



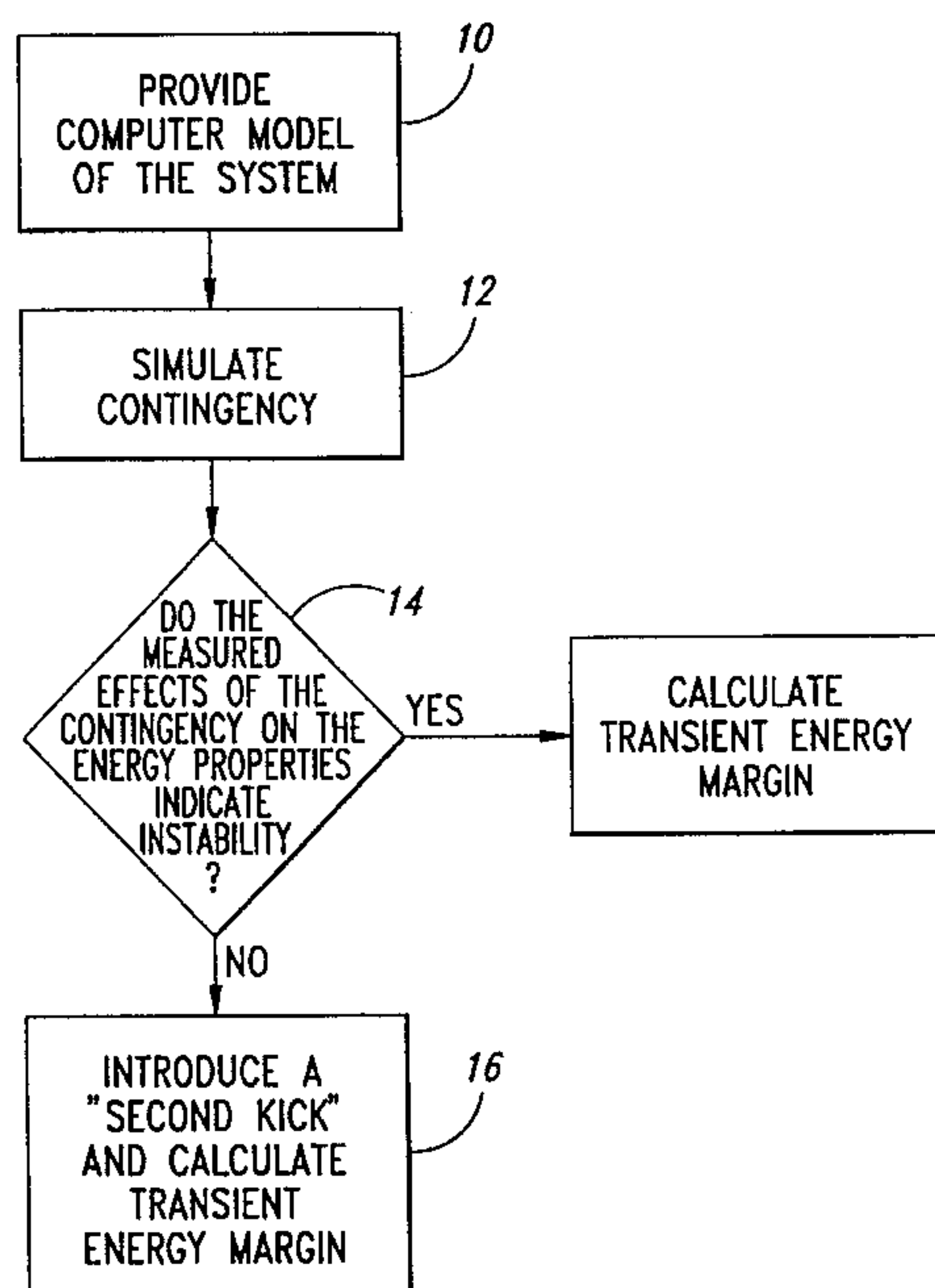
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(54) **METHODE DE SURVEILLANCE EN DIRECT DE LA STABILITE
DYNAMIQUE DE SYSTEMES D'ALIMENTATION EN
ELECTRICITE**

(54) **METHOD OF ON-LINE TRANSIENT STABILITY ASSESSMENT
OF ELECTRICAL POWER SYSTEMS**



(57) In the past, in electrical power networks, the effects on the system of particular contingencies, such as interruption of a power line, have been modelled off-line. Such models have generally been overly conservative, adding considerable cost to power systems. The present invention provides an on-line method of transient stability assessment referred to as the "second kick" method. It does this by providing a computer model of the system, simulating a study contingency, measuring the effect on the energy properties in the system of the study contingency, and if instability is indicated, calculating the transient energy margin from the corrected kinetic energy and, if the measured energy properties indicate stability introducing an artificial contingency into the model which is of sufficient duration to make this system unstable and measuring the transient energy margin as the difference between the corrected kinetic energy after the artificial contingency and the minimum value of the corrected kinetic energy after the artificial contingency, after compensating for the potential energy change introduced into the system by the artificial contingency.



**METHOD OF ON-LINE TRANSIENT STABILITY ASSESSMENT
OF ELECTRICAL POWER DISTRIBUTION SYSTEMS**Abstract of the Disclosure

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In the past, in electrical power networks, the effects on the system of particular contingencies, such as interruption of a power line, have been modelled off-line. Such models have generally been overly conservative, adding considerable cost to power systems. The present invention provides an on-line method of transient stability assessment referred to as the "second kick" method. It does this by providing a computer model of the system, simulating a study contingency, measuring the effect on the energy properties in the system of the study contingency, and if instability is indicated, calculating the transient energy margin from the corrected kinetic energy and, if the measured energy properties indicate stability introducing an artificial contingency into the model which is of sufficient duration to make this system unstable and measuring the transient energy margin as the difference between the corrected kinetic energy after the artificial contingency and the minimum value of the corrected kinetic energy after the artificial contingency, after compensating for the potential energy change introduced into the system by the artificial contingency.

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METHOD OF ON-LINE TRANSIENT STABILITY ASSESSMENT OF
ELECTRICAL POWER SYSTEMS

Technical Field

5 The invention relates to the field of electrical power systems, and more particularly to methods of assessing the transient stability of such systems.

Background Art

10 In any electrical power network it is desirable to attempt to predict the effects on the system of particular contingencies, such as a given power line being interrupted, so that the proper response to that contingency can be planned ahead of time and acted upon quickly in the event of such
15 contingency. For example, where a major power line is interrupted, by taking action to improve stability, such as high response static exciters, braking resistor, shedding generation capacity and high speed single and three pole reclosing, an entire system failure may be avoided.

20 In some systems, generation shedding has proven to be one of the most effective discrete supplementary controls for maintaining stability. For every foreseeable disturbance, the amount of generation shedding is calculated and provided to the system operators in a look-up table format. With these
25 tables, the operators preset the generator shedding controls for every major element outage. In the past, these tables have been prepared using off-line calculations. However in real system operation, the conditions frequently do not match those studied off-line, so the guidelines produced are
30 provided on the conservative side. Operating power system networks on such conservative guidelines can have significant cost implications. Therefore it is desirable to provide an effective on-line transient stability method which can assess the dynamic security limits of a power system (the maximum
35 transfer limit or the minimum required remedial action for the system to remain stable) for those contingencies likely to

cause dynamic security violations for the operating conditions encountered in real-time.

The North American Reliability Council sets criteria for system dynamic security which require the simulation of complex switching sequence of various equipment in a system at different locations following a fault, based on the actual system structure. Such series of simulated events in such simulations, which simulate possible real contingencies, are referred to herein as the study contingencies, or natural contingencies, as contrasted to artificial or unnatural contingencies.

Disclosure of Invention

The present invention provides a method of predicting the transfer limit or the amount of remedial action required to maintain stability of a power system in the event of a study contingency by determining a transient energy margin, comprising the steps of:

- a) providing a computer model of the system;
- b) simulating the study contingency using a step by step time integration method;
- c) measuring the effect on the energy properties in the system which resulted from the study contingency, and if the measured energy properties indicate instability, calculating the transient energy margin from the corrected kinetic energy; and
- d) if the measured energy properties indicate stability, introducing an artificial contingency into the model which is of sufficient duration to make the system unstable, and measuring the transient energy margin as the difference between the corrected kinetic energy after the artificial contingency and the minimum value of the corrected kinetic energy after the artificial contingency, after compensating for the potential energy change introduced into the system by the artificial contingency.

Brief Description of Drawings

In drawings which illustrate a preferred embodiment
5 of the invention:

Fig. 1 is a graph showing the variation of the corrected Kinetic energy over time in response to first and second contingencies;

Fig. 2 is a graph showing the dot product following
10 a fault;

Fig. 3 is a graph showing the limit calculation using sensitivity factors;

Fig. 4 to 9 are graphs illustrating an application of the method of the invention to a first study contingency;

15 Fig. 10 to 12 are graphs illustrating an application of the method of the invention to a second study contingency; and

Fig. 13 is a flow chart diagram illustrating the method of the invention.

