Smart RAS (Remedial Action Scheme)

Shimo Wang, *Senior Member, IEEE* George Rodriguez, *Member, IEEE*

***Abstract*— Remedial Action Schemes (RAS) have been increasingly used by utilities to mitigate instability problems following the loss of one or more transmission lines on a transmission corridor to prevent the power system from out-of-step conditions that may result in cascading system-wide outages. To resolve existing RAS limitations caused by growth of intermittent renewable generation and load mutability, a Smart RAS is proposed. Different from most of the existing logic variable triggered RAS, the Smart RAS takes synchrophasor-measured real power of tie lines between two grid areas and is triggered using an AIEM (Adaptive Impact Energy Method) application. Due to the special features of this no-parameter model and no-setting criteria, AIEM will respond faster and will adapt to a variety of situations in real time. The simulations demonstrate the validity of the model and criteria, as well as the efficiency of prediction and mitigation of instability. A current SCE C-RAS (Centralized RAS) project will provide the real time platform for a Smart RAS.**

***Index Terms*-- Power system stability, Power system transient stability, Power system protection, Power system control, Synchrophasor measurements, Synchronized phasor measurements, Smart RAS, Intermittent Renewable Generation, Smart Grid , C-RAS**

I. INTRODUCTION

Today's utilities are becoming increasingly reliant on the extensive use of Remedial Action Scheme (RAS) to make interconnected grids more stable. A RAS, also known as a System Protection Scheme (SPS), utilizes a set of fast and automatic control actions, protection relays and a telecommunications network to ensure the most reliable and safest power system performance following critical outages on a transmission network.

RAS are used to mitigate instability problems following the loss of one or more transmission lines on a transmission corridor. Their use helps protect the power grid system from out-of-step conditions that may result in cascading system-wide outages and the major degradation of power system security.

The primary functions of RAS are to monitor load flows on critical transmission lines, detect outage events, take pre-planned mitigation actions such as generation tripping and load shedding, and to signal system operators. Most of the existing RAS today are armed by transmission line load flow thresholds and triggered by transmission line status. RAS are pre-set according to a large number of off-line scenario simulations. To cover all possible operational conditions, RAS load flow threshold and trigger logic schemes are set quite conservatively.

California's Renewable Portfolio Standard (RPS) mandating that 33 percent of consumed electric energy comes from renewable sources by 2020 will greatly impact the state's electric grids. With the addition of greater amounts of intermittent renewable generation and the potential increased use of plug-in electric vehicles, a grid's power flow is expected to undergo frequent changes in direction and magnitude. The existing RAS logic may not handle these types of volatile grid conditions in an efficient manner. This paper proposes developing a synchrophasor-measured continuous variable triggered Smart RAS.

II. SMART RAS CONFIGURATION

Simply put, a modern power system is made up of power sources, demands (loads) and grids. The energy supply comes from a variety of conventional sources – thermal, hydropower and nuclear plants, which generate power on a scheduled basis. Renewable resources such as wind, solar photovoltaic (PV) and solar thermal are inherently intermittent and un-schedulable due to variables such as time of day and weather conditions. While conventional loads are typically in a fixed location, loads from plug-in hybrid electric vehicles (PHEV) and electric mass transportation are mobile, creating additional challenges.

Electric grids are systems of interconnected transmission and distribution lines that deliver electric power from different power sources to loads. Power systems are divided into areas based on geography and grid ownership. Generation and loads are balanced in each area at first, and then any unbalanced power is exchanged among areas through tie lines. This type of inter-area power system is illustrated in Figure 1.

Shimo Wang is with Southern California Edison, Rosemead, CA 91770 USA (e-mail: shimo.wang@sce.com).

George Rodriguez is with Southern California Edison, Rosemead, CA 91770 USA (e-mail: george.rodriguez@sce.com)

The Adaptive Impact Energy Method (AIEM) presented in this paper is pending US patent.

