Paper

Random Pulser for Use as a Pulse Train Simulator

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A mean rate controllable random pulser to use for a random pulse train simulator is presented in this paper. The control of the men rate is practiced with a personal computer by referring to the look-up table of time-variant rate. The random pulser with present design can be used as a model to simulate the random pulses delivered from detectors being exposed to a source which provides time-variant events. In practice an attempt was exercised to the partial discharge detection system which was used to predict the electrical breakdown of an insulator.

Keywords: random pulser, time interval distribution, M-sequence, TLP random number, personal computer

1. Introduciton

Various types of RPs(Random Pulsers) have been proposed so far to apply them for the correction of counting experiments[(1)-(5)], to test counting instruments[(2),(6)-(21)], or to simulate a phenomenon whose property is random in nature[(5),(22)-(26)]. One type of the RPs utilizes physical sources such as an avalanche noise in a p-n junction[(2),(6)-(9),(12),(13),(15),(16),(23)], thermal noise[(27),(28)] or signals delivered from a photon counting unit[(11),(17)]. Another type makes use of an artificial randomness, namely an algorithm consisting of an LFSR(Linear Feedback Shift Register) which can generate a PRBS(Pseudo Random Bit Sequence)[(1),(5),(20),(21),(24)-(26),(29)-(34)] or the algorithm[(10),(35),(36)] different from the LFSR. In terms of randomness the RPs driven by physical sources are superior to those driven by PRBSs in that the physical phenomenon concerned is truly random. And, in addition to the randomness, high rate is easily achieved with the RPs utilizing physical sources[(2),(7),(9),(11),(13),(16),(18)]. In spite of this superiority the PRBSG(PRBS Generator) is frequently used. This is because the randomness provided by the PRBSG is property-known and reproducible[(37)-(46)], whereas that provided with the physical source is sometimes exposed to a distortion caused by the operation condition of the electronics[(2),(7),(8)]. In a case the source itself distorts the randomness[(13),(17)]. In an application the disadvantage of the RP with a PRBSG may be avoided when the period of the PRBS is set long with high speed IC(Integrated Circuit) under current technology[(20),(25)].

Algorithms to produce a PRBS using a hardware logic have so far been proposed[(5),(21),(24),(25),(31),(41),(42),(44)-(47)]. The convenient algorithm to obtain a PRBS was discovered by Tausworthe[(39)]. Although the T-algorithm(Tausworthe algorithm) provides a good randomness, such a shortcomings appeared that a random number was not generated every one clock when a direct realization was attempted by a hardware algorithm[(41)]. In order to remove the shortcomings, a clever architecture was proposed and the every-one-clock generation of the T-algorithm RN(Random Number) became realized[(42),(43)]. The proposal, however, laid a hardware burden on the construction of the RP system because N LFSRs were required to make N-tuple RN and, in addition, N CMPs(comparators) were also needed to produce a TI(Time Interval) which obeys an exponential distribution. There was another example of a RP which successfully realized an M-sequence(Maximum-length sequence) PRBSG[(31)]. However, this also required a hardware burden of using N LFSRs to obtain the N-tuple RN. In actual construction, the reduction of the hardware burden is important. Therefore, we made an attempt to develop a RP system with less hardware burden and less deterioration of the RN. The solution was to employ the TLP(Tausworthe-Lewis-Payne) algorithm[(40)] by which one can obtain the T-algorithm RN with the every-one-clock operation. The point is to use N delayed M-sequences originated from a parent LFSR in order to generate an N-tuple RN. Since a delayed M-sequence is built only by a set of EOR(Exclusive OR) gates[(38)], the hardware burden is lessened and the circuit design becomes simpler than that of conventionally proposed RP system. Within our survey, no construction examples were seen on the direct hardware realization of the TLP algorithm. Although the idea using a CMP to generate an exponentially distributed TI is the same with the models having been reported so far[(31),(43)], our system which can reduce the hardware burden has definitely an advantage.

The principal purpose of our proposal is to construct a RPT(Random Pulse Train) simulator which furnishes a time-variant occurrence rate. Certainly, most of the reported models can set various occurrence rates. However, they cannot provide a continuous variation of the rates but merely can set them. In our setup, an arbitrary variation of the occurrence rate, still approximately though, can be provided by a computer control. This also is an advantage to the conventionally reported RP system.

