Resilience Assessment and Enhancement in Electric Distribution Networks

Claudio Carlini¹, Emanuele Ciapessoni¹, Diego Cirio¹, Pietro Marcacci¹, Diana Moneta¹, Andrea Pitto¹

¹ Ricerca sul Sistema Energetico RSE S.p.A. – Milan, Italy

claudio.carlini@rse-web.it, emanuele.ciapessoni@rse-web.it, diego.cirio@rse-web.it, pietro.marcacci@rse-web.it, diana.moneta@rse-web.it, andrea.pitto@rse-web.it

Abstract—Extreme weather events are getting more and more frequent and may lead to severe effects on electric distribution systems, in terms of damages to the infrastructure and failures in the energy supply to the customers. Thus, network operators call for tools able both to forecast contingencies on the basis of weather predictions and to suggest countermeasures to boost system resilience.

The paper describes the method and a tool for resilience assessment and enhancement for distribution networks in case of extreme natural events and, in particular, wet snow storms. The tool operates in two stages: a risk-based module to detect critical lines (more prone to fail due to wet snow sleeves), and an OPF module which assures minimum anti-icing currents on previously identified critical lines. The simulations performed on a model of a real-world High Voltage (HV)/Medium Voltage (MV) grid in the Italian Alps demonstrate the effectiveness of the proposed approach.

Keywords—distribution network, power system, resilience, wet snow, vulnerability

I. INTRODUCTION

The increasing frequency of extreme weather events, affecting both transmission and distribution networks, pushes Transmission System Operators (TSOs) and Distribution System Operators (DSOs) to evaluate the impact of multiple dependent outages of components, possibly leading to blackouts, and to propose preventive or corrective countermeasures to absorb the effects of such disruptive events and to recover fast, i.e. to increase system resilience [1][2]. In this context, current Italian regulation [3] imposes operators to publish and update yearly a plan for resilience enhancement.

The assessment of the effects of these extreme events on the grid and their mitigation, call for an in-depth analysis on the vulnerabilities of T&D components to natural threats, as well as on the deployment of suitable measures to prevent the resulting -also multiple, dependent- contingencies.

The difficulty of the analysis is also due to the fact that distinct tools are generally used to perform decoupled analyses on T&D systems, even though mutual potential effects can take place in case of a contingency, e.g. the outage of High Voltage (HV) lines can cause the loss of supply of HV/Medium Voltage (MV) substations with potential loss of supply of the customers at distribution level. Reference [1] proposes a tool to evaluate the benefits to resilience brought by the deployment of grid hardening measures: they are typically focused on the transmission system and on one or few specific threats, with ad hoc models for threats and component vulnerabilities. In [4] the authors present selected methods and technologies that can be taken to improve distribution networks’ resilience during different phases of a weather-related disruptive event.

The key and innovative features of the proposed methodology are: (1) the ability to identify the components more prone to fail under a wide set of natural threats (from wet snow to pollution, floods, etc.), and to simulate the response of the integrated T&D system to disturbances; (2) to propose operational measures at minimum costs to counteract one specific threat, i.e. wet snow events.

After an overview of the rationale, the paper describes the methodology and tool for resilience assessment and enhancement. A case study is presented in section III, regarding two MV feeders connected to the surrounding HV grid in Aosta Valley. Simulation results demonstrate the modeling flexibility of the tool and its potential in assessing critical components and suggesting cost effective operational measures to boost resilience. Conclusions are drawn in Section IV.

II. THE TWO-STAGE APPROACH FOR RESILIENCE ASSESSMENT AND ENHANCEMENT

This section describes the approach for resilience assessment and enhancement. It consists in two stages:

- the identification of the most critical components, on the basis of an extended risk-based approach which combines the probabilistic models of the weather threat and the vulnerability models of the grid components of the T&D network;

- the deployment of suitable operational measures (the scheduling of active and reactive powers of distributed generators, and the setting of HV/LV transformer taps) to avoid the damage of critical components due to wet snow events.

