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PS2 LATEST TECHNIQUES IN ASSETMANAGEMENT,
CAPACITY ENHANCEMENT, REFURBISHMENT

Resilience Assessment 400 kV Overhead Lines Stevin – Horta in Belgium

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SUMMARY

ELIA manages the Belgian high voltage network and its role is to transport electricity. ELIA's network is a key link between France, Europe's largest electricity exporter, and markets in Northern Europe. Elia is due to compensate the market parties in cases of “force majeur” or emergency. Elia thus must protect itself against this liability as much as possible and needs to perform its asset management in accordance with national and international standards and update its asset management to changes in its grid and connected users.

In Q1 2019, the HVDC (High Voltage Direct Current) Nemo link between UK and Belgium comes into commercial operation. The Nemo link is connected to the Elia grid via the 380kV Stevin - Horta antenna. In addition, in case of unavailability of the 380 kV Stevin-Horta axis, the offshore wind farms will not be able to inject into the grid and hence have to be curtailed.

This was one of the reasons to execute a resilience study for this connection , including its 400 kV substations and cable connections, in 2019. This study was executed by in cooperation with *DNVGL.* The scope of this paper is limited to the overhead lines. The aim of the resilience study was :

- To define and prepare the implementation of supplementary measures on towers, to reduce the probability of failure
- To deliver a specific resilience plan (specific emergency plan) to restore the operation as quick and as complete as possible in order to limit the impact in the case the unavailability of the 380 kV Stevin – Horta axis.

During the design phase the risk due to extreme environmental loads was already evaluated. Based on that is was decided to design the towers and foundations for more demanding criteria which differ from the usual practice in Belgium with respect to the reliability class, the wind class, ice loads and strength coordination.

These design criteria lead to an acceptable level of risk on unavailability of the Stevin-Horta axis. This was demonstrated once again in the resilience study.

Besides the confirmation of the structural design the executed resilience study prepared a plan with specific supplementary prevention and mitigating measures in case of an exceptional failure that will further enhance the availability of Stevin-Horta axis.

The paper will briefly describe the risk assessment process followed and the main residual risks that had to be mitigated . The main mitigation and supplementary measures for the OHL/Towers will be explained:

- In case of events with tower failures the Emergency Restoration System (ERS) owned by Elia can be installed. However it turned out that some additional specific components should be purchased to realize the transition of different type of conductors.
- In order to install the available ERS within the required timeslot for 6 specific critical locations, detailed scenario’s for the installation *of ERS* are required. These were developed in 2021.
- With respect to the risk of intentional human acts of sabotage at two locations, prevention measures are advised.

KEYWORDS

Overhead line – resilience - risk assessment - prevention measures - mitigation measures - emergency line

1 INTRODUCTION.

ELIA manages the Belgian high voltage network and its role is to transport electricity. The purpose of the high voltage network is to transport the electricity supplied by electricity producers to distribution grid operators and large industrial users. ELIA's network is a key link between France, Europe's largest electricity exporter, and markets in Northern Europe.

Elia is due to compensate the market parties in cases of "force majeur" or emergency. Elia thus must protect itself against this liability as much as possible and needs to perform its asset management in accordance with national and international standards and update its asset management to changes in its grid and connected users.

In Q1 2019, the HVDC (High Voltage Direct Current) Nemo link between UK and Belgium came into commercial operation. The Nemo link is connected to the Elia grid via the 380kV Stevin - Horta antenna. The Nemo link is connected to the new 380 kV GIS (Gas Insulated Switchgear) substation of Gezelle. In addition, in case of unavailability of the 380 kV Stevin-Horta axis, the offshore wind farms will not be able to inject into the grid and hence have to be curtailed.