The output of the presently-proposed RP is that of the TTL level. The minimum interval between pulses of the RPT is determined by the clock frequency f_{CLK} employed. In our setup the maximum frequency f_{CLK}=16.8 MHz produced by a quartz determines the minimum interval 60 ns. Maximum mean rate without a randomness deterioration, however, is limited up to 5.3×10^5cps due to the principle of the present model. Since our principal purpose is to construct a RPT simulator in the time domain, the RP output is prepared exclusively to the TTL level, whereas models having been capable of providing an arbitrary pulse shape[34] or tail pulse[2],[9] have already been reported. Some can either furnish a two-dimensional randomness[5],[6],[14],[19],[24],[33],[36], namely random pulse heights and random TIs.

2. Operation Principle

Only temporal randomness is required in our model. This results in a RPT whose TID(Time Interval Distribution) becomes exponential because the RPT scheduled for our simulation is the outcome of a Poisson-random source. In order to obtain an exponentially distributed TI, a comparator combined parallel with an N-bit PRBS is introduced[20],[21],[24],[29],[31]. The N-bit PRBS is constructed from an n-bit LFSR. When the LFSR is driven by a clock, it acts as a PRBSG.

2.1 Construction principle of a PRBSG

To obtain a series of N-tuple random numbers, such an N-bit PRBS is arranged from an n-bit LFSR as illustrated in Fig.1. The n-bit LFSR is a hardware realization of an n-th order M-sequence $\{a_{i+j} : j=0,1,\cdots,n\text{-}1\}$. The LFSR in Fig.1 is implemented according to the primitive trinomial[48]

$$f(x)=\sum_{j=0}^{n} f_j x_j = x^{31}+x^{13}+1 \quad \cdots\cdots\cdots\cdots\cdots\cdots \ (1)$$

where n=31. The N-bit PRBS in Fig.1, in case constructed from the n-th order $\{a_{i+j} : j=0,1,\cdots,n\text{-}1\}$ according to the TLP algorithm[39],[40], is the realization of the delayed M-sequence

$$\{a_i, a_{i+d}, \cdots, a_{i+Ld}, \cdots, a_{i+(N-1)d}\} \quad \cdots\cdots\cdots\cdots\cdots \ (2)$$

where d expresses a delay in the LFSR. In our arrangement N=10 and d=13 are furnished. The condition n=31, N=10, and d=13 satisfies $\{N<n,\ d>N\}$ which insures the TLP RN production. The period of the RN is sufficient to our current request of using the RP as a RPT simulator. The hardware algorithm we proposed uses only one parent LFSR and a set of delayed M-sequences derived from the LFSR. Our proposal is the direct representation of the TLP algorithm. No other examples of the TLP algorithm realization were found within our survey. With the condition above, the numbers of IC elements become saved and it enables the mounting on only one wiring board.

Each a_{i+Ld} is provided from the delay $x^{Ld}a_i$ and corresponding x^{Ld} is determined[38] from original $f(x)$ above. With regard to $x^{Ld}=x^{3d}=x^{39}$, for example, the delayed M-sequences $\{a_{i+3d}\}$ becomes

$$x^{39}=x^{21}\oplus x^{8} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \ (3)$$

where $\oplus$ in eq.(3) expresses a modulo 2 addition whose hardware description is an EOR drawn in Fig.1. The