A. Resilience assessment via extended risk approach

The resilience assessment methodology applies the model illustrated in [5] to describe the connections between threats, component vulnerabilities, and power system contingencies. Natural and/or human-related threats may lead to a contingency through a set of causes exploiting vulnerabilities, while the contingency might lead to different impacts depending on the circumstances. The initial impact may in turn affect other vulnerabilities, starting a cascading process that may eventually result into a blackout. In order to quantitatively assess the relationship between root causes (threats) and power system disturbances (contingencies), the methodology extends the classical concept of risk [6] as a set of triple (contingency, probability, impact) and defines risk as a set of quadruple (threat, vulnerability, contingency,
impact) where the probability term is replaced by the probabilistic models associated to threats and vulnerabilities.

This extended risk definition allows to link Probabilistic Hazard Assessment (PHA) studies to Security Assessment (SA) analyses, focusing on the root causes of disturbances. This step forward also allows to select the dangerous contingencies, to be simulated in detail, on the basis of current or expected environmental/weather conditions, thus complementing conventional security analyses based on the classical N-1 criterion.

B. Modeling threats and component vulnerabilities

Threat modeling requires the knowledge of the dependence of the stress variable pdf at location x. The tool allows to characterize the threat geospatial models in two ways:

1. in operational planning mode, where weather variable geospatial distributions come from a forecasting system available at the control centre;
2. in engineering mode, by analytical functions which characterize in probabilistic terms the intensity and extension of the threat.

The tool is capable to model a quite exhaustive set of natural threats, including wet snow events, pollution, earthquakes, floods, landslides, contact with trees, fires.

Each HV and MV component is characterized by a vulnerability function which is specific for each threat and can be derived from ad hoc tests, mathematical models, or qualitative information from experts.

Fig. 1 shows the architecture of the tool for risk-based resilience assessment [5].

- generate a comprehensive set of multiple, common mode and dependent contingencies involving the critical components;
- identify the riskiest contingencies establishing a minimum risk threshold $R_{min}$ by using a fast screening method, based on ex-ante topological risk indexes.

The retained contingencies are simulated using a quasi-static cascading outage simulator in order to evaluate the potential cascades triggered by the initiating events, thus computing indicators such as the amount of MW’s lost or the energy not served.

The risk-based resilience indicator in case of generic contingency $j$ is given by (1).

$$Resilience_{c,j} = \frac{1}{Risk_{c,j}} = \frac{1}{(p_{c,j} \times Imp_{c,j})}$$

where $p_{c,j}$ is the probability of the contingency while impact indicator $Imp_{c,j}$ is given by the loss of load.

Besides assessing the risk of loss of load, the tool provides the set of critical lines to the resilience enhancement tool described in subsection II.E.

C. Wet snow events: modelling aspects

Under specific conditions of temperature ($0^\circ$C-$2^\circ$C), the snowflakes can partially melt and settle on the conductor and join together not only by the mechanism of collision, but also for the strong coalescence due to the presence of Liquid Water Content (LWC) in the snowflakes that promotes the growth of sleeve typically cylindrical in shape around the wire (see Fig. 2).

$$\frac{dM}{dt} = \alpha_1 \alpha_2 \alpha_3 \ast W \ast A \ast V$$

where $\alpha_1$ is the collision efficiency; $\alpha_2$ is the sticking efficiency, and $\alpha_3$ is the accretion efficiency; $w$ is water content (kg/m$^3$); $A$ is the cross-sectional area (m$^2$) perpendicular to object; $V$ is the particle impact speed perpendicular to object (m/s). Sticking coefficient is a function of wind intensity $W$: $\alpha_2$ is equal to 1/$W^{0.3}$ if 1 m/s < $W$ < 10 m/s, while it’s equal to 0.1 and 1 respectively for $W$ = 10 m/s; and for $W$ = 1 m/s. The density of snow sleeve is calculated in [8] $\rho_s = 300 + 20 W$; $\rho_s = 500$ kg/m$^3$ if
$W > 10 \text{ m/s}$. Moreover, the model assumes a cylindrical wet snow accretion on conductor without sleeve shedding phenomena (conservative accretion). The empirical parameters have been deduced from measurements of icing station collected over the past three winters. More details can be found in [9].

The most vulnerable components to wet snow events are the OHLs with bare conductors in MV and HV/EHV grids, and the aerial cables in MV networks.