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Best Mode(s) For Carrying Out the Invention

The method disclosed is implemented using the Power Technologies Incorporated PSS/E transient stability program.
25 The automation process is achieved using an expert system, the design of which is disclosed in a paper by K. Demaree et al. entitled "An On-Line Dynamic Security Analysis System Implementation" presented at the February 1994 IEEE Winter meeting. In the present invention, the kinetic energy KE of the
30 simulated system, the corrected kinetic energy and the minimum of the corrected kinetic energy KE_{emin} are calculated according to the PSS/E program.

With reference to Fig. 1, in summary, the method of the present invention operates as follows. The vertical axis in Fig. 1 is the corrected kinetic energy, and the horizontal axis is time t . A first fault or study contingency is introduced into the model at $t=0$. After the contingency, at $t=T_{kemin1}$, the minimum of the corrected kinetic energy K_{emin1} is identified. If the minimum is greater than 0, indicating that the system is unstable, the margin is calculated from the value of the corrected kinetic energy at this point. If the system is stable at $t=T_{kemin1}$, then $K_{emin}=0$ at that time, and a second artificial contingency (referred to as the "second kick") which is long enough to make the system unstable, is applied and the simulation is continued until the second minimum of kinetic energy K_{emin2} is obtained. This point also reflects the crossing of the PEBS (potential energy boundary surface) as shown in Fig. 2, in which the vertical axis is the dot product of the machine acceleration and angle vectors ("the Dot Product") and the horizontal axis is time. The transient energy margin is then calculated using the values of the corrected kinetic energy at the second minimum of kinetic energy K_{emin2} , and the value of the corrected kinetic energy after the second fault recovery K_{erec2} taking into account adjustments due to potential energy change during the Second Kick. The corrected kinetic energy injected into the system by the Second Kick minus the value of the corrected kinetic energy left in the system at the crest of the potential energy hill (PEBS crossing) should give the transient energy margin, which should be adjusted for the potential energy change during the Second Kick. The transient energy margin therefore is calculated as:

$$TEM = K_{erec2} - K_{emin2} + D_{pe}$$

To determine the duration of the second fault, a long fixed duration fault is applied and the simulation is continued for one time step following the fault recovery. The duration of this fault should be long enough to make the majority of the stable cases following a single contingency unstable. In the B.C. Hydro system a fixed fault of 10 cycles proved to be sufficiently long to make all the cases surviving a contingency unstable. The dot product crossing of zero is estimated by its value at the inception of the fault and the recovery point. An interpolation or extrapolation is performed to get the value of T sustained fault when it crosses the PEBS as shown in Fig. 2. The reason for this estimation is that the values calculated for dot product during the fault conditions are not correct because they use faulted network as opposed to the post-contingency network.

The final outcome of the Transient Stability Assessment tool is guidelines for the operator for pre-contingency transfer limits and generation rejection immediately following a fault as a remedial action. In the present method, to find the transfer limit and generation rejection, sensitivity values are calculated for energy margin with respect to generation rejection or generation change in the case of transfer limit calculations. The existing analytical equations, as set out in "Power System Transient Stability Analysis Using Transient Energy Function Method" (Prentice Hall 1990) by A.A. Fouad and V. Vittal, are only used in the first step to calculate the conditions for the next step and are abandoned afterwards. After the second run linear interpolation is used to obtain the sensitivity values from the two previous energy margin calculations, as shown in Fig. 3.

The PSS/E program calculates for a model of the system the potential energy V_{pe} as follows:

$$V_{pe} = \sum_{i=1}^n \int_{\theta_i}^{\theta_2} P_{acc}(i) d\theta_i = \sum_{i=1}^n \int_{\theta_i}^{\theta_2} (P_{Mi} - P_{ei} - \frac{M_i}{M_t} P_{COA}) d\theta_i$$

where $P_{acc}(i)$ is the acceleration of machine i ;

P_{Mi} is the mechanical power of machine i ;

P_{ei} is the electrical power of machine i ;

5 M_i is the inertia constant of machine i ;

M_t is the sum of the inertia constants of all the system machines; and

P_{COA} is the acceleration associated with the centre of system inertia.

10 To avoid the numerical errors which can be created when there are two integration blocks one inside the other, the potential energy integration with respect to angle was modified to integration with respect to time according to the following formula which removes the need for a second integra-
15 tion within each time step:

$$V_{pe} = \sum_{i=1}^n \int_{\theta_{i1}}^{\theta_{i2}} P_{acc}(i) d\theta_i = \sum_{i=1}^n \int_{t_1}^{t_2} P_{acc} \frac{d\theta_i}{dt} dt$$

20 To calculate the Potential energy compensation, the above integration is approximated using the values of P_{acc} just before the fault and at the fault recovery. Using a trapezoidal rule, the change in potential energy can be calculated as:

25
$$\sum_{i=1}^n [P_{acc_i}(t_1) + P_{acc_i}(t_2)] * (Angle_i(t_2) - Angle_i(t_1)) / 2$$

As noted above, V_{pe} is calculated using the integration with
30 respect to time as follows:

$$V_{pe} = \sum_{i=1}^n \int_{t_1}^{t_2} (P_{acc}(i) \frac{d\theta_i}{dt}) dt = \sum_{i=1}^n \int_{t_1}^{t_2} P_{acc} Speed_{coi}(i) \cdot w_o \cdot dt$$

Therefore the derivatives of the above equation is used to calculate the potential energy compensation as follows:

$$5 \quad \text{Margin Compensation} = \sum_{i=1}^n \left[\frac{\partial V_{pe}}{\partial t} \Big|_{t_1} + \frac{\partial V_{pe}}{\partial t} \Big|_{t_2} \right] (t_2 - t_1) / 2.$$

The following steps are followed in the implementation of the algorithm according to the preferred embodiment of the invention:

1. Determine K_{emin1} and T_{kmin1} after the contingency.
2. If K_{emin1} is larger than zero, then the margin = - K_{emin1} . If $K_{emin1}=0$ go to step 3.
- 15 3. At T_{kemin1} apply a long fixed duration fault (e.g. 10 cycles) and continue the simulation for one more time step.
4. Get the values of Dot Product at T_{kemin1} and T_{rec2} and interpolate to get T_{pebs} using the relationship

$$20 \quad T_{pebs} = T_{kemin1} + (DP_{kemin1}) \frac{(T_{rec2} - T_{kemin1})}{(DP_{kemin1} - DP_{rec2})}$$

(See Figure 2)

5. Go back to step 1, apply another fault shorter than T_{pebs} and simulate until the corrected kinetic energy is minimum
- 25 (T_{kemin2}).
6. Determine the margin taking into account the margin compensation.

Other variations of the Second Kick method are possible, all of which involve inserting a second artificial contingency into the simulation after a first fault has recovered to a stable system. Such variations could vary the shape and timing of the "second kick" or the properties of the monitored energy. Other variations for example are a) a

sudden impulse change in mechanical power; b) a sudden impulse change in speed; or c) an intermittent sustained fault. The common feature of these variants, according to the invention, is that a simulation of the system is first produced with a the study contingency, followed by an artificial change or contingency ("second kick") to obtain the margin.

Example 1

A test was conducted for a simulated fault on a 500 kv line close to a generation system having two generating stations (GMS and KMO) according to the following sequence of events (the study contingency):

	<u>Time (cycles)</u>	<u>Event</u>
15	0	3 phase fault at a 500 kV bus
	2	Clear fault
	4	Bypass series capacitor if rating is exceeded
	9	Switch 200-400 MW of braking resistor on. Trip amount of generator required to maintain stability.
20	35	Reclose on fault at the master end of faulted line.
	39	Clear fault.
	44	Switch braking resistor off.

Fig. 4 to 6 show the simulation results following the contingency with one generation unit rejection. The angle on the vertical axis in Fig. 4 is the rotor angle. The vertical axes in Fig. 5 and 6 are the corrected kinetic energy and dot product respectively. Point A in Fig. 5 corresponds to the minimum corrected kinetic energy (K_{emin1}) of zero, indicating that the case is stable. The second curve in Fig. 5 shows the same results, this time applying a fault of 2 cycles following point A. The simulation is stopped at point B corresponding to the minimum kinetic energy following the Second kick. On the basis of these results, the transient energy margin was calculated at 0.3 (see Fig. 6). The fault

duration of 2 cycles was derived by applying a sustained fault of 10 cycles and by interpolation of Dot Products. Fig. 7 through 9 show the response of the system subjected to the same disturbance without any generation rejection. Again the angle on the vertical axis in Fig. 7 is the rotor angle. The vertical axes in Fig. 8 and 9 are the corrected kinetic energy and dot product respectively. In this case the margin determined was -1.6. On the basis of the sensitivity results given, the critical generation shedding is determined to be at 84 MW.

