

# Investigation of Influence of HTLS and Compact Design in Transmission Network Considering Transmission Capacity and Losses

Ivan PAVIČIĆ\*, Ivica PAVIĆ

**Abstract:** Process of transmission planning needs to provide the location and type of solution that will ensure quality and security of supply network users. Taking into account the stated requirements, the transmission network (TN) must have satisfactory electricity transmission capacities (TC) and it is necessary to determine the technical solutions at an acceptable financial cost. In this paper, a model will be presented how to determine the location and type of investment, taking into account the connection of future power plants, users, development plans of neighbouring countries and the energy strategy of Europe. The model evaluates the possibilities of implementation of high-temperature low sag conductors (HTLS) and compacted overhead transmission lines (OHL) on the existing infrastructure or construction of new transmission lines in the same right of way. The main idea of the presented model is to investigate the influence of a proposed investment based on measurement data taking into account losses and TC of the TN as important factors. In order to increase TC taking into consideration TN losses, a number of possible technical solutions will be investigated.

**Keywords:** compact lines; HTLS; transmission capacities (TC); transmission losses

## 1 INTRODUCTION

In the last ten years, with the increase of consumption and production from green power plants, existing capacity of TN is insufficient. Increasing TC on existing TN is the main task for the owners of TN and it can be achieved by implementing new technologies. The most common way to increase the capacity of TN is to increase the capacity on OHL by building new ones or increasing the capacity of existing. Building new OHL can be challenging and time consuming. The more efficient and dominant way is to explore options to increase capacity of existing OHL. The most popular way to increase capacity is to uprate voltage or current on the existing ones [1, 2].

Both methods, increasing current or voltage on existing OHL are achieved by using HTLS conductors or compaction of existing towers. Applying HTLS conductors makes it possible to significantly increase the current of conductors, while applying compact phase spacing on existing lines may result in upgrading to a higher voltage level or conversion from single to double system on the same voltage level with the same right of way. One of the main concerns with the new investment is to determine the costs during exploitation where the amount of losses can have a significant part in the lifetime of investment. Determining losses in the transmission network and its elements is known from a theoretical point of view, however in practice there are certain challenges in which the correlation of measured and calculated values can deviate.

The motive for this paper is to present challenges of transmission system operator (TSO) to determine locations and appropriate technical solutions in TN to increase TC considering TN losses. This paper presents the two main steps.

Theoretical background for calculation of losses and TC and their comparison with the measured data. The main objective is to compare theoretical with measured values and by comparing and analysing data to determine the cause and frequency of measured deviations values.

Methodology for identification of OHL for uprating and evaluation is developed where analyses are taken with account measurements and operating states of the TN with

consideration of future plans. For the weak points in TN, investment will be proposed and considered. Analysis of the proposed investments will be assessed with the representative model selection. Model of TN for all conducted analyses is part of the Croatian transmission system.

Based on given results, the focus is to determine potential locations for the application of HTLS conductors or compact lines and from calculated losses and TC propose the best locations and type of investment in TN. Final recommendation for each technology and type of investment will be presented.

## 2 INCREASING CAPACITY ON OHL

The most common way to increase the TC is to increase the capacity of existing OHL or to build new transmission lines. Current technologies in the world for increasing the capacity of existing transmission lines are implementing HTLS conductors or compacting OHL. HTLS conductors can withstand 2-3 times current of a similar conventional conductor. Compacting existing OHL can raise the capacity of existing line doubly comparing to conventional design. In both cases overall capacity of existing OHL is increased 2-3 times compared to original design [2-4].

### 2.1 HTLS Conductor

Implementing HTLS conductor in TN is mainly for insufficient capacity or safety reasons (height from ground or other object) on existing OHL. HTLS conductor, due to the lower weight and higher thermal current can satisfy both reasons. The increase in current is possible because HTLS conductors at higher temperatures do not lose their mechanical properties nor do their sag increase, all thanks to the use of new generation conductor core materials that have less temperature dependence [1-4]. The main types of HTLS in the world today can be divided into five types depending on conductor material and construction where the old categorization had two types; with composite cores and metal alloy cores [3-5]. Each of these conductors is structurally designed of aluminium alloy wires that can

resist annealing up to 210 °C for the required conductivity and a reinforced core of single or a set of steel alloy wires or composite materials [3, 5]. The application of HTLS conductor with different manufacturing technologies also takes into account how they will behave in the TN in terms of electrical and mechanical properties. Studies conducted to determine the properties of HTLS conductor in different conditions have shown that there are significant advantages of HTLS conductors in operation [4-6]. The main purpose of these tests was to determine the behaviour of conductors under extreme electrical and mechanical loads (high temperature loads and loads due to weather conditions). Tested conditions represent actual operating environment and enable the acquisition of confidence in the presented technology and knowledge of the technical limits of conductors and better understanding of their application in the system [5, 8-9]. HTLS conductor and accessories must resist a wide range of transient mechanical & thermal loads such as fault current, lightning strikes, galloping events and ice loading defined by design standards [3, 8]. Analysis of the test cases conducted on existing OHL that were reconstructed using HTLS or HTLS with compact phase spacing showed there is an approximate line length at which different designs are favoured [2].

