Loss–Prevention and Risk–Mitigation by Reducing False–Alarms in Equipment Protection Systems

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Abstract: Like death and taxes Equipment Protection System failures (alarms) are undesirable, unpredictable, unwarranted, and unexplainable. 95% of industrial[1] alarms are false, 99% in aircraft, and 99.9% in security systems. They excite management, incite environmentalists, spur regulatory agencies, and frighten many. Product loss and wasted resources are obvious consequences. Not so obvious is the negative impact on safety. Fail–safe... shutdown upon failure... *doesn't make the situation safer*. Instead, there's a high–risk of damage or catastrophe during restart.

Key Words: Fault–tolerant; Reliability; Fault–diagnostics; Predictive maintenance.

Technological Advance Inadequate: Pneumatics and relays were used initially. The '50s saw solid–state, PLC's emerged in the '70s, PC's in the '90s. This trend is a Paradigm–Shift... the unquestioned use of habitually employed hi–tech. Computers have improved, but I/O devices haven't... performance is still poor. This paradox is evident in the Process industry... advance is evident, but *false–trip rates haven't decreased.*

Failures Are Predictable: Overt failures are simple and obvious. Covert ones, aren't. There are just two types: *Electrical*– opens, shorts, grounds, corrosion, maloperation, etc; and *Transients*– intermittents, glitches, vibration, power disturbances, etc.

The Good, The Bad, and The Ugly: Reliability equations use a 2–state analysis, that is, components are either GOOD or NO–GOOD. *But, the results of this technique can be in error.* In reality there are 3–states: GOOD (successful); BAD (*unwarranted*); and UGLY (*unresponsive*), which require a 3–state analysis.

Probabilistic Engineering Techniques to Reduce False Alarms:

- The anatomy of a Protection–System is presented and its parameters evaluated.
- 2–state and 3–state analyses are compared.
- Sacred–cows are exposed, including the popular software–based TMR scheme.
- Mathematical models considering *Good, Bad, & Ugly failure–modes* are developed.
- Examples of the technique are illustrated.

The Anatomy of an EPS System: Fig. 1 identifies major elements of an EPS system.

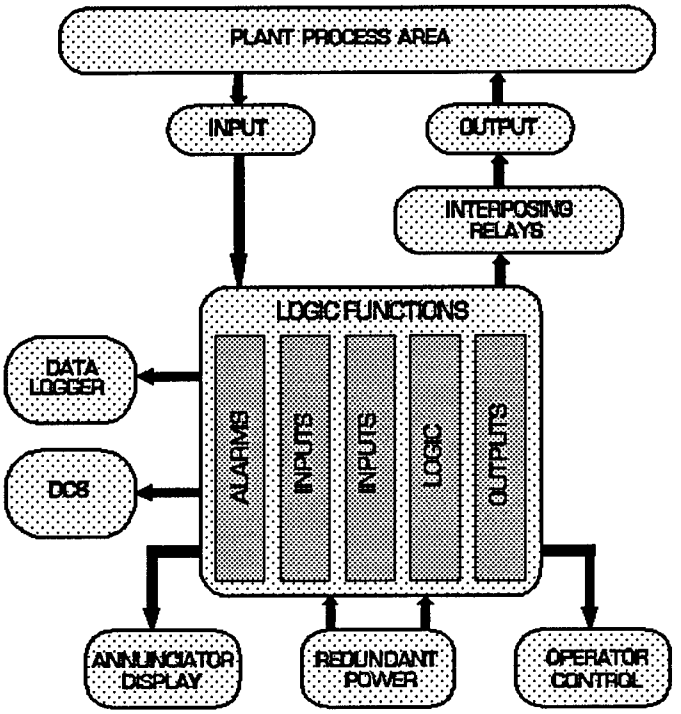

Figure 1: ESD Block Diagram.

Essentially an EPS consists of seven major components:

- Input, which are the tripping–variable sensors, their connecting field wiring and their terminations.
- Logic, which receives, processes, and then executes the pre–programmed logic. It may also include analysis of the final element's response (feedback).
- Output, which are the final output–action actuating devices (valves, breakers, etc.) their wiring, and their terminations.
- Operator Control, which provides the operator with the means to bypass, trip, reset, arm, etc.
- Operator Display, which provides concise information regarding EPS status.
- Data Acquisition, which sequentially tags and time–stamps the EPS events.
- Power Supply, which provides both the logic–level and output–action power.