Example 2

A second test was conducted for a simulated fault on a 500 kv line close to a system having two generating stations (MCA and REV) according to the following sequence of events (the study contingency):

Time (cycles) Event

20	0	Fault (single and 3 phase)
	2	Series capacitor control.
	4	Clear fault
	9	Trip generator to maintain stability
	90	Reclose on fault at the master end
	94	Clear fault.(3 phase)

25

Fig. 10 to 12 show the simulation results following the contingency with no generation unit rejection. The vertical axis in Fig. 10 is the rotor angle. The vertical axes in Fig. 11 and 12 are the corrected kinetic energy and dot product respectively. Point A in Fig. 11 corresponds to the minimum corrected kinetic energy (K_{emin1}) of zero, indicating that the case is stable. The second curve in Fig. 11 shows the same results, this time by applying a fault of 5.5 cycles following point A. The simulation is stopped at point

B corresponding to the minimum kinetic energy following the Second kick. On the basis of these results, the transient energy margin was calculated as 1.0 (see Fig. 12). The fault duration of 5.5 cycles was derived by applying a sustained
5 fault of 10 cycles and by interpolation of Dot Products.

As will be apparent to those skilled in the art in the light of the foregoing disclosure, many alterations and modifications are possible in the practice of this invention
10 without departing from the spirit or scope thereof. Accordingly, the scope of the invention is to be construed in accordance with the substance defined by the following claims.

WHAT IS CLAIMED IS:

1. A method of predicting the transfer limit or the amount of remedial action required to maintain stability of a power system in the event of a study contingency by determining a transient energy margin
5 from a corrected kinetic energy, comprising the steps of:
 - a) providing a computer model of the system;
 - b) simulating the study contingency using a step by step time integration method;
 - c) measuring the effect on the energy properties in the system
10 which resulted from the study contingency, and if the measured energy properties indicate instability, calculating the transient energy margin from the corrected kinetic energy; and
 - d) if the measured energy properties indicate stability, introducing an artificial contingency into the model which is of sufficient
15 duration to make the system unstable, and measuring the transient energy margin as the difference between the corrected kinetic energy after the artificial contingency and the minimum value of the corrected kinetic energy after the artificial contingency, after compensating for the potential energy change introduced into the system by the artificial
20 contingency.
2. A method of operating an electrical power network at a stable state by assessing the dynamic security limits of a power system by determining a transient energy margin, to predict the required remedial action in the form of transfer limits or remedial steps in the
25 event of a system disturbance in the power system, comprising the steps of:

- a) providing a real-time computer model of the power system;
- b) simulating a study contingency using a step by step time integration method;
- c) determining K_{emin1} and T_{kemin1} after the study contingency;
- 5 d) if K_{emin1} is larger than zero, then the transient energy margin $= -K_{emin1}$. If $K_{emin1} = 0$ go to step e);
- e) at T_{kemin1} apply a long fixed duration fault and continue the simulation for one more time step;
- f) get the values of the Dot Product at T_{kemin1} and T_{rec2} and
- 10 calculate T_{pebs} using the relationship;

$$T_{pebs} = T_{kemin1} + (DP_{kemin1}) \frac{(T_{rec2} - T_{kemin1})}{(DP_{kemin1} - DP_{rec2})}$$

where DP is the Dot Product.

- 15 g) go back to step c), apply another fault shorter than T_{pebs} and simulate until the corrected kinetic energy is minimum (T_{kemin2});
- h) determine the transient energy margin taking into account the margin compensation; and
- i) use the transient energy margin to calculate the transfer limits
- 20 or the remedial steps required to maintain the power system in a stable state in the event of the contingency;
- j) taking remedial action in the form of said calculated transfer limits or remedial steps in the event of an actual fault in the power system

- 25 wherein K_{emin1} equals the minimum of the corrected kinetic energy after the first study contingency;

T_{kemin1} is the length of time t at which K_{emin1} is identified;

T_{pebs} is the time at which the Dot Product crosses the potential energy boundary surface;

DP_{kemin1} is the Dot Product at time $t = T_{kemin1}$;

T_{rec2} is a time at which the second fault recovery of the
5 corrected kinetic energy is identified;

DP_{rec2} is the Dot Product at time $t = T_{rec2}$; and

T_{kemin2} is the time at which the second minimum of correct kinetic energy is identified.

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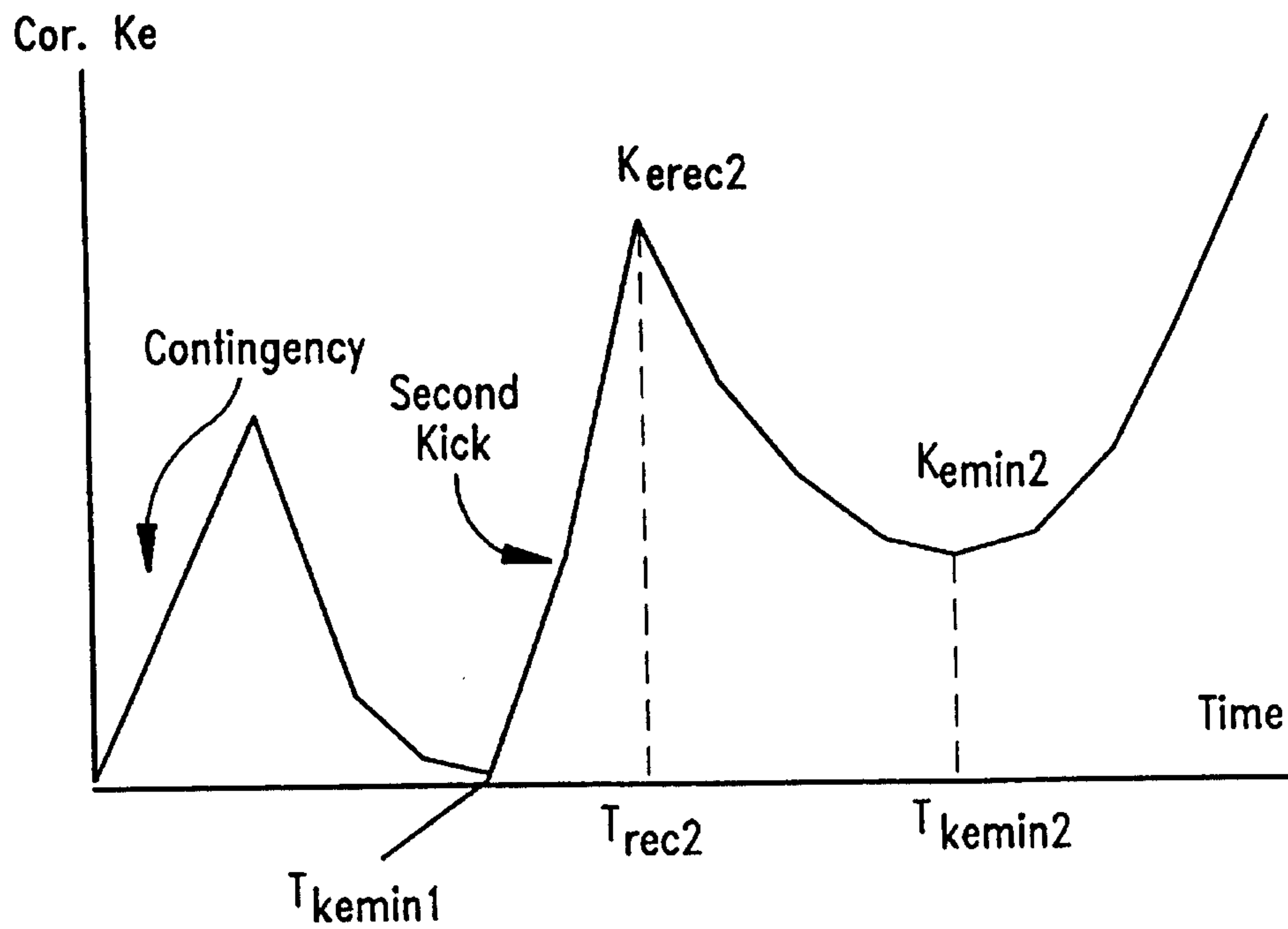