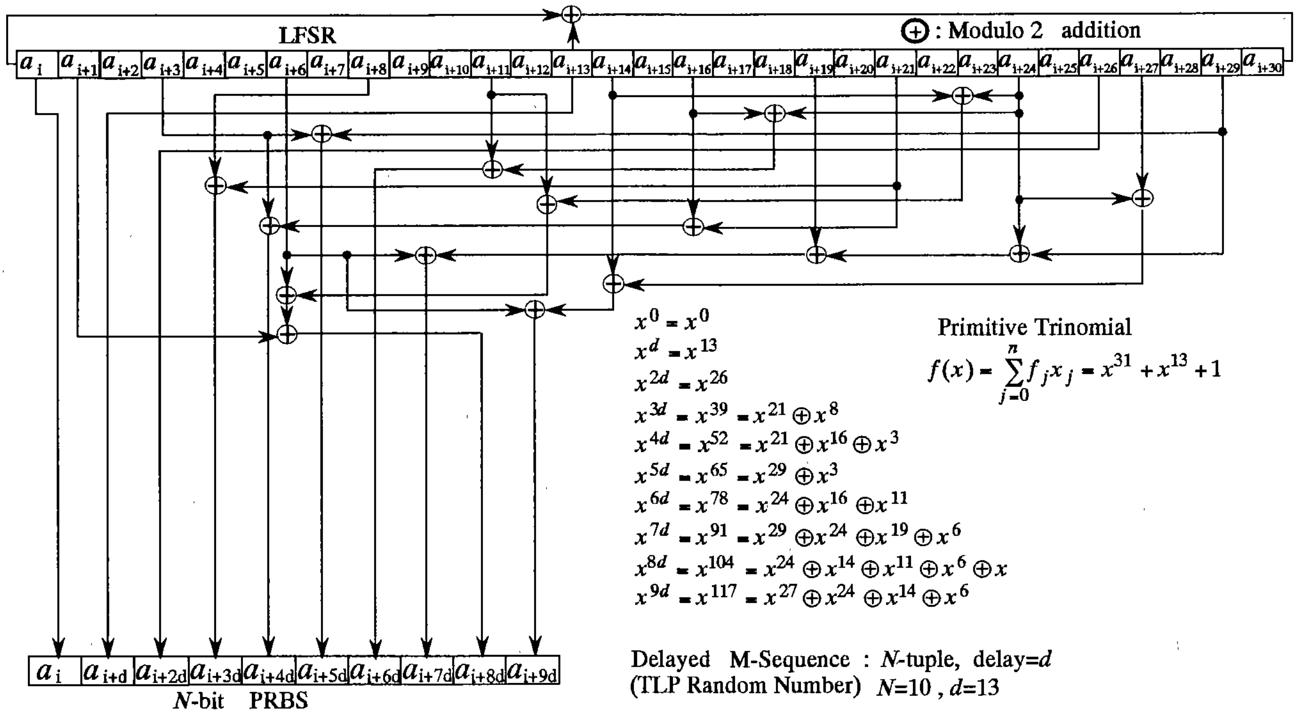


Fig.1 the scheme to obtain an N-bit Tausworthe-Lewis-Payne(TLP) PRBS from an n-bit LFSR. The N-bit PRBS is generated through N sets of delayed M-sequences derived form the original M-sequence.

expressions for the rest of the x^{Ld} are represented in Fig.1. A set of delayed M-sequence $\{a_{i+Ld} : L=0,1,\cdots,N\text{-}1\}$ arranged as in Fig.1 is generated every one clock, thus constituting the N-bit PRBS.

2.2 Evaluation of the TID determined by the PRBSG

As described in Fig.2, the N-bit comparator provides an exponentially distributed TID when it is combined parallel with the N-bit PRBSG. Below is the outlined description.

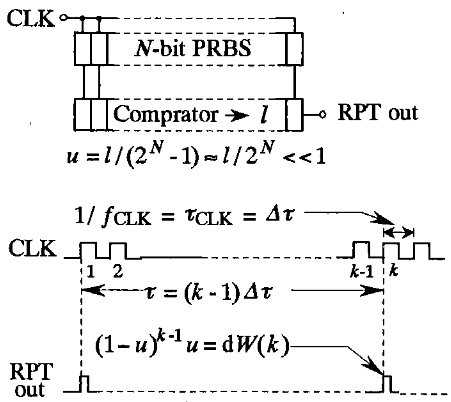


Fig.2 The explanation how the time interval becomes an exponential distribution by the combination of the PRBS and the comparator.

In case the comparator is arranged to output a pulse when

$$b_{\mathrm{PRBS}} < l \quad \cdots\cdots (4)$$

where b_{PRBS} is the bit magnitude of the PRBS and l is a predetermined value, then the probability u that a pulse is sent out of the comparator against one clock is

$$u = l/(2^{N-1}) \approx l/2^N \quad \cdots\cdots (5)$$

For the present purpose u in eq.(5) is so provided that

$$u \ll 1 \quad \cdots\cdots (6)$$

The probability $dW(k)$ that a random pulse occurs after k clock duration from the preceding pulse is expressed as

$$dW(k) = (1-u)(1-u)\cdots(1-u)u = (1-u)^{k-1}u \quad \cdots (7)$$

Under the condition in eq.(6)

$$\begin{aligned} dW(k) &= (1-u)^{k-1}u \\ &= \left\{(1-u)^{1/(-u)}\right\}^{-u(k-1)}u \\ &\approx \exp\{-u(k-1)\}u \end{aligned} \quad \cdots\cdots (8)$$