2-State Probabilistic Engineering Analysis: Fig. 2, illustrates that with a 2-state analysis (sensor is Good or NoGood) the probability[5] of system success increases with the addition of redundant elements, which is the perception with voting configurations:

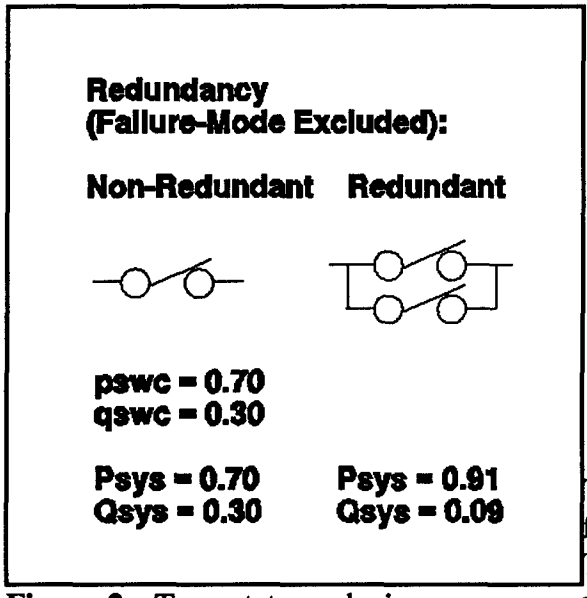

Figure 2: Two-state analysis.

Where:

p_{swc}=	**The probability of a sensor being GOOD (successful).**
$q_{swc}=1-p_{swc}$=	**the probability of a sensor being NO-GOOD (unsuccessful).**
$P_{sys}=p_{swc}$=	**the probability of system success.**
$Q_{sys}=q_{swc}$=	**the probability of system failure.**

The probability of success formula accounts for 2 states, one working, the other not. The Good and No-Good probabilities are p_{swc}, and q_{swc}, respectively. In this example P_{sys} increases to 0.91, a formidable improvement over the single switch case. Fig. 2 illustrates that in a 2-state analysis[6] the *probability of system success does increase with redundancy.*

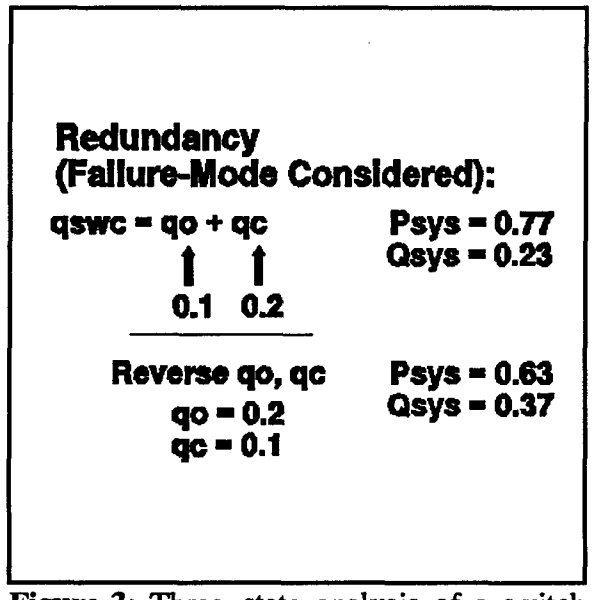

Figure 3: Three-state analysis of a switch system with overt and covert failures considered.

where:

p_{swc}=0.7=	**the probability of a sensor being GOOD (successful).**
q_o = 0.1=	**the probability of the sensor's BAD (unwarranted).**
q_c = 0.2=	**the probability of the sensor's UGLY (unresponsive).**

The probability of success formula has been modified (see Appendix) to include a sensor's fault-modes, overt and covert. The fault-mode probabilities are q_o, and q_c, respectively. Applying these values to the first example, the probability of system success becomes, P_{sys} = 0.77, which is considerably poorer than the expected 0.91. And, if q_o and q_c are interchanged the situation worsens... P_{sys} is further reduced to 0.63. In summary, when fault-mode is included, an EPS relying on redundant switches, *does not automatically result in higher reliability*.

Design Factors Affecting EPS Performance: Other design factors affect system performance and therefore must be considered. They include transients, connecting wire failures, termination failures, control power source grounding preference, and trip-mode philosophy.

