Modelling Techniques for Vanadium Detector Compensation

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1.0 Abstract

A software algorithm has been developed to compensate the PLGS vanadium detectors for their first-order delayed response. This paper describes the recent advancements in determining the detector and lead cable compensation algorithm and its testing with both simulated and actual flux transients. Although the effect of noise has not been rigorously analyzed to date, preliminary analysis results are described.

2.0 Vanadium (V) Detector Physics

The current produced by a V detector consists of two components:

(n,γ,e) Prompt contribution = about 8% of total detector signal

(n,β) Delayed contribution = about 92% of total detector signal with a 225 second half-life (V^{52}), 325 second time constant

(γ,e) Negligible

The inconel lead cable (LC) produces current from all three processes. The LC contribution is up to 2% of the detector signal.

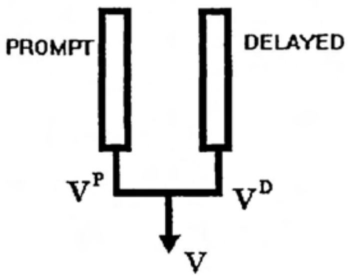
3.0 V Detector Compensation Techniques

Two methods of V detector compensation have been examined as follows:

Compensation Method	Description	Compensation Equation (see description of variables below)	Advantages	Disadvantages
1) First-Order	Models the 325 second delay component but ignores the prompt components of the detector and LC.	$\Phi(t) = V(t) + T_V \frac{dV(t)}{dt}$	• Relatively easy to model	• Possible noise errors • Response error in first 2-3 minutes
2) Prompt-Compensated	Models the delayed and prompt components, but possibly errs by not modelling other less significant detector time constants.	$\Phi(t) = V(t) + T_V \frac{dV(t)}{dt} - T_V F_P \frac{d\Phi(t)}{dt}$ (See Section 4.0 for derivation)	• Very accurate within first few seconds	• Possible noise errors • Hard to model (finding prompt component)

Variables: $\Phi(t)$ is the neutron flux at the detector at time t
$V(t)$ is the vanadium detector reading at time t normalized to Φ in steady state
F_p is the prompt fraction of the V detector plus LC
T_V is the V^{52} decay time constant (325 sec)

4.0 Derivation of Prompt-Compensation Algorithm



Assume the V detector is two detectors in parallel consisting of:

1) a prompt detector with contribution $V^P = F_P\Phi$ [1]
2) a delayed (n,ß) detector with contribution V^D

For this detector, the compensation equation is:

$$\Phi(t) = V^P(t) + V^D(t) + T_V \frac{dV^D(t)}{dt} \tag{4.1}$$

[1] This derivation assumes the LC contribution is negligible. The next refinement will model the LC dynamics as depicted in Figure 2.

Since $V^P + V^D = V$ and $dV^D = dV - dV^P = dV - F_p d\Phi$, then 4.1 becomes:

$$\Phi(t) = V(t) + T_V \frac{dV(t)}{dt} - T_V F_p \frac{d\Phi(t)}{dt} \qquad (4.2)$$

This is the derived prompt-compensation equation for PLGS.

<u>**For a digital system:**</u>

For a digital system sampled at a fixed rate (Δt), equation (4.2) can be approximated by[2]:

$$\Phi(t) = V(t) + T_V \frac{\Delta V(t)}{\Delta t} - T_V F_p \frac{\Delta \Phi(t)}{\Delta t} \qquad (4.3)$$

Since $\Delta V = V(t) - V(t-\Delta t)$, and $\Delta\Phi = \Phi(t) - \Phi(t-\Delta t)$, equation (4.3) reduces to:

$$\Phi(t) = \frac{V(t) + T_V \frac{(V(t)-V(t-\Delta t))}{\Delta t} + T_V F_p \frac{\Phi(t-\Delta t)}{\Delta t}}{1 + \frac{T_V F_p}{\Delta t}} \qquad (4.4)$$

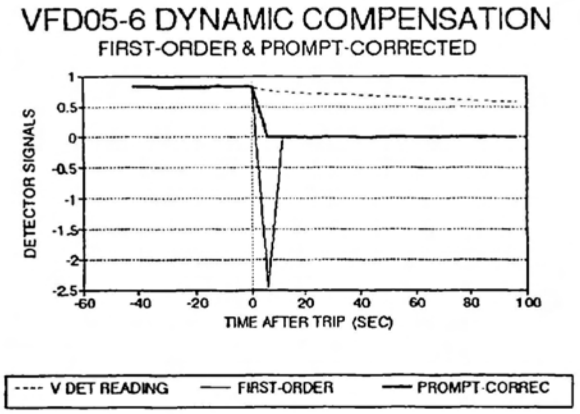
This V detector compensation function has been tested at PLGS using V data sampled every six seconds. The results are discussed in Sections 5.0 and 6.0.