The vulnerability probabilistic models for OHLs with bare conductors includes the vulnerability of:

a) the phase conductors and the shielding wires which are affected by the mechanical tension due to the combined ice-wind load;

b) the tower equipment (insulator chains, and bracings) subject to combined force due to wind and ice loads.

As for item a), a mechanical fragility curve is evaluated for each phase conductor and shielding wire consisting in a lognormal distribution of mechanical tension with a mean value equal to the expected tensile strength in kN for the conductor (e.g. 170 kN for a 31.5 mm ACSR conductor used for phase conductors of HV lines) and a standard deviation equal to 2% of the expected value. The failure probability of individual line span is calculated by combining the failure probability related to the phase conductors, the shielding wires and the tower equipment.

In MV networks OHL lines with bare conductors usually do not have shielding wires. Instead, the pole of a MV line can be severely affected by wet snow, thus its vulnerability curve cannot be neglected. On the contrary, for HV and EHV lines, the mechanical failure of the towers is neglected because lattice towers are much less vulnerable to ice and wind loads with respect to tower equipment like the bracings. Moreover, the most used configuration for MV aerial cable lines is characterized by three cables wrapped around a 9 mm diameter galvanized steel wire. The mechanical action on cable lines is essentially carried out on the supporting wire, whose vulnerability is given by a lognormal probability distribution with an expected value of 62 kN (for a 9 mm diameter steel wire) and a 2% standard deviation.

D. Countermeasure modeling

The measures to boost system resilience [10] in case of natural threats can be classified into two categories:

- passive approaches, aimed at improving the ability of the infrastructure to not be damaged in case of threats, by preventing and minimizing their impact via the introduction of redundancies, the hardening of the components, and the use of protective barriers;

- active approaches, aimed to minimize disruptions, to improve system absorption capability, recovery speed.

Two examples of passive and active measures are respectively the reconductoring, i.e. the upgrade of the mechanical strength of conductors by adopting larger diameters for the conductors, and the redispatching of generation to assure the minimum anti-icing currents to avoid wet snow sleeves formation on overhead lines.

Reconductoring can be applied both to the HV and to the MV grids, given that in some cases a potential upgrade of the physical supporting infrastructure (i.e. the towers/poles) must be performed in order to withstand the increased weight of the new conductors.

In order to introduce the abovementioned active measure, it’s worth noting that any conductor is characterized by a minimum anti-icing current, a function of the environmental factors: this current level allows to the maintain conductor at a specific skin temperature in order to keep it free from snow accretion. A suitable combination of actions (setting of transformer taps, and re-dispatching of active and reactive powers of dispatchable generators) may help achieve the minimum anti-icing current requirement.

E. Resilience enhancement via an OPF algorithm

Resilience enhancement is obtained by assuring a minimum anti-icing current on the lines identified as critical in stage 1. In [11], for HV/EHV transmission grids, the authors have proposed an algorithm aimed at redispatching the active powers among dispatchable generators and based on sequential mixed integer linear programming, in order to assure minimum anti-icing currents. The high values of minimum anti-icing currents required for HV/EHV bare conductors (often close to the conductor rated current) make the algorithm effective in case of moderate wet snow storms (with relatively low precipitation rates and wind speeds).

In the present paper, an AC OPF (Optimal Power Flow) based algorithm, where losses and integral constraints are taken into account, is applied to the MV feeders to get an optimal scheduling of active and reactive powers of distributed generators and setting of HV/MV transformer taps. Starting from forecasted load and generation, considering technical constraints and dispatching costs for active and for reactive power, the algorithm generates for each time period a set of commands for controllable resources that guarantees achievement of technical goals minimizing the overall dispatching cost [12]. ‘Costs’ can represent actual costs of dispatching or only a ranking criterion among the available controllable resources. The high flexibility of the approach allows to introduce some the minimum current constraint consisting in (3) to lines identified as “critical” in Stage 1.

\[
T_{ij} \leq \frac{1}{\sqrt{3} \cdot V_{ij} \sqrt{T_{A_{ij}}^2 + T_{R_{ij}}^2}} \leq T_{ij}^* \tag{3}
\]

where $T_{i,j}$ is the transit value from node $i$ to node $j$, $V_{ij}$ is the voltage value, $T_{A_{ij}}$ is the active power transit, $T_{R_{ij}}$ is the reactive power transit from node $i$ to node $j$.