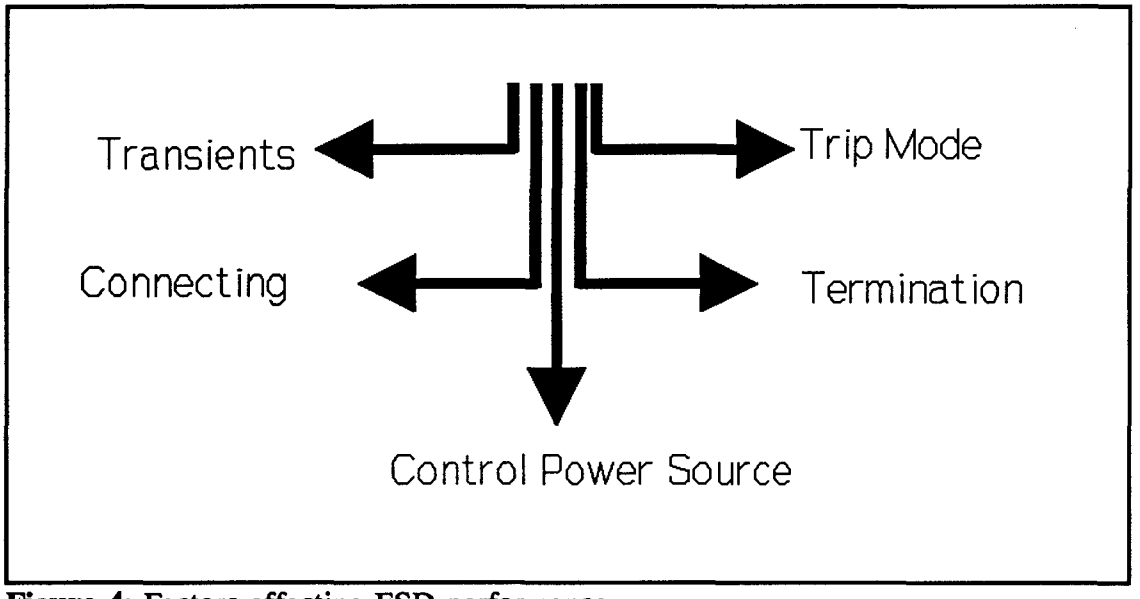

Figure 4: Factors effecting ESD performance.

Following is a description of each of the factors noted above:

- Transients include contact bounce, relay chatter, power dips, radio frequency interference (RFI), electromagnetic interference (EMI), X-ray effects, etc.
- Control-power source grounding refers to whether it is intentionally grounded or floating. Alternating-current control-power sources are usually grounded, while Direct-current control-power sources can be either grounded or floating.
- Trip-mode philosophy refers to the EPS response-mode: Energize-to-Trip or **ETT**, sometimes referred to as production-safe; and Deenergize-to-Trip or **DTT**, often referred to as fail-safe.
- Connecting wire failures consist of open-circuits, short-circuits, and ground-faults.
- Termination failures include corrosion or accidental bridging of wire-strands at adjacent terminals.

Many plants with machinery EPS (power plants in particular) use the ETT philosophy because of the *perception* that ETT is blind to overt or false-trip failure-modes. Conversely, boiler and furnace flame-guard systems have DTT as required by National Fire Protection Association (NFPA) Standards since DTT is better able to prevent covert or catastrophic failure-modes. An explanation of each type follows.

Example of a Typical ETT Input Loop: Consider the circuit shown in Fig. 5. A normally–open sensor is powered by a floating power–source. This circuit must *close to energize* the trip relay, which in turn actuates the final element such as, a valve, breaker, etc. Transients like power dips or bounce, will not cause false–alarms. On the other hand an open circuit in the sensor's connecting wires or its protective fuse operates prematurely, then the EPS will not trip when required, causing a catastrophic failure.

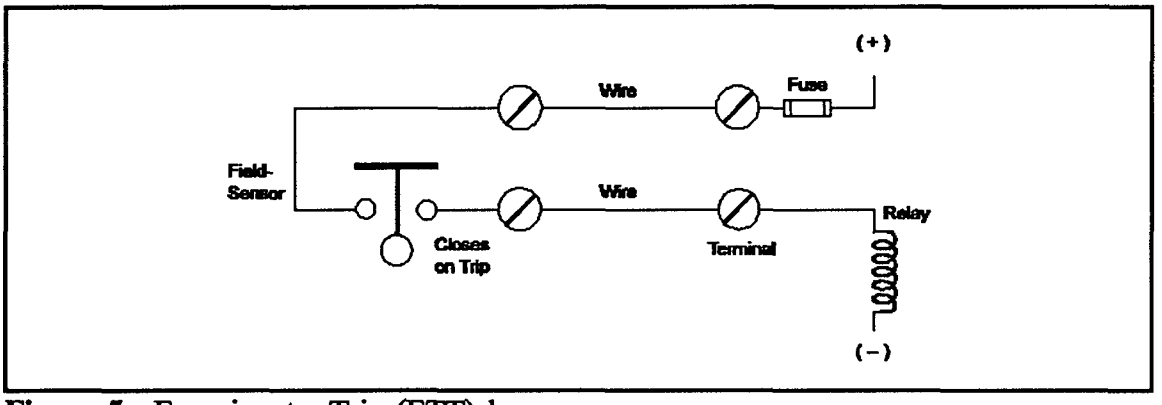

Figure 5: Energize–to–Trip (ETT) loop.