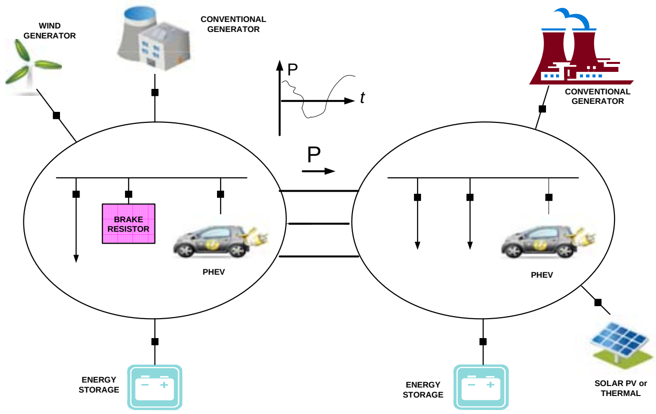

Figure 1. Inter-Area Power System

The proposed Smart RAS utilizes real power (P) measurements of tie lines between two areas collected by phasor measurement units (PMU). The resulting input is then transmitted via high-speed fiber optic lines to the Smart RAS controller as shown in Figure 2. A pending United States patent, Adaptive Impact Energy Method [1], is used in the Smart RAS controller to determine whether or not to trigger remedial actions to prevent the power system from going out-of-step. This new method is addressed in Section III of this paper and the authors expect to provide further details on adopting these various remedial actions in a subsequent paper.

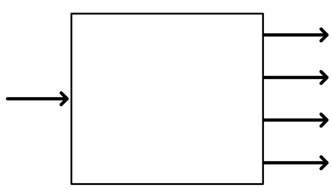

Figure 2. Inputs and Outputs of Smart RAS

III. ADAPTIVE IMPACT ENERGY METHOD

A power system can be considered as two portions in Figure 3, the concerned area A1 and the remaining area A2.

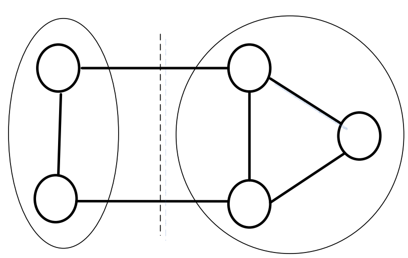

Figure 3. Two Portions of a Power System

Each area can be represented as an equivalent generator in Figure 4.

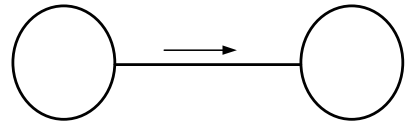

Figure 4. Two Machine Inter-Area Model

The active power from G1 to G2 is a function of time:

$$P(t) = P(\delta(t)) = \frac{E_1 E_2}{X}\sin\delta(t) \quad (1)$$

where $\delta(t) = \delta_1(t) - \delta_2(t)$ (2)

$\delta_1(t)$ and $\delta_2(t)$ are subject to:

$$\frac{d\delta_1}{dt} = \omega_1 - \omega_0 \quad (3)$$

$$\frac{d\delta_2}{dt} = \omega_2 - \omega_0 \quad (4)$$

$$M_1\frac{d\omega_1}{dt} = P_{M1} - P(t) = \Delta P_1(t) \quad (5)$$

$$M_2\frac{d\omega_2}{dt} = P(t) - P_{M2} = \Delta P_2(t) \quad (6)$$

where $M_1$and M_2 are the inertial coefficients of G1 and G2; P_{M1} and P_{M2} are the mechanical powers of G1 and G2; and $\Delta P_2(t)$ are the impact (disturbance) powers G1 and G2 received. Since P_{M1} and P_{M2} can be considered as identical and unchanged during the study period of the first-half-swing, assume:

$$P_{M1} = P_{M2} = P(t_0) \quad (7)$$

Subtracting Equations (4) and (6) from Equations (3) and (5) yields:

$$\frac{d\delta_1}{dt} - \frac{d\delta_2}{dt} = \omega_1 - \omega_2 = \Delta\omega \quad (8)$$

$$\frac{(M_1\frac{d\omega_1}{dt} - M_2\frac{d\omega_2}{dt})}{2} = P(t_0) - P(t) = \Delta P(t) \quad (9)$$

Impact energy is defined as:

$$IE = \int_{t_0}^{t_1} \Delta P(t)dt \quad (10)$$

where:

T_0 is the time when the impact starts, and T_1 is the time when ΔP (t) changes sign.

IE is the impact energy the power system receives in the first-half-swing as shown in Figure 5. Reverse energy (RE) is defined as:

$$RE = \int_{t_1}^{t_2} \Delta P(t)dt \quad (11)$$

where:

t_2 is the time when $\Delta P(t)$ changes sign again.

