system is unstable.

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VIII. Biographies

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