Example of a Typical DTT Input Loop: Now consider the circuit shown in Fig. 6. A normally–closed sensor is powered by a grounded power–source. This circuit must *open to deenergize* the final element. The system will fail catastrophically if the sensor, its connecting wires or its terminations are short–circuited and none of the faults are detected. Furthermore, any open–circuit, ground–fault, contact–bounce, premature fuse operation, or power dip will result in a false–trip.

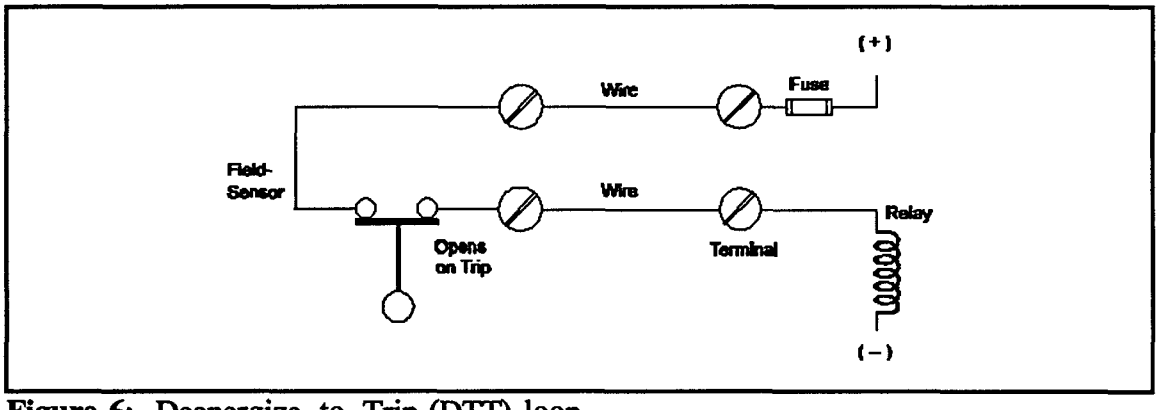

Figure 6: Deenergize–to–Trip (DTT) loop.

Thus, Fig. 5 is better for reducing effects of faults resulting in false–alarms, but it masks those failures which could result in catastrophic failure. Conversely, Fig. 6 has opposite characteristics. Each method has features useful in mitigating particular consequences. ETT is more widely used in machine EPS where inadvertent loss of continuity of the machine is intolerable. Conversely DTT finds use in *fired–equipment* such as, boilers, furnaces and heaters where the consequences of failure to trip could be disastrous.

3-State Analysis (w/o Diagnostics) for Machinery: Data obtained from IEEE[7], AICE[8], MIL-Handbook[9], and US Navy Handbook[10] were used to develop Table Nº 1. Five system configurations are considered, all based on DC relay logic, ETT trip-mode, a floating control-power source, but, fault-mode detection is excluded:

Table Nº 1: Energize-To-Trip System Performance.

LOGIC	P_{swc}	P_{sys}	Q_{ftr}	Q_{cat}
1 of 1	0.95740	0.88978	0.01927	0.09095
1 of 2	0.97439	0.95356	0.03817	0.00827
2 of 2	0.94041	0.82601	0.00037	0.17362
2 of 3	0.99686	0.97559	0.00110	0.02331
2 of 4	0.99898	0.99502	0.00217	0.00280

Where:

1 of 1 = 1/1, or 1oo1, or One-of-One
1 of 2 = 1/2, or 1oo2, or One-of-Two
2 of 2 = 2/2, or 2oo2, or Two-of-Two
2 of 3 = 2/3, or 2oo3, or Two-of-Three (TMR).
2 of 4 = 2/4, or 2oo4, or Two-of-Four (Nuclear).

P_{swc} = sensor success probabilities. Calculated using the 2-state technique, considers only that the sensor is Good or NoGood, and ignores the effects of fault-mode.

P_{sys} = system success probabilities. These are calculated with the 3-state method and includes fault-mode effects of the sensor, interconnecting wiring, terminations, control-power source grounding preference, and trip-mode philosophy.

Q_{ftr} = false-trip failure probabilities.

Q_{cat} = catastrophic failure probabilities.

