Enhancement of Slovenian Electricity Transmission System Resilience spurred by experience and new approach

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Abstract— ***this paper aims to report primarily on new measures encompassed and introduced with respect to the relevant technical regulations put recently in force and on endeavors in immediate mostly technical modifications of assets imposed by lessons learned during past emergency events, as well.***

Emphasis was given particularly to enforcing of asset's mechanical withstand capability based on scrutinized analyses of loads experienced during past emergency events. Increasing withstand of critical structures was selectively made.

This paper gives an overview of various essential long-term activities and shows the level of new developments achieved after encountering bitter experiences during last decade. The paper deals also with assessing loading limits of selected essential network components aiming to reduce system vulnerability during emergencies hence increase its resilience. Majority of the experienced emergencies were produced by harsh weather impacts in the wintertime. There were many cases of OHL failures, which triggered in the aftermath scrutinized analyses aiming to determine the mechanical loads, encountered. Suitable refurbishing of OHL critical parts have been done respecting new standards. Aiming to allow for expedite restoring of OHL operating capability in emergencies the introduction of Emergency (modular) towers usage was selected and successfully implemented.

Owing to the notorious fact, that OHLs' and power transformer's loading limits can be extended, several projects were launched to assess, evaluate and eventually up-grade the limit capacity implementing advanced monitoring equipment. Intensive support to asset management was done, such as maintenance optimization, state-of-the-art approach, condition monitoring of HV equipment, assets life cycle assessment and evaluation, etc.

One of all-important steady processes remains to encourage the political decision makers to support the erection of new facilities notably OHL through simplifying and facilitating the spatial planning procedure (OHLs Right of Ways!) as well as mediating the social public-private dialogue. All these endeavors being in favor of upgrading the power system resilience.

Keywords— resilience, transmission network, innovative approaches

I. INTRODUCTION

The ENTSO-E drafted new Network Codes on Emergency and Restoration early in 2015, the pertaining ACER Recommendations followed later in the same year. The Directive concerning measures for a high common level of security of network and information systems across the Union was issued in 2016, and finally, but not less significant, the experiences encountered during past recent years additionally lead many of the TSOs in the Union and across the world to intensify the defense planning. Slovenian TSO responded by intensifying its efforts, which have been already introduced being triggered by numerous emergency events encountered during past few years.

The focus of these endeavors was an improved and partly new approach in dealing with system assets, changing the design of new assets and of the refurbished/repaired damaged assets as well. Additionally, several state-of-the -art monitoring systems were introduced allowing for much more sophisticated insight into selected and for jeopardizing of components most relevant mechanical, electrical and thermal stresses, leading to a reliable evaluation of higher acceptable operation load in emergency circumstances.

In 2014 and 2015, Slovenia was affected by severe icing storm as well as severe wind (Fig.1, 2). Extreme weather conditions covered almost all territory and triggered red alarm. Damages of electricity network infrastructure were catastrophic as never before. In one week, in February 2014, all damages in different infrastructures exceeded 600 million Euros for all country. Considering electricity sector damages amounted about 80 million Euros.

Fig.1: Collapsed tower in Transmission network, February 2014

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In Transmission sector 62 towers collapsed and seven transmission OHLs were out of operation, what counts 52 km or 1.9% of all OHLs. Complete restauration of assets lasted 3 months costing 8.5 million Euros but recovering period of energized Transmission network was much faster using Emergency towers in the meantime. In Distribution sector, of course, damages level was much higher, and amounted on 68 million Euros (917 km of MV and 655 km of LV networks, or together over 13% of distribution network).

In 2015, Slovenian electricity infrastructure were affected by severe wind exceeding 200 km/h causing high level of damages in the transmission infrastructure. In following years, we indicate more severe weather events, and utilities devoted more attention to defense activities considering new approaches.

Fig. 2 Winds over 100 km/h become common in Western part of Slovenia.

