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Advanced Prediction of Technical Losses on Transmission Lines in Real Time

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***Abstract*— Active power losses occur during transfer of electricity through transmission grid from power plants to end users. This is a well-known consequence of the current flow through power system elements. The value of the losses on the transmission grid is a few percentages at each voltage level and the value increases with proximity to the grid users. Losses in the transmission network consist of losses on tie-lines and transformers. The paper presents an advanced model for loss monitoring that can provide solutions for verifying measured data and for isolating and analyzing the sources of errors. Monitoring system is based on measurements from electricity meters, SCADA system and PMU (Phasor Measurement Unit). Used equipment must provide measurement standard, assuring highest accuracy, reliability and repeatability.**

***Index Terms*— tehnical losses, monitoring systems, losses estimations.**

I. Introduction

Losses in the transmission network can be divided into technical and non-technical losses. Under the non-technical losses are considered losses for which it is impossible to determine the origin (the exact amount and location of formation), such as stealing, inaccurate measurements, poor records and calculation itself. Technical losses are known physical effects of electricity transmission and can be reduced to acceptable levels. Losses in the transmission network are made of losses on transmission lines and transformers. Due the amount of losses on tie-lines comparing to losses in transformers main focus on prediction losses will be on tie-lines. Electricity losses on transmission lines are caused by the known physical effects of the flow electricity current and can be reduced to acceptable levels. Standard ways of calculating losses on transmission lines is from measurement data. Recently due to a business environment where losses are treated as financial costs, there is a need to determine amount of electricity losses by calculation or predicted/estimation in daily and hourly basis. There are more methods how to predict electricity losses from known electrical parameters in the system. The estimation of losses is an important economic indicator and at the same time it serves to determine the types of losses considering transmission electricity in the transmission network [1]. In the paper it will be described types of losses on transmission lines and the expected losses levels. In the paper a model for advance prediction on measurement data from Wide Area Monitoring System (WAMS) and other type of measuring systems will be proposed [2], [3], [4]. Measuring data from Supervisory Control And Data Acquisition (SCADA) system in control room [5], [6] can be used for that purpose. Today TSO have many data available in control room and it is possible to design new smart grid applications [7], [8] for various purposes. The model will present witch data can be used as input parameters for the proposed technical solution. The main goal is to use large a set of metrics from different systems per hierarchy regarding accuracy and reliability of metrics in the purpose for better calculating losses in real time.

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II. Losses on Transmission Line

Losses in the transmission network can be classified as technical losses and non-technical. Technical losses refer to electricity consumed on power line losses and transformer losses. Non-technical losses consist of theft of electricity, unreliable data processing and measurement errors. Non-technical losses are relatively less significant for the transmission network and dominantly appear within the distribution network and will not be discussed in this paper.

Technical losses in the transmission network can be split on losses on transmission lines and transformers where losses on the transmission lines are dominant. The losses on the transmission line can be divided into Joule losses, losses due to corona effect and losses on insulators [9], [10], [11].

A. Joule losses

Losses on the transmission lines are mainly (≈ 90%) Joule losses due to the heating effect caused by current flow through the lines. The resulting losses depend directly on the amount of current passing through the conductors and therefore the transmission losses can be up to ≈2-3% (depending on the length of the transmission line and cable routing) for power lines. According to formula 1 we can calculate Joule's losses [9]:

$$\Delta P = 3 \cdot R \cdot \left[\frac{\sqrt{P_1^2 + \left(Q_1 - \frac{U_1^2 \cdot B}{2} \cdot 10^{-6} \right)^2}}{\sqrt{3} \cdot U_1} \right]^2 \tag{1}$$

B. Corona losses

Losses due to corona occur when the system voltage on conductors of the transmission line is higher than the critical value of air (breakdown the dielectric strength of air). Consequently, the air is ionized and energy losses occur. The amount of energy loss may vary from each case separately. Determination of corona losses is carried out experimentally and based on measured data. According to Peek's formula (2) it is possible to calculate the loss of the corona, which is also based on experimental work [10], [12], [13]. The calculation itself is limited by a set of parameters but satisfies the calculations for frequencies of 50 to 60 Hz [10]:

$$P_{kor} = \frac{241}{\rho} \cdot (f + 25) \cdot \sqrt{\frac{r}{D}} \cdot (U - U_{kr})^2 \tag{2}$$

