Determining the Best Frequency for Testing Protection, Automation and Control Systems

Iony Patriota de Siqueira
Tecnix Engenharia Arquitetura e Representação Ltda
iony@tecnix.com.br
Brazil

I. INTRODUCTION

Modern Protection, Control and Automation (PAC) Systems are built using digital technology, supported by layers of distributed software and communication networks. It is now possible to deliver many functions in a single IED (Intelligent Electronic Device), or distributed among several IEDs, monitored locally and remotely using the same technology. In the following, the term IED will be used to denote a single device or several devices making an entire PAC system, even if they are (non-intelligent) electromechanical devices.

The increase in the number of IED functions has enlarged the possibility of hidden failures and malfunctions, increasing the impact of recent blackouts around the world. Testing has been the traditional way to discover hidden failures. The addition of on-line monitoring and self-test raises the question about the real need for periodic testing, but may also result in additional hidden failures in on-line monitoring and self-test schemes. Testing continues to be the main preventive maintenance task for PAC systems. The assessment of its need and frequency may be of interest to many professionals:

- Technical personnel involved in planning, maintenance and operation of PAC systems.
- Utilities and insurance managers and technicians interested on economic and business consequences of major accidents in the electric industry.
- Environmental, financing and regulatory agencies and personnel, seeking legal and/or social safety assurance against large blackouts.

In this paper a statistical optimization methodology is proposed for the determination of test requirements and ideal frequency for PAC systems. Based on maintainability and reliability data usually available to electrical utilities, the method pursues the minimization of impacts of testing to the utility and their clients.

Besides this **Introduction**, the paper is organized in four more sections. The second section, **Modeling,** will propose a statistical model suited to simulate the stochastic behavior of an IED, including preventive and corrective tasks. This section will also show how the model can be parameterized based on relay historical data, to simulate the availability and performance of any IED, in transient and steady state. On the third section, **Optimization**, a strategic set of enterprise indexes will be defined and correlated with traditional performance indicators of power systems, using the model. Each index can be used as an objective function in a standard optimization problem, as a decision support model on IED testing. As a case study, on the **Application** section, tests conducted with the model by Companhia Hidro Elétrica do São Francisco (CHESF), the largest electric utility company in Brazil, will be reported with some proposed extensions. The last section, **Conclusion**, will summarize the results, and suggest further applications.

II. MODELING

Two main decisions a maintenance engineer has to take, regarding the prevention of IED or PAC hidden failures:

- Is it necessary to periodically test a PAC function?
- If necessary, at what frequency should it be tested?

To answer these questions, the following steps are proposed:

- Characterization of PAC systems;
- Definitions of failure modes of PAC systems;
- Probabilistic modeling of PAC systems;
- Identification of hidden failure rates of PAC systems;
- Estimation of consequences for each failure mode;
- Decision on the need of testing;
- Optimization of testing frequency.

To attain these steps, the following tools and data can be used:

- Failure history of protected equipment and PAC functions;
- Maintenance records and policies for PAC apparatus;
- Markov chains for modeling equipment and PAC functions;
- Mathematical modeling software to optimize the results.

An IED model must represent its dominant hidden failure mode and functional failure. The first is defined as the undetected event of the start of a functional degradation, also known as a defect; the second is the inability of the IED to supply its required function when requested. These two states can be better viewed in a graph (Fig. 1) relating the time evolution of an IED resistance to failure, where three states are identified:

- Normal – before a potential failure;
- Defect – between a potential and functional failure;
- Failure – after a functional failure.

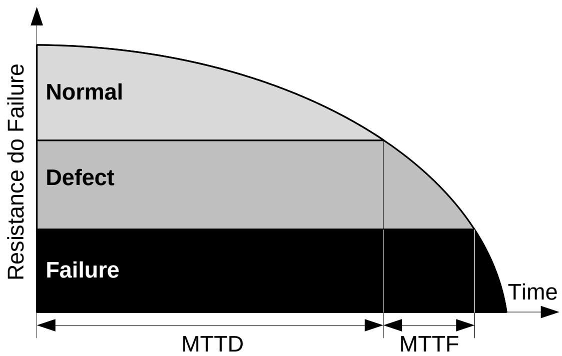

Fig. 1. IED Failure Resistance Curve

Besides these conditions, an IED can be found on a state of test or corrective maintenance. Following this line, five IED probable states can be defined, at any time:

- Normal – apt to play its function;
- Test – under preventive maintenance;
- Failure – unavailable, after a functional failure;
- Defect – available, but with a potential hidden failure;
- Corrective – under maintenance, due to potential failure.