The mean $<k>$ of k becomes, by using eq.(7)

$$<k> = \sum_{k=1}^{\infty} k\,dW(k) = 1/u \quad \cdots\cdots (9)$$

When the clock interval τ_{CLK} determined by

$$\tau_{\mathrm{CLK}} = 1/f_{\mathrm{CLK}} \quad \cdots\cdots (10)$$

is interpreted as a small TI $\Delta\tau$, then

$$\Delta\tau = \tau_{\mathrm{CLK}} = 1/f_{\mathrm{CLK}} \quad \cdots\cdots (11)$$

A mean rate f_0 of the RP is represented by a mean interval τ_{M} as

$$f_0 = 1/\tau_{\mathrm{M}} \quad \cdots\cdots (12)$$

Combining τ_{M} in eq.(12) with $<k>$ in eq.(9), the relation

$$\tau_{\mathrm{M}} = <k>\Delta\tau = \Delta\tau/u \quad \cdots\cdots (13)$$

holds. An arbitrary TI τ is so defined as

$$\tau = (k-1)\Delta\tau \quad \cdots\cdots (14)$$

Since the following expression is obtained by using eqs.(13) and (14)

$$u(k-1) = u \times \tau/\Delta\tau = \tau/\tau_{\mathrm{M}} = f_0\tau \quad \cdots\cdots (15)$$

the probability $dW(k)$ in eq.(8) finally reaches

$$\begin{aligned} dW(k) &= \exp(-f_0\tau)u \\ &= \exp(-f_0\tau)\Delta\tau/\tau_{\mathrm{M}} \\ &= f_0\exp(-f_0\tau)\Delta\tau = dW(\tau) \end{aligned} \quad \cdots\cdots (16)$$

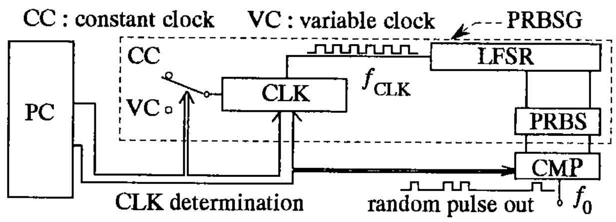
by referring to eqs.(12) and (13). Equation (16) is the familiar expression for the TID obtained from a Poisson-random source. The mean rate f_0 is also expressed as

$$f_0 = 1/\tau_{\mathrm{M}} = u/\Delta\tau = u/\tau_{\mathrm{CLK}} = u \times f_{\mathrm{CLK}} \quad \cdots\cdots (17)$$

The fact must be kept in mind that the TID realized above is not a continuous distribution but essentially a discrete one. In case the TI resolution $\Delta\tau = \tau_{\mathrm{CLK}} = 1/f_{\mathrm{CLK}}$ is high enough, the RPT can be used as a simulator source of a continuous event. With the maximum f_{CLK}=16.8 MHz, the resolution or the minimum interval of our RP reaches 60 ns.

3. RP Performance

Conceptual operation of the RP is schematically represented in Fig.3. The clock frequency f_{CLK} is provided by a quartz-based CLK(Clock generator), and f_{CLK} can be set 1 Hz through 16.8 MHz with the PC. The PC also furnishes a CC(Constant Clock) or a VC(Variable Clock) to the CLK.



Fgi.3 The block diagram illustrating the conception of generating the random pulse train by the PRBSG whose clock is controlled by a personal computer.

3.1 Performance under constant mean rate

In our setup the mean rate f_0 is theoretically determined, according to eq.(17), by two parameters f_{CLK} and u. Since u can be set arbitrarily between 1 and $2^{N\text{-}1}$, f_0 can also be arbitrarily set by u as well as by f_{CLK}. The result of f_0

variation either by f_{CLK} or by u is represented in Fig.4 or in Fig.5. Both in Fig.4 and Fig.5, the theoretical mean rate f_0 is represented by full lines. Dot expresses the measured mean rate n_0.