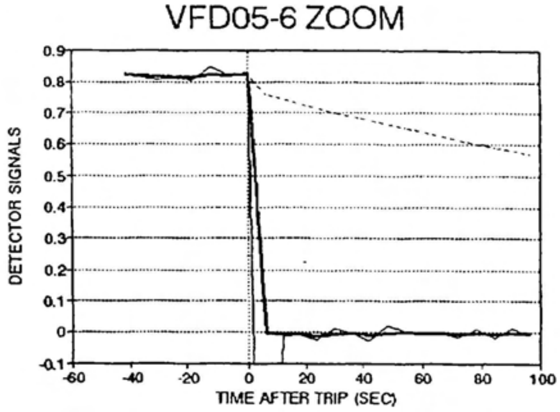
[2] Substituting Δt for dt creates a small error in the computed flux which can be corrected by modifying the V detector time constant (T_V) from 325 seconds to 322 seconds. This analysis is shown in Appendix 1.0.

5.0 Test Results

The plots below show the compensator test results for V detector VFD05-6 during the SDS2 trip in Jul'92. The plots show:

1) the V detector reading from System Engineers Data Extraction (SEDE) with six-second sampling
2) the compensated V detector reading using the first-order compensation only
3) the compensated V detector reading using prompt-compensation[3]





The prompt-compensated response quickly falls to a near-zero value immediately after the trip as expected. The first-order response has a large over-compensation at the trip time since it doesn't account for the prompt response.

6.0 Comparison Against a Platinum Detector and Ex-Core Ion Chamber

An assessment of the compensation scheme was done using data from a PLGS trip and recovery. The planned SDS1 trip was performed from 75% FP with a recovery to 39% FP. During the recovery several adjuster banks were withdrawn. The prompt-compensated response of a V detector was compared to a neighbouring inconel-clad platinum (Pt) RRS detector which also was compensated. The RRS detector by itself is 89% prompt. Figure 1 shows the compensated responses for V detector VFD01-RE3C, the Zone 1 Pt detector, and the ion chamber (IC) response.

The comparisons show that the compensated Pt and V signals are a reasonably good match to the out-of-core IC although there is some over-shoot in both signals immediately following the trip due to the finite sampling time, uncertainty in the prompt fractions, and lead cable effects.

During the slower ramp up in power the agreement is remarkably good. Both signals can be seen to track the insertion of the adjuster banks as they drive in. Due to the spatial redistribution of flux, the comparison to the IC signal at the power plateau is less meaningful.

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[3] The prompt fraction (F_p) used for this detector is 5.0% obtained from the method detailed in [1] for determining V plus LC prompt components.

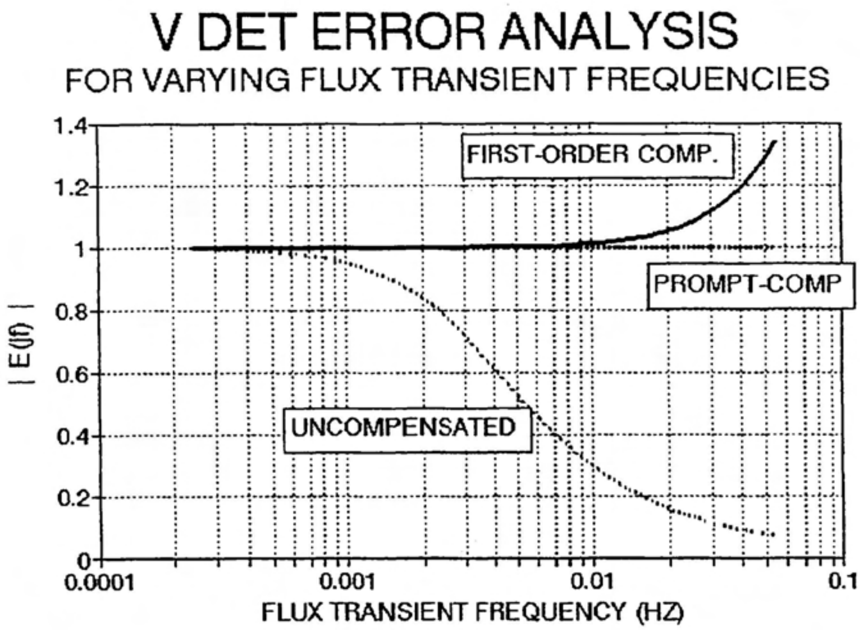
7.0 Frequency Domain Error Analysis

The transfer function, E(s), for modelling the compensator error in the frequency domain is:[2]