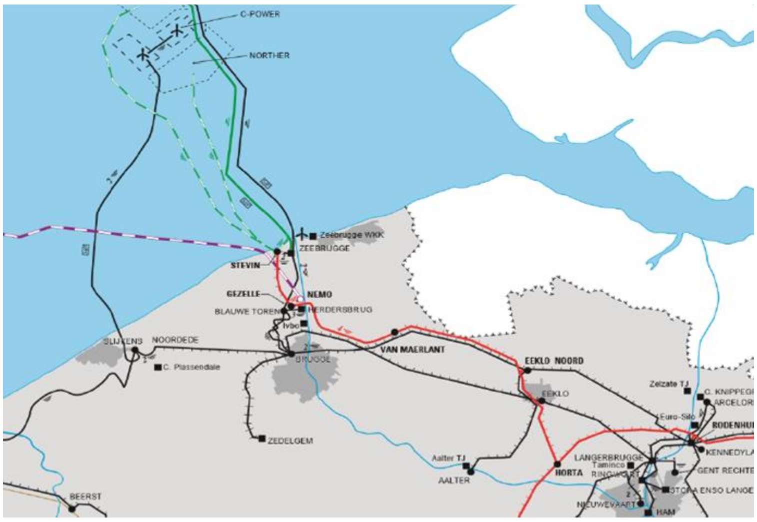

Figure 1 Stevin-Horta line

This was one of the reasons to execute a resilience study for this connection , including its 400 kV substations and cable connections, in 2019 . The scope of this paper is limited to the overhead lines. The aim of the resilience study was :

- A prevention plan. To define and prepare the implementation of supplementary measures on towers, to reduce the risk on unavailability of the Stevin-Horta axis
- A mitigation plan To deliver a specific resilience plan (specific emergency plan) to restore the operation as quick and as complete as possible in order to limit the impact in the case the unavailability of the 380 kV Stevin – Horta axis should occur.

2 RISK ASSESSMENT; RATIONALE AND APPROACH.

Figure 2 provides an overview of the frame work of the executed risk assessment . The assessment also includes some feasibility studies regarding the installation of the ERS at specific sites.

Inputs for this risk assessment were the project related documents about installation, maintenance, and operations, and the design information of the overhead lines assets. Also information about the available Emergency Restoration System was used as input.

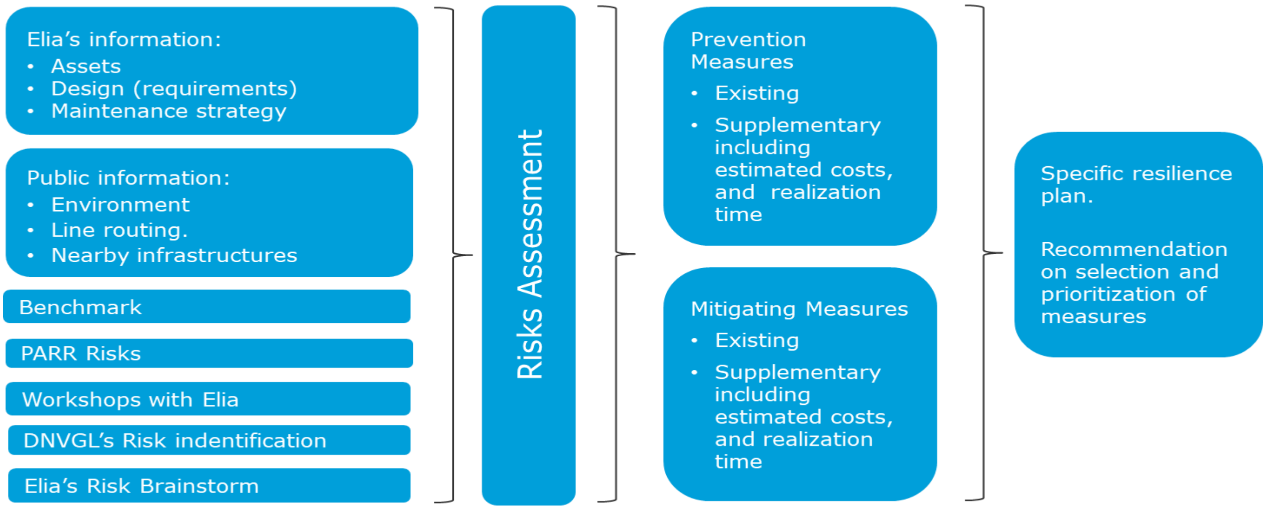

Figure 2 Risk assessment framework

During the design and execution of the Stevin-Horta project, Elia developed a risk matrix; PARR - Stevin 2015, including the Completed_Action_Documentation.

