14th IMEKO TC10 Workshop Technical Diagnostics
New Perspectives in Measurements, Tools and Techniques
for system's reliability, maintainability and safety
Milan, Italy, June 27-28, 2016

Outage Severity Analysis on Italian Overhead Transmission Lines from a Regional Perspective

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***Abstract* – Power transmission lines represent the core of the High Voltage Network since they are responsible for the transport of the electrical energy from the generation power plants to the electrical substations. In this paper, an analysis of the outages occurred to the Italian Overhead Transmission Lines (OHTLs) from 2008 to 2015 is carried out. A new simple and effective reliability index, namely the Severity Factor, is introduced in order to prioritize the most relevant outage causes. The analysis has been performed focusing on the geographical distribution of the OHTLs. The obtained results have shown that the impact of the different outage causes on the OHTLs reliability is generally not uniform across the country but depends on the considered region. Further, for each analyzed region, the voltage levels more prone to failure have been determined. It can be concluded that the proposed methodology, thanks to the introduction of the Severity Factor, is a useful and effective tool for the identification of the transmission network criticalities and the enhance of the related maintenance activities.**

I. INTRODUCTION

Transmission networks represent the core of the electrical system and their failure implies a waste of energy and significant financial losses [1]-[2]. Consequently, the aim of the Transmission System Operators (TSO) is to increase the maintainability of the network and plan its development in order to minimize the rate of outages and make the grid able to withstand failures without serious consequences on the loads.

Overhead Transmission Lines (OHTL) are definitely the most important elements in the High Voltage (HV) network, since they are responsible for the transport of the electrical energy from the generating plants to the loads. It follows that industries and facilities give a great attention to their reliability [3]-[7]. At the same time, however, from a study conducted by the same authors in [8], it results that OHTLs are still the most critical network components considering both the number of failures and the corresponding interrupted power. The analysis presented in [8] was based on the data published by TERNA, the Italian TSO, about the outages of the Italian OHTLs in the period from 2008 to 2014. During the surveyed period 12594 forced outages were registered, with a total power interrupted of 81379 MW. The authors made an analysis on the failure modes occurred at different voltage levels introducing a novel factor, namely the Severity Factor (SF), which allowed to synthetize the information on the number of forced outages, power interrupted and outage time, in order to prioritize the maintenance activities.

The results presented in [8] provide a general overview on the Italian OHTLs reliability, but no study has been done on the distribution of the failures among the different Italian regions. In this paper, a new analysis about the reliability of the Italian OHTLs is presented. The main contribution is the emphasis put on the localization of the failures, in order to determine the most relevant failure modes affecting the different country areas, with the purpose to provide more detailed information useful for an effective maintenance strategy. Further, in doing this, a new formulation of the SF is presented in order to make it more effective on the analysis of the impact of the different failure modes.

II. THE ITALIAN SCENARIO

Italian network operator, TERNA, is one of the most important in Europe in terms of lines extension (63,900 km of high voltage), power generation (120 GW) and energy flowing (300 billion kWh per year).

TERNA yearly publishes an annual report about the outage events occurred in its transmission network [9]. For each failure the following corresponding data are provided: identification number of the outage, event location, date and time of occurrence, damaged component, voltage level, outage cause, kind of interruption (transient, short or long), grid configuration, amount of interrupted power and time to repair.

In the followings, the regional partition, the voltage levels and the failure modes considered in the analysis are described.

A. Regional partition

In order to make a uniform division of the Italian territory, TERNA identifies in its reports eight macro regions (MRs), different from the political regional division of the country. In *Table 1,* the eight MRs, together with the corresponding Italian regions, are presented.

Table 1. TERNA geographical division

MR	Italian regions
CA (Cagliari)	Sardegna
FI (Firenze)	Part of Emilia Romagna - Toscana
MI (Milano)	Lombardia – Part of Emilia Romagna
NA (Napoli)	Campania - Puglia - Basilicata - Calabria
PA (Palermo)	Sicilia
PD (Padova)	Friuli Venezia Giulia - Veneto - Trentino Alto Adige
RM (Roma)	Lazio - Umbria - Abruzzo - Molise – Marche
TO (Torino)	Piemonte - Liguria - Valle d'Aosta

B. Voltage subpopulations

For an efficient statistical analysis of the OHTLs outages data, it is useful to consider, besides the geographical partition of the failures, also the voltage level at which they occur. It is reasonable, indeed, to expect that the predominant outage causes for a transmission line may depend on its rated voltage. The classification of the voltage ratings used in the analysis is the following: 380 kV, 220 kV, 150 kV, 132 kV and less than 100 kV.