$$E(s) = \frac{\Phi(s)}{\Phi^T(s)} = \frac{(F_P s + \sigma)}{(F_{PA} s + \sigma)}$$

Where: $\Phi(s)$ is the compensated V detector reading
$\Phi^T(s)$ is the true flux at the detector
σ is the decay rate of vanadium (1/325 s^{-1})
F_P is the actual prompt fraction (5.0% used here)
F_{PA} is the assumed prompt fraction

Below is a plot in the frequency domain of $|E(jf)|$ versus flux transient frequency:



1) It can be seen that the uncompensated V detector response (F_{PA} = 1.00) models the flux adequately up to about 0.001 Hz, a response time of about 16 minutes. For faster flux transients it under-responds.

2) The first-order compensator (F_{PA} = 0.00) models the flux adequately up to about 0.01 Hz, a response time of about 100 seconds. For faster flux transients it over-compensates the response.

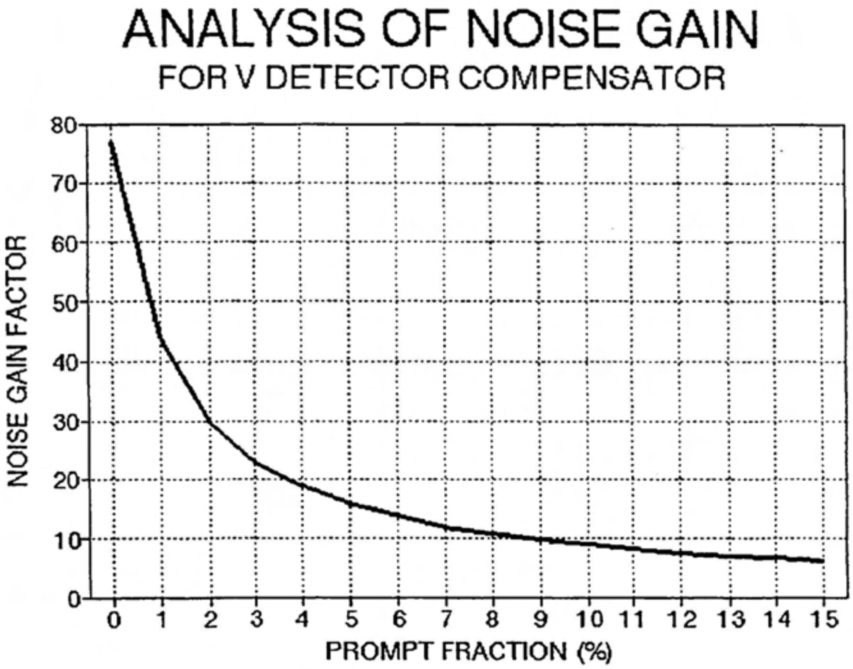
3) The prompt-compensated response (F_{PA} = F_P) models the flux reasonably well at all transient frequencies and is a flat line at 1.00. Any error in the prompt fraction causes the compensator to under(over)-estimate high-frequency flux transients by a ratio of F_P/F_{PA}. For this reason it is important that the correct prompt fraction is used.

8.0 Preliminary Noise Analysis

A preliminary analysis was conducted to assess the effects of noise propagation through the V detector compensator. Below is the process:

1) Run random noise through the compensator with a steady-state detector signal.
2) Compute the standard deviation of the input and output noise.
3) Compute a noise gain factor = STD[output noise] / STD[input noise].

Below is a plot of the compensator noise gain factor versus the prompt fraction of the compensator for a steady-state detector signal.



Since the detector prompt fractions will be in the range of 5-10%, the noise gain will be about 10. It is expected that the mapping itself should filter out much of this noise.