The following events or actions can change an IED state:

- Test – programmed inspection or testing;
- Correct – programmed correction of a potential failure;
- Repair – forced correction after a functional failure;

- Defect – partial or potential functional (possibly hidden) degradation;
- Failure – functional failure due to a hidden defect.

An IED Failure usually results in a refusal to trip when demanded, or a needless trip in the absence of a fault. The term "Correct" refers to a planned event aiming to correct a known defect, before its evolution to a functional failure. It differs from a planned "Test" event (and state) when it is not known if there is a potential failure. These events trigger the transitions between the states as shown on the state diagram of Fig. 2.

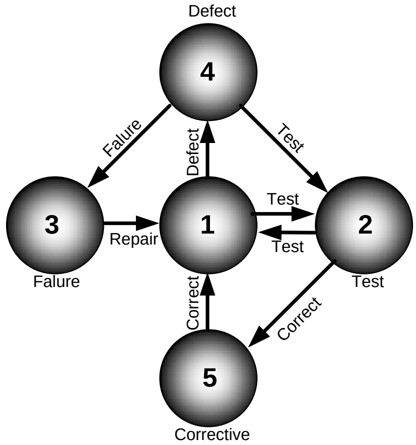

Fig. 2. IED State Model

Once there is a model, it is possible to apply Chapman-Kolmogorov [2,8] equations to quantify each state probability, with the numbering shown on Fig. 2:

$$dP_i/dt = \sum_j (P_j \lambda_{ji}) - P_i \sum_j \lambda_{ij}, \qquad i = 1,2...5, \tag{1}$$

where P_i = probability of state i; and λ_{ij} = rate transition between states i and j. To parameterize this model we need the failure rates of IED hidden modes, and of external events that trigger IED operation. These can be resumed on two generalized parameters that define the IED failure behavior:

- Defect Rate – probabilistic density of IED hidden defects in interval dt, conditioned to absence of defect at time t;
- Failure Rate – probabilistic density of IED functional failure in interval dt, conditioned to previous IED defect or potential failure at time 0.

Identification of these parameters in each population of IEDs is a complex endeavor, in modern power systems, due to the progressive or hidden characteristic of most defects, with no evidence of the exact instant of their happening. In consequence, the failure rate ($\lambda_f=\lambda_{43}$), and defect rate ($\lambda_d=\lambda_{14}$) of each IED must be inferred from other measurable variables, using the model. These variables are observable events and their mean duration, taken from a database of IED maintenance records, such as:

- IED malfunction frequency ($F_f=F_{43}$);
- IED test frequency (F_p);
- IED corrective maintenance frequency ($F_c=1/T_{42}$);
- IED mean time to test ($T_p=MTTT=T_2$);
- IED mean time to repair ($T_r=MTTR=T_3$); and
- IED mean time do correct ($T_c=MTTC=T_5$),

where the numbered subscripts refer to the states and transitions in Fig 2. Given a population of IEDs, these parameters result from a pondered contribution of each item, according to its quantity in the system, as given from statistics and sampled means from their population. The final values may be estimated from the history data of each set of IEDs, in a time window where the maintenance policy and test frequency was held constant, sufficient to transform equation 1 in steady state into an algebraic equation:

$$dP_i/dt = 0\,, \qquad\qquad i = 1,2...5\,. \tag{2}$$

Solving this system of equations provides the IED functional failure rate (λ_f=λ_{43}) and IED defect rate (λ_d=λ_{14}) as a function of measured parameters as:

$$\lambda_f = \frac{F_f F_p}{F_c} = \frac{1}{MTTF}\,, \tag{3}$$

$$\lambda_d = \frac{F_p\left(F_c + F_f\right)}{F_p - F_p^2 T_p - F_p F_f T_r - F_c - F_p F_c T_c} = \frac{1}{MTTD}\,. \tag{4}$$

These are characteristic parameters of each IED, subject to their specific operational environment, depicted on the failure resistance curve of Fig 1. The mean time to defect ($MTTD$) is the expected period of IED operation, without testing, before gradual contamination by a latent defect, which may result in a malfunction. The mean time to failure ($MTTF$) defines the expected interval between the IED contamination and its evolution to a malfunction; it is similar to a disease incubation period, before evolution to a failure.