RE is the reverse energy the power system releases in the second-half-swing to suppress the swing shown in Figure 5.

$$\Delta E = |IE| - |RE| \tag{12}$$

is defined as the surplus impact energy of the first swing. If

$$\Delta E > 0 \tag{13}$$

it will drive the sequential swings to divergence. If

$$\Delta E < 0 \tag{14}$$

it will suppress the sequential swings to convergence.

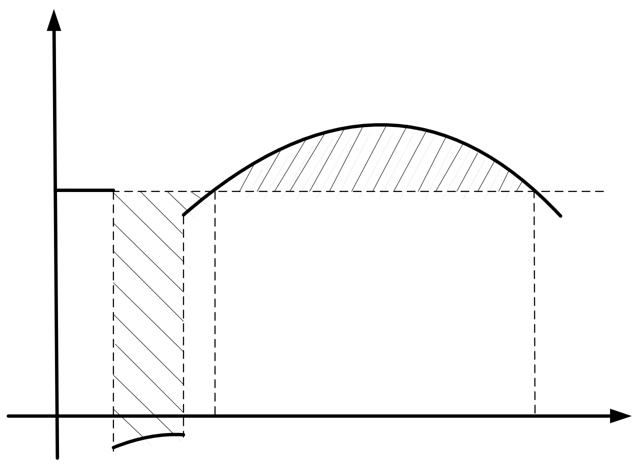

Figure 5. Impact Energy and Reverse Energy

X, E_1 and E_2 in Equation (1) vary in pre-fault, fault and post-fault due to the changes in system operation mode, fault type and location, and grid configuration. Regardless, all information for the model parameters, state variables and their variations have been included in $P(t)$. X, E_1 and E_2 are not needed for the inter-area model above. The active power $P(t)$ on an interface between areas A1 and A2 is real-time measurable using synchrophasor measurement technology.

IV. EXAMPLES

Computer simulations of the WECC power system were done using GE PSLF16 to test the model and the instability prediction criterion above. Figure 6 is a one-line diagram of the Big Creek area. The interface between Big Creek project and the remaining system is Rector-Springville 230 kV buses. The sum of active powers from the north is P(t).

P(t)

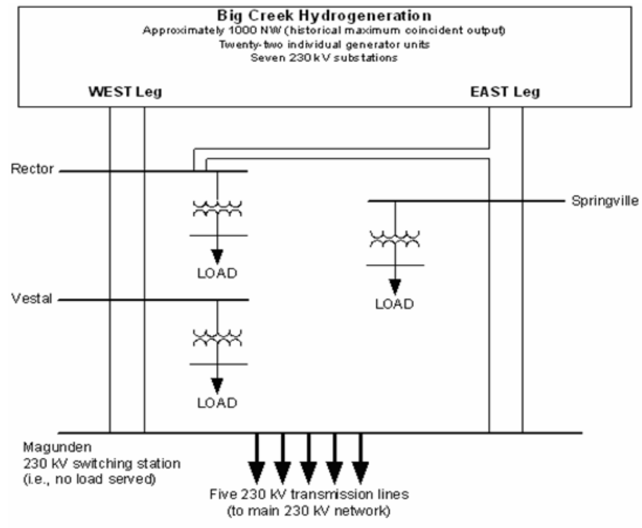

Figure 6. Big Creek Area One-Line Diagram

A. Example 1

The active power flow direction at the Magunden 230 kV bus is from north to south. The fault is a three-phase short circuit on Big Creek 3 to Rector 230 kV transmission line near Big Creek 3 end. The fault lasts 6 cycles from 0.1 second to 0.2 second then is cleared by tripping the line. The simulation plots and results are shown in Figures 7 and 8 and Table 1.