IV. Case Study

This section presents a case study referring to threat “wet snow”, describes the grid model, the threat scenarios and discusses the simulation results obtained from the risk-based resilience assessment tool.

A. Grid Model

The test system under study integrates two MV feeders, Smart Grid“ Deval project promoted by ARERA [13], with a portion of the surrounding HV/EHV transmission grid in Aosta Valley, specifically around HV/MV primary substation at Villeneuve, particularly critical in terms of operation and maintenance as it provides energy to a very large area (about 770 km²).
Fig. 3 provides an overview of the integrated MV and HV grid under study. The dashed lines in Fig. 3a) are MV feeders excluded from the present analysis.

![Fig. 3. The integrated MV/HV/EHV grid: (a) map of MV feeders and HV grid, (b) the one-line diagram of the two feeders](image)

The resulting MV/HV grid model is derived from Aosta Valley map [14], Deval [13], as well as ENEL and Terna standards [15][16], and it includes 92 MV electrical nodes, of which 60 nodes are MV/LV substations, 29 transit nodes in correspondence of line poles, and 3 the HV and MV busbars at Villeneuve HV/MV substations. Three main counterfeeds can connect the following nodes: Champagne – Thumel Caverna (#12 - #46); Bouillet – Camping (#26 - #31); Bouillet-Dir. Bouillet (#26 - #63). The rated transformation power at MV/LV substations is estimated on the basis of the size of the population served by each MV/LV substation: 50, 100, 160 and 250 kVA. The model also includes 10 HV (132 kV) nodes, 8 EHV (220 kV) nodes as well as 20 OHLs, 6 generators and 3 EHV/HV transformers.

It’s worth noting that a unique model is used in the platform to represent the overall system; the hazard analysis and the simulation of the system response to the disturbances are performed only once on the same integrated grid model.

**B. Simulation scenarios**

Table 1 reports the main features of the wet snow storm scenarios adopted in the simulations.

<table>
<thead>
<tr>
<th>Hazard parameter</th>
<th>S1 (moderate)</th>
<th>S2 (severe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak wind speeds</td>
<td>10-15 m/s</td>
<td>10-15 m/s</td>
</tr>
<tr>
<td>Precipitation rate</td>
<td>1 mm/h</td>
<td>5 mm/h</td>
</tr>
<tr>
<td>Initial precipitation</td>
<td>10 mm</td>
<td>20 mm</td>
</tr>
<tr>
<td>air temperature</td>
<td>-0.5°C to -1.5°C</td>
<td>-0.5°C to -1.5°C</td>
</tr>
</tbody>
</table>

The resilience assessment stage is applied to the two basecases while the resilience enhancement stage is applied to a representative case involving a single sample branch along one of feeders.

For all the simulations the following parameters for the wet snow events are assumed as fixed parameters:

- diameter of the wet snow precipitation area = 80 km;
- diameter of the wind-swept area = 35 km;
- threat center around Villeneuve substation.

Unless differently specified, the fraction of explained total failure probability is set to 0.95. Moreover, all the components with a failure probability higher than (or equal to) 10% are considered as critical components.

**C. Resilience assessment in the basecases**

For all the overhead conductors in MV and HV grids Fig. 4 reports the expected values of the stress variables (i.e. the mechanical tension) on the conductors, and the loads due to wet snow and wind for basecase S1.

![Fig. 4. Mechanical tension (a) in kN, and wet snow sleeve thickness (b) for MV and HV lines, scenario S1 moderate wet snow](image)

In Fig. 5 the critical components (in particular, branches) are represented using a specific colour to represent their conditional probability of failure (white for probabilities lower than 0.2, cyan for probabilities between 0.2 and 0.4, yellow for probabilities between 0.4 and 0.6, red for probabilities between 0.6 and 0.8, magenta for probabilities higher than 0.8).