C. Leakage losses

Losses on insulators on transmission lines are not large during dry weather, especially on new power lines. On the other hand, on older lines and where the pollution of the atmosphere along the transmission line corridor is significant, special attention is needed due to the fact that the insulation becomes imperfect and becomes very sensitive to weather conditions. In those cases, it is necessary to determine possible amounts of loss on insulating chains when calculating total losses [9], [11]. The following formula allows calculating losses [11]:

$$P_{iso} = \left(\frac{U}{\sqrt{3}} \right)^2 \frac{n_p}{R_{iso}} \tag{3}$$

III. CALCULATING LOSSES IN TRANSMISSION SYSTEM

Methods for loss calculation in the transmission system depend on daily, monthly and annual time periods that are calculated. The ways in which the losses in the transmission network are currently being determined vary according to the procedures, data collection method and the use of software tools. For each of the above calculations methods it is necessary to emphasize that requirements for different methods of collecting metrics and their further use and purpose are not applicable to other methods. Due to this, each process is elaborated on how to calculate losses in the transmission network for the business process that is being applied [14], [15].

A. Monthly calculation losses in transmission system

Calculation of monthly level losses is based on the existing metering system installed in the transmission areas, which takes measured data from electricity meter from exchanged el. energy. Accordingly to the existing configuration of the metering system, the service of gathering, processing and storage is performed by local users and the metering points on the transmission network interface with network users. Measurement data is further collected at the central system where collected metrics data is processed. The calculation method takes into account the energy received and delivered on the transmission network interface with the other users, calculating the difference to the total losses in hour resolution within a month.

B. Day ahead calculation losses in transmission system

Day ahead planning is done in NetVision DAM program package. Input data includes consumption plan, production per power plant, cross-border exchange and historical measurements (last 24-h or last week). NetVision DAM software also includes network topology, model of network grid with planned availability of each transmission grid element and availability of renewable sources. A model is calculated for each hour and the final result consist of day ahead losses for each hour.

C. Intraday calculation losses in transmission system

For the time being, the procedure for intraday calculations is not established yet. The plan is to establish an intraday calculation losses on hourly basis (1h, 3h, 6h and 12h). The main objective is to establish a deviation calculation of on-line measured losses and losses forecast from the day before. Accordingly to the deviation, various projection methods can be applied for the loss forecast in next few hours. Methods that are currently used in TSO within the ENTSO members include AI, machine learning, different programming methods, prediction on historical data, statistical approach etc. For input data, each TSO use wide and different set of sources (load flow, renewable sources, weather forecast, temperature, spot prices, deterministic factor, neighbored production, etc…). The above mentioned calculation methods are of recent date, so experience is limited. Each of mentioned approach has in common that each TSO adapted a method compatible to the characteristics of its own transmission grid. In this paper it will be presented a method that will be based on on-line measurement and the intraday prediction of losses will be made from historical data. Applied method will primarily be based on historical statistical data, while ultimately the goal is to establish predictions based on machine learning or some type of programming.

IV. REQUIREMENTS FOR COLLECTING AND PROCESSING MEASURED DATA

Existing system for the collecting measured data in the transmission network are from various devices that are connected on instrument transformers (current and voltage). Various devices that are intended to monitor main electrical values are connected to the specified measuring devices. The systems that measure and collect electrical data and their main features are listed below:

- Electricity meter
- SCADA
- Power Quality Monitoring Systems
- PMU

To establish a system for loss prediction, basic technical features and mathematical models of different power lines and weather conditions on the transmission line corridor are needed. Some of the information needed is:

- Load estimation on line
- Measured load on line
- Historical data on line
- Comparison of estimation and measured data
- Historical measured and estimated data on line depending on weather conditions

Above mentioned information allow better and more accurate prediction of losses. The proposed process of calculating loss projections is an iterative process that uses existing measured data primary from electricity meter and PMU and compares them with historical data. A more detailed description of the process and proposed model is given in the next chapter.