In *Table 2*, the OHTLs territorial distribution for each voltage subpopulation is reported. Such data have been obtained from the TERNA report of 2013. As the surveyed period, that goes from 2008 to 2015, is limited, however, the eventual grid expansions that may have occurred in such years are assumed negligible with respect to the total network extension, hence the reported values can be considered an accurate estimation of OHTLs distribution.

Table 2. Length of OHTLs (in km) per each Macroregion and voltage level

MR	380 kV	220 kV	150 kV	132 kV	<100 kV
CA	314.19	554.39	1995.3	-	200.07
FI	2052.5	703.06	2831.1	2842.9	79.021
MI	1285.6	2144.7	-	5667.1	-
NA	2675.9	1101.7	6646.0	-	704.21
PA	252.59	1530.1	3170.5	-	40.980
PD	772.23	2533.4	-	5550.8	190.47
RM	1953.4	1006	3626.5	2503.6	437.23
TO	889.63	1667.9	-	4343.2	210.78

C. Outage categories

TERNA divides the outages into five different categories. In particular, each of them is labeled with a given code, as defined in *Table 3*.

Table 3. Outage categories

Category	Description
1CD	Lack of resources
2FM	Unpredictable events
3CE	External causes
4AC	Other causes
5DP	Scheduled maintenance

It is worth to underline that since the focus of this paper is to present a statistical analysis about OHTLs forced outages, scheduled outages, belonging to category 5DP, are not considered in the analysis [10].

III. SEVERITY FACTOR

The Severity Factor has been introduced by the authors in [8], defining it as an index that enables a rapid and effective comparison of the impact of the different outage categories, listed in Table 3, for the OHTLs of each voltage subpopulation (paragraph B in section II). In particular with the symbol $SF_{i,j}$ it was denoted the severity factor of a generic outage category i for the OHTLs of the voltage category j. The proposed classification of the data, however, is not the only one possible. Another interesting categorization, for instance, comes from the analysis of the distribution of the failures in a given macroregion among the different voltage levels. In such case, following the notation above, category i would refer to the voltage level, whereas category j would refer to the geographical region to consider. In the following, for the sake of the clearness, in order to distinguish between categories i and j, we will refer to the category j as macrocategory, inside which the effects of the category i are analyzed.

More in detail, the SF was defined in an analogous way with respect to the Risk Priority Number (RPN) adopted in the Failure Mode, Effects and Criticality Analysis (FMECA) [11]. In particular, given:

- $N_{i,j}$: number of recorded outages belonging to category i and macrocategory j;
- $PI_{i,j}$: sum of the interrupted power related to outage events belonging to category i and macrocategory j;
- $IT_{i,j}$: overall inactivity time due to outage events belonging to category i and macrocategory j;

the parameters n, p, t are obtained as:

$$\begin{cases} n_{i,j} = \dfrac{N_{i,j}}{N_j} \\ p_{i,j} = \dfrac{PI_{i,j}}{PI_j} \\ t_{i,j} = \dfrac{IT_{i,j}}{IT_j} \end{cases} \qquad (1)$$

Where N_j, PI_j, IT_j are computed as described above but considering only macrocategory j.

Finally, the severity factor was defined as

$$SF_{i,j} = n_{i,j} \cdot p_{i,j} \cdot t_{i,j} \qquad (2)$$

The aforementioned severity factor has been introduced in order to synthetize in a unique simple index the severity of each outage cause in terms of interrupted power, time to repair, and number of interruptions. In [8], for instance, it was exploited in order to compare the severity of different outage causes for each voltage subpopulation. The formulation proposed in (2), however, has some drawbacks. First of all, the sum of severity factors of different categories i for a given macrocategory j (e.g. severity factors of different outage categories for a given voltage level) is generally different from 1, so that they do not represent the impact, in terms of percentage, that each category i has inside the macrocategory j. This implies also that, if considered singularly, the value $SF_{i,j}$ does not provide a significant information about the severity of the category i, but, in this sense, the comparison and the ranking of the different $SF_{i,j}$ is needed in order to determine the most critical categories. Finally, the SF, as defined in (2) does not have a proper physical meaning. All the described considerations have motivated the need for a reformulation of the SF in order to increase its clearness and informative strength. In this paper, a different analytical definition of the severity factor SF for a category i given a macrocategory j is proposed as reported in (3):

$$SF_{i,j} = \frac{\gamma_i \sum_{n_i=1}^{N_i} \left(P_{n_i} \cdot t_{n_i}\right)_{i,j}}{\sum_i \left(\gamma_i \sum_{n_i=1}^{N_i} \left(P_{n_i} \cdot t_{n_i}\right)_{i,j}\right)} \qquad (3)$$

where the terms P, t are, respectively, the interrupted power and inactivity time caused by an outage event belonging to both category i and macrocategory j (N_i is the number of recorded outage events that satisfies both categorizations). The factor γ_i, instead, is a normalization coefficient that takes into account the length of the OHTLs in the different macroregions, as it will be discussed in the next section.