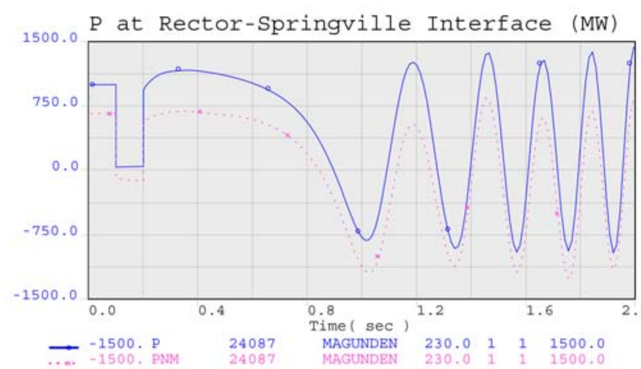

Figure 7. P(t) without Remedy

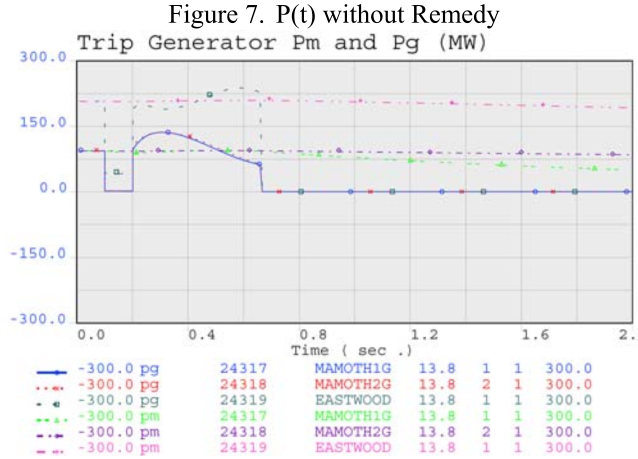

Figure 8. Generators Tripped

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$P(t_0)$

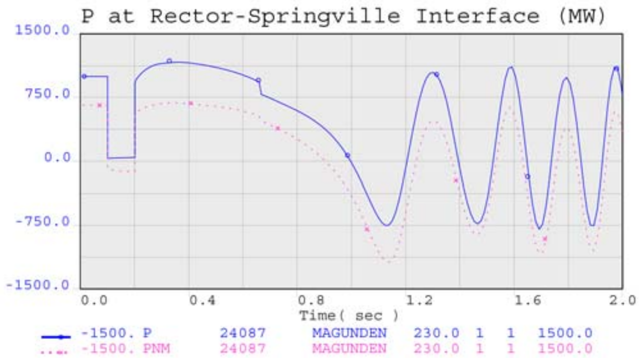

Figure 9. P(t) with Remedy

B. *Example 2*

The active power flow direction at Magunden 230 kV bus is from south to north. The fault is a three-phase short circuit on Rector to Vestal 230 kV common tower transmission lines near Rector end. The fault lasts 6 cycles from 0.1 second to 0.2 second then is cleared by tripping the lines. Simulation plots and results are shown in Figures 10 through 12 and Table 1.