**Fig. 5. Geo-localization of critical components, scenario S1 moderate wet snow storm**

Fig. 6 reports the contributions (in terms of expected lost MW) of each contingency category to the total risk of loss of load. The largest contributions to the total risk are associated to high order common mode branch outages (N-13 and N-14): in fact, most of the selected critical lines have a very high probability of failure.

**Fig. 6. Contributions to total risk of each contingency category, scenario S1**

The application of the severe wet snow event S2 to Villeneuve area determines a set of 52 critical branches, of which 37 have a failure probability higher than 90% and 15 a failure probability between 0.9 and 0.1.

The high severity of S2 event determines a very high probability of damage not only on small section branches but also on branches in high order common mode branches.

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- diameter of the wind-swept area = 35 km;
- threat center around Villeneuve substation.

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(35 mm²) section but also on main branches of the two feeders (such as 40-41) with higher sections (70 mm²). The risk of losing a very large set of branches (up to 52) is much higher than in moderate wet snow scenario S1.

**D. Resilience enhancement**

The resilience enhancement stage is applied on a simplified form of network in terms of similar topology, load and generation estimation. Lack of load and generation data implies only preliminary studies, mainly addressed to verify the minimum current constraints functionality on a sample branch in order to achieve a future extension to all identified critical branches. Minimum current constraint of selected sample branch, corresponding to #53 - #57 and 70 A of rated current, is set sequentially and successfully on increasing values until 150 A, in order to reach and overtake the considered anti-icing reference current (1 A/mm²) according to [17][18]. The minimum current constraint insertion causes upheavals in typical network values like high power counter-fluxes, low voltage at extreme sample branch node and on Primary Substation (PS) MV busbar (through OLTC tap position) as exposed in Table 2 and Table 3.

Table 2: Network power fluxes in sample branch for different minimum current values

<table>
<thead>
<tr>
<th>Minimum current value [A]</th>
<th>#53 - #57 Active Power [kW]</th>
<th>#53 - #57 Reactive Power [kVar]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-282</td>
<td>-126</td>
</tr>
<tr>
<td>25</td>
<td>27</td>
<td>-70</td>
</tr>
<tr>
<td>70</td>
<td>1127</td>
<td>-116</td>
</tr>
<tr>
<td>125</td>
<td>3369</td>
<td>-143</td>
</tr>
<tr>
<td>150</td>
<td>3894</td>
<td>-176</td>
</tr>
</tbody>
</table>

Table 3: Network voltage values for relevant nodes for different minimum current values

<table>
<thead>
<tr>
<th>Minimum current value [A]</th>
<th>#57 voltage [p.u.]</th>
<th>PS MV busbar voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.965</td>
<td>0.965</td>
</tr>
<tr>
<td>25</td>
<td>0.964</td>
<td>0.961</td>
</tr>
<tr>
<td>70</td>
<td>1.010</td>
<td>0.990</td>
</tr>
<tr>
<td>125</td>
<td>1.036</td>
<td>0.961</td>
</tr>
<tr>
<td>150</td>
<td>1.038</td>
<td>0.915</td>
</tr>
</tbody>
</table>

The obtained results show how the resilience enhancement stage reach and overtake reference anti-icing values guaranteeing other constraints within typical limits. Further actions will consider the extension of this device to all critical sections, according to cases S1 and S2.

**V. CONCLUSIONS**

The paper describes a two-stage methodology and a tool for resilience assessment and enhancement for integrated transmission and distribution networks in case of extreme natural events and, in particular, wet snow storms.

The application results on a real world integrated HV/MV grid in the Italian Alps, show the ability of the resilience assessment tool to identify the critical lines and to simulate the integrated HV/MV network response to contingencies in case of threats with different intensities. In particular, very severe snow events are characterized by high load loss indicators associated with widespread multiple, common-mode line contingencies (involving tens of components out of service). Moreover, the OPF application results show that the provision of active and reactive powers from MV distributed generators, calculated by the OPF algorithm, can effectively counteract the formation of wet snow sleeves on MV lines. This provision of ancillary services from generators is not yet established in the current regulatory framework. The future activities on this tool, including a technical-economic comparison of the different solutions, could contribute to the discussion of that framework.

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