This Project Asset Risk Register (PARR)

- Aimed at gathering the risks related to the asset design of the current solution of a project;
- Used to manage the risks in order to minimize the occurrence of events impacting the grid.

This PARR gave an overview of the mitigated risks and the assumed risks of the chosen solutions for the Stevin-Horta connection. Those were used as input for the risk assessment. In this risk assessment the risk appetite was qualified according to the risk matrix provided by Elia In this risk assessment the risk dimension "continuity of supply" is taken into account.

3 RISK INVENTORY AND QUANTIFICATION

Risk Inventory

The result of risk inventory for the overhead line is a list of 12 risks divided into two categories:

- **Primary risks**; risks related to failure of the line or a damaged line which could lead to failure caused by another event.

    1. Tower/foundation failures due to extreme environmental loads (wind and ice).
    2. Instability of V-brace suspension due to accidental environmental loads.
    3. Intentional human acts of vandalism or terrorism.
    4. Unintentional human acts
    5. Flashover due to accidental environmental loads.
    6. Maintenance strategy (not) aligned with higher reliability requirement.
    7. Unforeseen generic material defects leading to common mode failures
    8. Changes in the direct environment of nearby infrastructures.

- **Secondary risks**; risks directly related to the (temporary) restoration of the line after failure which take too much time. The maximum restoration time is defined as one week for temporary restoration and 6 months for final restoration.

  9 Temporary restoration not possible/ takes too much time. In case of exceptional/accidental loads or events in general cause conductors and towers failures.

  10 Final restoration takes too much time. In case of exceptional/accidental loads or events in general cause conductors and tower failures.

Risk quantification, mitigation and prevention measures.

The risks 1, 2, and 5 are related to environmental loads and were taken in account during the design phase , as well as risk 7 related to material strength and quality of the components of the line .

During the design of the line, including the towers and the foundation, the risk failure of the line due to extreme environmental loads like wind and ice is normally mitigated by proving that the strength of the tower, foundation and other components fulfils the prescribed set of design requirement.

The new tower and foundation structures of Eeklo Noord – Stevin are designed following criteria which differ from the usual practice in Belgium (NNA EN 50341-2-2). The differences are :

- Reliability class 2 instead of class 1 for usual pratice;
- Wind class I (Flat horizontal areas without obstacles) instead of wind class II (Rural areas with isolated obstacles) for usual pratice;
- Ice loads for altitude > 400m with strong (not extreme) wind instead instead no ice for altitudes <400m;

The existing tower and foundation structures of Horta –Eeklo Noord are re-designed following criteria which differ from the usual practice in Belgium:

- Wind loads according to de Belgium standard NBN B03-002-1, so called “2qb”-level, which results in de reliabilty between calls 1 and 2 for 20 existing towers, For 2 existing towers reliability class 2 was applied.
- Wind class II (Rural areas with isolated obstacles)
- Ice loads for altitude > 400m in combination with reduced wind instead of no ice for existing lines at altitude < 400m.

These designs approaches results in a probability of structural failure of the line, which is lower than for the existing 380 kV lines in Belgium. One order of magnitude lower for Eeklo Noord – Stevin and Half order of magnitude lower for Horta –Eeklo Noord.

For this risk the probability of failure is considered as low as reasonably possible. The consequence of failure is theoretically category 4 according to the Elia risk matrix : no power supply for a significant area. However, the risk appetite of risk 1,2,5 and 7 is rated as “low” assuming that timely temporary and final restoration is possible. This is because an Emergency Restoration System (ERS) is available, . ERS is a solution for restoring power quickly in an emergency situation; creating construction bypasses or reducing outage time required during maintenance.However there is still a risk that temporary restoration using the available ERS system is not possible or takes too much time (more than one week) and that final restoration take too much time (longer than 6 month). This is addressed in Risk 9 and 10.