Fig. 1

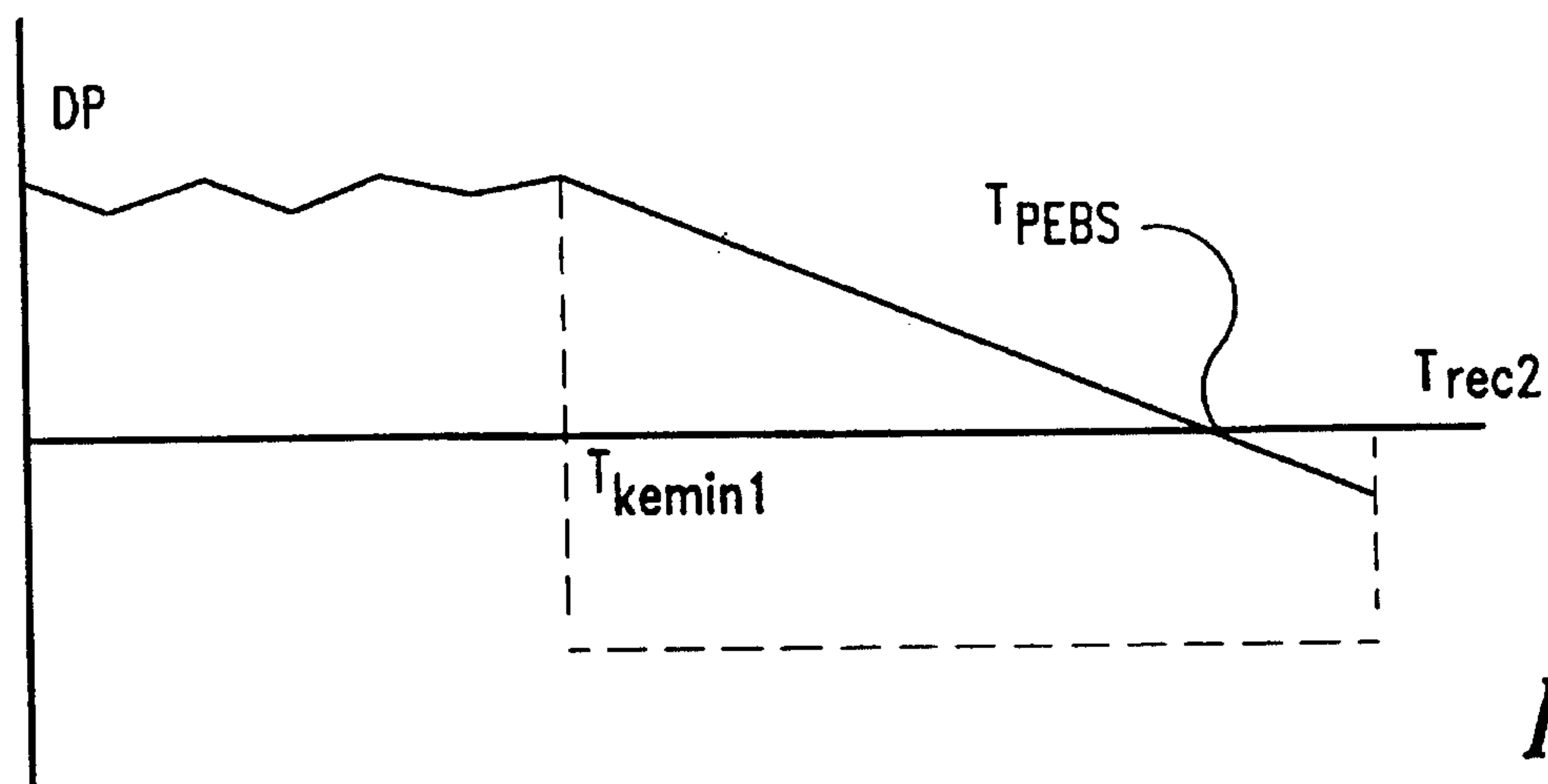


Fig. 2

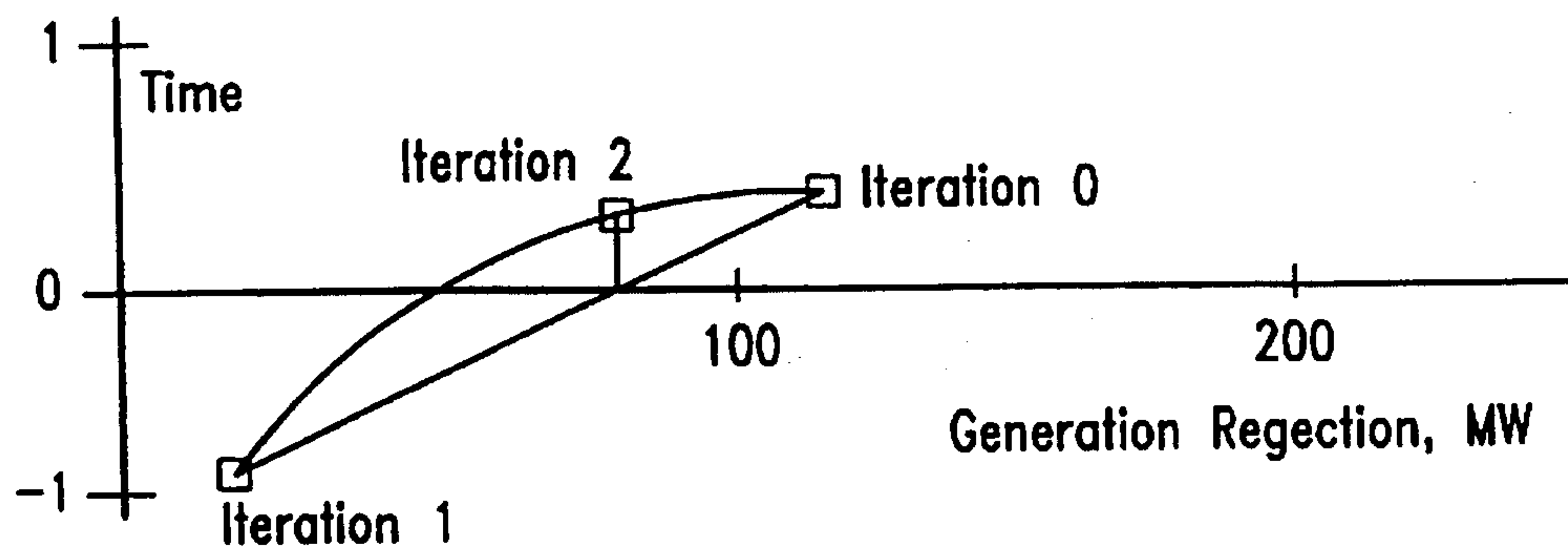