Summarizing, what we have learned from recent years about weather conditions, the conclusions are (R.5, R.6):

a) Designing and construction of lines is not appropriate to clime changing conditions, so upgrading of standards is one of the first action to be done,
b) In new framework of national normative aspects in standards there are needs for increasing reliability factors as well as increasing number and values of icing zones,
c) For distribution network new approach with cabling MV network was accepted, particularly in forests,
d) Importance of Management guides in crises, and staff trainings are crucial.
e) Communication assets improvement and well-organized cooperation with neighbors are very important.

Obviously, the large disturbances caused by unfavorable weather conditions are not predictable but using new approaches e.g. Artificial Intelligence (AI) it is possible to improve observability.

The long-term past experiences learned from frequent components failures caused by using low material manufacture quality incited and stimulated the maintenance personnel to introduce quite early the dedicated diagnostics activity to prevent from excessive outages. From time-based diagnostics at the very begin to condition based diagnostics and finally to diagnostics supporting reliability-oriented maintenance. Lightning arresters, instrument transformers, power transformers, OHLs, underground cables and rotated machinery were included in that customary defense program.

That was the reason for a much easier step forward while introducing enhanced procedure with the purpose to respect the new Network Code prerequisites and requirements.

II. IMPROVEMENTS OBTAINED WITH NEW DESIGN AND BETTER OBSERVABILITY OF OHLS

A. New standards and reinforcing of Transmission lines

Increasing number of weather storms that affected overhead lines require new approaches in designing, monitoring of and planning of lines, considering and putting forward resilience of the grid. In weather disaster, in February 2014, which caused collapse of 52 OHL towers, all of them were designed considering old standards from 70s and 80s. In 2009, Slovenia approved new NNA (national normative aspects) based on Std. EU 50341-1-2001, as transitional approach with 3 icing zones but upgraded values for loads. Ongoing project of new NNA version of standard, which have to be harmonized with new European standard EN 50341-1-2012, will consider four icing zones plus 30% wind, as well as new probabilistic approach (R.6). This will bring hardening of components and better resilience parameters.

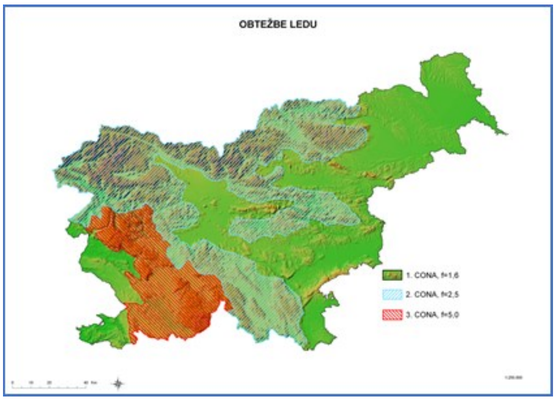

Fig.3: Existent Slovenian NNA : SIST EU 50341-2:2009 (Considering 3 zones for glaze ice with density 900kg/m^3)

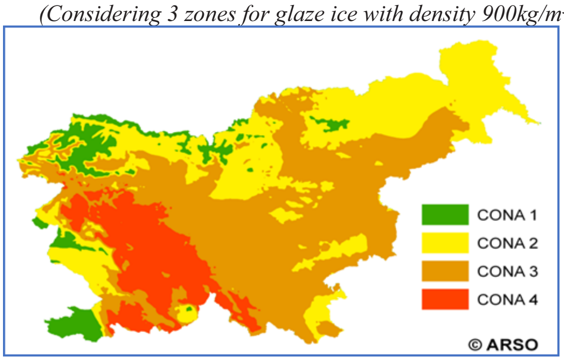

Fig.4: New proposal for NNA considering EU 50341-1:2012 (There are 4 zones for glaze ice with density 900kg/m^3)

B. Introduction of OHL Surge arresters (LSA)

There had been several methods used for the improvement of lightning performance of existing transmission lines, such as: tower footing resistance reduction, increase of line insulation level, installation of additional ground and guy wires, addition of under-built ground wires, etc. Some of them have shown limited effect, while others resulted in very high costs and the corresponding difficulties. Intensive meticulousness was devoted to the application of LSA for the lightning performance improvement of OHLs erected in regions with very intensive lightning activity and difficulties to achieve a good line grounding.