**Table 1** Line length favoring HTLS and/or compact designs

Voltage / kV	Length favouring HTLS / km	Length favouring HTLS/compact OHL / km	Length favouring compact OHL / km
230	$l < 105$	$105 < l < 206$	$l > 206$
345	$l < 156$	$156 < l < 312$	$l > 312$
500	$l < 225$	$225 < l < 448$	$l > 448$

Tab. 1 shows indication of the line lengths at which HTLS and compact designs are favoured taking into account assumed conditions of thermal and security limits of OHL [2].

## 2.2 Compact Lines

Planning to increase the TC can be challenging with traditional solutions in all cases; therefore, for this purpose, the possible application of compact OHL is considered. Compacted transmission lines are primarily from the need to increase transmission capacity on existing transmission lines without the need to increasing right of way compared to conventional transmission lines. Increasing the voltage or converting single to double transmission lines is the most common way to increase the capacity of existing transmission lines [10-12]. Compacted transmission lines are very similar to conventional transmission lines, but the distance between the conductors is significantly smaller and the construction of the pole head is significantly smaller. When considering compacted transmission lines, new and advanced solutions will be applied. The main characteristics of compact design are new geometry of tower, new design of the pole and the use of composite insulating rods. When designing compact transmission lines, it is necessary to take into account the above considerations that require new analyses and calculations compared to the conventional approach. Reduction of the distance between the conductors is the main challenge in designing conductor configuration and it is necessary to

develop new constructions/geometries in the tower head [13-16]. Conducted studies with focus on how to optimize the conductors' configuration show that the procedure depends on many factors and that each of them has a great influence on the final solution [14-16]. In cases when it is necessary to keep the same width of the corridor, it is necessary to keep the amounts of electric and magnetic field on the ground within the legal framework, [11, 13-14]. Due to the smaller geometric distance between conductors compared to conventional transmission lines, the electrical parameters also differ. Compact lines have lower reactance and consequently higher natural power. One of the main challenges in designing compact OHL are overvoltages. Compact OHL have slightly higher overvoltages because of the smaller distance so selection of insulator equipment is of great importance for each compact design separately [10, 14, 17]. Designing compact lines is taken with a wider consideration for each of the mentioned areas comparing to conventional OHL and in some cases that can lead to higher costs that cannot justify the investment.

## 3 DETERMINE LOSSES IN TRANSMISSION NETWORK

Losses in TN are calculated as a difference between all electricity that enters the network and the electricity that is delivered (accounted/billed). The main cause of losses in the TN is current flow through the network elements (transmission lines and transformers). Transmission network losses can be divided into technical and non-technical losses, with non-technical losses being relatively small in the transmission network. Technical losses can be divided into fixed and variable where fixed amounts depend on the network itself and do not depend on the power flows. The variable amount is directly dependent on the amount of energy passing through the network and will change as demand/transmission of electricity is changing [18]. Majority of losses occur on OHL and cables, and their amount can go up to 80% of total losses in TN [19].

It has already been stated that for the purposes of determining losses in the transmission grid a method that only considers the difference between entered and exited electricity energy in the TN is applied. This way total losses are determined not the losses on individual network elements. For this reason, accurate determination of losses by individual network elements can be a challenge based on the collected measurement. In this paper, separate analyses are carried out with the goal to determine differences between theoretical and measurement values for each transmission line separately.

### 3.1 Losses on OHL

Losses on OHL are dominant in TN and can be divided into Joule losses, corona losses and insulator losses. There are other losses on OHL, but their amount and impact on total losses is negligible (losses due to the skin effect and proximity effect).

#### 3.1.1 Joule's Losses

Losses on transmission lines mainly consist of ( $\approx 90\%$ ) Joule losses due to the heating effect when current passes

through the conductor. The amount of losses directly depends on the amount of current passing through the conductor, and the losses are a function of the square of the current flowing and therefore Joule's losses on transmission lines in the transmission network range from 1-3% of transmitted energy. For 110 kV and 220 kV Joule losses are dominant and can be  $\approx 95\%$  of total losses on OHL [19 -21].

### 3.1.2 Corona Losses

Corona losses occur when the system voltage at the transmission line is higher than the critical dielectric value of air. As a result, air is ionized and energy losses occur i.e. amount of losses depends on the electric field and air properties. Determination of corona losses is performed experimentally based on measured data in laboratory conditions [22]. Corona losses can be significant for 400 kV OHL and strongly depend on the construction of the transmission line itself and the geographical and weather conditions where the transmission line is placed [22, 23].