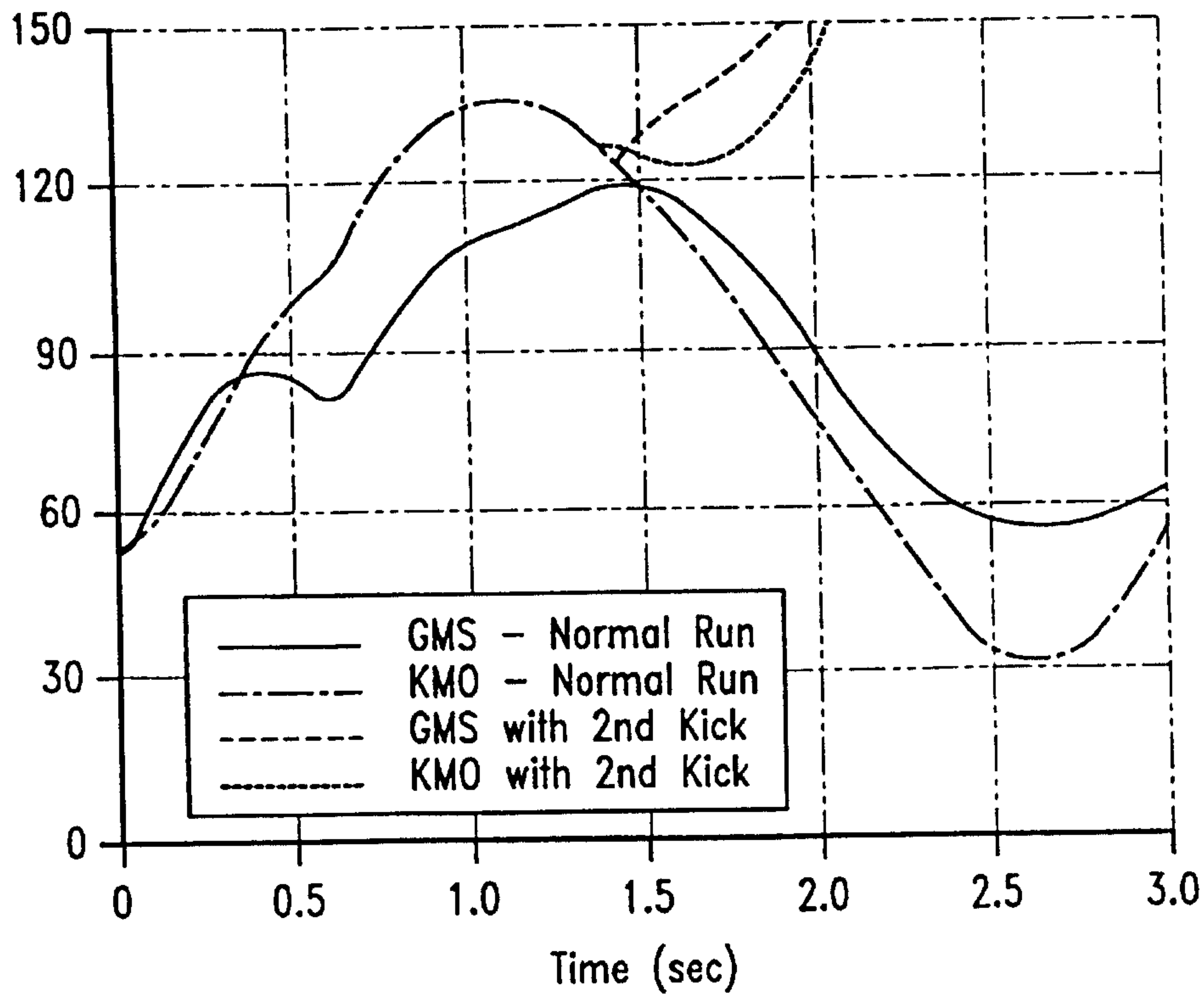
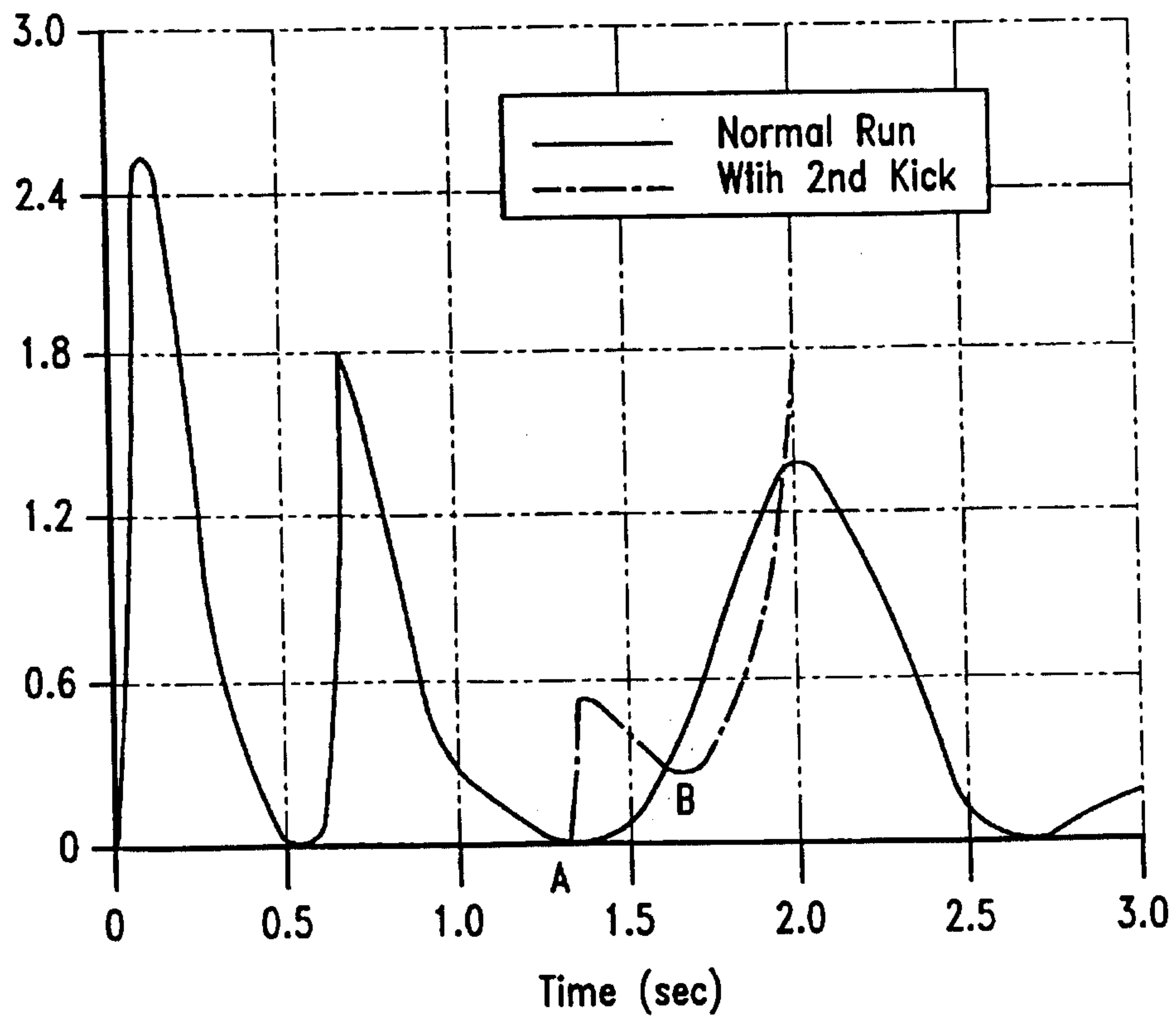