Risk 9 deals with the possibility that temporary restoration by the Emergency Restoration System (ERS) available at Elia is not possible or takes too much time.

The evaluation of this risk started with a generic assessment for the whole line, followed by specific assessment for line sections which are rated as critical for using the ERS.

The ERS is a supremely practical system, used for emergency response, maintenance works, new construction and even to create medium-term temporary measures to alleviate system grid constraints.

ERS is made of standard, interchangeable components, that make it straightforward to adapt the structures for site-specific situations. All tower types use the same basic components. Towers can be erected within four hours, without heavy equipment; the heaviest parts weigh only 140kg, making manual assembly possible

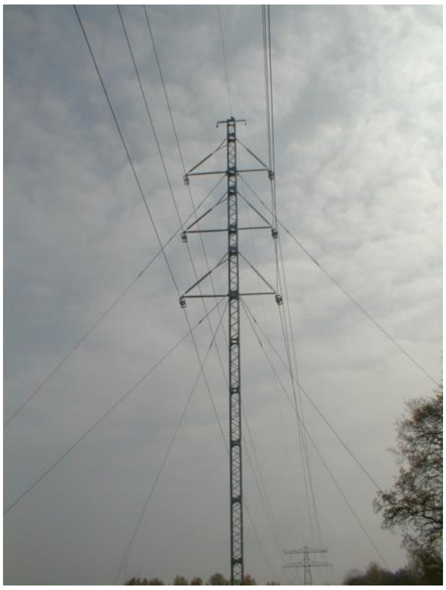

Figure 3 Emergency Restoration System (suspension tower)

During the design and the construction of the line different failure containment measures are taken. For the evaluation of this risk is of relevance that the line contains anti-cascading towers every 4 km (maximum), except between tower 1-12 near Horta (4,8 km).

The ELIA ERS system contains 28 towers ((16* RA (Running Angle) and 12*AT (Angle Tower). For the risk assessment the following characteristics are of importance :

- Maximum possible span length about 180 m for the 4*707AMS-2Z conductor
- Angle tower and suspension tower with height extensions require 1 tower body per phase.
- The installation of ERS is not tested using the ACCC-Z Antwerp conductor or a HTLS conductor in general as used in the Stevin Horta connection. It is also regarded as not preferable, because the ERS is designed to install fast, using traditional conductors.

The conclusion of the generic assessment was that in general restoration of the worst-case length (4 km) is possible within a week considering the flat terrain and without extraordinary obstacles or crossing with other infrastructures under the condition that:

- Some additional equipment is in place to realize the transition between 2*ACCC-Z Antwerp conductor and 4*707AMS-2Z conductor.
- The installation of structures for horizontal configuration of the phases is trained.
- Enough spare AMS conductors are in store for 5 km (one circuit 380 kV) ERS.

The second step in the evaluation of risk 9 was a site exploration executed using Google maps. All line sections were checked for the use of the available ERS system on the following criticalities:

- Availability of space for locating ERS tower with guy wires;
- Crossing with other critical infrastructures;
- Demanded height of the conductors;
- Section length longer than 4 km.

In total 6 critical locations are identified for which a baseline plan was prepared to check the feasibility for (timely) installation of the ERS.

It was concluded that for these sections enough basic assets are available also for the long section between tower 1-12 near Horta (4,8 km). However, some situations require structures with horizontal configuration of the phases, which is not trained by the crew. Remaining criticalities are the availability of potential ERS spots and the interfaces with other infrastructures.

The following prevention measures are required:

- Purchase additional spare AMS conductors (35 km) in order to be able to install 4,8 km of ERS. 60 km is needed, and 32,4 km is available in store yet.
- The installation of structures for horizontal configuration of the phases should be trained.
- Prepare detailed restoration scenario's for specific critical situations.

Risk 10 is directly related to the basic assumption that after temporary restoration the final restoration takes place within 6 months in order to minimize line is operated with one circuit on the ERS. This risk deals with the possibility that final restoration takes more than 6 month. The criticality of this risk is the possibility that critical components are not available within 6 months. Critical component with delivery time of probably more than 6 months are conductor and insulators.