Thanks to the development of polymer housed LSA with and without an external gap it was possible to maintain complete control on the line lightning performance in several cases.

The selective analysis to determine of satisfactory number and installing locations of LSA was achieved by means of a suitable computer tool, which became a customary approach in dealing with LSA application in the country. The "Sigma slp" software is used for the determination of the arrester installation configuration and for the computation of arrester energy duties. All statistical simulations are performed on the section of the line model represented by ten towers (without reflections from the section ends). The following data and representations are used when applying this tool:

- Data gathered by the Lightning Localization System (SCALAR)
- Insulation flashover is modeled between phase conductors and towers, using the leader propagation model.
- Tower footing resistance is represented by a soil ionization model.
- For each study, one thousand simulations are usually performed.
- The power frequency initial voltages are randomly selected.
- Transients on the tower top are modeled using inductive branches with parallel damping resistors. The bottom section of the tower is represented by surge impedance.
- The volt-time curve of the complete arrester is taken in account.
- A three-dimensional Electro geometric model is used.

The improved accuracy of lightning positioning and lightning current amplitude measurement accomplished by new development achievements [R.1] contributed to the much more advanced procedure giving better results.

The experience derived from such an approach has proven in how far the OHL lightning performance can be improved:

- ✓ The best solution is installing of LSA between all phase conductors and tower arms,
- ✓ Substantial improvements can be obtained reducing the number of LSA according to the lower grounding resistance in selected line sections,
- ✓ The installing of LSA can particularly reduce the lightning impact of compacted OHLs.

C. Improving observability of lightning flashes related with line failure data

Another step forward allowed the increased location accuracy of SCALAR LLS. A usable correlation between SCALAR and SCADA gathered data became practically applicable.

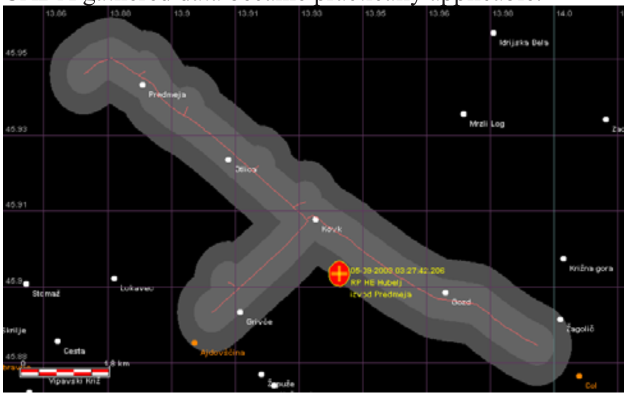

Fig.5: An example of 20 kV line fault correlated with lightning on September 5, 2008 at 3:27:42.206

Slovenian lightning location system (LLS) offers real–time observation, access to archived lightning data for statistical evaluation and beyond that also advanced correlation service, which was developed primarily to automatically correlate the data in real-time to identify the line faults caused by lightning [R.2, 4]. The correlation service is based on information received from SCADA system, LLS (SCALAR), and the geography and topology database, too.

The real-time correlator of line faults due to lightning developed for distribution lines offers fault location information supporting a better coordination between the distribution system control operator and maintenance crews in the field. The practical use of the correlator has proven considerable help in shortening the time necessary for detecting fault location.

D. Real-time assessment and short-term forecast of network operational limits (SUMO) [R.3]

Cared for and concerned about the network operation in contingencies and in emergencies, the TSO encouraged experts to provide for a suitable method and tool facilitating the evaluation of the network operational limits.