### 3.1.3 Losses on Insulators

Losses on OHL insulators are not significant, especially not on new transmission lines and during favourable weather conditions. On the other hand, on older transmission lines and where the pollution of the atmosphere is higher, there is a significant possibility of losses along the transmission line route due to the occurrence of leakage current on the surface of the insulator. It is necessary to pay special attention to the fact that the insulation becomes imperfect and very sensitive to weather conditions. Losses on insulators for 400 kV transmission lines must be taken into account when calculating the total losses [19, 24].

## 3.2 Measuring and Calculating Losses

When determining losses on transmission lines, all available measurements were used. For 110 kV voltage level, data from the central billing system and SCADA was used, while for 220 kV and 400 kV data was additionally used from phasor measurement unit (PMU) and power quality devices. Measurements are taken from the last 5 years and collected for analysis with respect to the voltage level and time of year (summer/winter). For the observed transmission lines data quality and metrics analysis was performed comparing measured losses with theoretically expected losses. It was observed that there was a higher deviation for losses on 400 kV OHL. Additional comparison of measurements was done taking into account weather conditions, winter and summer period, to determine their frequency and amount of losses. Results show that losses for the 400 kV OHL are significantly different between summer and winter periods due to the weather conditions. Separate analysis was conducted to better understand losses. For the 220 kV and 110 kV transmission lines, significant differences for most of the observed OHL were not noticed [20].

Fig. 1 shows specific losses for 110 kV and 220 kV transmission lines. For 110 kV transmission lines, it can be

concluded (OHL1-OHL7) that there is a good correlation between the measurements and the calculated values and there is no significant scattering of the measured results (different curves are due to different conductor cross-sections). On 220 kV transmission lines (OHL-AI/St 360/60 mm<sup>2</sup>; OHL2-AI/St 2 × 240/40 mm<sup>2</sup>) it is visible that there is a certain scattering of results, but not a significant amount. The reason for such a result is in measuring devices and the appearance of extremely bad weather conditions that contribute to smaller increased losses due to the corona and insulators losses.

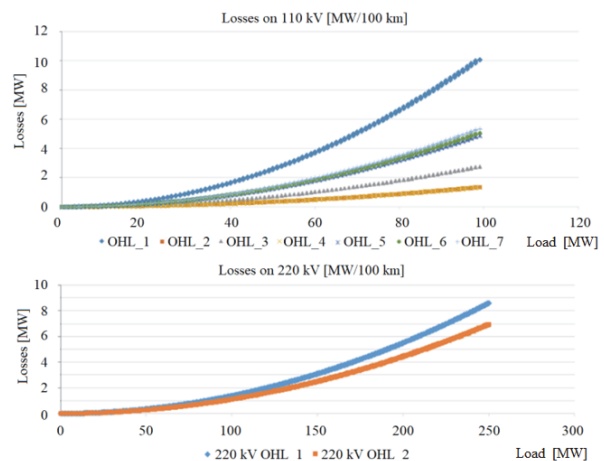


Figure 1 Losses for 110 kV and 220 kV OHL

The biggest attention is dedicated to losses on 400 kV OHL due to significantly higher losses and influence of weather conditions on losses that can be relatively frequent during the year.

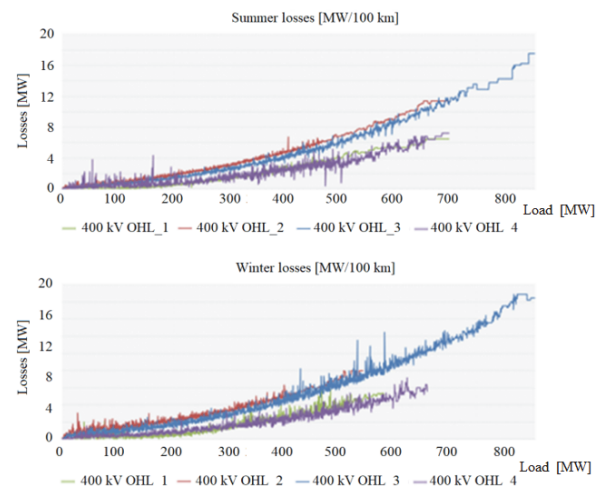


Figure 2 Summer and winter losses for 400 kV OHL

From Fig. 2 it can be seen that there are certain differences between summer and winter. It can be concluded that there is a slightly higher frequency in terms of the number of repetitions and the amount in winter, compared to summer. It can also be concluded that for some OHL there are significantly higher losses compared to the others. The reasons for such deviations are found in the terrain configuration where these transmission lines pass through a mountainous area with a very hard climate and a large amount of precipitation throughout the year [20].

#### 4 METHODOLOGY FOR IDENTIFICATION OF POSSIBLE INVESTMENTS IN TRANSMISSION NETWORK

The main goal of this paper is to identify a place in TN to increase capacity of TN taking into account OHL capacity and losses for each OHL. For that purpose methodology was developed. Proposed methodology collects historical data of TN and considers type of investments in TN. For each investment the evaluation of influence on losses and capacity of TN is made. The methodology consists of three main steps shown in Fig. 3.