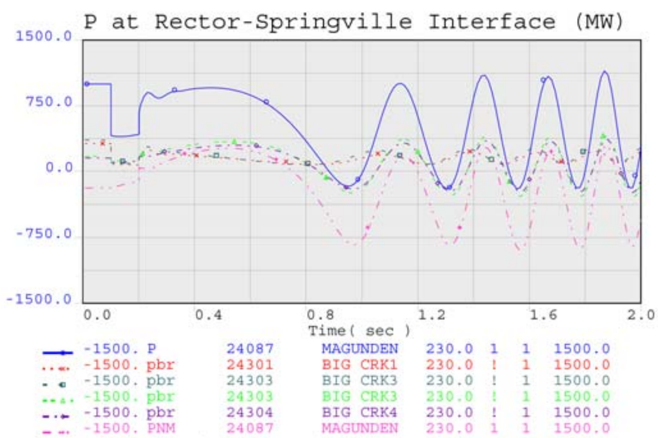

Figure 10. P(t) without Remedy

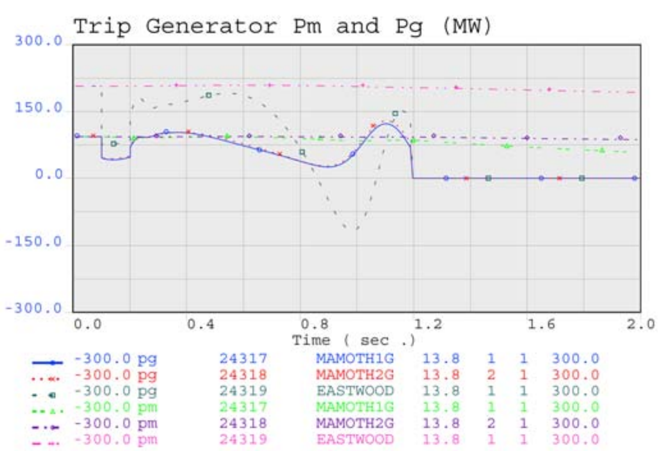

Figure 11. Generators Tripped

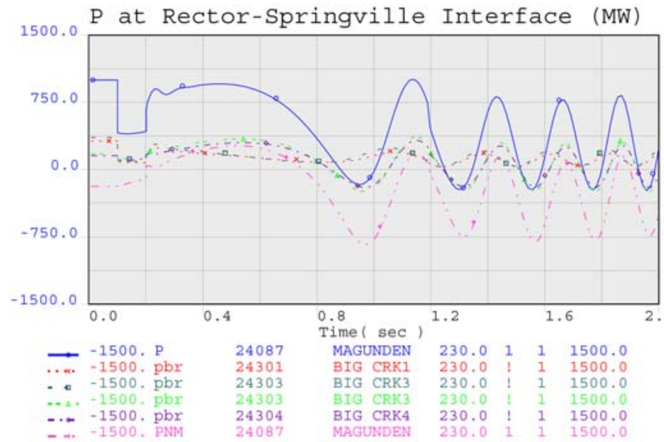

Figure 12. P(t) with Remedy

Table I. Simulation Results of Examples 1 and 2

Ex.	Stability without remedy	|IE| (mw·sec)	|RE| (mw·sec)	Prediction	Remedy	Result
1	unstable	96.86	45.49	unstable	trip generators at 0.67 sec.	unstable
2	unstable	421.11	0.11	unstable	trip generators at 1.19 sec	unstable

The instability predictions for Examples 1 and 2 are correct and the remedies of tripping generators are performed within three cycles after predictions. However, these remedies do not sufficiently return the system to a more stable state. Prediction time is key to restoring stability; therefore, the algorithm must be improved to speed up the instability prediction.

V. ALGORITHM IMPROVEMENT

To handle the circumstance of $\Delta P(t)$ not changing sign in the first swing as shown in Figure 13, Equation (10) is modified to:

$$IE = IE' = \int_{t_0}^{t'_1} \Delta P(t)dt \qquad (15)$$

where:

t_0 is the time when the impact starts,

t'_1 is the time when $\frac{d\Delta P(t)}{dt}$ changes sign before $\Delta P(t)$ changes sign.

Hence:

$$RE = 0 \qquad (16)$$

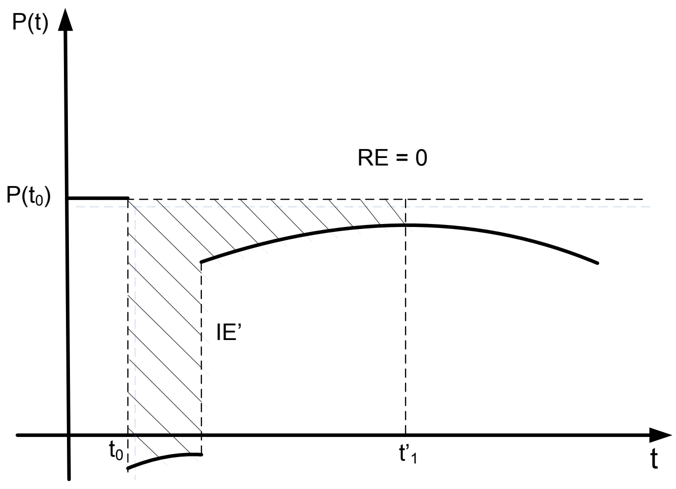

Figure 13. Early Determined RE = 0

To handle the circumstance of RE integration time too long as shown in Figure 13, Equation (11) is modified to:

$$RE = 2RE' = 2\int_{t_1}^{t'_2} \Delta P(t)dt \qquad (17)$$

where:

t_2 is the time when $\frac{d\Delta P(t)}{dt}$ changes sign after $\Delta P(t)$ first changes sign.

