Progress in Nuclear Energy 83 (2015) 177–185

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

A comparison of traditional and hybrid radiation detector dead-time models and detector behavior

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ARTICLE INFO

Article history:
Received 26 February 2015
Received in revised form
20 March 2015
Accepted 21 March 2015
Available online 11 April 2015

Keywords:
Dead-time
Paralyzing
Non-paralyzing
Hybrid dead-time model
High intensity measurements

ABSTRACT

High intensity radiation measurements are confounded by detector dead-time and pulse pile-up problems. A computational method was used to compare the traditional dead-time models with recently proposed hybrid dead-time models. A computational algorithm based on a decay source method was used to study the behavior of various dead-time models. Validation of the code was performed for the hybrid models by confirming that the predictions lie between the two ideal dead-time models; the paralyzing and the non-paralyzing model. It was interesting to note that two seemingly similar hybrid dead-time models produced significantly different results. Lee and Gardner's model based on two dead-times and Patil and Usman paralysis factor based model are inherently different in their logic as well as results. For Lee and Gardner's model altering the orders of dead-times produced significantly different response. These hybrid models should be studied further to investigate both the dependence and the variation of model parameters on detector design and operating conditions. It is well accepted that one dead-time does not apply to all detectors and even for the same detector applicability of the same model under all operating condition is questionable. Therefore, dead-time model should be chosen carefully for the specific detector, operating conditions and radiation to be measured to correctly represent the physical measurement phenomenon.

1. Introduction

Radiation detection is a process starting from interaction of radiation in detector producing pulses which then pass through various signal processing modules (pre-amplifier, amplifier, discriminator, and counter) and finally recorded by the counter or Multichannel Analyzer as shown in Fig. 1. Every pulse processing device needs a minimum amount of time to process the signal. Thus, the device is unavailable for some duration of time. The amount of time for which a device is unable to process a new signal or the minimum time that must separate two detectable events (Knoll, 2010) is known as dead-time.

Detector dead-time has been an area of active research since the inception of radiation detection. Dead-time phenomenon is significant in radiation detection, particularly at high intensity radiation (e.g., spent fuel monitoring and spectroscopy, medical application etc.). Researchers have been working for decades to formulate a generalized mathematical relation for dead-time that could be used to correct the measured counts. Akyurek et al. (2015) recently reported GM counter's dead-time dependence on the operating voltage, temperature and even the age of the detector. Therefore, the efforts for a generalized model to fit all detectors under all operating conditions may not have good scientific foundation.

A radiation detection system contains two types of elements that contribute to total dead-time; the detector's physical dead-time and the system's pulse processing dead–time. For gas filled detectors, the largest dead-time contribution comes from the detector itself (Tsoulfanidis and Landsberger, 2012). For GM counter, a pulse is generated due to radiation interaction and ionization of the gas. The pulse must now pass through a series of instruments before being recorded. Every individual instrument has its own characteristics dead-time to process these pulses but the value of the electronic dead-time is negligible as compared to the GM dead-time and hence can be neglected.

The Nuclear Instrumentation Modules (NIM) can typically be used to obtain two types of information; the count rate, or the pulse's height distribution information (spectroscopy application).

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http://dx.doi.org/10.1016/j.pnucene.2015.03.018

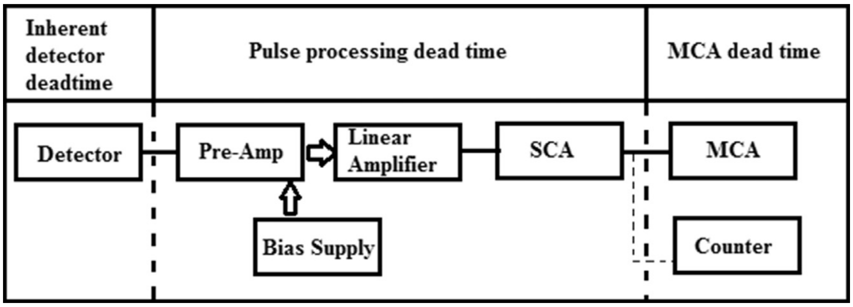

Fig. 1. Radiation detection system showing all instruments in an NIM.

Pulse pile-up also plays a significant role in count losses, where the collected charge is the partial sum of the two individual events rather than the second pulse being lost with no impact on the shape and/or size of the recorded pulse. Pomme (2007) provided a detailed explanation of the phenomenon of pulse pile-up in radiation detection.