The first one is to analyse TN and identify OHL with insufficient capacity. Identification of OHLs in TN that cause congestion is made taking into account their impact on security ( $N - 1$ , voltage security), flows (capacity of OHL and TN) and losses. Based on conducted analysis the elements in TN for upgrading are determined. For each location multiple solutions will be presented.

In the second step of the proposed methodology the representative grid conditions that resemble the actual real-time conditions are determined to assess the influence of proposed solutions. Based on limitation of proposed OHL calculation of el. parameters is made and integrated in TN model. For each solution calculation of limiting factor by electrical effects (voltage drop and phase shift) and by the maximum temperature (maximum conductor temp) is made.

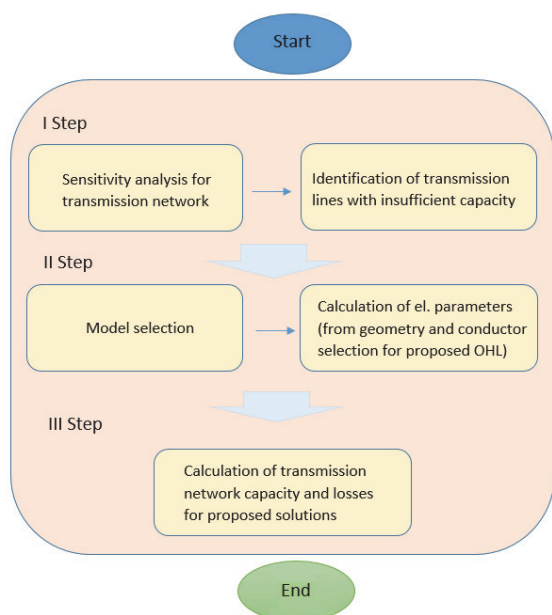


Figure 3 Methodology for evaluation of proposed investments

In the final step of methodology for each solution the calculation of evaluation on flows for each OHL line and the calculation of losses on TN comparing to base model are made. Calculation of losses for each OHL and voltage level is calculated from the mentioned historical measured data by each individual element.

##### 4.1 Determination of Investment

Analyses of transmission grid will be performed on historical data, where the focus will be on capacity determination for each voltage level, losses on each voltage level and losses for each OHL. For each voltage level,

sensitivity analysis will be performed as analysis of each OHL. For the mentioned analyses base model of transmission grid with normal topology (chosen years have normal amounts of imports/exports, generation and load) will be used. The conducted analyses will identify flows on each voltage level and losses in the TN depending on the trends.

The way of determination for suitable locations of advanced technologies installation is based on the mentioned methodology. Ranking of possible places is identified through the analysis of power flows and network elements that have an increased flow i.e. have insufficient capacity on OHL compared to other transmission lines. Increasing the capacity of individual OHL can solve overload or congestion of the same OHL, but to solve the problem of TC it is necessary to consider a complete solution i.e. the impact of increasing capacity of individual OHL on the total TC.

Once the OHL or area in the transmission grid have been determined, a solution will be proposed. Implementation of technical solutions that include the application of HTLS conductors and/or compacted transmission lines is the main choice. Conducted analysis will have electrical and mechanical steps to evaluate each solution shown in Fig. 4.

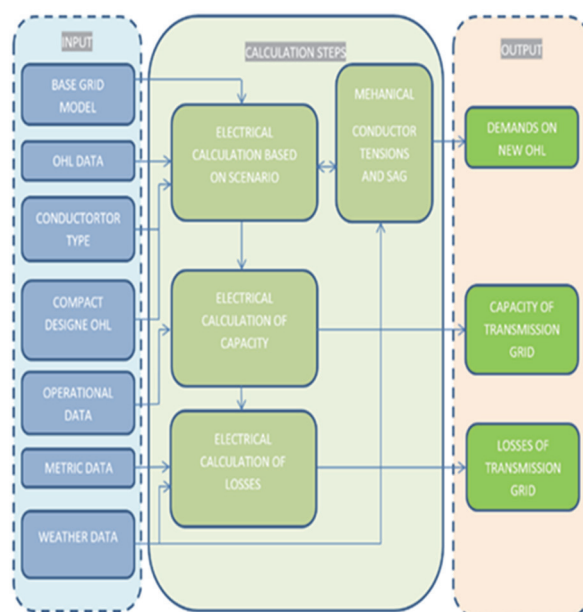


Figure 4 General approach for possible investment

Calculation is carried out in such a way that topology and measurements are taken from historical results with scenarios of TN. In this paper mechanical analysis will be carried out to confirm that existing tower can satisfy the tension and sag of the proposed HTLS solution. Analysis of OHL tower properties for the possibility to install HTLS conductor with higher tension or to convert head tower to compact lines is not performed. Above mentioned process and calculation steps are presented in Fig. 4.