Fig. 3

Angle Comparison for a Stable Contingency

*Fig. 4*

Corrected KE Comparison for a Stable Contingency

*Fig. 5*

Dot Product Comparison or a Stable Contingency

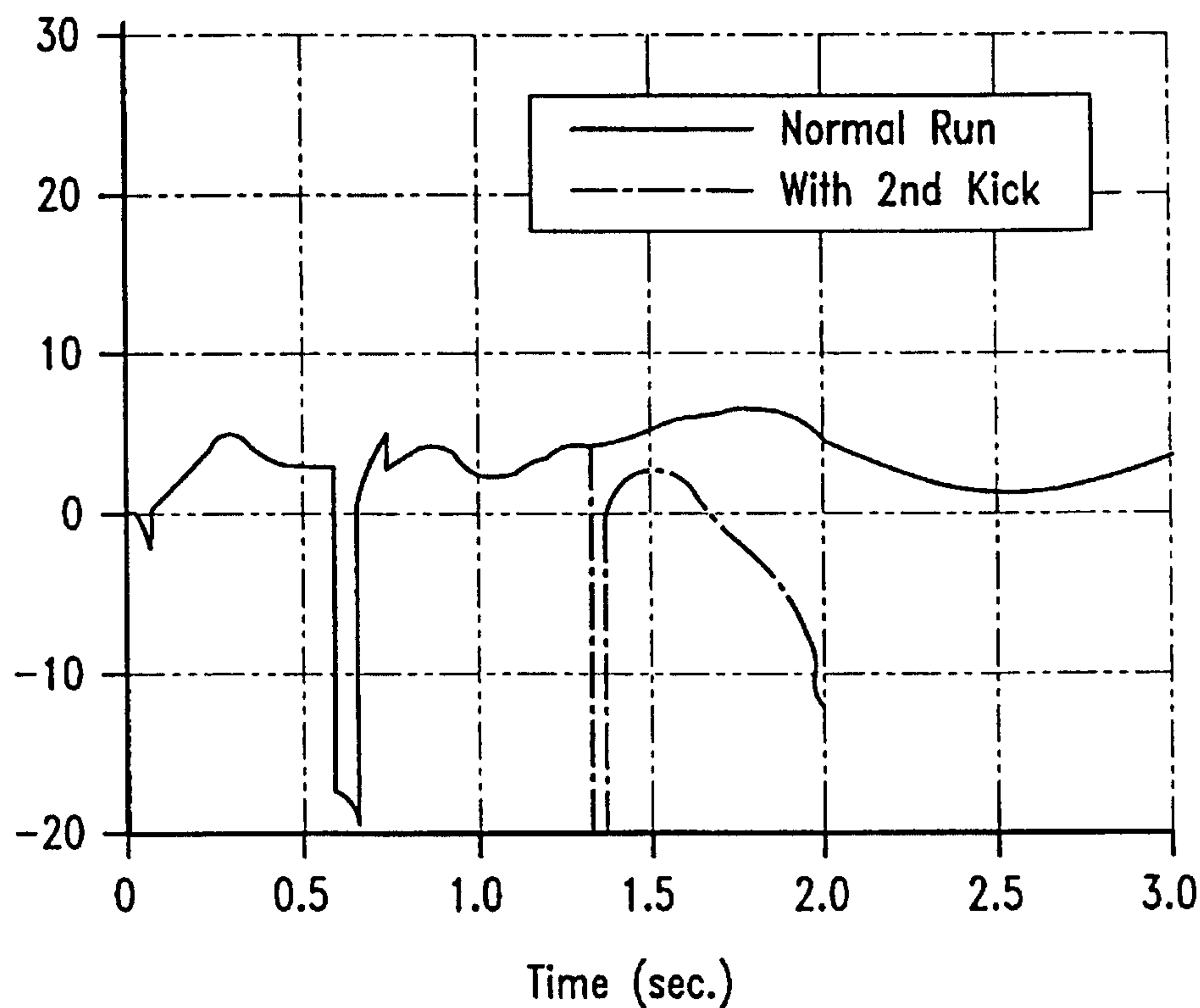


Fig. 6

Angle Comparison for an Unstable Contingency