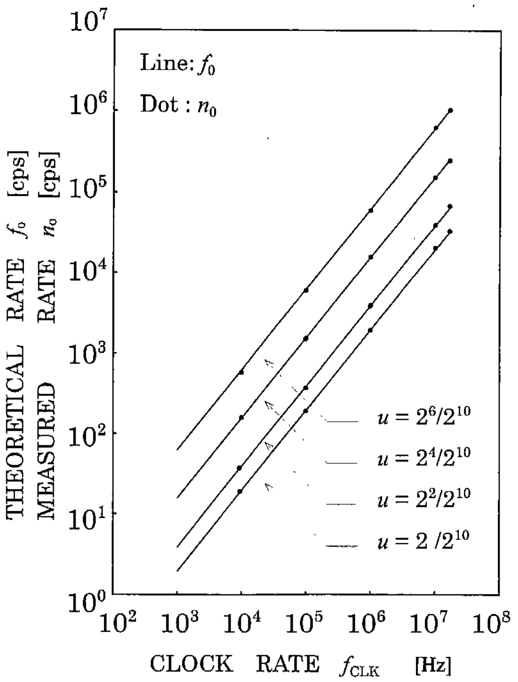


Fig.4 The result of the comparison between the theoretical and the measured count rate under the constant probability u of the pulse occurrence against one clock as explained in Fig. 2. Count rate variation is achieved by the clock rate variation.

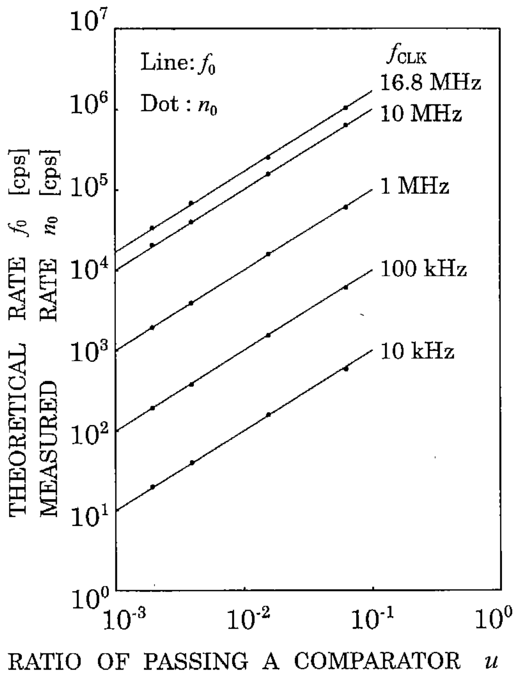


Fig.5 The result of the comparison between the theoretical and the measured count rate under the constant clock rate. Count rate variation is achieved by the u variation.

In Fig.4 the theory agrees with the experiment under various u. The agreement between f_0 and n_0 under various f_{CLK} settings is the same as well in Fig.5. This seems, at a glance, that we may employ either parameter, f_{CLK} or u, to provide arbitrary f_0 in the RP. Definite attention, however, must be paid to the fact that a trade-off exists in whether f_{CLK} or u is chosen.

With respect to u, a limitation is imposed on its magnitude as in eq.(6), namely $u<<1$. If u does not satisfy that condition, then the TID of the RPT deviates from the exponential distribution $dW(\tau)$ in eq. (16). This is investigated by evaluating various sets of experimentally obtained $dW(\tau)$. One of the examples is represented in Fig.6 which expresses the TID under various u. All examples showed exponential distributions. A χ^2-test also insured the fit of the experimental TID to the theoretical $dW(\tau)$ for such u as

$$u<2^5/2^N=2^5/2^{10} \quad \cdots\cdots (18)$$

Concerning f_{CLK}, a limitation is placed in terms of the TI resolution. This means, as has already been pointed out[31], that an unnecessarily low f_{CLK} is not favorable. A criterion governing the f_{CLK} limitation, for example, is prescribed by the resolution R_{CLK} in connection with the dead period d_τ of the outcome to be simulated. If R_{CLK} is defined as

$$R_{CLK}=\Delta\tau/d_\tau=\tau_{CLK}/d_\tau=1/f_{CLK}d_\tau \quad \cdots\cdots (19)$$