9.0 Application

This V detector compensation scheme will be introduced and tested in MICROMAP, an on-line fluxmapping program currently being developed at PLGS. MICROMAP will be coded and installed on the Control Room PC to provide operations with mapping capabilities that are not available with the on-line fluxmapping program (FLX). This includes:

- mapping with an updated rippled fundamental fluxshape
- allowing any number of fluxshapes to be used for mapping
- using burn-up corrected vanadium readings
- computation of power limits based on channel-specific and bundle-specific limits

With these features, MICROMAP can map off-nominal operations such as stuck rods and shim to provide best-estimate bundle and channel power calculations which will reduce the uncertainties in these parameters. This will allow the reactor bulk limits to be raised and reduce the likelihood of reactor poison-out events. Once V detector compensation is installed and validated, the MICROMAP program will model flux transients much faster. This will allow the Operator to react quickly to manage new flux-shapes.

10.0 Further Work to do

The above results suggest that an adequate compensation scheme has been derived using the prompt-compensation technique. Further work to be done before installing it in MICROMAP is:

- More analysis on the effects of noise and data corruption on the compensation algorithm.
- Analysis of the prompt components of the V detectors and LCs. This is scheduled to be done using high-speed data responses from a trip test in Sep 97.
- Quantification of the errors in mapped channel/bundle powers for setting operating limits.
- Analysis of limits for determining when the fast-map is bad, and using the slow-map as a back-up.

11.0 References

1) John Handbury, "Analysis of Lead Cable Prompt Responses", Presented at CNS Symposium, Jun 97.

2) Stuart Craig, "Compensated Vanadium SPFD Transfer Function", AECL report, 17 Oct 96.

Appendix 1 - Calculation of Quantization Correction Factor F_{corr}, $(dV/dt)/(\Delta V/\Delta t)$

By computing a correction factor, $F_{corr} = (dV/dt)/(\Delta V/\Delta t)$, the V detector compensator can be corrected for the digital data sampling rate. Below is an analysis for the first-order compensator which can also be applied to the prompt-compensator.

1) Calculation of dV/dt:

$$\Phi = V(t) + T_v \frac{dV(t)}{dt} \qquad \textbf{(first-order compensator)}$$

thus,

$$\frac{dV}{dt} = \frac{(\Phi - V)}{T_v} \qquad \textbf{(1)}$$

2) Calculation of ΔV/Δt

Rearranging Equation (1),

$$-\frac{dt}{T_v} = \frac{dV(t)}{(V(t)-\Phi)}$$

integrating from (t-Δt) to t,

$$\int_{t-\Delta t}^{t} \frac{-dt}{T_v} = \int_{V(t-\Delta t)}^{V(t)} \frac{dV}{(V-\Phi)}$$

assume flux Φ has re-stabilized and is constant,

$$\frac{-\Delta t}{T_v} = \ln\left[\frac{V(t)-\Phi}{V(t-\Delta t)-\Phi}\right]$$

therefore,

$$V(t)-V(t-\Delta t) = \Delta V = V(t) - [V(t)-\Phi]\, e^{\frac{-\Delta t}{T_v}} - \Phi$$

dividing by Δt and rearranging,

$$\frac{\Delta V}{\Delta t} = \frac{(1-e^{\frac{\Delta t}{T_v}})(V-\Phi)}{\Delta t} \qquad \textbf{(2)}$$

Appendix 1 - Calculation of Quantization Correction Factor F_{corr} (CONT'D)

3) Calculation of Correction Factor $F_{corr} = (dV/dt)/(\Delta V/\Delta t)$

Equation (1) divided by Equation (2),

$$F_{corr} = \frac{\dfrac{dV}{dt}}{\dfrac{\Delta V}{\Delta t}} = \frac{\dfrac{(\Phi - V)}{T_v}}{\dfrac{(\Phi - V)(e^{\frac{\Delta t}{T_v}} - 1)}{\Delta t}}$$