First mathematical relation for dead-time was formulated by Feller (1948) and Evans (1955) which is known as non-extending or non-paralyzable dead-time model. For non-paralyzable dead-time model, the observed count rate is;

$$m = \frac{n}{1 + n\tau} \tag{1}$$

Feller (1948) and Evans (1955) derived a type II formula for extendable or paralyzable model which is based on the assumption that any event occurred during the dead-time will extend dead-time. For this case, a relationship between the true and measured count rate is given by;

$$m = ne^{-n\tau} \tag{2}$$

No real world detector exactly follows any one of these ideal models. The reality is always somewhere in between these two extremes (Lee and Gardner, 2000). These ideal models should be considered as a mathematical convenience rather than a phenomenological representation of dead-time.

Dead-time correction methods are proposed to extend the useful range of operation of radiation detector as suggested by Lee and Gardner (2000). Alber and Nelson (1953) proposed a probability-based model to estimate the dead-time losses. They assumed that the dead-time would be extended within a probability of p. Gardner and Liu (Gardner and Liu, 1997) derived a modified dead-time model which was introduced for a paralyzable model;

$$\tau = an^b \tag{3}$$

where a and b are either constants or fitting parameters that are specific for a given GM counting system. All of these models successfully extended counting range of GM detector but only to some extent (Gardner and Liu, 1997).

Müller (1973) proposed several dead-time models by combining the two dead-times and using different permutation of their orders. Lee and Gardner (2000) recently attempted to extend GM detector's counting range by using a hybrid dead-time model that combines two idealized models into one mathematical relation;

$$m = \frac{ne^{-n\tau_P}}{1 + n\tau_{np}} \tag{4}$$

This expression is similar to the one given by Müller (1973). This hybrid formulation combines paralyzing and non-paralyzing dead-time models into a single analytical expression (Lee and Gardner, 2000). Lee and Gardner assumed a non-paralyzing dead-time as a physical dead-time of detector which depends on physical characteristics of detector. This almost constant non-paralyzing dead-time is followed by a paralyzable dead-time till the point when a pulse of recordable amplitude is produced. Thus paralyzable dead-time depends on the detection system's discriminator level setting, see Fig. 2. Any pulse generated in the detector below a certain discrimination level will not be detected unless the amplitude of the pulse is higher than the discriminator setting. The paralyzing portion of the dead-time depends on both the discrimination level and the pulse processing electronics. Lee and Gardner (Lee and Gardner, 2000) used the decay source method to validate their model. They reported an agreement within 5% of the true count rate up to a count rate of 3×10^4 counts per second. However, they did not justify their choice of the dead-time orders (putting a non–paralyzable dead-time before a paralyzable dead-time). A modified two-source method was required because the traditional two-source method can only provide one parameter; that is, dead-time (either paralyzable or non-paralyzable) (Lee et al., 2004).

Patil and Usman (2009) recently proposed another hybrid dead-time model, which is essentially a modified form of Müller's model (Müller, 1973). They proposed a probability-based paralysis factor f. They also claimed better accuracy with their approach of using a single dead-time and a paralysis factor. This paralysis factor is defined as the probability of paralyzing a detector system. The probability lies between 0 and 1 therefore, the model also satisfies the two idealized dead-time models as the asymptotic cases. For example, if a paralysis factor is zero (no paralysis), their hybrid equation reduces to non-paralyzing model (Patil and Usman, 2009). Mathematically, the measured count rate is given by;

$$m = \frac{ne^{-n\tau f}}{1 + n\tau(1 - f)} \tag{5}$$

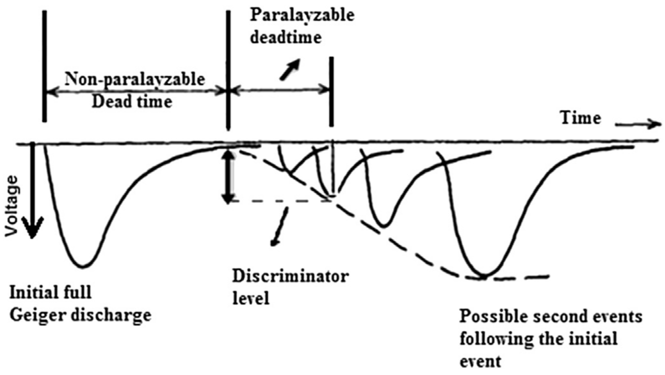

Fig. 2. Lee and Gardner's hybrid dead-time model.