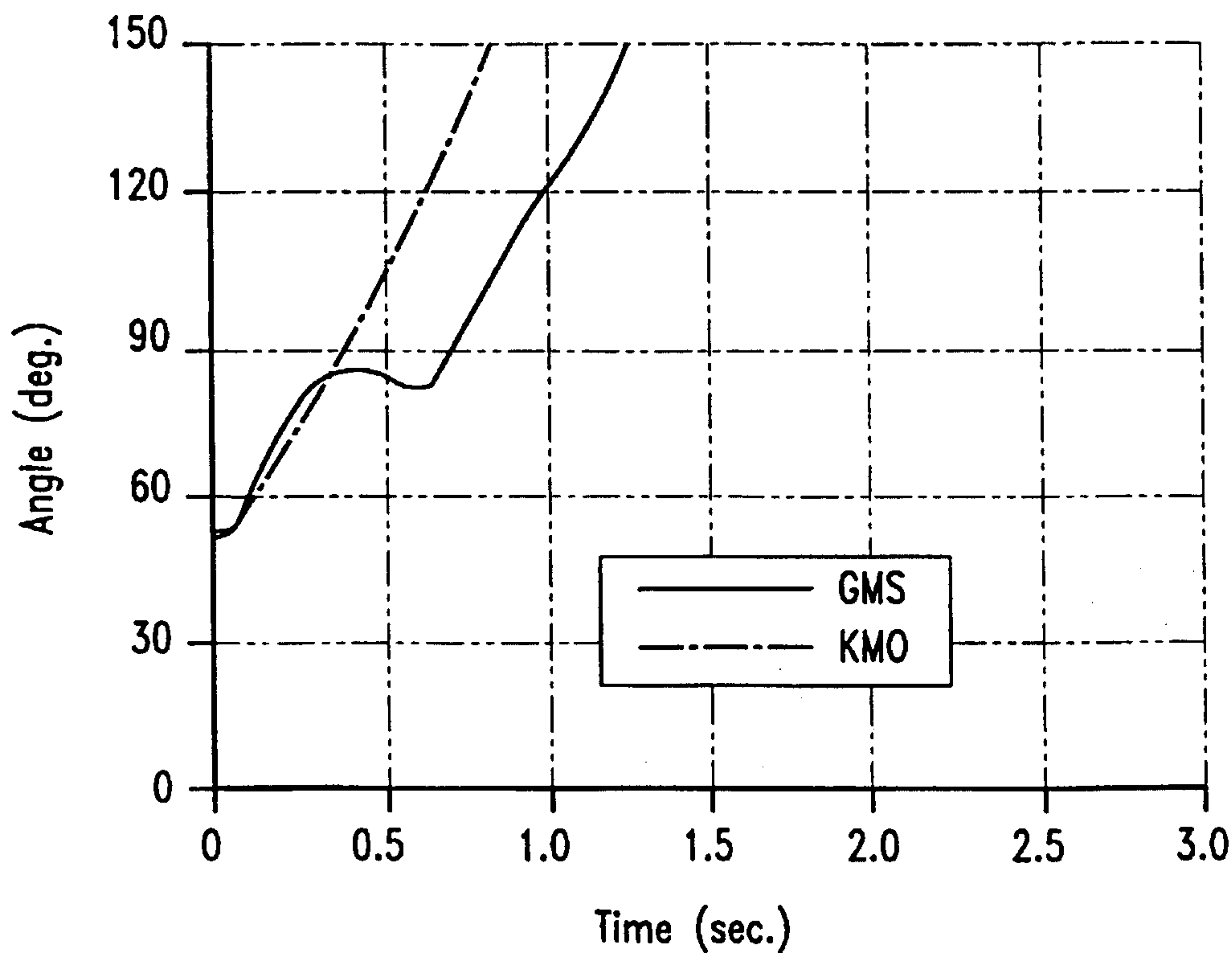


Fig. 7

Corrected KE Comparison
for an Unstable Contingency

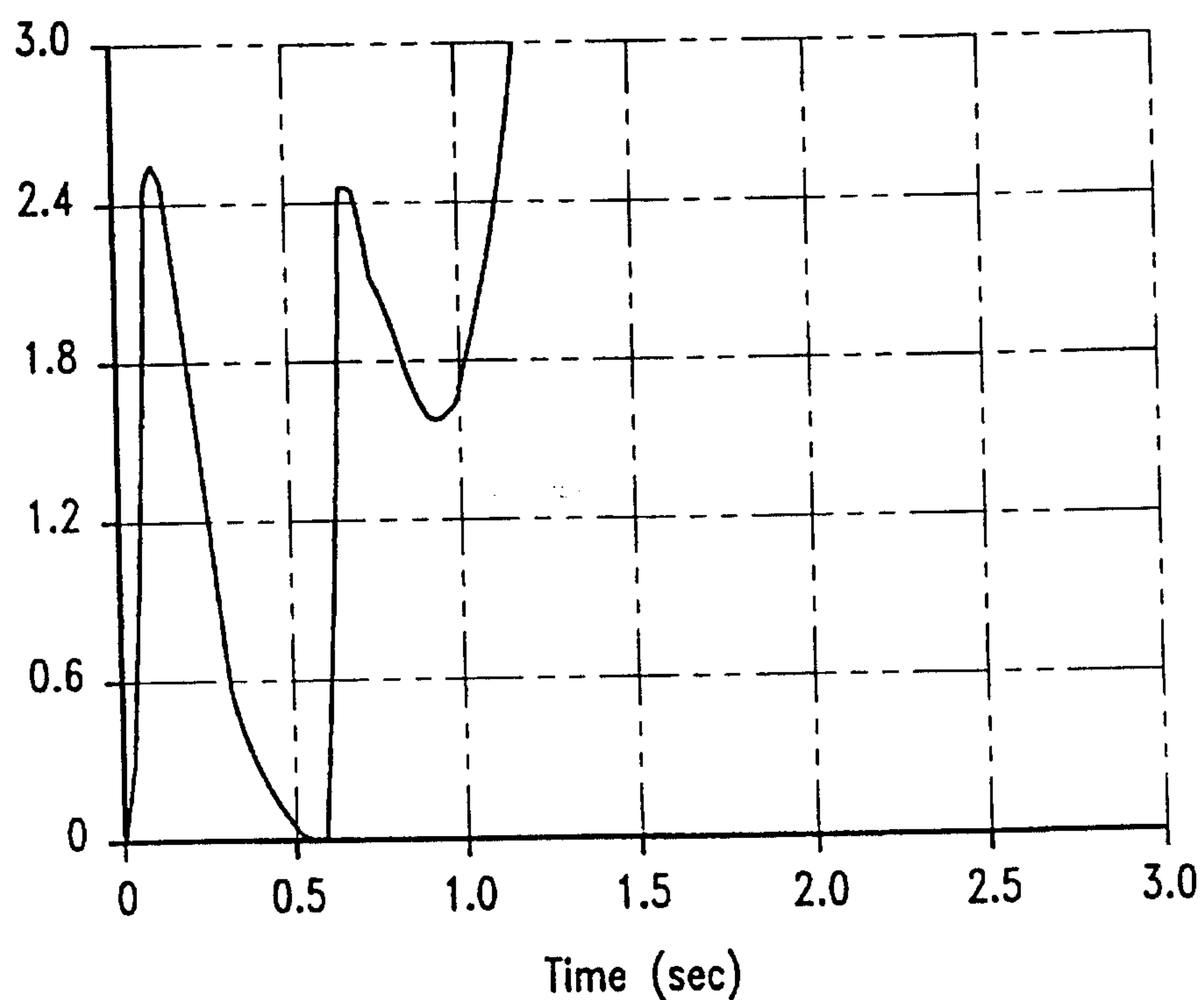


Fig. 8

Dot Product Comparison
for an Unstable Contingency

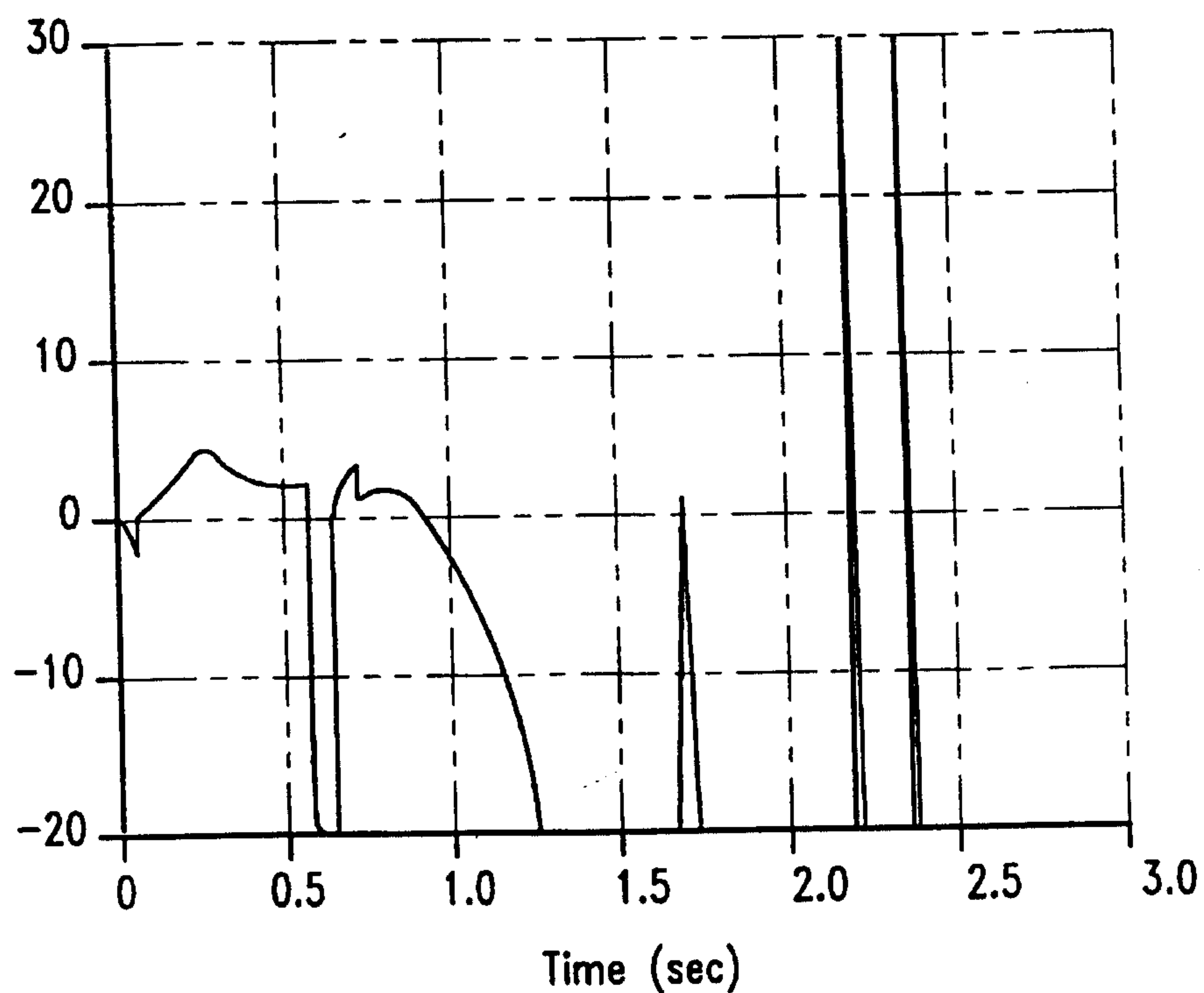


Fig. 9

