A new FMECA model for reliability computations in electrical distribution systems

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Abstract: – Electrical distribution systems usually have complex configurations with a number of missions corresponding to the many different requested functions. The levels of reliability and availability of each function depend on both the length of each reliability chain and on the devices involved in each path starting from the power supply node and terminating at an end-user supply. This paper describes a new procedure for an FMECA (Failure Mode Effects and Criticality Analysis), since the classical FMECA procedure usually applied to analyze electronics and mechanical systems is inadequate to analyze electrical power systems. Actually, the classical procedure using the so-called bottom-up approach implies that components (the "sons") are responsible for failures in a system (the "father"). In electrical radial systems where primary power supplies are placed upstream and the end-users are downstream, the failures of the upstream components (fathers) affect the final supplies (sons). This implies a reversal of the hierarchy reliability logic. In addition, there is a further difference because in electronics and mechanical systems a great number of causes can provoke system failure (end-effect) while in electrical systems very few causes (connected to primary power supplies) can involve very numerous end-effects on a myriad of end-user supplies. In order to overcome these difficulties, the FMECA method here described proceeds by subdividing a system into levels, then examines the failure causes and the linked effects level by level, starting from the end-users (top-events), and going upwards to the power-supply nodes (first-causes). After a general overview of the difficulties arising when the classical FMECA is applied to electrical systems, the new method is thoroughly described and discussed.

Key-Words: Reliability and quality in design, Electrical distribution systems, FMECA (Failure Mode Effects and Criticality Analysis).

1 Introduction

In electrical distribution systems a reliability analysis mainly deals with equipment failures and end-user interruptions. Under normal operating conditions all apparatuses (except stand-bys) are energized and all users are supplied. Both scheduled and non-scheduled events [2] can cause damages and failures to apparatuses and consequently energy interruptions. Though not usually directly involved in system failure problems, users are however affected by energy interruptions. If the supply is restored within a few minutes, the interruption is called temporary otherwise it is named prolonged. The time duration of a temporary interruption can vary from 1 to 5 minutes depending on a customer's energy supplier.

The reliability of electrical distribution systems is defined by indexes drawn from sample statistics of loads, components and users. These indexes usually take the average values of certain reliability features in a whole system, an operating region, a substation, a feeder, etc. In the last decade a great number of these indexes have been defined, the most important of which are the following:

- The SAIFI (System Average Interruption Frequency Index), which represents the average frequency of sustained interruptions per customer occurring during the analysis period.

- The SAIDI (System Average Interruption Duration Index), which represents the average interruption duration per customers served during a specified time period.

- The CAIDI (Customer Average Interruption Duration Index), which represents the average length of an interruption, weighted by the number of customers affected, per customers interrupted during a specific time period.

- The ASAI (Average Service Availability Index), which represents the fraction of time (often as a percentage) when a customer has received power during a pre-defined period of time.

- The ASIFI (Average System Interruptions Frequency Index), which represents the ratio between the interrupted kVA and total kVA served.

- The ASIDI (Average System Interruption Duration Index, which represents the ratio between the hours of interrupted kVA and total kVA served.

In practical cases, a reliability analysis is usually completed by means of an additional procedure known as FMECA (Failure Mode Effects and Criticality Analysis). This procedure examines each possible failure mode of every component in a system as well as its causes, evaluating how each failure affects the correct operating conditions of the system [4], [5], [6].