##### 4.2 Selection of Scenario

To better understand the variety of losses and capacity in TN, several scenarios were applied. During load growth,

or increasing production from renewables, there are certain transmission lines whose upgrade becomes necessary due to insufficient TC. Uncertainty in load or generation forecast may cause an error in estimation of type of investment or time frame of building it. To better understand the difference between today's and future topology in TN, a scenario that covers projects with a higher probability of realization was developed.

In order to determine weak places in TN, further analysis will be conducted in a way to determine sensitivity for each voltage level. Conducted analysis will include changes in topology data taken from future development plans compared to base case and will include the following scenarios:

- a) Increase of electricity import in 3 steps
- b) Increase of electricity export in 3 steps
- c) Increase of load - 8 scenarios
- d) Increase of generation - 9 scenarios

For each scenario the amount and character of individual step is based on historical achievements. For import and exports historical values are taken for each border and applying linear function historical values are brought to the desired level for each scenario. The same approach has been applied for generation and load increase where increase of generation is represented as 40% on 110 kV, 20% on 220 kV and 40% on 400 kV of existing and planned production capacities.

After conducted analysis and better understanding of TN in order to increase capacity on each voltage level, technical solution will be proposed.

### 4.3 Calculation of TC and Losses in TN

The calculation of the TN capacity is made for each OHL and for each voltage level in the way that it represents the calculated value of power flows compared to total transfer capacity (TTC) power flow in percentage as it is shown in Eqs. (1) to (3). TTC is calculated as part of NTC calculation and represents the maximum feasible power exchange that can be transmitted between the systems A and B reliably and without affecting the system security. In this way TN capacity represents theoretical fulfilment of TN and describes the efficiency and character for each voltage level of TN. Total TC is calculated as a capacity of each voltage level and is shown in Eq. (4).

$$C_{110\text{ kV}} = \frac{\sum_i^n \frac{P_{\text{flow}_i}}{P_{\text{TTC}_i}}}{n}, \% \tag{1}$$

$$C_{220\text{ kV}} = \frac{\sum_i^n \frac{P_{\text{flow}_i}}{P_{\text{TTC}_i}}}{n}, \% \tag{2}$$

$$C_{400\text{ kV}} = \frac{\sum_i^n \frac{P_{\text{flow}_i}}{P_{\text{TTC}_i}}}{n}, \% \tag{3}$$

$$C_{\text{NT}} = C_{110\text{ kV}} + C_{220\text{ kV}} + C_{400\text{ kV}}, \% \tag{4}$$

Calculation of losses involves the capacities calculation to determine power flows for each OHL for the calculated point in time. For each power flow, losses are calculated from historical measured data as was described in chapter 3.2.

$$P_{\text{losses}} = P_{\text{Joule}} + P_{\text{Corona}} + P_{\text{Ins. los.}}, \text{ MWh} \tag{5}$$

$$P_{400\text{ losses}} = P_{\text{Joule}} + P_{\text{Corona}} \cdot k_{\text{Comp}} + P_{\text{Ins. los.}}, \text{ MWh} \tag{6}$$

Eqs. (5) and (6) show a way how to determine losses on OHL and for compaction of 400 kV OHL. Losses for 400 kV contain described losses in chapter 3.2 plus losses due to the compaction. Factor  $k_{\text{comp}}$  describes additional losses due to OHL compaction. With the compact design of OHL, the distance between conductor and other element of tower is shortened which increases electrical field that causes additional losses. Factor  $k_{\text{comp}}$  has the range between 1,05-1,17 and is estimated based on electrical field for compacted OHL [23-26]. For each new line, geographical location is also considered and the amounts of losses is correlating with influence of weather conditions as was described in chapter 3.2.

## 5 DETERMINING THE MODEL AND POSSIBLE INVESTMENTS IN TRANSMISSION NETWORK

In order to better assess the required technical characteristics of the proposed investments and their impact, analysis of the existing transmission grid is made. In this way, it will be possible to determine the real state of TN by each voltage level and the desired impact of the proposed investments. Therefore, the proposed investments will have chosen places and characteristics by their influence on capacity and losses on TN. Determination process of influence and characteristic of investments in TN is a simple function of hourly threats of individual elements in the TN on yearly basis.

### 5.1 Model of TN

To calculate power flows and the capacity of the described model, regional model that includes TN of 20 TSOs will be used. The area of the TN on which the analysis will be conducted includes 79 OHL and 42 nodes at 110 kV, 220 kV and 400 kV voltage levels.



Figure 5 Model of Croatian transmission system

The model is part of the Croatian transmission system as part of the South-East European regional model and the model is made in Siemens PSS/E (Power System for Engineering) software package (Fig. 5) [27].