then such an R_{CLK} as

$$R_{CLK}=\varepsilon_{RSLN} \quad \cdots\cdots (20)$$

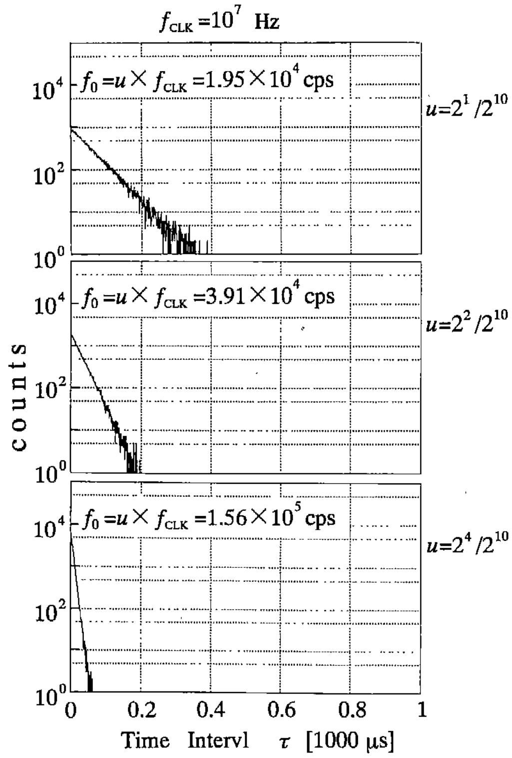


Fig.6 The TID of the random pulse train under the constant clock frequency. The mean rate variation is set by the pulse occurrence probability.

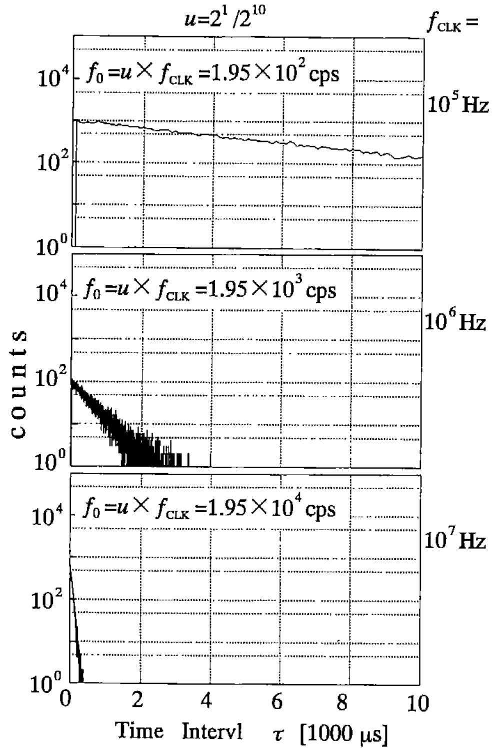


Fig.7 The TID of the random pulse train under the constant u, the pulse occurrence probability. The mean rate variation is set by the clock frequency.

determines the lower limit of f_{CLK}, namely

$$f_{CLK} \geq 1/d_{\tau}\varepsilon_{RSLN} \qquad (21)$$

The TID examples obtained under various f_{CLK} are represented in Fig.7. Actually the TID curve drawn by polygonal lines consists of line spectra as described in eq.(8). The width between spectra is seen in Fig.7 for the case $f_{CLK}=10^5$ Hz as the discrepancy between the rise of the TID curve and the ordinate.

3.2 Performance under time-variant mean rate

In case a time-variant mean rate $\lambda(\tau)$ is introduced, a generalization in order to treat nonstationary Poissson processes is required. Although one instance[15] which provides a time-variant mean rate was found within our survey, it only could provide a linear variation. In the present paper an arbitrary variation is treated as generalized $\lambda(\tau)$.

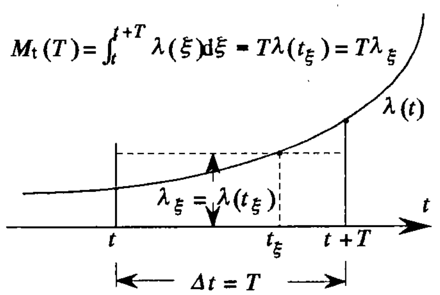


Fig.8 The method to prepare a time-variant mean rate by applying the first mean theorem of the integral.

Let $\lambda(\tau)$ be that illustrated in Fig.8, and let us introduce such mean value functions as

$$m(t)=\int_0^t \lambda(\xi)d\xi \qquad (22)$$

and

$$M_t(T)=m(t+T)-m(t) \qquad (23)$$
$$=\int_t^{t+T}\lambda(\xi)d\xi \qquad (24)$$

where T is regarded as a small time $\Delta t=T$. Then $W_r(t, t+T)$, the probability which dominates the occurrence of r pulses between $[t, t+T]$, is determined by a counting process $R(t)$[49],[50] as

$$W_r(t, t+T)=\mathrm{Prob}\{R(t+T)-R(t)=r\} \qquad (25)$$
$$=\{M_t(T)\}^r\exp\{-M_t(T)\}/r! \qquad (26)$$