The preconception was initiated by knowing the use of Dynamic Thermal Rating (DTR), which covers the thermal assessment of components in the entire transmission system.

The boundary conditions for the system were determined as follows:

- SUMO must be developed for the operator's use in the Slovenian Power System National Control Centre (NCC). The NCC operator, besides obtaining information on the current capacity of power lines and transformers (independent DTR), at first requires a simultaneous N-1 calculation and short-term forecast loading capability for N-1 topology.
- The uncertainties of SUMO evaluation results should be known. By validating individual DTR algorithms and estimated forecast of environmental air data, TSO requests

obtaining information on uncertainties, which are induced by DTR during operation. Only when all the uncertainties become known, SUMO will be ready for regular operational use.

It was found very soon, that the SUMO architecture became much more important than anticipated in the initial start-up proposal. In the aftermath SUMO obtained an additional boundary condition:

• SUMO must be modular. Modularity enables the use of minor and major improvements, further development and continuous inclusion of new technological solutions.

Due to some other reasons explained in [R.1] SUMO had to meet one more condition:

• SUMO must provide for the operator information on extreme environmental operating conditions. TSO implements various data on atmospheric ambient conditions along the power lines, which can have a significant impact on operating safety in N and N-1 condition.

These results are crucial in terms of operation resilience, enabling the operator to focus on those power lines, which operate under more difficult conditions facing higher risk of failure. After the catastrophic ice damage in 2014 the proposed further target of the SUMO system was to eventually forecasting ice storms and introducing efficient technical measures for their remedial.

III. Weather forewarning system

The long-year SCALAR operation, newly developed technologies, especially JavaFX and Web Services have emerged and standardized. They are nowadays widely available and are, together with much more powerful computers and easy Internet access, becoming a platform of choice for new development. Therefore, TSO decided to improve the old user interfaces based on years of experience with much more advanced mapping capabilities and functionalities. The TSOs and other users, too, can now access the lightning data much easier and are enabled to perform data analysis and monitor weather data in real time [R.4]. Custom GIS, alarming and correlation services are now integrated in a useful and user-friendly new way.

Based on the lightning discharges detection records obtained by SCALAR and correlating the pertaining data with whether forecasting system database, an efficient computer tool was developed and introduced by some TSO in the Southeast European Region as a suitable overall alarming system. Its adopted brand name is ScalarFlashClient (SFC). This system integrates several previously introduced tools and allows TSO to perform:

- Reliable delivery of real-time lightning data and visualization of the data in an easy applicable way,
- Real-time correlator of power line outages caused by lightning,
- Real-time selective alarming notification of the lightning activity close to overhead power lines and substations,
- Advanced analytics,
- Utilizing of high resolution flash density data for analysis of lightning threat and impact on electric power facilities,
- Utilizing of lightning data archive for statistical analyses such as amplitude distribution and probability in coordinating each component basic insulation level of transmission and distribution power facilities.

IV. Improved power transformer loading

Power transformers count for one of the most critical and valuable assets within electrical transmission and distribution networks and are expected to provide reliable operation for decades. Transformer lifespan is considered primarily as function of the winding insulation state, which degrades highly depending on operating temperature. A higher winding operating temperature results in faster insulation degradation and therefore decreasing of transformer residual life. Transformer loading constrains have for this reason traditionally been managed conservatively, defining transformer maximum rated power by its steady (nameplate) current, to secure operational reliability and longevity of the transformer.

Transformer overloading may be necessary and can occur during power system emergencies. Depending on the utility's criteria, transformers may be overloaded to keep the continuity of system operation in hazard circumstances as well as during system restoration. Power transformers are customarily protected by suitable carefully selected and setup thermal protection schemes that rely on a steady temperature limits to detect thermal abnormalities and prevent accelerated premature ageing of the transformer insulation system.