III. OPTIMIZATION

Testing optimization is achieved by determining values of test interval (T_{21}) and other parameters, such as Mean Times to Test ($MTTT$), to correct ($MTTC$) and Repair ($MTTR$), which maximize or minimize an objective function. Some variables must also obey some restrictions, such as physical viabilities, available resources and security requirements. As $MTTT$, $MTTC$ and $MTTR$ are limited by available test and IED technology, and assuming they are already at minimum or possible values for the utility, the optimization must be sought by adjusting the test frequency. The objective function must reflect the desired result, such as reliability, dependability, economy, risk, etc., estimated by a probabilistic scalar indicator of the cost/benefit of state transitions in the system. Each transition can be pondered by a return coefficient (K_{ij}) that measure the gain/loss in the process for each maintenance event. That is:

$$I = K_p F_p + K_r F_r + K_c F_c \tag{5}$$

where I = scalar indicator or objective function;
K_p = test return rate;
K_c = corrective return rate;
K_r = repair return rate;
F_p = test frequency;
F_c = correction frequency;
F_r = repair frequency.

This is a general expression that can be applied to many indicators of interest to the utility [6], by suitable choice of the return coefficients ($K_{p,r,c}$), like the following:

- IUN IED Unavailability
- EFO Equipment forced outage;
- EFD Equipment forced duration;
- LPF Loss of production duration;
- LPP Loss of production probability;
- DNS Demand not supplied;
- PNS Production not supplied;
- EOF Equivalent outage frequency;
- EOD Equivalent outage duration;

- PDI	Production discontinuity index;
- EVC	Enterprise variable cost;
- CVC	Client variable cost.

For instance, the IED unavailability (IUN) can be estimated by making $K_p=MTTT$, $K_r=MTTR$ and $K_c=MTTC$. The ideal test frequency that optimizes any of these indicators, taken as an objective function I, can be determined by expanding F_p, F_c and F_r on expression (5), from the model equations in steady state. This allows us to build the following canonical non-linear programming system:

Minimize the objective function
$$I = AF_p + \frac{D(B-F_p)}{C+F_p} + \frac{E(B-F_p)F_p}{C+F_p}, \tag{6}$$

subject to the restriction
$$\frac{1}{MTTC} \geq F_p \geq 0 \tag{7}$$

where A, B, C, D and E are positive parameters given by:

$$A = K_p \tag{8}$$

$$B = \frac{1}{MTTT} \tag{9}$$

$$C = \frac{\lambda_d + MTTR.\lambda_d\lambda_f + \lambda_f}{1+\lambda_d MTTC} \tag{10}$$

$$D = \frac{K_r MTTT \lambda_d \lambda_f}{1+\lambda_d MTTC} \tag{11}$$

$$E = \frac{K_c MTTT.\lambda_d}{1+\lambda_d MTTC}. \tag{12}$$

In these expressions, λ_d and λ_f are functions inherent to the IED technology, while $MTTT$, $MTTC$ and $MTTR$ depend on available maintenance technologies. The single controllable parameter is the test frequency. The inferior and superior limits for F_p ((1/$MTTT$) ≤ F_p ≥ 0) are related to physical viability, as the test frequency cannot be negative or greater than the inverse of the mean time to do it. Figure 3 shows a typical plot for these expressions, as a function of test frequency.