To minimize this risk enough spares should in place to restore a damaged line section of maximum of 4 km. The likelihood that the whole 4,8 km section of tower 1-12 of Harto-Eeklo will fail is regarded as very low because it deals with 12 towers.

In order to have enough spares in place to restore a damaged line section of maximum of 4 km the assessment showed that the following the supplementary prevention measures should be taken :

- purchase extra spare AMS conductors for another 3 km of double circuit, 4-bundle 380 kV line (75 km conductor wire length)
- purchase extra spare insulators for another 2 km line in order to have enough for 4 km of double circuit 380 kV.
- special clamps/components have to be purchased for the transition of HTLS to AMS conductors. It was decided that the ERS will be installed with AMS also for all line parts.

An acceptable, less costly, alternative measure to minimize this risk as reasonable as possible is :

- Limit the spare conductors to install 1 circuit on the ERS. This is acceptable since the delivery for new conductors is about 3-4 months;
- Execute final restoration of one circuit as quick as possible with the spare insulators and the new conductors, in case of an event and keep the ERS longer in place for the other circuit. This is acceptable because restoration of 4 km is worst case and not probable to happen;
- Purchase in the meantime new insulators for 4 km of one circuit and new spare insulators .

Risk 3 and 4 concerns different types of intentional human acts of vandalism or terrorism and unintentional human acts as such, which can cause damages and failures of the line as consequence.

Risk appetite is rated as medium. Prevention or mitigation measures are needed if reasonably possible.

The mitigation measures for the consequences of line failures are in general independent of the different types of intentional or unintentional human acts. The most relevant mitigation measures are the ERS for temporary restoration and having spare parts in store to execute final restoration as soon as possible.

Another generic required mitigation measure is to implement an adequate inspection regime with identifies damages of towers and foundations which did not lead to immediate failure. It is advised to execute visual inspection on a yearly basis in order to execute repairs before the winter season.

The prevention measures (if possible or adequate), on the other hand, are dependent of the different types of intentional and unintentional human acts. In table 1 an overview of assessed failure causes is given.

Unintentinal human acts	Intentional human acts
Collision of a vehicle with foundation and or tower legs	Collision of a vehicle with foundation and or tower legs
Construction work nearby the line	Bullet shooting
Fire.	Fire
Plane hits conductors.	Anti-tank missile
Nearby windturbine rotor blade breakage	Cutting torch
	Member theft

Table 1 Assessed human act failure causes

For most causes of failure prevention measures were regarded as hardly impossible, impossible or economically unjustifiable, except for collision of a vehicle with foundation and or tower legs and for the failure of nearby wind turbines.

Based on a site exploration executed, using Google maps, an overview is generated of tower locations with potential risk of collision with a vehicle. As criteria was used that a tower is in the vicinity of 100m of a road and that tower can be hit by a vehicle without having to make a significant curve off road.. Based on the public information on Street View most risks seems to be mitigated by an existing ditch or guardrail. In case of doubts the situation was checked at site . Two towers remain to have potential risk of intentional collision with a vehicle. It is planned to realize road blocks and/or a ditch at those locations.

A similar a site exploration was executed to generate an overview of tower locations with potential risk of damage and failure due to wind turbine failure (rotor blade breakage). As initial criteria were used that a wind turbine within 200 m distance from the line is of potential risk.[1] At two locations this criteria was met.

The applicable guidelines at that time, require for the type of wind turbines at those locations a distance of more than 150 m without having to execute a location specific risk analysis. The only condition is that dampers have to be installed in the endangered spans , which has been done in the Stevin – Horta line. According to similar guidelines, e.g. from the Netherlands , in this kind of cases the distance without increased risk should be at least 180-220 m.