Angle Comparison

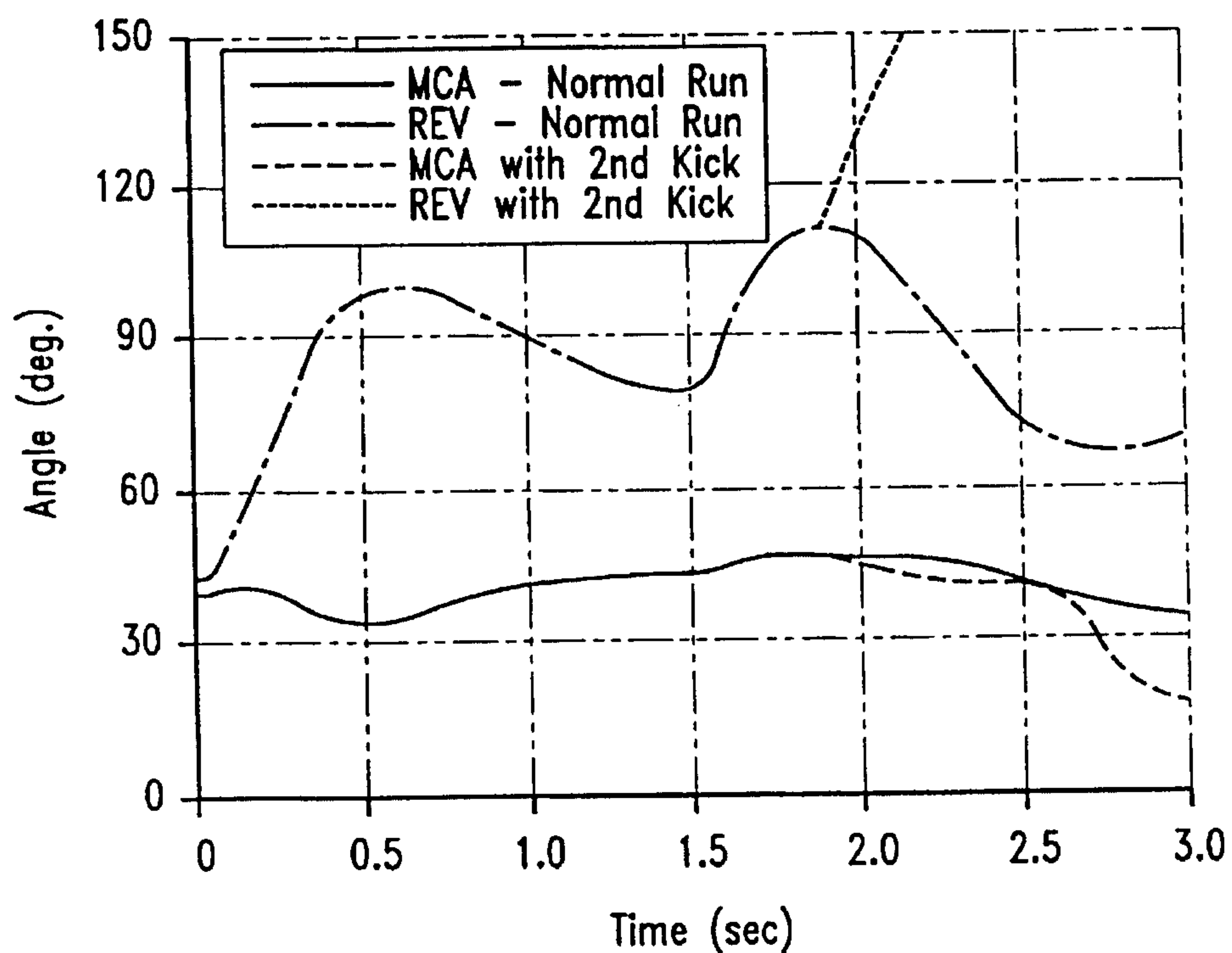


Fig. 10

Corrected KE Comparison

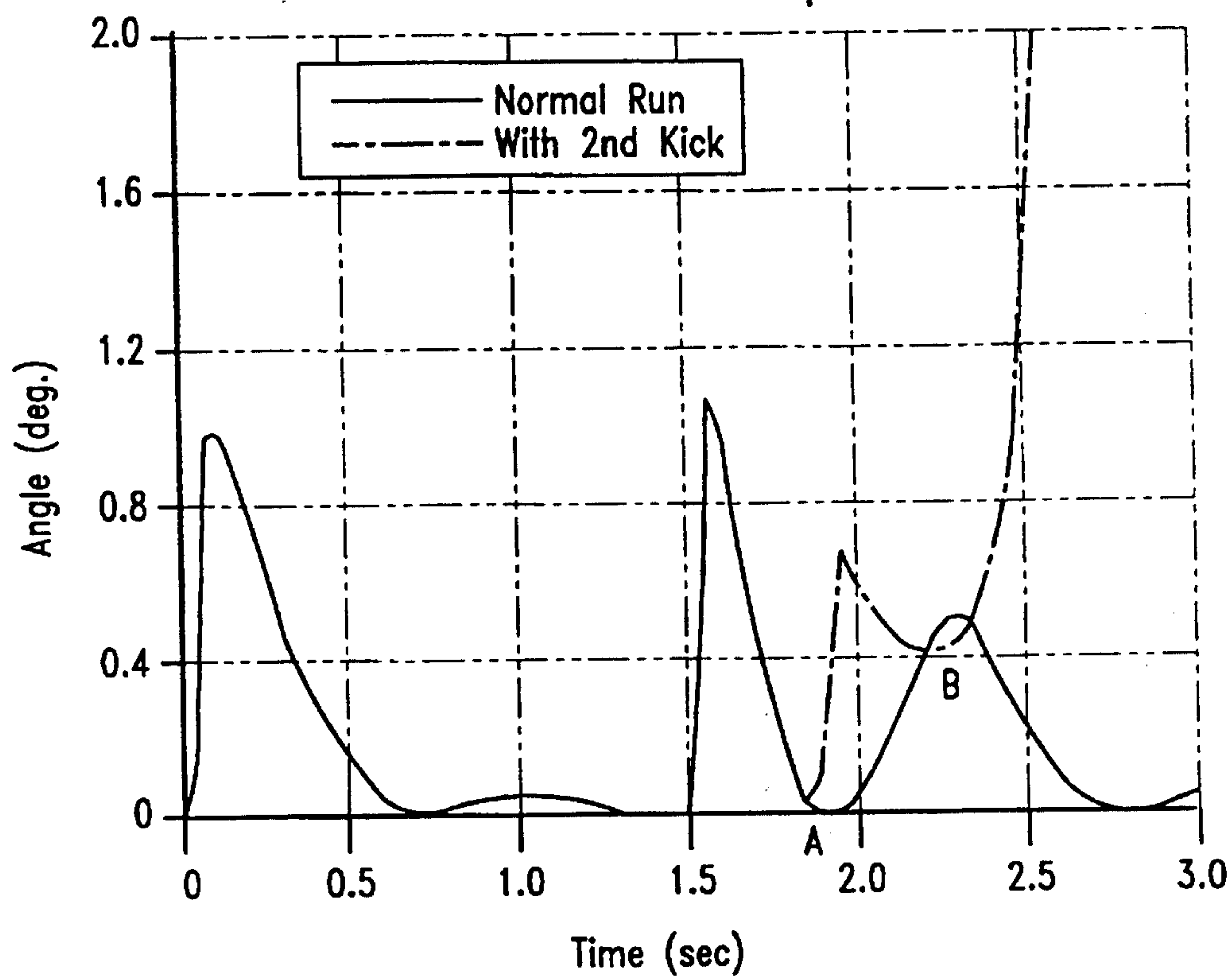
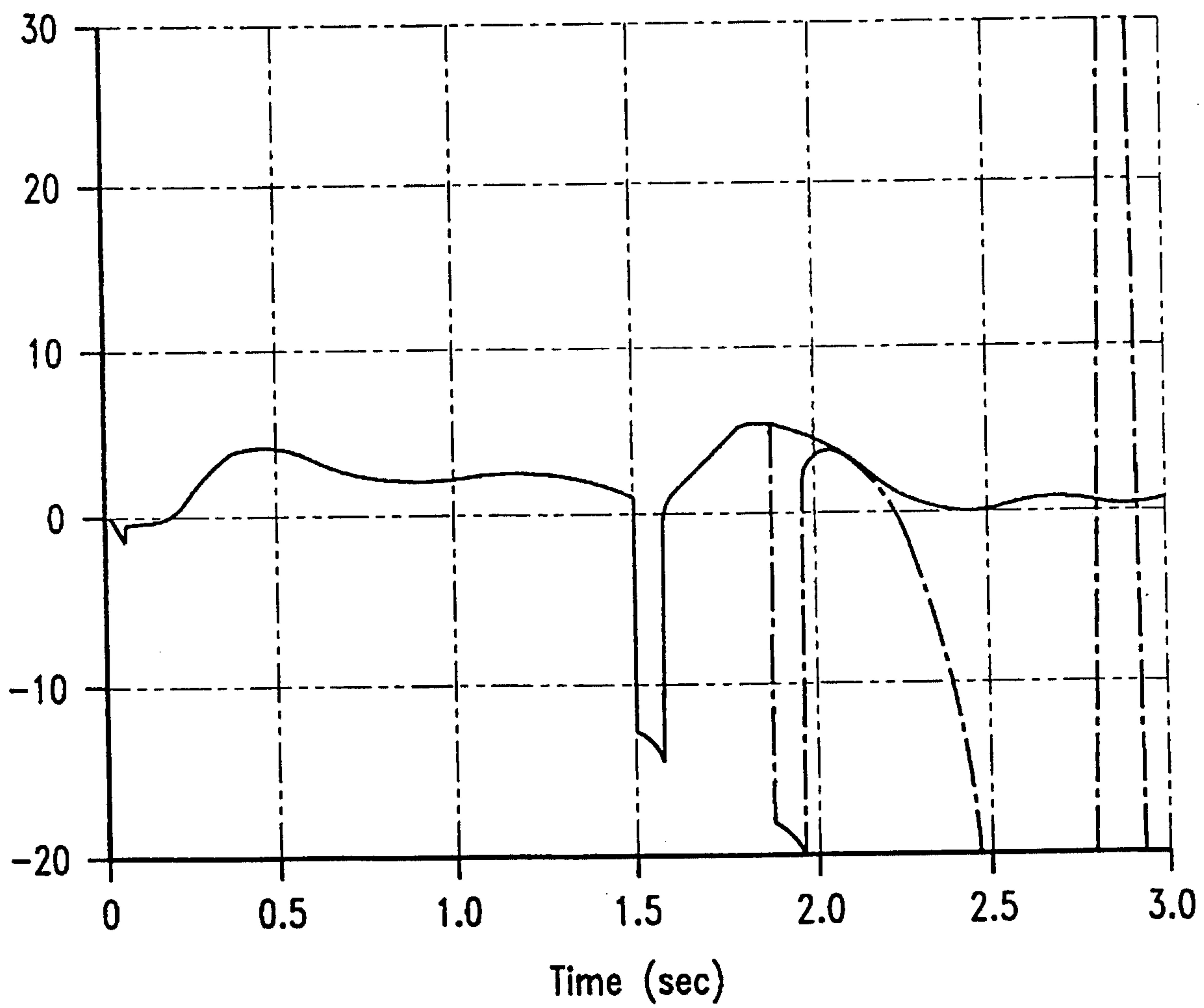
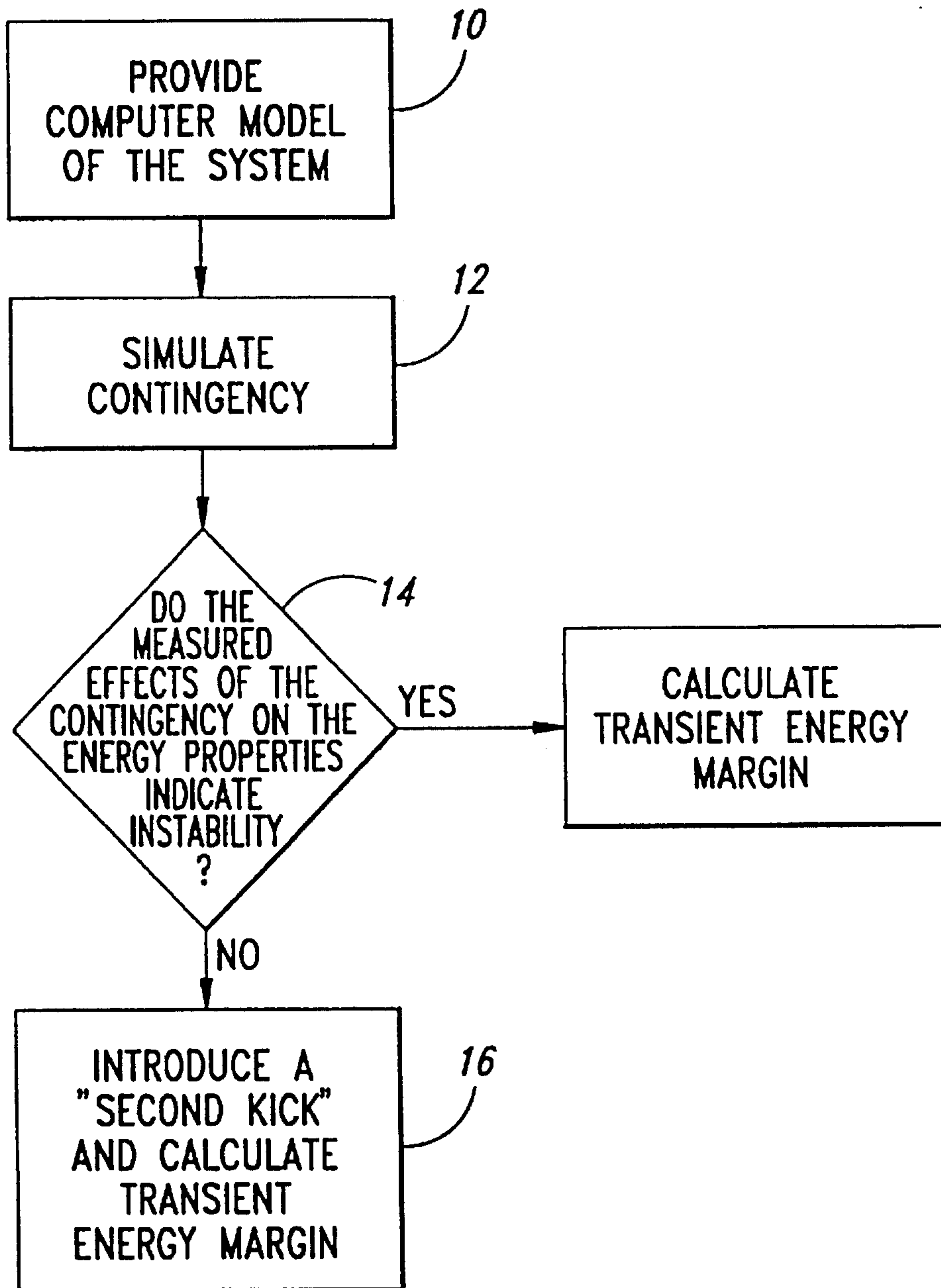


Fig. 11

Dot Product Comparison

*Fig. 12*

*Fig. 13*