Thermal protection trip is initiated when the winding hottest-spot temperature exceeds the pre-set limit values typically taken over from the loading guides. However, such a protection scheme might be rigid while fencing the operation options in a much conservative manner. In emergency circumstances, the risk of station outage might be significantly reduced if a reliable information on acceptable short- term overloading range is provided.

Application of Transformer Dynamic Thermal Rating (DTR) provides a numerical tool to increase transformer operational flexibility and simultaneously retain supervision of operational reliability at handling emergencies. It enables calculation of the maximum thermal loading limit and allowed loading time, based on the dynamic transformer thermal model and forecasted loading and ambient temperature profiles. The maximum loading limit of a transformer is predominantly limited by the winding's hottest-spot.

The information on the DTR gives to the operator the possibility to overload the unit not jeopardizing its future safe operation. The Slovenian TSO came to conclusion that such approach would enable mitigating of critical situations and took the decision to undertake a pilot project, which was successfully achieved.

V. USE OF EMERGENCY (MODULAR) TOWERS

The initial incentive for introduction of modular temporary use towers was to use it as method for "by-passing" of existing transmission lines. It was considered as universal solution (temporary tower) not dependent on the type and height of the transmission line, the voltage level, foundation and the situation on the ground. Besides that and later on, a quick restoration of the transmission line function (in case of damages and reconstructions) should be carried out.

The main advantages proven during it first executed implementing were the following:

- Quick assembly of the tower (one day) - modular structure
- Flexibility to terrain and ground
- Adjustable height of the tower
- Voltage level flexibility
- Towers are used multiple times
- Appropriate storage and logistics (containers)

The experience identified some disadvantages, such as:

- The modular towers require relatively large space for installation (anchoring)
- There have been found some terrain limitations

The Fig.6 shows the situation of an experienced application ase.

Fig.6

With the purpose to keep the personnel ability level in good condition, periodic training of OHL Maintenance crew is scheduled at the location of Substation Maribor, every 2 years for 3 days. It comprises at least the following:

- Tower assembling,
- Determining of the tower and anchor location,
- Preparation of anchors,
- Erection of the tower

It is worth to mention just few of executed application cases, which are shown in the Fig.7:

Case 1: Line 2x110 kV Slovenj Gradec-Velenje: Two Towers collapsed; Cause: Ice-storm

Case 2: Line 2x110 Gorica-Ajdovscina: Two Towers collapsed; Cause was bora wind: 200 km/h velocity

Case 3: Line 110 kV Cirkovce-Kidricevo: OneTower replacement, Weakened foundations

VI. CONCLUSIONS

The endeavors presented in this paper may not be considered as being immediately relevant to the System defense plan as devised and formulated in the ENTSO-E NC ER - Chapter 2 or even to those in Chapter 3. Many other aspects must be carefully considered, and suitable actions implemented to successfully cope with the danger brought by natural and other disasters.

Significant portion of the OHLs overall around the world were designed and erected around 30 and 60 years ago according to the designing standards considered at that time. Increasing of weather storms frequency which affected overhead lines require new approaches in designing, monitoring of and planning of lines, considering and putting forward resilience of the grid.

There are some concerns with longer-term exposure of old and not properly designed OHLs to cope with severe climatic events and their impact on future resilience and reliability. From this reason, Slovenian TSO decided to improve resistance of Transmission network and to enhance resilience of grid. For this purpose, it is important to upgrade standards for designing and construction of overhead lines. Hardening of components, new designs, monitoring systems, and placing distribution lines to underground, will make future network more resilient.

Our experience led us into persuasion how important the assets are while facing limit stress and which information the operator needs to take best decisions. The telecommunication and information technology offer nowadays a variety of valuable devices and tools and much more efficient novel products are to be expected in the next future. It is worth to mention how many expectations we have introducing new assets, remarkably changing the power systems structure that immediately require new automation, control and protection systems.

Much more flexible operation of assets producing unsteady loading is expected and consequently additionally intensified aging. That is the reason for an enhanced approach.

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