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[1] References for this assessment are:

- Advies door Elia bij het oprichten van windturbines in de nabijheid van de hoogspanningslijn
- Handboek Risicozonering Windturbines, versie 3.1 september 2014 (Rijksdienst voor Ondernemend Nederland)

The basic principle for the assessment of this risk is that the failure risk of the line is not increased with more than 10% based on the generic failure rate of a line. In the guidelines this 10% is related to the generic failure rate of a line in Belgium. As stated before the failure of this specific line is almost an order of magnitude lower than the generic failure rate. Therefore the relative increase of the line failure rate is probably more than 10% if the requirements of the guideline are exactly followed. Taking this in account the Risk Appetite is regarded to be medium. Therefore, it was concluded that a specific risk analysis is needed to prove that the risk is acceptable. Results of this analysis are not available yet.

Risk 6 concerns an adequate maintenance regime. Because the line is designed for a higher reliability level than other lines in Belgium the usual maintenance strategy could not be adequate enough. Because the actual maintenance strategy is condition based, the risk appetite is however considered to be low. It was concluded to start with the usual maintenance regime and evaluate the inspection results taking in account the higher reliability level of this line.

Risk 7 deals with changes in the direct environment of the tower and its foundation and at nearby infrastructures which can have negative impact on the stability and sustainability of the foundation and the tower structure. This will be imposed by displacements of the foundation and the tower.

The risk appetite is rated as moderate but not urgent. It was concluded to develop and implement an adequate monitoring/survey system to monitor upcoming changes in the direct environment and nearby infrastructures to be able to define timely mitigation measures. During the assessment the development of the system was already in progress.

4 RESULTS OF THE ASSESSMENT.

Based on the assessment it was concluded that the design of the overhead line /towers to resist environmental loads and permanent loads is adequate. Also, failure containment measures are qualified as good as reasonably possible.

However some supplementary measures have to be taken in order to restore the operation as quick and as complete as possible to reduce the risk on unavailability of the Stevin-Horta axis.

In case of events with tower failures the ERS is the key mitigation measure available. However for the effective use the system owned by Elia, additional spare AMS conductor wires are required as well as and some additional specific components to realize the transition of different type of conductors. Furthermore maintenance and contractor crews should be training for specific structures with horizontal phase configuration which can be assembles with the available ERS.

In addition detailed scenarios have to be prepared for the installation of the ERS for specific critical situations. The detailed scenario focusses on

- The criticality is the availability of ERS spots with enough space for the guy wires.
- A scenario for the installation of the ERS at some sites should be developed together with road and rail infrastructure owners to prevent unacceptable ERS installation delays during an event.

Furthermore the following measures were suggested to implement:

- At two locations prevention measures should be taken to prevent the collision of a vehicle .
- An inspection regime to identify intentional and unintentional damages due to human acts which do not lead to immediate failure in order to assure timely repairs;
- A process to monitor changes in the direct environment and nearby infrastructures is in place and that the critical spare part policy is adequate.

It was recommended to execute an additional stability analysis of the V-brace system for unequal ice or snow loads and a location specific risk analysis for nearby wind turbines.

5 DETAILED ASSESSMENT OF IDENTIFIED CRITICAL LOCATIONS

The resilience study on the risk of unavailability of the Stevin-Horta axis was followed by a detailed assessment of the installation risks with respect to the available emergency restoration system for 6 critical locations. For each of the six locations the positions for temporary masts and guy wires of the ERS system and checked on the practical feasibility at site and the availability of standard and special parts.
For each of the identified locations, two connection options were designed. A dead-end option (DE option) and a no dead-end option (NDE option).

The purpose of the DE option was to simulate a situation in which the existing towers at either end of the line section are damaged and cannot be used as part of the emergency connection. To reduce the loads on the existing towers, dead-end ERS towers were placed adjacently and connected via jumpers.

The NDE option assumes that the existing towers at either end of the line section are still in good condition and can be used as part of the emergency connection for the ERS line.