3-State Analysis (w/o Diagnostics) for Fired-Equipment: To illustrate that different results will be obtained for boiler or heater EPS's, the same failure-rates and configurations are used to develop Table Nº 2. This time, however, design factors are based on AC relay logic, the DTT Trip-mode philosophy, and a grounded power source:

Table Nº 2: Deenergize-To-Trip System Performance.

LOGIC	P_{swc}	P_{sys}	Q_{ftr}	Q_{cat}
1 of 1	0.97227	0.88949	0.08306	0.02745
1 of 2	0.97488	0.84002	0.15922	0.00075
2 of 2	0.96967	0.93895	0.00690	0.05415
2 of 3	0.99885	0.97823	0.01955	0.00222
2 of 4	0.99906	0.96297	0.03695	0.00008

Impact Of Fault-mode Detection On EPS Performance: Will fault-mode detection still satisfy the EPS requirements without compromising safe and continuous operations? Different philosophies were a reasonable course of action to meet the unique and divergent operational requirements of machinery and fired-equipment shutdown systems. However, with the advent of fault-mode detection and the application of 3-state analysis, now both applications can be served with one type of EPS. A major advantage is that operator and technician understanding of the system is simplified. They do not need to wear two hats, one for machinery, the other for fired-equipment protection systems.

The same failure-rates which were used to develop Tables Nº 1 and Nº 2, were used in the development of the Probability values shown in Table Nº 3, except that failure-rates were adjusted to exclude all detectable failures. Four of the protection system types evaluated earlier were evaluated. A fifth type, HIQ, was also evaluated. It exceeds 2 of 3 or TMR expectations for half the cost. Following is a list of the 5 configurations based on solid-state discrete-logic, the DTT philosophy, powered from a grounded control-power source, and with fault-mode detection and diagnosis included:

Table Nº 3: Fault-Detection System Performance.

LOGIC	P_{swc}	P_{sys}	Q_{ftr}	Q_{cat}
SNV	0.97227	0.96472	0.02013	0.01514
DNV	0.97488	0.95991	0.03986	0.00023
DUV	0.96967	0.96969	0.00004	0.03027
TMV	0.99885	0.99919	0.00012	0.00069
HIQ	0.99892	0.99937	0.00016	0.00047

Where:

SNV = Simplex-Non-Voting.
DNV = Duplex-Non-Voting.
DUV = Duplex-Unanimous-Voting.
TMV = Triplex-Majority-Voting.
HIQ = High-Integrity-Quad (2x1/2) Voting.

This example indicates that the probability of system success, P_{sys}, of an EPS having fault-mode detection, shows considerable improvement over the earlier examples which do not have fault-mode detection. Correspondingly, the False Trip-rate Probability, Q_{ftr}, and the Catastrophic Failure Probability, Q_{cat}, are substantially reduced.

3-State Analysis On A Large Turbo-Machine: This case illustrates the application of the 3-state analysis to an FCCU machinery-train located in a Gulf-states area refinery. The goal... to achieve a four-year continuous run. Obviously, false-trip reduction of the EPS was an essential consideration. The original system is compared to one having fault-mode detection and diagnostics. Failure-rate data shown is specific to the trip variable's input-sensor type:

CASE STUDY: EPS PERFORMANCE STUDY COVERING GULF-STATES-AREA REFINERY FCCU MACHINERY-TRAIN

Scope of Study: Original Relay System vs Fault-detection Equipped EPS System
Basis of Study:
Base Case: AC Relays; ETT Logic; Grounded-Power; w/o Fault-Mode Detection
Alt' Case: Solid-State; DTT logic; Grounded-Power; with Fault-Mode Detection