2 The proposed FMECA procedure

The FMECA is a well-established procedure traditionally used to analyze mechanical and electronic systems with a bottom-up approach, which means starting from the failure modes and causes in the single LRUs (Line Replaceable Units) and investigating the effects on the final system and the linked criticalities. Usually the LRUs are named “sons” and the final system “father”. Actually, while in traditional FMECA applications the LRUs (sons) contribute to a system’s (father) performances, in radial electrical systems the hierarchy structure is very different. As a matter of fact, since energy proceeds from upstream to downstream, the failures affecting upstream components (generators, circuit-breaker, bus-burs, etc.) cause effects to downstream supplies. Therefore causes depend on the upstream components while end effects are localized at the terminations of the final circuit breakers [7]. This leads to a remarkable reversal of hierarchy logic since upstream elements (fathers) are responsible for the causes while downstream components (sons) are affected by the associated consequences. A further difference to be mentioned is that while in traditional FMECA applications the hierarchy structure is pyramidal, i.e. many dozens (or hundreds) of causes produce very few top events, in electrical radial systems this pyramid is upside-down since very few causes (linked to the main power supply nodes) produce a great number of final effects usually involving many end-users.
A traditional FMECA procedure applied to electrical radial systems may be carried out starting from downstream components (sons) to ascend the hierarchy scale towards the main power supply node (or nodes). In this case the bottom-up approach is applied but following causes instead of effects. The inconvenience may be overcome approaching the problem with the FTA (Fault Tree Analysis), a traditional procedure used to identify the causes that lead to certain system faults [1], [3]. The FTA is a top-down procedure with two main advantages:

- It allows the prompt use of both the AND/OR operators.

- It allows the placement of identical system items at different points in the tree representation.

Unfortunately, in electrical radial systems an FTA approach involves a number of limitations:

- it does not allow to take different failure modes into consideration directly;

- partial effects cannon be considered;

- it is not possible to declare possible solutions to presumed effects;

- it does not allow to take into consideration the conditional probabilities of a faulted system once a component is assumed to be faulted.

For all these reasons, a new tabular procedure was introduced with the following advantages:

- a clear, functional description of the system;
- an effective representation of redundancies;
- a modular configuration joining FMECA and FTA capabilities;
- a representation based on a reversed pyramidal structure.

The proposed method requires a preliminary subdivision of the system into different levels and then, starting from end-users (Top-Events), analyzes both internal and external causes of failures as well as their effects at each system level, going upwards to the main power-supply nodes (Primary-Causes).

3 Application of the method

To better understand the proposed method, in this section an effective application is described and discussed. The application regards the radial electrical system shown in Fig. 1.

The application of the proposed method, which assumes the system mission to be the supply of an end-user *L1*, is concisely resumed in Table 1. The meaning of the symbols adopted in Table 1 is explained in the following:

1) *Level* – It consists of a bus-bar with the connected circuit-breakers and the switch-disconnector placed upstream the same bus-bar. The "0" level corresponds to the final-user (Top-Event), while the last level corresponds to system power supply block. The levels listed in cascade on the first column of the table are placed functionally in series connection.

2) *Function* - It describes the function performed by the level.

3) *Level failure mode* – It describes in which way the level or the LRU can fail. The failure mode can be of two kinds: either internal to the considered level, or external, which means it depends on causes coming from the level above.

