Reliability Estimation and Enhancement of PLC Relay Output Units Using FMECA

Mahfoud CHAFAI and Larbi REFOUFI
Signals and **S**ystems **L**aboratory (SisyLab)
DGEE, FSI, University of Boumerdes, Algeria
E-mail : sisylab@yahoo.com

***Abstract* - Failure Modes Effects and Criticality Analysis in association with reliability estimation using part count method, are used together to determine failures which may affect the relay output circuit of programmable logic controller (PLC) systems in a dusty cement industry. Once the critical points are identified, reliability enhancement measures are proposed in view of increasing the overall availability of the process.**

Keywords: *failure rate, reliability Enhancement, FMECA, criticality, relay, stress and environment.*

1. INTRODUCTION

Field data indicates that the output circuits based on relays suffer from high intermittent failure rate because of being interfaced to high power actuators and exposed to harsh environmental stresses such as dust, electrical and thermal stresses in an existing cement process.

The failure mode effect and criticality analysis (FMECA) study and reliability evaluation of this electrical control circuit, are therefore needed and used in the framework of revamping operation The FMECA, which is an inductive method, seeks to identify the origin of potential failures and weak points in this electronic unit, classifies them in term of criticality and then determines the way of reducing their probability of occurrence in view of enhancing reliability. The circuit reliability improvement is accomplished using several methods such as: redundancy, protection against aggressive environment, replacement by better technology and the best way is chosen to achieve a higher level of operational availability of the overall control systems in cost effectiveness manner.

2. OUTPUT UNIT CIRCUIT DESCRIPTION

The function of the output unit is to amplify the command signals to drive different actuators such as electrical motors, electrovalves and contactors. The fact that a number of output circuits of the studied PLC system are based on relay circuits, it is needed to improve the reliability of these driver . and particularly those controlling fast and important actuators

For many years, hardwired logic relay was the standard technique for controlling industrial electrical systems. The principle of relay logic as illustrated in Fig.1 is based on magnetically operated relays which energize and deenergize associated moving contacts.

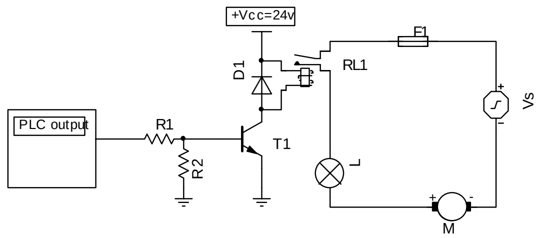


FIG.1 Relay output circuit.

They can be modeled as a combined electrical and mechanical parts in series configuration as shown in Fig .2

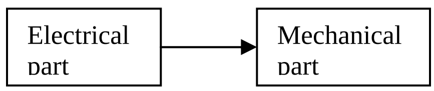


Fig. 2 Relay system model.

Failures of this electromechanical device are generally due to electrical as well as mechanical abnormal operation. For example the coil can be in an open circuit failure mode or the contact becomes mechanically bound preventing normal operation.

3 . RELIABILITY MODEL

The curve of exponential form of the reliability is generally representative of electronic systems. In particular, after rather inconspicuous wearin period, there is long span of time over which the failure rate is essentially constant [1]

Upon simplifying assumption that the failure rate of the mechanical part of the relay is constant for a given time interval, the entire relay device reliability on n demands will follow the exponential model given by:

$$R = e^{-\lambda_E t} \cdot e^{-\lambda_M t} = e^{-\lambda_R t} \qquad (1)$$

Where λ_E =failure rate of the relay electronic part
λ_M= failure rate of the relay mechanical part
λ_R= failure of the relay device
$t= n.\Delta t$
Δt= *average time interval between demands*

and the failure probability:

$$F(t) = 1-R(t) \quad . \qquad (2)$$

In fact, the control relay life cycle or the Mean Time to Failures (MTTF) is evaluated as:

$$MTTF=1/\lambda_R \quad . \qquad (3)$$

4. RELIABILITY ESTIMATION OF THE ELECTRONIC OUTPUT UNITS

Among factors affecting the reliability of electronic components and therefore circuits are [3]:
- the quality of the parts used
- the electrical and thermal stresses impressed on the parts
- the environmental stress on the parts (humidity, dust, vibrations).

the MIL-HDBK-217F contains Reliability data of failure rates for electronic components, taking into account the above factors, as well as two methods for reliability estimation using these data: the part count method and the part stress analysis method. Both methods apply to modules and equipment where it may be assumed that the item fails when any of its parts fail; that is, the item failure rate is equal to the sum of the failure rates of its parts [2].