When such $\lambda_\xi=\lambda(t_\xi)$ and t_ξ as

$$M_t(T)=\int_t^{t+T}\lambda(\xi)d\xi = T\lambda(t_\xi)=T\lambda_\xi \qquad (27)$$

is prepared according to the first mean value theorem, then $W_r(t, t+T)$ in eq.(26) is equivalent, in an average, to

$$W_r(t, t+T)=\{\lambda_\xi T\}^r\exp\{\lambda_\xi T\}/r! \qquad (28)$$

which provides a basis to realize the time dependent RPT. A series of $\{(\lambda_{\xi i}, t_{\xi i})\ ;\ i=0,1,\cdots\}$ over the duration concerned is prepared as a LUT(Look-Up Table). Time-variant mean rate $\lambda_{\xi i}$ is furnished in the PC as the LUT above. The implementation of each $\lambda_{\xi i}$ is practiced by f_{CLK} variation. This is performed by the PC as illustrated in Fig.3. The rate control can also be practiced by the u variation as well. Variable clock was chosen in the present setup because both the PC control and the hardware implementation were easy.

Realized examples of $\lambda_{\xi i}$ are represented in Fig.9, in which case the small time Δt is set to Δt=1 s. All of the set mean rates in these instances agreed with the observed mean rate $\lambda_{OBS}(t)$. Monotonously increasing cases are in Fig.9-(a) and (c), and in Fig.9-(b) and (d) are monotonously decreasing cases. The example in Fig.9-(d) is applicable to a relaxation process or to a nuclear disintegration[51], and that in Fig.9-(c) may be applied as a simulator, for example, to event which provides an increasing count rate.

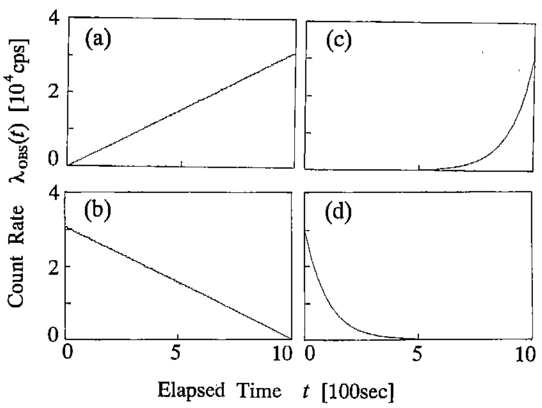


Fig.9 The various examples of the time-variant mean rate attempted.

3.3 Operation as a simulator

The results described in section 3.2 render a basis to apply the RP as a RPT simulator for events resulting in both increasing and decreasing time-variant count rate. An application example is represented in Fig.10, in which is drawn the count rate variation along with the insulator deterioration process in a magnet relay exposed to an overcurrent flow[52]. In the insulator deterioration process, discharge pulses appear before the insulator reaches an electrical breakdown. Such pulses are called partial discharges[53]. They produce RPTs whose count rate become a time-variant $\lambda(t)$. Represented in Fig.10-(a) is the experimentally obtained count rate variation $\lambda(t)$, whereas that in Fig.10-(b) is the simulated and then observed RPT output $\lambda_{OBS}(t)$. It is seen in Fig.10 that $\lambda_{OBS}(t)$ agrees with $\lambda(t)$.

The small time Δt in this case was 1 s and u was fixed at $u=2^5/2^{10}$ which was the upper limit in terms of the fit with the χ^2-test. With our RP, f_{CLK} was variable 1 Hz through 16.8 MHz. Therefore, the variable range of f_0 without regard to the resolution R_{CLK} defined in eq.(19) was

$$1\ \text{Hz}\times 2^5/2^{10} < f_0 < 16.8\ \text{MHz}\times 2^5/2^{10}$$

that is

$$3.1\times 10^{-2}\ \text{cps} < f_0 < 5.3\times 10^5\ \text{cps} \qquad \cdots\cdots\cdots\cdots\cdots (29)$$