Dividing by (Φ-V) and rearranging (assuming V doesn't equal Φ),

$$F_{corr} = \frac{\Delta t}{T_v(e^{\frac{\Delta t}{T_v}} - 1)}$$

For Δt = 6 seconds, F_{corr} = 0.9908

Therefore the new first-order V detector correction equation for 6-second sampling is:

$$\Phi = V(t) + F_{corr}\, T_v \frac{\Delta V}{\Delta t}$$

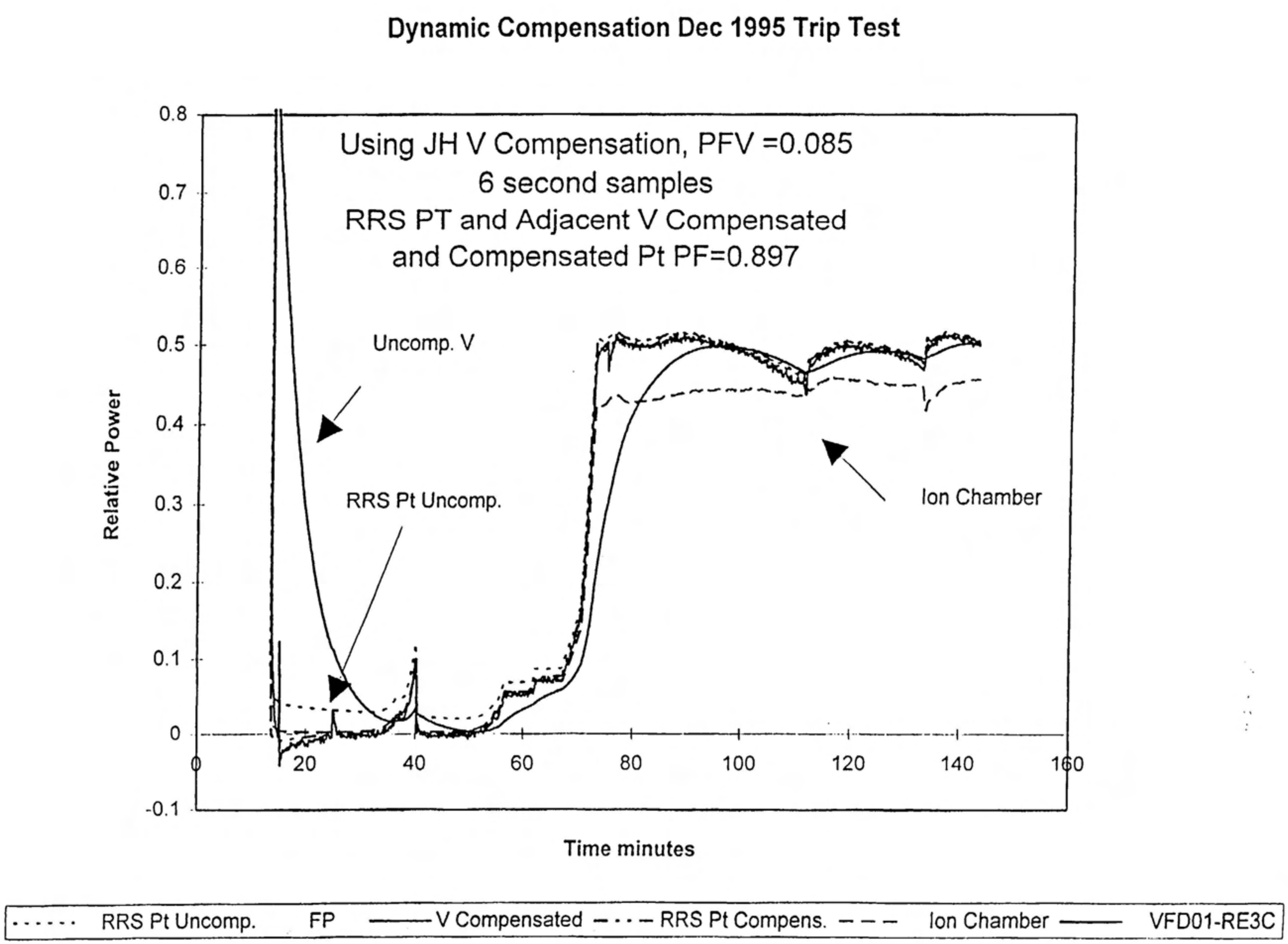
$$\Phi = V(t) + 322.4 \frac{\Delta V}{\Delta t}$$

Assuming this can be extended to the prompt-compensator, we conclude:

$$\Phi = V(t) + 322.4 \frac{\Delta V}{\Delta t} - T_V F_P \frac{\Delta \Phi}{\Delta t}$$