4.1 Part count method :

The Application of this method requires that the following information to be available: Generic part types and components quantities quality levels-equipment environment. The general expression for circuit failure rate categories with this method is given by :

$$\lambda = \sum_{i=1}^{n} N_i \left(\lambda_G \pi_Q\right)_i \quad , \qquad (4)$$

For a given environment where:
λ = the total circuit failure rate per 1 million hours
λ_G = the generic failure rate for the i_{th} generic part
π_Q = quality adjustment factor
n = the number of different generic part
Ni = the quantity of the i_{th} generic part

4.2 Part stress-analysis method

The most commonly used source for the application of this method is based on the use of large scale data collection to obtain the relationship between engineering parameters (temperature , stress ..) and reliability variables (part quality, failure rate…). Part failure models vary with different part types and each component failure rate is expressed as base failure rate and series of multiplicative correction factors with the following general form is:

$$\lambda p = \lambda_b .\ \pi_Q . \pi_E . \pi_T . \pi_S \qquad (5)$$

λb = base failure rate
π_Q = quality adjustment factor
π_E = environment adjustment factor
π_T = temperature adjustment factor
π_S = Electrical stress adjustment factor

Using equation (5), the calculated failure rates of electronic components of the output unit are given in tables A_4 and A_5 of appendix A2.

5. FAILURE MODE EFFECTS AND CRITICALITY ANALYSIS

5.1 Application of FMECA to Output units

This inductive method consists of listing, for each component, the failure modes, their possible effects and criticalities on the system output unit as shown in Table Appendix 1.
In order to increase the availability or MTBF of the PLC, the total failure rate λ_t is reduced resulting in an improved reliability of the overall system. The FMECA method is used for such purpose.This bottom to top approach could be used in the design stage as well as in operational phase of an existing system to improve its reliability. It is made as complete as possible using table A_1 and A_2 shown in Appendix A1.

5.2 Criticality analysis

The purpose of the criticality Analysis is to rank each failure mode as identified in the FMECA, according to each failure mode's severity Se classification, its probability or frequency of occurrence (P) or its importance factor I_P. Generally, it is desirable to determine the relative importance of different primary failures in contributing to the top event which can also express the criticality of individual component. Then the importance factor is defined as:

$$Ip = P\{Mi\}/P\{T\}\ , \qquad (6)$$

Where *P{Mi} and P{T}* are respectively the failure probabilities of one i_{th} component and the output unit.
According to the equation (1) and (2) and for an operating time of $t=10^4\ h$:

$$P(t)=F(t) = 1 - Exp(-\lambda_T . t) \qquad (7)$$

According to table A4 of appendix 2 the components relay, transistor and neon lamp presents the highest values of importance factor and are respectively classified as A and B levels of severity as shown in the table:

Component	**Ip**	**Severity**
Relay	**0.5449**	**A**
Transistor	0.2557	A
Neon lamp	0.1245	B

Table 1 critical component classification

6. RELIABILITY IMPROVEMENT

Subsequent to the identification of potential failure origins and weaknesses, the following solution to improve the reliability are suggested:

6.1 Protection against environment

Electromechanical devices are more prone to circuit failure than a semiconductor device due to their partially mechanical nature and greater susceptibility to environmental stresses The relay failure rate is expressed as base failure rate and series of correction factors the following general form [3] :

$$\lambda_R = \lambda b.\ \pi_Q . \pi_E . \pi_L . \pi_C . \pi_{cy} . \pi_F \qquad (8)$$

λ_b = base failure rate
π_Q = quality adjustment factor
π_E = environment adjustment factor
π_F = application and construction factor
π_L = Load tress factor
π_C = Contact form factor

Assuming that each of the factors π_C and πcy are equal to one and that π_F remains unchanged. The reduction of the operational failure rate of the equipment is obtained by minimizing the environment correction factors (π_T, π_E,π_S) according to Equation [8] .