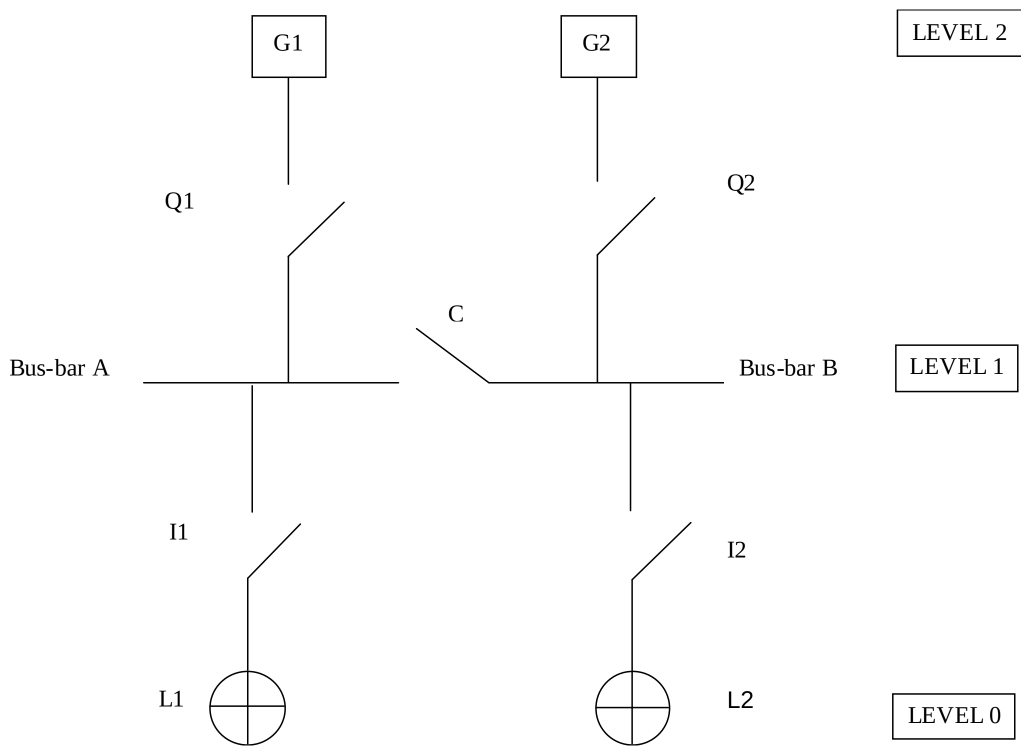

Fig.1. Diagram of the examined radial electrical system.

4) *Failure causes of the level* - It describes how internal components of the level contribute to the failure of their own level.

5) *Failure local causes of the level (internal)* – It describes the failure modes of the internal components that contribute to the failure of their own level.

6) *Symbol of the failed component* – Symbol of the component undergoing failure. Under a reliability point of view the elements located inside a level are connected serially. If redundancies are present, the different groups of the serially connected components are separated by a symbol *&*.

7) *Component failure rate* – In this column the failure rates of the components in column 4 are reported.

8) α – It is the failure rate ratio, which is similar to the ratio used in traditional FMECA procedures. It is important to note that for each LRU the following condition must be verified: $\sum_i \alpha_i = 1$.

9) *Level failure rate* – It is the summation of the failure rates of the elements composing the level. The components are those reported in column 4.

10) *Causes from the above level (external)* – These are the failure causes due to the components of the level above.

11) *Equivalent failure rate* – It is the total failure rate due to all causes, both internal and external. In the case of internal causes this rate corresponds to the failure rate of the LRU examined while for external causes it is the summation of the failure rates of the LRUs encountered in the series connection.

12) *Local effects* – It describes the local effects of the failure.

13) β - It is the conditional probability ratio, i.e. the probability that both internal and external causes can produce the end-effect. For elements connected in series, this coefficient is equal to 1. In fact, as shown in Fig. 2, in this case just one failed element is able to cause a system's failure ($\beta_A = \beta_B = \beta_B = 1$).

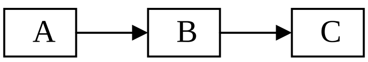

Fig. 2. Elements connected in series.

For elements connected in parallel, the β coefficient is lower than 1 because, as shown in Fig. 3, redundancies are present.

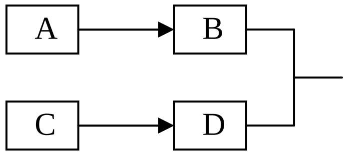

Fig. 3. Elements connected in parallel.

In this case the following conditions can be assumed:
A,B $\subset$ S1; C,D $\subset$ S2 and S1,S2 $\subset$ S
Applying the Bayes theorem, it can be written:

$\beta_A^S = \beta_{S2} \cdot MTTR_A$, that corresponds to the probability that S2 fails when A is subject to a repair process.

$\beta_B^S = \beta_{S2} \cdot MTTR_B$, that corresponds to the probability that S2 fails when B is subject to a repair process.