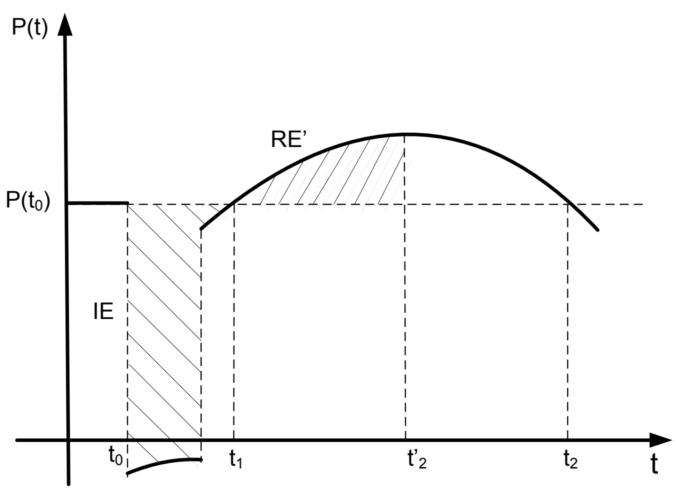

Figure 14. Early Determined RE

The improved algorithm is applied to the previous Examples 1 and 2. The simulation plots and results are shown for each example in Figures 15 to 18 and Table 2.