6.1.1 Reducing the temperature environment

The Arrenhius equation shows that the failure rate of electronic components increases when there is a rise in the hot spot temperature of the components.
Control relay should not be operated above rated temperature because of resulting increased degradation and fatigue. Common practice is to derate 25° from the maximum rated temperature life, and this is obtained by decreasing electrical value (lowering the make and breaks current) or by reducing the operating temperature through more cooling.
According to the following equation [3]:

$$\lambda_b = .00555\, Exp\left(\frac{T_a + 273}{352}\right)^{15.7} . \qquad (9)$$

Where Ta is the ambient temperature

The base failure rate λ_b of the relay decreases from .0072 (at Ta=50°) to .0060 $F/10^6h$ (at Ta=25°) , while the π_T of the driving transistor will be reduced to the a lower value of 1.2 so that the new value of transistor failure rate becomes:

$$\lambda r = \lambda b.\ \pi_Q . \pi_E . \pi_T . \pi_A = 0.4115\ F/10^6 h$$

where λ_a is the application adjustment factor

6.1.2 Load factor (π_L)

The over-voltage as well as the inrush current may cause an open circuit or a partial short circuit of the relay coil. Furthermore, the arcing from the switching action may cause electrical erosion or welding at contact tip. In this case, the protection against transient and over voltage could be improved by connecting a varistor whereas against arcing by the use of explosion proof tips.
The load factor is given by [3] as:

$$\pi_L = \exp(S / L)^2 \qquad (10)$$

S= operating load current/rated resistive load current
L= cste for load type (L=.8 (inductive), L=.4 (resistive))

The load current derating is obtained by reducing the current stress factor from s=.4 to 0.3. As result, the load factor will drop from the value 2.72 down to 1.76.

6.13 Environment factor (π_E)

Relays are also affected by the harsh environment of the cement industry. Dust or dirt may deposit and cause bad contact, the tip can burn or the vapor may greatly decrease the contact tip life expectancy (MTBF). It desirable to use an enclosed system or ventilator with a specific temperature to dry the air and fans associated with filters to remove the dust in the room environment of the relays. With this air conditioning the environment factor π_E (initially equal to 5) will be reduced to a value less than 5. The new relay failure rate will be :

$$\lambda r \leq \lambda b.\ \pi_Q.\pi_E.\pi_L\ .\pi_F=0.9504\ F/10^6h$$

and the failure rate of the overall relay circuit as indicated in theA4 will be reduced to less than or equal to a value of 2.034 .

6.2 Redundancy

Reliability can be increased by applying a stand-by redundancy at a unit level. A similar output circuit is added in parallel so that one can fail without causing system failure. This improvement is obtained if adequate precautions are to be taken to ensure that the redundant module has a very low probability of failing simultaneously from common causes and that it will not imply excessive additional cost and size [7].

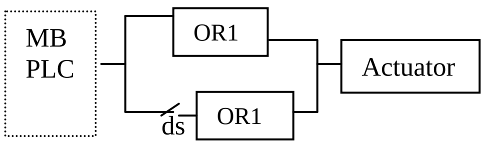


Fig.4 Redundancy in output circuit

It is assumed that redundant output circuit has an identical failure rate and that the detection switching device has failure rate of $\lambda ds=.1F/10^6$.The new reliability of the circuit will be:

$$R(s0)=R(1+Rds-R.Rds)=.9987 \quad . \qquad (11)$$

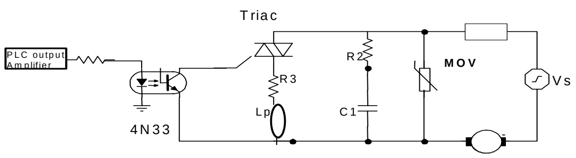
This reliability is greater than the initial one of the output unit:

$$R\ (so) \geq Ri(.967)\ . \qquad (12)$$

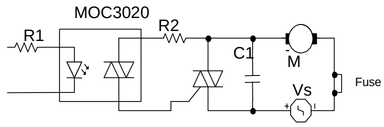
6.3 Replacement by better performance component

Static switches such as Triac *or SCR* have many advantages over conventional electromechanical relays: very high switching speed, no moving parts, no contact bounce upon closing [6] .