$\beta_C^S = \beta_{S1} \cdot MTTR_C$, that corresponds to the probability that S1 fail when C is subject to a repair process.

$\beta_D^S = \beta_{S1} \cdot MTTR_D$, that corresponds to the probability that S1 fails when D is subject to a repair process.

If the system is made of two stand-by elements, where A is the default element and B the element activated only when the default element fails:

$\beta_A^S = \beta_B \cdot MTTR_A$, that corresponds to the probability that B fails when A is subject to a repair process.

$\beta_B^S = 1$, because a failure in B causes the whole system to stop.

14) *Criticality* – It is the criticality computed as $\alpha \cdot \beta \cdot \lambda \cdot t$ where *t* is the mission time.

15) *Severity* – It is the failure severity defined by the following four levels:

I= catastrophic;

II= critical;

III= important;

IV= minor.

Table 1 – Demo application of the proposed FMECA procedure.

Level 1	Function 2	Level failure mode 3	Failure causes at level 4	Failure local causes (internal) 5	Symbol of the failed component 6	Component failure rate 7	α 8	Level failure rate 9	Causes from the above level (external) 10	Equivalent failure rate 11	Local effects 12	β 13	Criticality 14	Severity 15

0	L1 supply	L1 interruption (Top-Event)	Voltage absence	Failure on L1	L1	λ_{i1}	1	λ_{i1}	Level 1 does not feed energy	$\lambda_{i1}+\lambda_{Lev1}+\lambda_{eqD\&R}$	Mission missed	1		II
1	End-users supplies	L1 does not supplies energy	I1 missed closing	Mechanical failure	I1	λ_{i1}	$\alpha 1$	$\lambda_{i1}+\lambda_a$	Level 2 does not feed energy	$\lambda_{Lev1}+\lambda_{eqD\&R}$	Unfed End-users supplies	1		II
			I1 incorrect opening	Electrical or mechanical failure		λ_{i1}	$\alpha 2$							
			A bus-bar failed	Electrical or mechanical failure	A	λ_a	1							
		L1 does not receives energy	-	-	-	-	-	-						
2	Power supply	Absence of the D default power supply	Q1 missed closing	Mechanical failure	Q1	λ_{q1}	$\alpha 1$	$\lambda_{q1}+\lambda_{g1}$		$\lambda_{eqD\&R}$	Unfed all down-stream users	$\lambda_R \bullet mttr_{Q1}$		IV
			Q1 incorrect opening	Electrical or mechanical failure	Q1	λ_{q1}	$\alpha 2$							
			G1 generator failed	Electrical or mechanical failure	G1	λ_{g1}	1					$\lambda_R \bullet mttr_{G1}$		
		&	&											
		Absence of the R reserve power supply	Q2 incorrect opening	Electrical or mechanical failure	Q2	λ_{q2}	$\alpha 1$	$\lambda_{q2}+\lambda_c+\lambda_b+\lambda_{g2}$	-			1		II
			Q2 missed closing	Mechanical failure	Q2	λ_{q2}	$\alpha 2$							
			C disconnector opened	Mechanical failure	C	λ_c	1							
			B bus-bar failed	Mechanical failure	B	λ_b	1							
			G2 generator failed	Electrical or mechanical failure	G2	λ_{g2}	1							

4 Conclusions

Electrical radial systems are characterized by a peculiar hierarchy structure since power supply comes from upstream to downstream, which makes upstream elements responsible for the causes with the end-effects occurring at the terminations of the breakers feeding end-users. This leads to a reversed hierarchy logic since the structures placed upstream (fathers) generate the causes and the structures downstream (sons) are affected by the consequences. To solve this problem, a new FMECA procedure was proposed. After subdividing a system into levels, the new procedure employs a tabular representation to study the system, taking also redundancies into account. Starting from the end-users, internal and external failure causes and their consequent effects on the final system are analyzed level by level.

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