Thanks to the new formulation in (3), the generic $SF_{i,j}$ has now a physical meaning since it represent the not transmitted energy amount for a macrocategory j, associated to a category i, making it meaningful and informative even if considered alone. Moreover, the sum of the SF of the different categories i for a macrocategory j is now equal to 1 by definition. These improvements makes the severity factor more easy to understand and offer a more intuitive representation of the OHTLs faults trend so that it can result as a useful tool for the maintenance personnel in the coordination of the maintenance activities.

IV. OUTAGE DATA ANALYSIS

Once defined the new SF, it is possible to carry out a statistical analysis on the OHTL outages. This analysis is divided into two parts: first, the severity of different categories for every MR has been evaluated. Then, the evaluation has been focused on the impact of the outages for different MRs and different voltage levels.

A. Outages Categories Analysis

Scope of this section is to evaluate the severity of the different outage categories for different MRs. The SFs have been evaluated considering pooled data during the observed period, from 2008 to 2015. In order to make the analysis more meaningful, the severity factor has been computed also for the total national data, marked with IT. The obtained results are reported in *Fig. 1*.

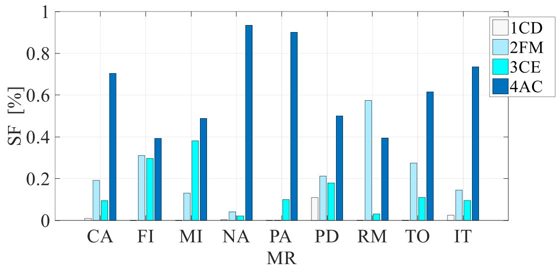

Fig. 1. Outage category SF for different MRs

As expected on the basis of the analysis carried out in [8], one of the most severe category for the MRs is the one related to the environmental conditions (4AC). This, however, is not verified in Roma and Firenze, where the lines result more sensitive to the outages categorized as “not expected environmental condition” (2FM) and to the outages of the grid connected to the transmission system.

B. Voltage Subpopulation Analysis

A deep outage data analysis has been carried out considering the voltage population as the macrocategory *j*, and the regional subdivision as the category *i*. Therefore, the normalization coefficient γ_i will be every time equal to 1 as the subpopulations are uniform.

Thanks to the new definition (3) of the severity factor, it is possible to carry out a meaningful SF comparison between different macroregions. Furthermore, the relative SFs for each MR considered have been also compared with the results obtained at national level.

The analysis results are shown in *Fig. 2*. It must be reminded that, as it can be observed in *Table 2*, only the MRs Roma and Firenze have all the considered OHTL voltage levels. Therefore, in the following table, the symbol “-“ indicates absence of the voltage level of the corresponding column in the MR referring to that row, and so is not sufficient to look *Fig. 2* in order to have a complete view of the pooled data. It can be noticed that the values of SFs of a region sum up to 1.

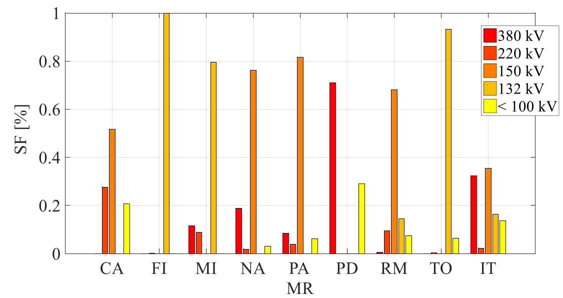

Fig. 2. Voltage levels SF for different MRs

Table 4. Severity Factor per each Macroregion and voltage level

MR	380 kV	220 kV	150 kV	132 kV	<100 kV
CA	0.00	0.28	0.52	-	0.20
FI	0.00	0.00	0.00	1.00	0.00
MI	0.12	0.09	-	0.79	-
NA	0.19	0.02	0.76	-	0.03
PA	0.08	0.04	0.82	-	0.06
PD	0.71	0.00	-	0.00	0.29
RM	0.01	0.09	0.68	0.15	0.07
TO	0.00	0.00	-	0.93	0.07
IT	0.32	0.02	0.36	0.16	0.14

The focus on the category 132 kV allows to make some interesting considerations. At national level (column IT in *Table 4.*), indeed, this voltage level does not present particular criticalities if compared to other voltage populations. Moving the analysis to a regional level, instead, highlights how this voltage level is the most critical case for three important macroregions as Firenze, Milano and Torino. It follows that the voltage category 132 kV has to be monitored in the aforementioned regions and that some measures has to be taken in order to increase the related reliability and availability.