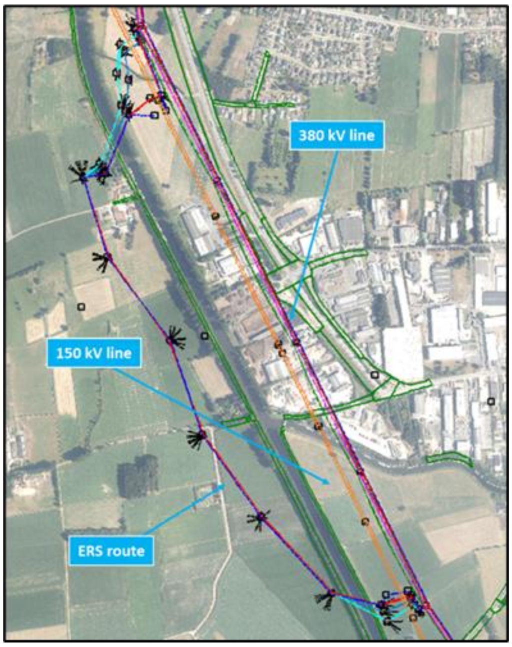

Figure 4 Profile drawing complex section of the line.

Figure 4 contains an example of a more complex location. It is relative complex due to the surrounding infrastructure which includes a 150 kV line as well as the protected trees lining the canal. The route starts by crossing underneath the 150 kV line and then over the canal in successive spans which warranted the use of special structures to obtain sufficient clearance. The structures adjacent to the canal are comprised of 13 - 16 2.9m-sections . Each structure carries one phase . To ensure earthwire continuity, dedicated structures are used to carry the earth wire underneath the 150 kV line.

After crossing over the canal, the route is a bit simpler. Structures there have sufficient space and are the standard ones. Special structures were required to cross back over the canal. The heights of the structures were influenced by the height of the protected trees as indicated in the survey data.

Subsequently all external and internal clearances were assessed and if needed a braced V modification was utilized to ensure sufficient clearance. To meet the internal clearance requirements, additional components have been designed which increased the capability of ELIA’s existing insulator assemblies to provide sufficient clearance.

After the design stage a site- inspection was carried out at each location to ensure the feasibility of our ERS line design. Access roads, possible (future) tree & bushes obstructions were looked upon and if needed the design was slightly altered. For each ERS tower location a site plan was made as it shows in the figure 5.

An extensive soil survey was carried out in which the soil resistivity was established on each location of an ERS tower. In that way the best possible approach for the anchoring of the guywires was established up front. For each location also so called "capacity planning" was developed in which a detailed building, maintenance and decommission planning format has been provided in order to minimize response time in case of an emergency situation on one of the locations concerned.

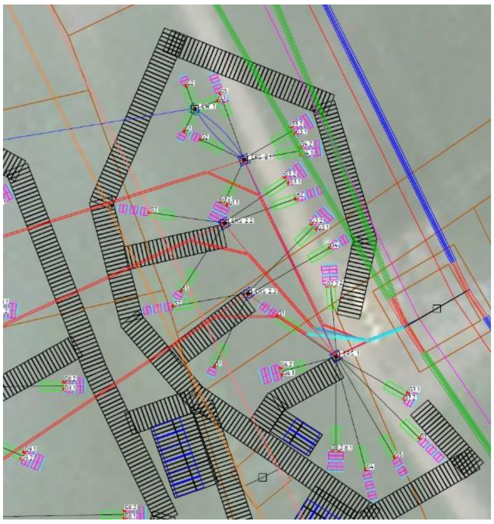

Figure 5 Site plan example

6 CONLUDING REMARKS

Besides the confirmation of the structural design the executed resilience study prepared a plan with specific supplementary prevention and mitigating measures in case of an exceptional failure that will further enhance the availability of Stevin-Horta axis.
This paper briefly described the risk assessment process followed to specify supplementary prevention and mitigating measures in case of an exceptional failure that will further enhance the availability of Stevin-Horta axis, which already was on a higher level than the rest of the grid. The key supplementary measures are the following :

- In case of events with tower failures the Emergency Restoration System (ERS) owned by Elia can be installed. However some additional specific components should purchase to realize the transition of different type of conductors.
- In order to install the available ERS within the required timeslot for 6 specific critical locations detailed scenario's for the installation are developed in detail. Unique structures were required in some cases, as the surrounding infrastructure poses challenges for routing.
- More over at two location prevention measures are advised. With respect to the risk of intentional human acts of sabotage.

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[2] Mitigation plan Elia-Stevin-Horta lines \ (DNV report, September 2021)