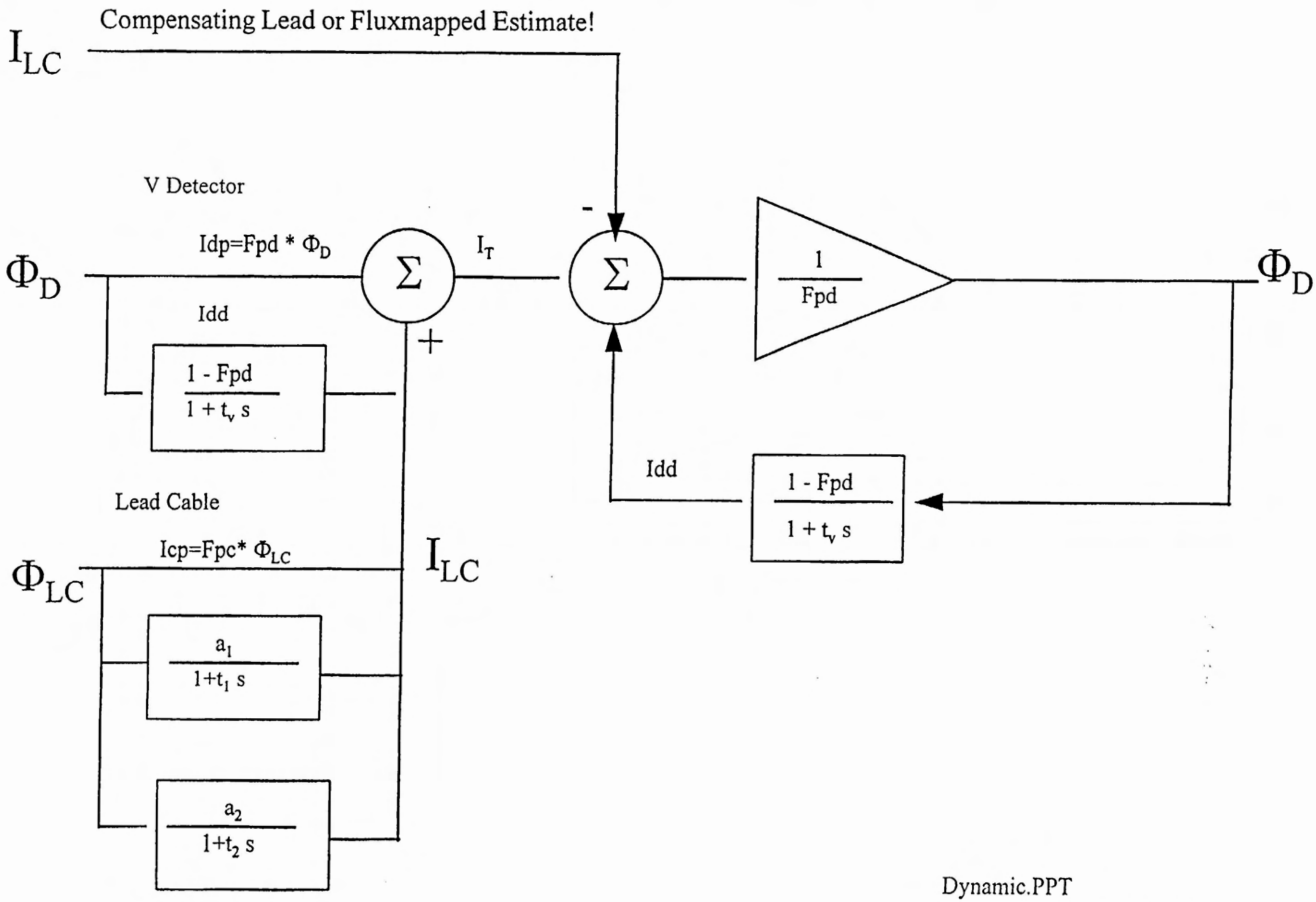
This corrected compensator has been tested during trip tests and been shown to improve the compensated V responses.

FIGURE 1


Dynamic Compensation Dec 1995 Trip Test
Using JH V Compensation, PFV =0.085
6 second samples
RRS PT and Adjacent V Compensated
and Compensated Pt PF=0.897
Uncomp. V
RRS Pt Uncomp.
Ion Chamber
Relative Power
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
20
40
60
80
100
120
140
160
Time minutes
RRS Pt Uncomp.
FP
V Compensated
RRS Pt Compens.
Ion Chamber
VFD01-RE3C

FI E 2

"Ideal" Two "Wire" Compensated V Loop



Dynamic.PPT
By: C. Newman PLGS 1997