Measurements from SCADA (Supervisory Control and Data Acquisition) and electricity meters were used for all elements of TN, while for 220 kV and 400 kV additional data is used from phasor measurement unit (PMU) and power quality devices.

### 5.2 Model Selection

For better understanding the influence of proposed investments in the future the selection of model is carried out on yearly basis. Starting from the whole set of 8760 hourly models' point in time, the process of model selection is divided in three steps. Fig. 6 shows the principle of finding a set of models that represent whole year.



Figure 6 General approach for model selection

Losses distribution in TN and 400 kV grid for 8760 hours is conducted and is shown in Fig. 7. Yearly losses in TN consist of losses on transformers, 110 kV, 220 kV and 400 kV OHL. Due to the influence of weather conditions on 400 kV OHL losses and different frequency during the year histogram of yearly losses only for 400 kV network is additionally presented and taken into account in the process of model selection.

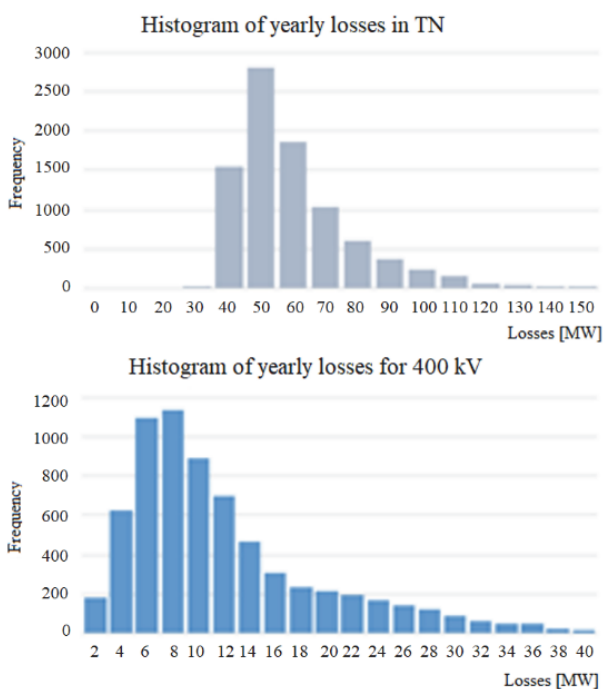


Figure 7 Losses distribution on TN and 400 kV

In the second step weight factor and delta is calculated:

$$w_r = \frac{\sum_{i \in Y} Losses_{r,i}}{\sum_{r \in R} \sum_{i \in Y} Losses_{r,i}} \tag{7}$$

Computing delta mean and delta standardization for losses is done in accordance with the following equations:

$$\Delta x_{i,p} = \text{mean}(Losses_{i,p}) - \text{mean}(Losses_{i,p \in G}) \tag{8}$$

$$\Delta y_{i,p} = \text{std}(Losses_{i,p}) - \text{std}(Losses_{i,p \in G}) \tag{9}$$

For equal impact of two indicators, standardization and weighting is calculated:

$$K_{x,i,p} = \frac{x_{i,p} - \text{mean}(\Delta x_{i,p=G})}{\text{std}(\Delta x_{i,p=G})} \tag{10}$$

$$K_{y,i,p} = \frac{y_{i,p} - \text{mean}(\Delta y_{i,p=G})}{\text{std}(\Delta y_{i,p=G})} \tag{11}$$

Through calculating Euclidian distance of two indicators, a combination that best represents yearly losses is chosen.

$$E_p = \sqrt{\sum_{r \in R} w_r \left[ (K_{x,i,p})^2 + (K_{y,i,p})^2 \right]} \tag{12}$$

### 5.3 Consideration of Different Solutions

The aim of the methodology presented in chapter 4 is to make an identification of transmission lines that needs to increase capacity based on real situation in grid. Analysis described in chapter 4.1 will show the needs to increase TC. Given results show future needs for increasing TC taking into account the mentioned scenarios. The proposal of possible solutions by implementing the mentioned technologies will consider the following cases:

- base case,
- implementation of HTLS,
- compacted transmission lines,
- HTLS and compact OHL.

Selection of the proposed investments will be evaluated based on analysis of historical measurement.

### 5.4 Electrical Parameters of Suggested Solutions

Characteristics of HTLS conductors and compact lines that are applied in this paper are from test cases of OHL or that are operational in the world. For the HTLS conductor, a conductor that can withstand 2-3 times more current compared to classic aluminium - steel conductors will be used [5]. In addition, the price of individual HTLS conductors varies significantly and this paper did not consider economical aspects during the final selection. The main feature of compacted lines is the reduction of the distance between the conductors and the grounded parts of the pole structure (pillar head configuration). Therefore, the used electric parameters of compacted transmission

lines differ from the classic ones. Bringing the conductors closer together leads to a reduction in the reactance of OHL. This leads to a reduction in the total impedance of the transmission line and a contribution to the increase in the natural power of the transmission line [11]. Due to all above mentioned reasons compact OHL can have a wide range of electrical parameters. Taking into account configuration, diameter and number of conductors in the bundle on OHL this study used electrical parameters that are similar to existing lines of the Croatian transmission system.