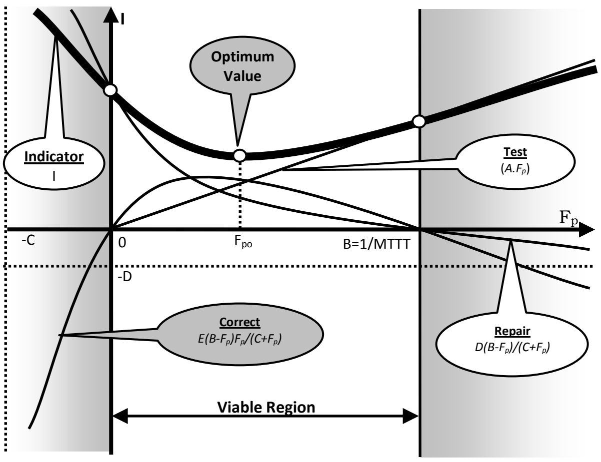

Fig. 3. Quality Indicators

Note that the positive region of indicator I is formed by three parcels. The first, ($A.F_p$), grows with the increase of test frequency, as a cost onus over the desired objective. The second parcel, [$D(B-F_p)/(C+F_p)$], decreases with test frequency, as a benefit brought by corrective maintenance before an IED failure. The third parcel, [$E(B-Fp)Fp/(C+Fp)$], ponder the effects of repair tasks and IED failure on the indicator. This mix is typical of optimization problems, conducting to an equilibrium point among the parcels. Fig. 3 also shows how the three controlled parameters ($MTTR$, $MTTT$ and F_p) affect the result. The greater the $MTTR$, the greater will be the value of D, and the test frequency that minimizes the indicator. The same can be said of $MTTT$ and B. Following the classical methods to solve this problem, the optimum test frequency will be given by a non-negative real root of the differential equation:

$$\frac{dI}{dF_p} = 0 \quad . \tag{13}$$

By substitution, this equation reduces to a quadratic form, with two real roots [1,2,3]. Solving it gives the optimum test frequency:

$$F_{po} = \left[C^2 - \frac{AC^2 - D(B+C) + EBC}{A-E} \right]^{1/2} - C \quad . \tag{14}$$

It can be shown that the other root of eq. (14) must be neglected, as it will be negative, contradicting restriction (6). Note that, depending on parameters A, B, C, D and E, both roots will be negative. In this case, the test frequency that optimizes the objective function will be zero (!), at the border of the viability region of Fig 3. That is, no test is recommended as it will degrade the objective function. If, in addition to IED reliability, there is interest in minimizing other indicators such as those from Table II, a much more complex, multi-criteria decision problem (MCDM), will have to be solved. The same model will still be valid for each indicator, and a compromise solution will have to be negotiated among IED reliability, and other enterprise results.

In summary, according to expression (15), the optimum IED test frequency will be a function of the following data, for each IED:

Maintainability	Mean time to test ($MTTT$) Mean time to repair ($MTTR$) Mean time to correct ($MTTC$)
Reliability	Defect rate (λ_d) Failure rate (λ_f)
Productivity	Return rate to test (K_p) Return rate do repair (K_r) Return rate to correct (K_c)
Periodicity	Actual test frequency (F_p)

With the exception of the last item, all other are difficult data to obtain, considering the lack of reliable statistical information about IED. For new IEDs, good engineering estimation and judgment must be used to get initial data. Bayesian methods can be used to refine these estimations as experience is gained with the system. Accelerated life tests may be an option for small and inexpensive components. Once used for the first time, successive application of the model will improve the original estimation and results. For those utilities that have a structured database of maintenance records, these parameters can be inferred from equations 3 to 4.

IV. APPLICATIONS

This methodology was applied to all IEDs and PAC systems of more than 90 high-voltage stations operated by CHESF (Companhia Hidro Elétrica do São Francisco), supplier of electricity to the Northeast of Brazil. After optimization of the IED test interval, to minimize their unavailability, maintenance and operation records were compared to previous years, to check the results of the method. As a main result of this project, all functional tests involving tripping of breakers from IEDs were cancelled since then, as the mathematical model recommended a negative frequency for this task! Other maintenance activities, such as relay setting checks, were optimized, resulting in annual gains superior to US$ 500,000.00/year (2).