<--- INPUT SENSOR ---->	<----- ORIGINAL (Base Case) ------>			<---- FAULT DETECTION EPS -------->		
	Logic	Psys	Qftr	Qcat	Logic	Psys	Qftr	Qcat
PROCESS VARIABLES								
Regen'r Pressure	1/1	0.88970	0.01150	0.09880	HIQ	0.99981	0.00001	0.00018
Lube Oil Pressure	1/1	0.88970	0.01150	0.09880	HIQ	0.99981	0.00001	0.00018
Separator Inlet Temp	1/1	0.89887	0.01530	0.08583	HIQ	0.99981	0.00015	0.00004
Instr Air Pressure	1/1	0.88970	0.01150	0.09880	DUV	0.98642	0.00001	0.01357
AIR BLOWER VARIABLES								
Axial Displacement	1/2	0.93958	0.05126	0.00916	DUV	0.98770	0.00008	0.01222
Rad Vibr'n, Gear End	1/2	0.93958	0.05126	0.00916	DUV	0.98770	0.00008	0.01222
Rad Vibr'n, Xpnd End	1/2	0.93958	0.05126	0.00916	DUV	0.98770	0.00008	0.01222
EXPANDER VARIABLES								
Axial Displacement	1/2	0.93958	0.05126	0.00916	DUV	0.98770	0.00008	0.01222
Rad Vibr'n, Cplg End	1/2	0.93958	0.05126	0.00916	DUV	0.98770	0.00008	0.01222
Rad Vibr'n, Idle End	1/2	0.93958	0.05126	0.00916	DUV	0.98770	0.00008	0.01222
Overspeed	1/2	0.95967	0.03188	0.00846	DUV	0.99006	0.00003	0.00991
BULL GEAR VARIABLES								
Rad Vibr'n, Cplg End	1/2	0.93958	0.05126	0.00916	DUV	0.98770	0.00008	0.01222
Rad Vibr'n, Idle End	1/2	0.93958	0.05126	0.00916	DUV	0.98770	0.00008	0.01222
PINION GEAR VARIABLES								
Axial Displacement	1/2	0.93958	0.05126	0.00916	DUV	0.98770	0.00008	0.01222
Rad Vibr'n, Gear End	1/2	0.93958	0.05126	0.00916	DUV	0.98770	0.00008	0.01222
Rad Vibr'n, Xpnd End	1/2	0.93958	0.05126	0.00916	DUV	0.98770	0.00008	0.01222
MOTOR/GEN'R VARIABLES								
Rad Vibr'n, Cplg End	1/2	0.93958	0.05126	0.00916	DUV	0.98770	0.00008	0.01222
Motor Run Contact	1/1	0.87932	0.01916	0.10152	SNV	0.98471	0.00004	0.01525
AVERAGE VALUES	---	0.92677	0.03978	0.03345	---	0.98961	0.00007	0.01032
EQUIV FAILURE-RATE	---	8.68 per million hours			---	1.19 per million hours		

PERFORMANCE IMPROVEMENT FACTORS	Original	Altern'v
OIF, Overall Improvement Factor	1.0	7.3
FTR, False-Trip Reduction Factor	1.0	591.7
CRF, Catastrophic Risk Factor	1.0	0.3
BCR, Benefit-To-Cost Ratio	1.0	6.7

DEFINITIONS:

Psys = The probability of System success.
Qftr = The probability of System false-trips.
Qcat = The probability of System catastrophic risk.

OIF = The ratio of the Original-system equivalent failure-rate to the Alternative-system equivalent failure-rate.
FTR = The ratio of the Original-system average false-trip failure-rate, Qftr, to the Alternative-system average false-trip failure-rate.
CRF = The ratio of the Alternative-system average catastrophic failure-rate, Qcat, to the Original-system average catastrophic-failure-rate.
BCR = The ratio of the Overall-Improvement-Factor achieved, to the cost (normalized) paid for the improvement.

Result: This unit not only achieved its original four-year goal (1,400 days), but thus far, has reached 6,800 days, *more than 18-years*, without failure.

The Sacred Cows of EPS Design: When it comes to design of EPS, the only ones who can change rules are people most involved and responsible... engineers who design them.

"Sacred cows" are the untouchable designs, specifications, etc., that EPS designers cherish most. They are easy to recognize... *anything that is vehemently defended with "we've always done it this way."* Some of the most recognizable are:

- Triplicate Modular Redundancy (TMR).
- Personal Bias Establishes Trip–Mode Philosophy.
- Designers Disregard Operators' Input[11].
- Floating Control–Power Sources Improve Probability of success.
- Uninterruptible Power Systems (UPS) Eliminate False–alarms.
- Flame–Scanners and Vibration Monitors Are Notorious for Causing False–alarms.

What About This TMR "Stuff" Anyway: Imagine that in 1994 you bought a new vehicle and to keep the engine in good working order you perform monthly engine tune–ups. In 1997, you drive that car to the JOAP Conference 500 miles away. Would you expect the vehicle to perform exactly as it did in 1994? No, because in order for the car to successfully complete the trip, the tires, shocks, brakes, etc., also need to be maintained in addition to the monthly tune–up.