## 6 RESULTS

### 6.1 Sensitivity of Transmission Grid

As was mentioned earlier, analyses are done based on measurements where base model is presenting trends of power flows on each voltage level as average power flow for each voltage level. Sensitivity analysis will be performed comparing based model with the proposed scenarios presented in chapter 5.2. Figs. 8 to 10 show the result of sensitivity analysis. The performed analysis of imports/exports was conducted following the trends of the existing power flow direction. In case of import power flows were gradually increased on each voltage level and in the case of exports, increase of production on each voltage level respecting generation capacity was done. The main principle of conducted import/export analysis is to change parameters in line with maximum import/export historical measurements.

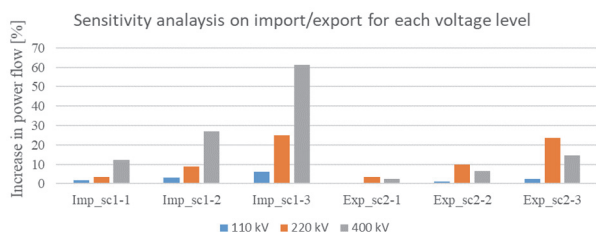


Figure 8 Sensitivity analysis for import and export

The analysis for generation is conducted increasing production on each voltage level in steps of 100 MW, 200 MW and 500 MW at the 110 kV voltage level, 300 MW, 500 MW and 700 MW at the 220 kV and 400 kV voltage level. In all cases, load was not changed but the import was reduced and export increased because of excess production. Fig. 9 show result for nine mentioned scenarios.

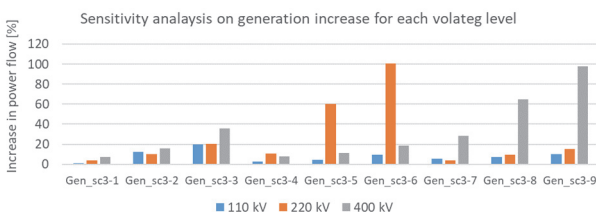


Figure 9 Sensitivity analysis for generation increase

Sensitivity analysis for increase in load is made in steps of 100 MW and 200 MW, the energy was replaced from the generation on 110 kV, 220 kV, 400 kV and

imports from the surrounding TN. In Fig. 10 results for the mentioned scenarios are shown.

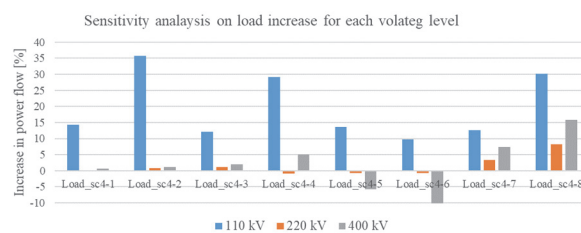


Figure 10 Sensitivity analysis for load increase

Conducted analyses show that 110 kV grid has sensitivity mainly on increasing the load and in some scenarios with higher generation at 110 kV, with the higher flow on some OHL. The 220 kV grid has shown the greatest sensitivity to imports/exports and for increased generation and at certain times there is a lack of capacity. In the case of higher imports, most of the imported energy goes through the 400 kV grid. 400 kV grid did not show significant changes due to the increase in load.

Table 2 List of proposed investment in TN

Inv	Description of investment
Inv_11	Implementation of HTLS on two 110 kV OHL
Inv_12	Compact existing 110 kV in to 2 × 110 kV OHL
Inv_21	Implementation of HTLS on 220 kV OHL
Inv_22	Compact existing 220 kV in to 2 × 220 kV OHL
Inv_23	Implementing HTLS and compacting existing 220 kV into 2 × 220 kV OHL
Inv_31	Compact existing 220 kV in to 400 kV OHL
Inv_32	Compact existing 400 kV in to 2 × 400 kV OHL

According to the sensitivity analysis, investments for certain OHL in 110 kV, 220 kV and 400 kV voltage levels are proposed based on presented methodology in chapter 4.1. Tab. 2 represents a scenario that includes investment by each voltage level in TC.

### 6.2 Analysis of Suggested Solutions

#### 6.2.1 Capacity Calculation for Proposed Investments

For each investment, analysis was performed compared to base model and the results are presented in Fig. 11. It is easy to see that Invest\_31 and Invest\_32 have a greater impact on losses and capacity compared to other investments, due to the greater impact on 400 kV TN. Most promising investments are in 220 kV because they are close to results from investment in 400 kV, but can be assumed to have significant lower construction costs. Investment in 110 kV grid did not significantly contribute to increase TC and for investments that include HTLS, TC of TN does not significantly change.