A. Example $\overline{1}$

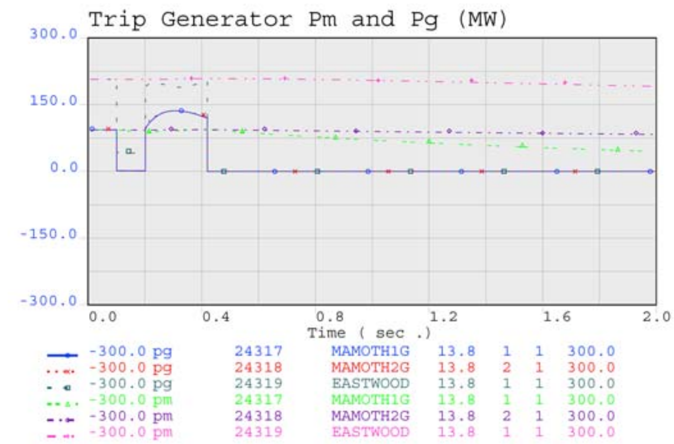

Figure 15. Generators Tripped

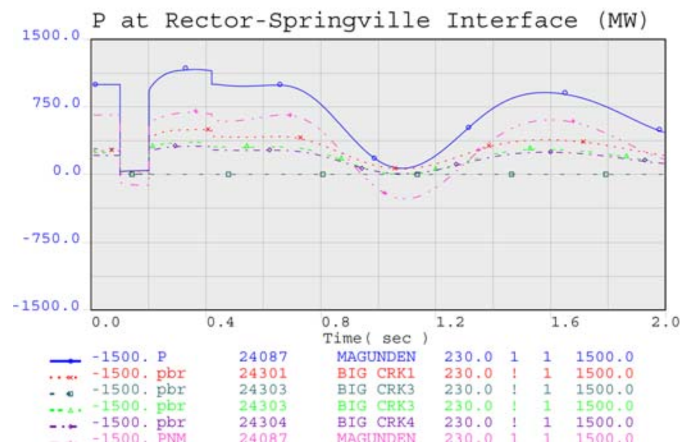

Figure 16. P(t) with Remedy

B. Example $\overline{2}$

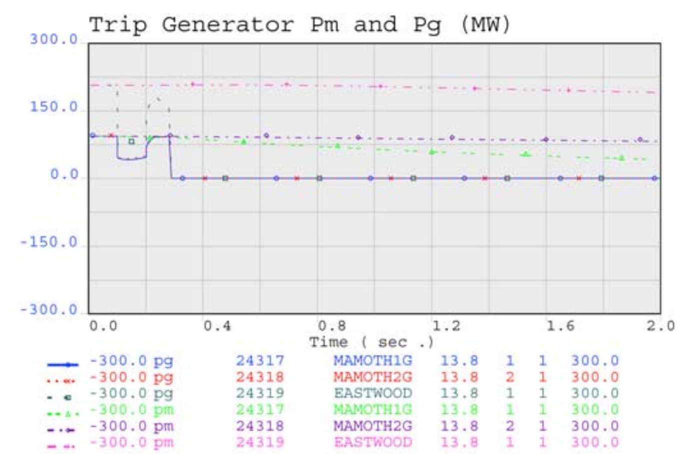

Figure 17. Generators Tripped

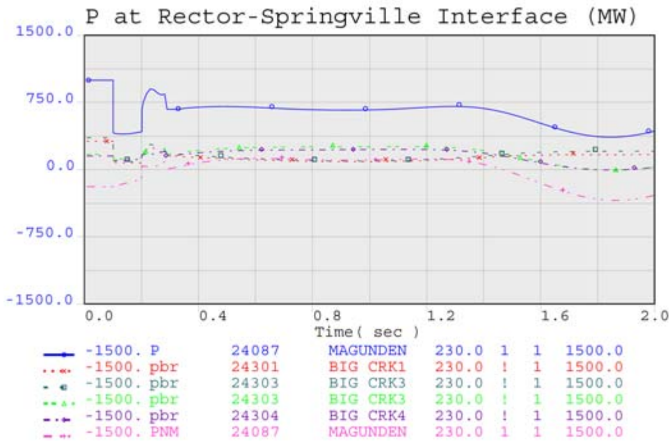

Figure 18. P(t) with Remedy

Table II. Simulation Results of Examples $\bar{1}$ and $\bar{2}$

Ex.	Stability without remedy	$\lvert IE \rvert$ (mw·sec)	$\lvert RE \rvert$ (mw·sec)	Prediction	Remedy	Result
$\bar{1}$	unstable	96.86	38.97	unstable	trip generators at 0.42 sec.	stable
$\bar{2}$	unstable	64.79	0	unstable	trip generators at 0.29 sec	stable

VI. CONCLUSIONS

To resolve existing RAS issues caused by growth of intermittent renewable generation and load mutability, a Smart RAS is proposed. Smart RAS inputs synchrophasor measured real power of tie lines between two areas. The innovative Adaptive Impact Energy Method (AIEM) is used in the Smart RAS controller to determine whether or not to trigger remedial actions. AIEM consists of inter-area models without parameters and adaptive instability prediction criteria without settings. These special features make AIEM response fast and adaptable in a variety of real-time grid situations. Simulation examples show the accuracy of the model and the criteria of AIEM. Also, the efficiency of AIEM to predict instability and mitigate the unstable circumstances back into stability is demonstrated in simulations. Further synchrophasor measurement data verifications and various remedial action studies will be performed. SCE is actively pursuing a C-RAS (Centralized RAS) project [2], which will build high speed fiber optic and microwave telecommunication networks and utilize advanced IT technology to process RAS real-time data at protection level speed, it will provide a good platform to implement Smart RAS.

VII. ACKNOWLEGMENT

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VIII. REFERENCES

[1] Shimo Wang, Anthony Johnson and George Rodriguez, "Adaptive Impact Energy Method for Synchrophasor Measurements Based Inter-Area Instability Prediction and Remedy", Proceeding of IEEE PES 2008 General Meeting, Pittsburgh, PA, 20-24 July 2008.

[2] Patricia L. Arons, "SCE Pilots the Next Level of Grid of Grid Protection", Transmission & Distribution World, December, 2007

IX. BIOGRAPHIES

Shimo Wang (M'96-SM'05) received his B.S. (1977) in electrical engineering from Tsinghua University, Beijing and his M.S.(1982) and PhD. (1986) in electrical engineering from Xi'an Jiaotong University, Xi'an. He was associate professor at Xi'an Jiaotong University. His professional experience includes: Siemens EMIS, EPRI Solutions, and Burns & McDonnell, etc. He is currently a senior engineer with Southern California Edison. His research interests are in power system dynamics, reliability, operations, planning, synchrophasor measurements applications, intermittent renewable generation integration, and smart grid. Dr. Wang is a professional engineer licensed by the state of California.

George Rodriguez (M'76) is currently Manager of Edison's Power System Technologies group of the TDBU Engineering Advancement organization. He has over 30 years of electric utility program and project management experience in the development, demonstration, and commercialization of power system technologies for Edison and its customer's needs. He graduated with a B.S. in Electrical/Electronic Engineering from the California State Polytechnic University in Pomona. He also earned his M.S. Degree in Engineering from the same university. Mr. Rodriguez is a registered professional Electrical Engineer in the State of California. He is also a long time member (30 years) of the IEEE.