To avail the results of this program, the following picture shows the evolution of protection reliability index, correlated to the demand for trip on all 90 CHESF stations, during 10 years (1982 to 1992) before and 4 years (1993 to 1996) after this program started.

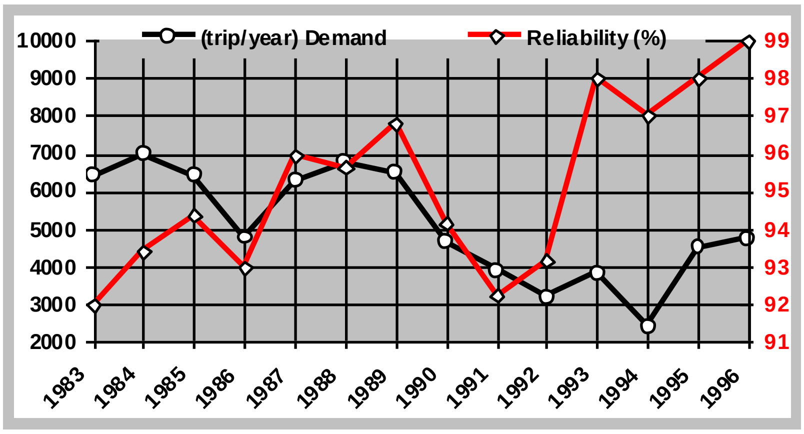

Fig 3 – PSR - Protection System Reliability

Prior to 1993, test interval for all IEDs was held constant in 3 years. During this period, protection reliability varies according to trip demand, as expected from the model. After the start of the program in 1993 (January), a significant jump in protection reliability was observed, following again the trip demand changes in the next years. Similar plots were obtained for many other indexes, like the ones shown on Fig. 4, 5 and 6, for the months prior and after the adoption of this program.