When a low trigger voltage is applied to the gate, the triac will conduct fully in both direction and will continue to conduct as long as the Anode-cathode voltage is not zero. The optical coupler is used as an isolation between PLC and the load.



a- Discrete circuit



b- IC package

Fig.5 Triac output circuits.

Another popular type of static switch combines the opto coupler and the triac or/and phototriac in an IC package known as triac driver as shown in Fig. 5-b. The output of the triac driver controls the gate of the large triac. This type of circuit provides an excellent electrical isolation between low voltage of the control circuit and the high voltage of the load. Many triac driver incorporate zero-crossing practice these power device requires a protection from: Thermal runway by heat sinks; high dv/dt and di/dt by snubbers, reverse recovery and supply transients by varistors and fault conditions by fuses.

7 . COMPARISON STUDY

A comparison of the three proposed reliability enhancement techniques are shown in table 3.

The criteria used for comparison are : λp and effect on total failure rate of the PLC reliability for operating $t=10^5$h, maintainability, cost and component characteristics with a specific attention to reliability and cost. With the lowest failure rate, moderate cost, better characteristics and less susceptibility to dust, the opto-triac technology replacement appears as the optimum reliability enhancement technique and particularly for a number of relay output units exceeding 10 which is the case for cement process.

8. CONCLUSION

The identification of critical component using failure mode effect and criticality analysis is in agreement with field data feedback. The environment aggressivity particularly in terms of dusty ambient space, has a very strong detrimental impact on the critical component reliability

In comparison with the redundancy solution and relay circuit protection for the sake of reliability improvement, the solution of replacing existing electromagnetic relay technology by better performing solid state one is the best way to achieve a higher level of reliability and therefore a better operational availability of the overall PLC systems.

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Performences / **Methods**	λt	Effect on total λ_T of PLC with N=10 relays	Reliability for $t=10^5$h	Maintainability	Cost	Characteristics & Engineering aspects
Initial Existing circuit	3.257	32.57	.9679	High		Slow speed, high operating voltage **,** sized packaging,
Environnement enhancement	2.034	20.34	.9798	High	High	Slow speed, high operating voltage ,magnetic isolation
Redundancy	1.207	12.07	.988	Moderate	High	Slow speed, high operating
Replacement by more performent technology	1.0308	10.308	0.9897	Low	Moderate	High speed, low operating gate voltage, optical isolation, better packaging

Table 3 comparison of the reliability enhancement techniques.

- APPENDIX

Table A_1 FMECA of the relay output circuit.

Item	**Function**	**Failure mode**	λ F/10-6 h	**Cause**	**Effect**	**C**	**Recommandations**
Latch Logic cKT	Store tempor. command bit	O.C, or S.C	.029	Overvoltage digital Errors	No command		
R1, R2	Voltage divider	O.C or D	. 0031	Loss of V, or Overvoltage	No output		Oversizing (rating R)
Transistor	ON-OFF switch for dc mode	- Q1 S.C or O.C	. 11	- Surge -Overvoltage	-No output command -Overheat	A	Fast clamping circuit
Relay	ON-OFF switch for ac or dc mode	-Contacts Fail Shorted Welded - Contacts Fail Open , to pick up or Bad contact intermittent	.90	-Electrical erosion due arcing -Dirt, dust , corrosion	Continuous operation of Actuator No command	A	Systematic preventive maintenance -Cleaner –good contact vaporizer & explosion proof -Adequate ventilation and dust removing (HVAC)
		-Coil Fails Open		overvoltage, inrush current	No command		- Replace by larger coil (oversizing) - Varistor and free wheeling diode
		-Mechanical binding or Contact reed broken		Mechanical fatigue	No command		-Reducing the level of the stress by changing the active region or the joint form of the contact reed
-Diode (Fr-wheeling)	Protection , inductive load	S.C ; SC	.036	Spike or Transient V.	Operation witout protection	B	Protecction
Neon	indicator	O.C	.20	Overvoltage	No command		
Fuse	-Protection against external overvoltage	-Fuse Fs O.C	.020	-Overvolt. -Load SC or overload	-No Vcc supply to system -if Repeatitive Fuse O.C can provide failure(s) on the load		-voltage regulator -Good quality : - G.rounding - Shielding -UPS
wire-connect	connection	O.C	.029	Contact loss	No command		