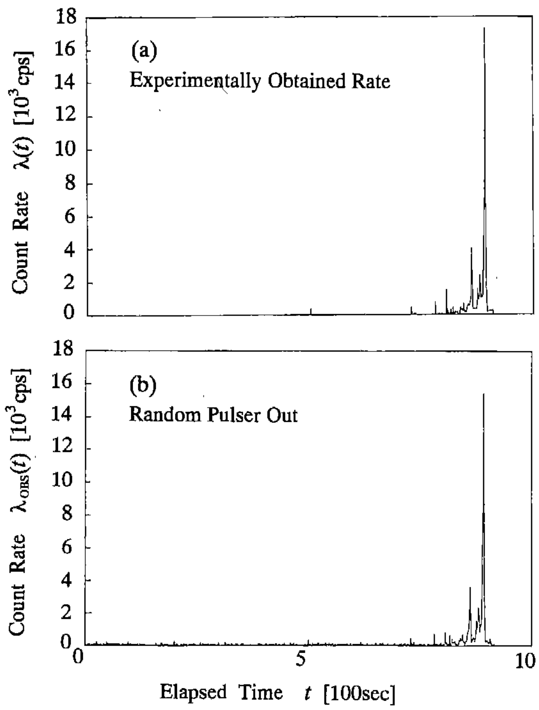


Fig.10 The application example of the time-variant mean rate to the temporal variation of the count rate of partial discharge pulses which are observed in the insulator deterioration processes.

However, a compromise must be taken between the resolution and the achievable range of f_0. The d_τ in eq.(19) in this instance is $d_\tau=d$, where d is the system dead period of the partial discharge setup. Since d in the setup is $d\geqq 50\mu\text{s}$, such a resolution, for example, satisfying eq.(20) as

$$R_{CLK}=\Delta\tau/d=\tau_{CLK}/d=1/(f_{CLK}\times d)\leqq \varepsilon_{RSLN}=0.1$$

provides

$$f_{CLK}\geqq 1/(d\times\varepsilon_{RSLN})=1/(50\mu\text{s}\times 0.1)=200\ \text{kHz}$$

The f_0 range determined by this limitation becomes

$$200\ \text{kHz}\times 2^5/2^{10} < f_0 < 16.8\ \text{MHz}\times 2^5/2^{10}$$

namely

$$6.3\times 10^3\ \text{cps} < f_0 < 5.3\times 10^5\ \text{cps} \qquad \cdots\cdots\cdots\cdots\cdots (30)$$

In a case where $\Delta\tau$ extension up to $\Delta\tau=d$ is tolerated, the rate range can be expanded up to

$$6.3\times 10^2\ \text{cps} < f_0 < 5.3\times 10^5\ \text{cps}$$

As long as the partial discharge pulses are concerned, the rate range in eq.(30) is sufficient. This is because the prediction of the insulator breakdown became critical around the count rate above[52]. However, the rate range extension

$$3.1\times 10^{-2}\ \text{cps} < f_0 < 5.3\times 10^5\ \text{cps}$$

described in eq.(29) is applicable to our partial discharge facility because the pulse occurrence successive to a pulse within the duration less than τ_{CLK} is negligible, in practice, in the low rate extreme.

4. Conclusion

The performance and the application example of the PC-controlled RP was described. The RP output was that of the TTL level and could provide such a temporal randomness that obeys an exponential distribution. The comparator combined with the PRBSG driven either by a CC(Constant Clock) or a VC(Variable Clock) could generate the RPT. The VC was controlled by the PC. With the CC the mean rate f_0 became constant enabling the RP to use as a stationary Poisson-random source. By the VC, in turn, a time-variant rate $\lambda(t)$ was realized. With this $\lambda(t)$, nonstationary Poisson process could be generated and this was used as a simulator for the partial discharge detection system which can predict the electrical breakdown of an insulator.

The mean rate $f_0=f_{CLK}\times u$ could be determined either by f_{CLK} or by u, where f_{CLK} is the clock frequency and u is the probability of a pulse occurrence against one clock. The f_0 variation was practiced by the f_{CLK} control in our RP because the control and the construction for the present model was easy with that. The quartz based clock range was 1 Hz$\leqq f_{CLK}\leqq$16.8 MHz and by having employed u with its upper limit $u=2^5/2^{10}$, the f_0 range attainable was 3.1×10^{-2} cps $< f_0 <$ 5.3×10^5 cps.

Acknowledgement

The authors are indebted their research work to Mr. K.

Miura, Mr. A. Okazaki, Mr. Y. Takahashi and to Mrs. M. Sugawara.
(Manuscript received October 24, 2000, revised July 2, 2001)

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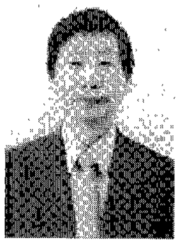

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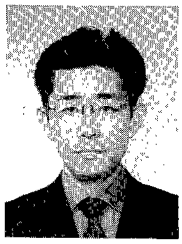

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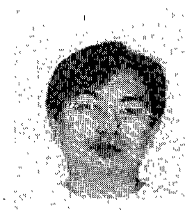

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