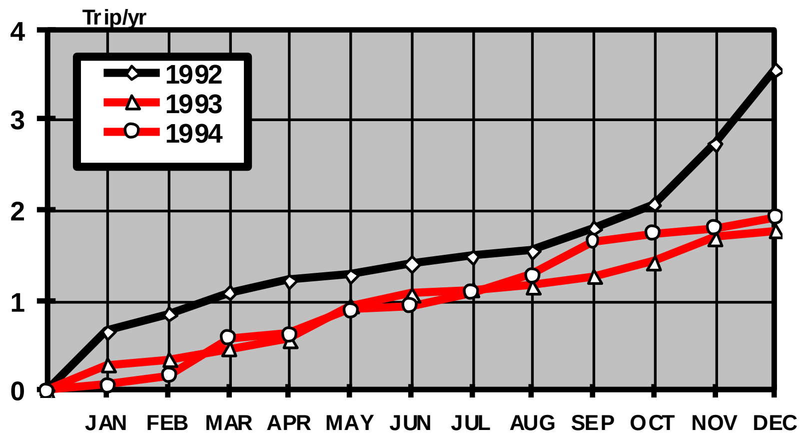

Figura 4– EOF -Equivalent Outage Frequency

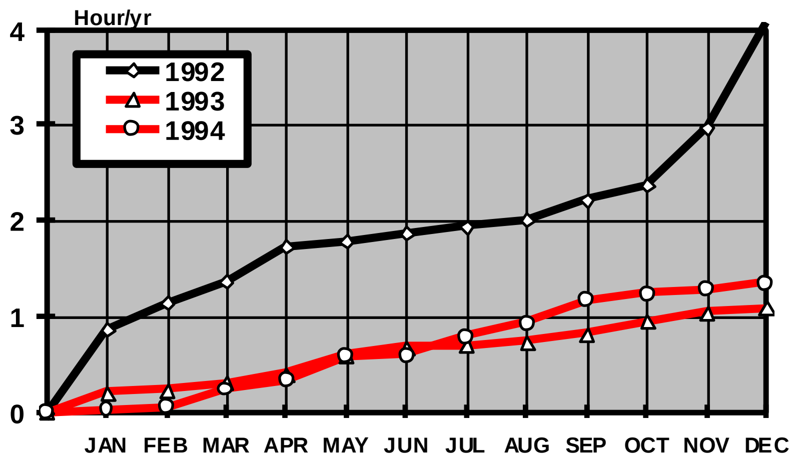

Figura 5 – EOD - Equivalent outage duration

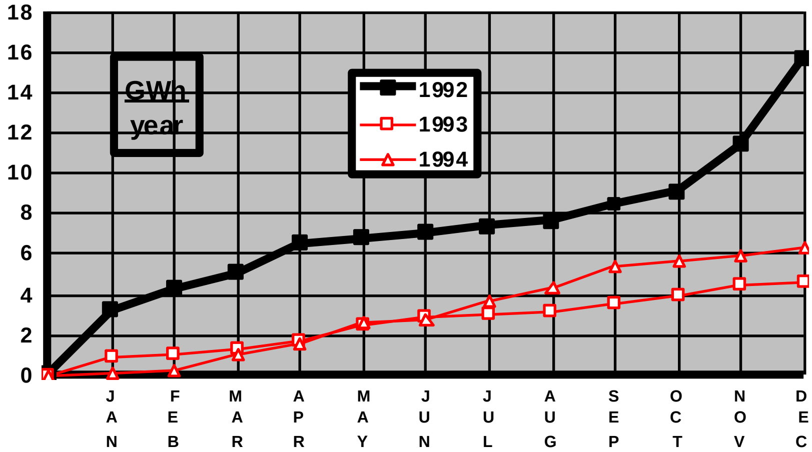

Fig. 6 – PNS - Production not supplied

These plots also show that the impacts on all indexes were immediate and permanent after the adoption of the new test program.

V. CONCLUSION

This paper has shown a statistical model of IED defects and failures, and an approach to optimization of test frequency. Its application to a large power system, with more than 80 high voltage installations, has demonstrated its validity. Statistics were determined from maintenance and operation records, covering a time window of 9 years. During this period, maintenance policy was held constant, assuring the steady state of equation (1). The IED models were parameterized to represent several partitions of the power system, according to voltage, manufacturer, technologies, etc., covering the protection of 1248 high voltage equipments. After optimization of IED testing, maintenance and operation records were compared to previous years, assuring optimum results for all quality indexes. Of special interest, all functional tests involving tripping of breakers from protection were cancelled since then, as the model recommended a negative frequency for this task! Other maintenance activities, such as relay checking, were optimized, resulting in annual gains superior to US$ 500,000.00/year [2].

Due to the general nature of the model, any kind of IED can be modeled and classified. By regional modeling, for instance, besides environment influences, one can avail local crew productivity by their mean times to correct, repair and test, and network deficiencies by losses of load and generation. Comparison among different families of IEDs can be simulated by modeling their corresponding population, and referencing to benchmarks of the electrical sector. The uniform structure of the model, being independent from IED type, easies the interchange of experiences among companies, and adoption of uniform policies by utilities. Measuring the impact of these decisions on power system performance must account for their long term results. By presenting a real case, it is hoped that this approach will contribute to spread the benefits of probabilistic modeling and assessment of IED testing and PAC functions to the electric industry.

VI. ACKNOWLEDGMENTS

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VIII. ABSTRACT

This paper presents a probabilistic methodology to determine the optimum interval for testing PAC systems subject to hidden failures. Hidden failures are common to equipments whose normal state is in stand-by, being required to operate after the occurrence of an external event, typical of most protection, control and automation functions. Each IED failure mode can be simulated by a customization of the model. Using a set of quality and productivity indexes typically used to evaluate utility systems, a standard optimization model is built, whose analytical solution yields the best IED test frequency. Results of its application to a large power system are reported.

Index Terms — Intelligent Electronic Devices, Test Optimization, Power System, Modeling.

Biography - Iony Patriota de Siqueira was born in 1951 in São José do Egito, Brazil. He graduated in Electrical Engineering, with an M.Sc. degree in operations research from Federal University of Pernambuco and an MBA on Information Systems from Catholic University of Pernambuco. He is a member of Cigré and IEEE, Manager of Protection and Automation at Chesf (Hydro Electric Company of San Francisco River), Regional Vice-Director of Abraman (Brazilian Maintenance Association), and Secretary of Cigré Technical Committee B5.