TMR or Triplicate–Modular–Redundancy is the most touted of EPS configurations. The fallacy lies in how its performance is measured. MTBF is a valid means of evaluation, but, it falls short when used as a measure of TMR performance. MTBF which ignores the effects of input and output device failure probabilities is a misleading indicator of performance. When considering the time–dependency effect of not only its computer (example, the car's engine) but also upon its input/output components (example, the car's tires, shocks, etc.), a surprisingly different performance picture emerges, as shown below:

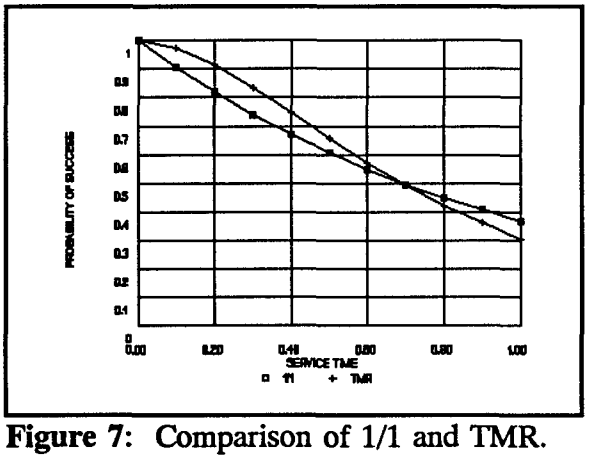

Figure 7: Comparison of 1/1 and TMR.

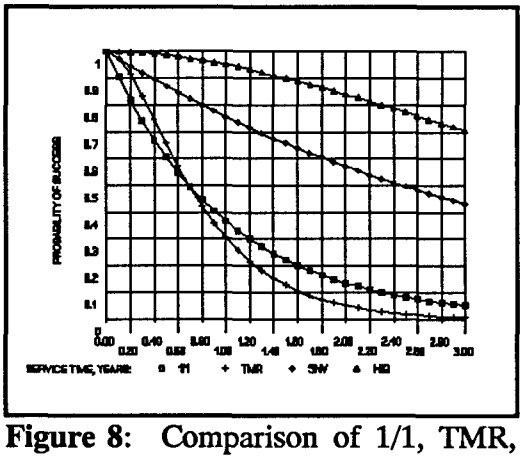

Figure 8: Comparison of 1/1, TMR, SNV, and HIQ.

Fig. 7, illustrates the fallacy of the TMR system by comparing it to the 1/1 system over a mission or service time of one year. *Input device failure probability is included.* Fig. 7 shows that the probability of success of the TMR is better than that of 1/1, until the cross-over point at eight months (t= 0.693). The TMR system declines after this point. If the 1/1 system sensor is maintained yearly, then, TMR's three sensors must be maintained at eight month intervals in order for it to maintain its lead in probability of success. These additional considerations negatively impact on TMR's Overall-Improvement-Factor. Its Benefit-to-Cost ratio is also reduced because the maintenance multiplier is 4⅓ (3+0.693) times that of 1/1.

Fig. 8, compares four systems, 1/1, TMR, SNV, and HIQ, over a longer service-time of three-years. The probability of success curves show that systems with fault-mode detection yield much better performance. After about 2½-years, SNV's probability of success equals that of 1/1 and TMR at their cross-over point. Thus, they are out-performed by twenty-two months. HIQ illustrates the impact of higher-level redundant configurations with fault-detection. Although not shown on the graph, at 4½-years HIQ's probability of success is still above the value at 1/1 and TMR cross-over point.

The conclusions of this presentation are:

- To effectively evaluate performance, catastrophic-risk and false-alarm modes of Inputs and Outputs must considered. This necessitates the use of a 3-state analysis (Good, Bad, & Ugly) instead of the usual 2-state (Good & NoGood) one.
- An EPS, using a DTT mode philosophy with an intentionally grounded DC power source, and fault-mode detection, will achieve the highest Overall-Improvement-Factor and False-Trip-Reduction factor and the lowest Catastrophic-Risk-Factor.
- Of all logic configurations investigated, the HIQ configuration results in the highest Overall-Improvement-Factor, the highest False-Trip-Reduction factor, the lowest Catastrophic-Risk-Factor, and the highest Benefit-to-Cost-Ratio.
- The fallacy of TMR claims when used for EPS, is that they do not include input/output probability of success over an anticipated mission or service-time. When these parameters are included, then TMR systems will show decreased probability of success factors, and a reduced Benefit-to-Cost-Ratio.
- EPS can be configured with the safer Deenergize-to-Trip logic without the fear or concern about power dips or transients causing false-alarms.
- Case studies for typical fired-equipment EPS like boilers and heaters, also show marked improvements, similar to those of turbo-machinery EPS.
- Mathematical models used to evaluate EPS designs should consider the following: sensor type (eg, pressure, flow, temperature, etc); logic configuration (non-voting, 1/1, 1/2, etc); overt-failure and covert-failure effects; control-power parameters (AC, DC, grounded or floating); logic element selection (relay, solid-state, software-programmable types); and output-action devices (starter, valve, breaker, solenoid, AC, DC, grounded or floating).