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Table A2 -FMECA of triac circuit [8]

Item	Function	Failure mode	λp (F/10⁶ h	Cause	Effect	C	Recommandat
Latch Logic cKT	Store tempor. command bit	O.C, or S.C	.029	Overvoltage digital Errors	No command		
IC CNY 17	Isolator	O.C, or S.C	. .21	Transient V	No command		
R1, R2	Voltage divider	O.C or D	. 0031	Loss of V, or OverVoltage	No output		Oversizing (rating R)
TRIAC Switching Ckt	ON-OFF switch for dc mode	- Q1 S.C or O.C	.16	- Surge Overvoltage -Overheat	-No output command -Overheat		Fast clamping circuit
R3,R4	Snubber	O.C	044	-Overvoltage	// //		
Lamp			020				
Fuse	-Protection against external overvoltage	-Fuse Fs O.C	.20	-Overvoltge -Load SC or overload	-No Vcc supply to system -if Repeatitive Fuse O.C can provide failure(s) on the load		-voltage regulator -Good quality : - G.rounding - Shielding -UPS
Varistor Th	Protection	S.C , OC	.0013	- High transient voltage	Operation with high vulnerability		
C	Snubber	OC; SC	.023				
wire-connect	connection	O.C	.029	Contact loss	No command		

Table A_3 Severity Level according to MILHDBK.

Level of severity	Probability	P
A	Extremely unlikely	> 0.2
B	Remote	0.1 < P < 0.2
C	Occasional	0.01< P < 0.1
D	Reasonable	0.001< P < 0.01
E	Frequent	< 0.001

Table A4 Failure rate and severity level of the relay output circuit

Component	λb F/10-6 h	πE (GF)	πQ	πT	πS	λp	F	Ip	Level of severity
Latch	.029	2	1	πF=1		.058	0.0006	0.0181	C
R1,R2	.0031x2	3	5	1	.3	.0279	0.0003	0.0087	E
Transistor Switch	.039	2	2.0	2.4	πA=2.2	.823	0.0082	0.2557	A
Relay	.0072	5	3	πF =6	πL =2.72	1.762	**0.0175**	**0.5449**	**A**
F.W diode	.036		2.4	1.6 (50°)	1	.138	0.0014	0.0430	C
Neon lamp	.20	2	1			.4	0.0040	0.1245	B
Fuse	.020	1	1			.02	0.0002	0.0062	E
Wire – connection	.029	1	1			.029	0.0003	0.0090	E
					Total λ_{Rt}	**3.257**			

Table A5 Failure rate and severity level of the triac circuit

Component	λb F/10⁶	πE (GF)	πQ	πT	πS	λp	F	Ip	Level of severity
Latch	.029	2	1	πF=1		.058	0.0006	.0565	C
-Opto-coupler IC2	.013	2	2.4	1.6(40°)		.0998	0.0003	0.0973	C
R1,R2	.0031x2	3	5	1	.3	.0279	0.0010	0.0272	C
Triac Switch	.0022	6.0	2.4	2.2	πS=1 πr=2.5	.174	0.0017	0.1695	B
R3 or R4	.022	2	5	1	1.7	.374	**0.0020**	**0.3640**	**A**
Lamp	.20					.2	0.0037	0.1948	B
Fuse	.020	1	1			.02	0.0002	0.0195	
-Varistor S.C	.0013	6	2.4(Jan	2.2 (50)	1	.0411	0.0004	0.0401	C
Capacitor C	0039	2	3(mil) 7(com)	πCv=1	.5	.007	0.0001	0.0068	E
Wire - connection	.029	1	1			.029	0.0003	0.0283	C
					Total λ_{Tt}	**1.0308**			