On the other hand, at national level the most severe voltage categories are represented by 150 kV and 380 kV populations, having a SF equal to 0.35 and 0.32

respectively. From a regional perspective, however, it can be noticed that 150 kV grid is the most critical level in all the MRs in which it is presents (Cagliari, Napoli, Palermo and Roma), whereas the 380 kV grid shows only a critical situation in Padova with a SF equal to 0.71. Further, the fact that this grid is not the more extent in Padova (*Table 2*) makes this case even more interesting and consequently it can be stated that a more detailed investigation must be performed by the maintenance and management personnel. It is worth to highlight how an analysis focused only at national level could not allow to reach this level of detail in the analysis of the results. Further, it would have been also misleading as it would have induced the analyst to think that the national situation would be replicated at regional level, whereas the analysis carried out in this paper demonstrates that this is not the case.

A different analysis can be carried out from the opposite point of view, that is considering the regional subdivision as macrocategory *j*, and the voltage population as category *i*. In this kind of analysis, the subpopulations are not uniform (the length of the lines at a given voltage level are not the same in each region), hence the normalization coefficient γ_i of (3) is defined as follows:

$$\gamma_i = \frac{L_j}{L_i} \tag{4}$$

where L_j is the total line lengths for a defined voltage level, and L_i is the length of the lines at that voltage level in the ***i***-th MR. Thanks to γ_i, the resulting analysis is not biased by the different voltage network extension in the different regions. Therefore, it is possible to evaluate outages severity of each Italian region for a given voltage level. The achieved results are shown in *Fig. 3*.

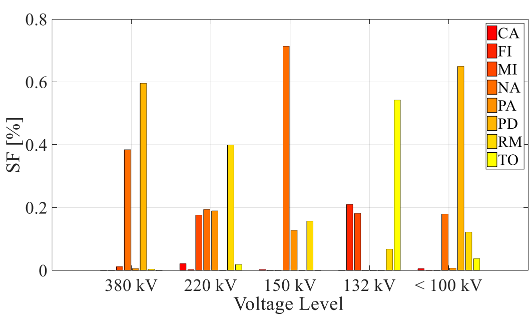

Fig. 3. SF for different voltage levels

The results confirm the aforementioned considerations made in the comments of *Fig. 2*. It is evident, in fact, that Padova and Napoli are the MRs most affected by outages in 380 kV voltage grid.

It is meaningful underline that Padova and Napoli present high SFs in the two different analysis. Therefore, it can be concluded that these MRs must be considered for the prioritization of the maintenance activity.

Finally, considering Torino and Cagliari, the outages analysis shows that the least reliable voltage grid is the 132 kV level, whereas the SF related to the remaining voltage levels is negligible.

The results obtained up to now can be synthetized in the following table (*Table 5*) where the most critical levels are defined considering each region separately (Local Impact), or the contribution of that region to the national outages for a defined voltage level (National Impact).

Table 5. Worst voltage subpopulation (Local and National Impact)

MR	Local Impact	National Impact
CA	150 kV	220 kV
FI	132 kV	132 kV
MI	132 kV	220 kV
NA	150 kV	150 kV
PA	150 kV	220 kV
PD	380 kV	< 100 kV
RM	150 kV	220 kV
TO	132 kV	132 kV

The table underlines that the national analysis is not sufficient to depict the actual regional impact of the outages on the transmission grid. In fact, this approach shows that the stronger impact of the outages are related to 380 kV and 150 kV OHTLs. This statement, as can be seen from *Table 5*, is not replicated on all the MRs, and so it makes the regional perspective consistent.

The analysis of the results has highlighted the effectiveness of the proposed SF index for the identification of the most critical voltage levels for the transmission levels at both national and regional levels, resulting as a useful tool for an optimal planning of maintenance activities.

V. CONCLUSION

In this paper, an analysis of the outages occurred to the Italian Overhead Transmission Lines (OHTLs) from 2008 to 2015 has been carried out. In particular, a new reliability index, namely the Severity Factor, has been introduced in order to provide a useful tool for the prioritization of the most relevant outage causes. The analysis has been performed focusing on the geographical distribution of the OHTLs and the obtained results have shown that the impact of the different outage causes on the OHTLs reliability is generally not uniform across the country but depends on the considered region. Further, for each analyzed region, the voltage levels more prone to failure have been determined. The same analysis has been carried out also at national level and the results have shown that the situation depicted at such level is not necessarily replicated at regional level, justifying the classification of outages data according to regional criteria, as proposed in this contribution. Finally, it can be stated that the proposed methodology, thanks to the introduction of the Severity Factor, is a useful and effective tool for the identification of the transmission network criticalities and the enhance of the related maintenance activities at both local and national levels.

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