APPENDIX: 3–State Probability of Success Analysis

An EPS input protective device, such as a pressure sensor, has *one working state* and *two failure states*. Its two fault–mode states can be described as "o" for overt (unwarranted tripping) or "c" for covert (unresponsive to demand). EPS elements (devices) are connected in parallel or in series in order to implement various logic configurations.

A) Parallel Networks

A parallel system comprised of active, independent, 3–state devices will only fail if all devices fail in the overt–mode, q_o, or at least one of its devices fails in the covert–mode, q_c. The system time–dependent Probability of Success, $P_s(t)$, is given by

$$P_s(t) = \prod_{i=1}^{n} [1 - q_{oi}(t)] - \prod_{i=1}^{n} q_{ci}(t) \qquad (1)$$

where:

- t is time.
- n is the number of 3–state devices in parallel.
- q_{oi} is the overt–mode probability of the *i*th device at time t.
- q_{ci} is the covert–mode probability of the *i*th device at time t.

The system overt–mode probability, Q_{ftr}, is given by

$$Q_{ftr}(t) = 1 - \prod_{i=1}^{n} [1 - q_{oi}(t)] \qquad (2)$$

Similarly, the system covert–mode probability, Q_{cat}, is given by

$$Q_{cat}(t) = \prod_{i=1}^{n} q_{ci}(t) \qquad (3)$$

For the *i*th device overt–mode and covert–mode failure–rates, λ_{oi} and λ_{ci}, respectively, and equating their sum to A_i, then its time–dependent relationship is given by

$$P_s(t) = \prod_{i=1}^{n} [1/A_i]\{\lambda_{oi} + \lambda_{ci}\, e^{-B}\} - \prod_{i=1}^{n} [\lambda_{oi}/A_i]\{1 - \lambda_{ci}\, e^{-B}\} \qquad (4)$$

where:

$$B = A_i t \qquad (5)$$

B) Series Networks

A series system is the reverse of the parallel one. It will only fail if all of its elements fail in a covert–mode or any one element fails in an overt–mode. Then, by duality, its system time– dependent Probability of Success, $P_s(t)$, is given by

$$P_s(t) = \prod_{i=1}^{n} [1/A_i]\{\lambda_{ci} + \lambda_{oi}\, e^{-B}\} - \prod_{i=1}^{n} [\lambda_{ci}/A_i]\{1 - \lambda_{oi}\, e^{-B}\} \qquad (6)$$

REFERENCES

[1] Corso, Philip P., *Reduce Maintenance, Increase Productivity Via Shutdown System Design*, Philadelphia, Pennsylvania, Presented at NPRA Refinery and Petrochemical Plant Maintenance Conference, February 23–25, 1977.

[2] Paul, Jeff, *Extending Turbo–Generator Life*, Utility Maintenance Magazine, Spring, 1994.

[3] Riordan, Maurice A., *The IR Drop Paradigm Calls for a Change*, Pipe Line Industry Magazine, March, 1991.

[4] Foster–Miller, Inc., Principal Investigators: Lee, Robert A. S.; Campbell, Margaret C., *Turbine Protection System Evaluation*, EPRI NP–5416, Project 2641–1, Electric Power Research Institute, Final Report March 1987.

[5] Shooman, Martin L., *Probabilistic Reliability: An Engineering Approach*, McGraw–Hill Book Company, New York, New York, 1968.

[6] Dhillon, Balbir S., *Reliability Engineering in Systems Design and Operation*, Van Nostrand Reinhold Company Inc., New York, New York, 1983.

[7] The Institute of Electrical and Electronics Engineers, Inc., *IEEE Guide To The Collection And Presentation of Electrical, Electronic, Sensing Component, and Mechanical Equipment Reliability Data For Nuclear–Power Generating Stations, IEEE–Std–500*, IEEE, New York, New York, 1983.

[8] The American Institute of Chemical Engineers, Center For Chemical Process Safety, *Guidelines for Process Equipment Reliability Data*, AICE, New York, New York, 1989.

[9] US Department of Defense, *Military Handbook Reliability Prediction of Electronic Equipment, MIL–HDBK–217F*, Including Notice 1, 10 July 1992.

[10] US Department of the Navy, *Handbook For the Prediction of Shipboard and Shore Electronic Equipment Reliability*, NAVSHIPS 93820, April 1961.

[11] Ward, Kenneth A., *Retrofitting Old Turbo–machinery with Vibration Monitors*, Hydrocarbon Processing Magazine, January, 1991.

[12] Carman, Jan., *Trends in Alarm Annunciation*, InTech Magazine, July 1995.