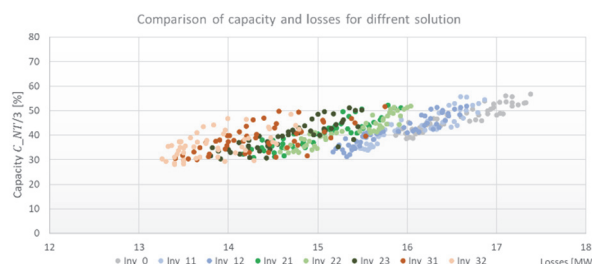


Figure 11 Comparison of capacity and losses for proposed investments

## 6.2.2 Calculation of Losses in TSO Grid

Losses are calculated from power flow calculation for each OHL as was described in chapters 4.1 and 4.3. Performed calculation of losses was done for one-year period on hourly basis. Power flow for each OHL was calculated on selected 25 models. Losses for each OHL are calculated and it is possible to determine losses for each investment.

Fig. 12 shows total yearly amounts of losses and percentage ratio for each voltage level.

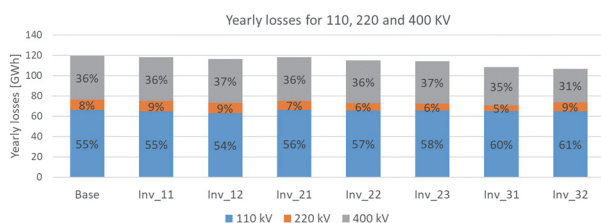


Figure 12 Yearly losses for proposed investments

Overall losses are lower for all investments, but for OHL where investment is applied, losses have a significantly lower amount and for that reason the largest reductions in losses are observed for investments on 400 kV. Implementation of compact lines has a significant influence in changing power flows on grid and higher corona losses due to the higher electrical field on conductor comparing to the conventional 400 kV OHL. On a yearly basis, for 400 kV that are geographically placed in hilly or mountain locations, corona losses have significant influence on total losses and usage of compact design can have significant influence on losses on particular OHL.

Through the conducted research, the following conclusion is obtained:

- Implementing HTLS on existing OHL has significant increase in capacity of existing OHL, but does not increase significantly TC and does not change flows in TN.
- Compacting existing OHL has significant influence in power flows in TN. Due the changing electrical parameters of OHL can lead to significantly change TC and capacity of OHL.
- For 400 kV OHL that have significant number of hours with corona losses, compacting has significant impact in additional corona losses.

## 7 CONCLUSION

This paper presented a model for increasing TC, applying modern technologies. The focus is to determine existing TC and losses based on past measurements. The proposed model contains the sensitivity analysis of the existing TN on future trends (import/export, generation and load) and the calculation of power flow and losses for each OHL and each voltage level. The conducted analysis proposes upgrading methods, primarily conductor replacement and compact design on existing OHL in the TN and in accordance with the development plans. Adaptation of considered solutions on existing OHL results in the increase of OHL capacity and partial increase overall TC. Calculation of TC and losses for proposed investments

is based on historical measurements which depending on the specific OHL can show significant improvement in loss projection and can have a significant impact on estimated financial cost. Performed analysis of solution presented in paper showed following characteristics

Calculating TC and losses for proposed investments is made on historical measurement which in some cases proved to be a significant improvement in loss projection and can have a significant impact on estimated financial cost. Performed analysis of solution presented in paper showed following characteristics:

- Reconductoring with HTLS is reasonable in cases where thermal rating is insufficient for individual elements in TN if existing OHL structures are in good condition and do not require additional modifications.
- Reconductoring only one OHL with HTLS did not show significant increase in TC or decrease losses in TN. Increasing TC with HTLS is possible by applying HTLS conductor in multiple places.
- Compact lines on 220 kV and 400 kV voltage level have better overall influence in increasing TC and decreasing losses.
- Compact design 400 kV OHL can increase power flows and transit of electricity and as a consequence contribute to additional losses in TN for owner.

Conducted research provides accurate determination of losses and capacity of TN on hourly basis. To fully evaluate the possibilities of proposed investments, some additional studies must be performed:

- Evaluation of feasibility for mechanical and electrical design of proposed solutions, primarily compact design.
- In market environments, the cost of losses plays a significant role in choosing investment. Predicting amounts of losses in economic analysis for each investment is one of the main indicators in the process of investment selection.

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**Contact information:**

**Ivan PAVIČIĆ**  
(Corresponding author)  
HOPS,  
Kupska 4, Zagreb, Croatia  
E-mail: [ivan.pavivic@hops.hr](mailto:ivan.pavivic@hops.hr)

**Ivica PAVIĆ**, Full Professor  
University of Zagreb,  
Faculty of Electrical Engineering and Computing,  
Department of Energy and Power Systems,  
Unska 3, Zagreb, Croatia  
E-mail: [ivica.pavic@fer.hr](mailto:ivica.pavic@fer.hr)