V. Design of the Model for Prediction of Tehnical Losses on Transmission Line

In 2018, there were considerable deviations of day ahead planned losses and the actually effectuated losses in the transmission grid. Two dominant causes were identified:

- unplanned electricity flows,
- weather conditions.

The main focus is to develop a model that is capable to determine the amount and flow of electricity that is unplanned and the impact of weather conditions in relation to the plan.

The model would consist of geographically divided regions consisting of 110 kV network (energy transformers (TR 400/220, 400/110, 220/110 kV), 220 kV lines and 400 kV lines [16]. The idea behind the model is to track the loss values by individual areas, and thus achieve the following benefits:

- detection of measurement errors,
- transit movements,
- the influence of weather conditions,
- determining directions of energy flows,
- determining losses by elements of the network,
- better planning of losses in advance,
- monitoring of the efficiency by elements of the network,
- transmission grid development.

For day ahead, the calculation of power flows in the Croatian network is done and the planned values of the power flows on all the transmission lines are stored in the base. For the specified power flows for each single line, historical losses are taken from the measured data considering external temperature, estimated conductor temperature or estimated ohmic resistance, precipitation of the weather and the type (type and intensity of rainfall, snowfall, ice, mists, storms, etc.). Based on this, for each 400 kV transmission line losses estimations are done for the day ahead [16]. For the intraday losses forecast, the above data is taken as the starting point and compared with the received metered data. Given the different time in received metering data, comparisons and corrections are made. It is possible to get the measured values from the electric power quality systems and the PMU instantly, while within 15-min it is possible from all devices. The collected data are compared with each other, and the deviation measured in relation to the planned data is determined and then in relation to the deviation the re-calculation is made based on the new data taking into account temperature range, the precipitation of weather and the type of weather.

The main objective of the proposed model and method is to establish better loss planning and improve day ahead and intraday loss planning. At the moment, the largest issue in day ahead loss planning is unplanned electrical flows and weather conditions. The proposed method can determine in which area occurs the increase in losses amount and make prediction based on historical data to determine the amount and duration in time. In the next chapter it will be presented the way of collecting and processing metering data and tracking losses on 400 kV lines. The main focus is to detect losses caused by corona and leakage from measurement.

VI. Results of Proposed Model And Possibilities For Application

The model presented before contains 400 kV lines aggregated as one group. In this chapter the main focus will be to determine losses for each 400 kV in the transmission network with equal design characteristics. Three transmission lines and their range of possible scenarios will be presented and therefore presenting the 400 kV network of Croatian TSO. Measurement data are connected from metering points that are connected to electricity meter, SCADA and PMU devices. For now there is no central system that unites 100% of all measured data, but the plan is to connect missing data to existing DWH (*Data warehouse).*

A. Main characteristic monitored 400 kV overhead lines

As already mentioned in this paper, three 400 kV transmission lines that have significantly different geographically routes, but the technical characteristics of each line are similar, will be presented. Table 1 gives technical data on the type of conductor, tower, distance and ohmic resistances for each line.

TABLE I. Main technical characteristics of 400 kV lines

Overhead line Name	Conductor [mm^2]	Tower	Distance [km]	Ohmic resistance [Ω]	Resistance [Ω/100 km]
Erenstinovo - Žerjavinec	2×490/65 Al/S	Steel latice	230,3	7,167	3,112
Tumbri - Melina	2×490/65 Al/S	Steel latice	127,5	3,826	3,001
Melina - Velebit	2×490/65 Al/S	Steel latice	178,8	5,875	3,286

B. Winter and summer statistical data

Since 400 kV transmission network extends across the country with a variety of terrain configurations and with respect to the network transmission configuration and their impact/role, a separate analysis has been carried out for each transmission line based on historical data for one year. Given the characteristic periods of the year and accordingly to weather conditions, separate analysis were conducted for winter and summer period. For the purposes of calculation and estimation of losses it is necessary to understand the method and quality of the data collected. Therefore an overview of collected measured data on the 400 kV line Tumbri - Melina is given. The analysis gives the average error for all measurements and the maximum error between the data metered with electricity meter and the statistical average of measurement in the figure 1. These statistical data will be used as data to presented estimator. It can be seen that during winter period there is a bigger error than in the summer figure 2. It is also noticeable that on the lower power flow average and maximal error is bigger for both periods.

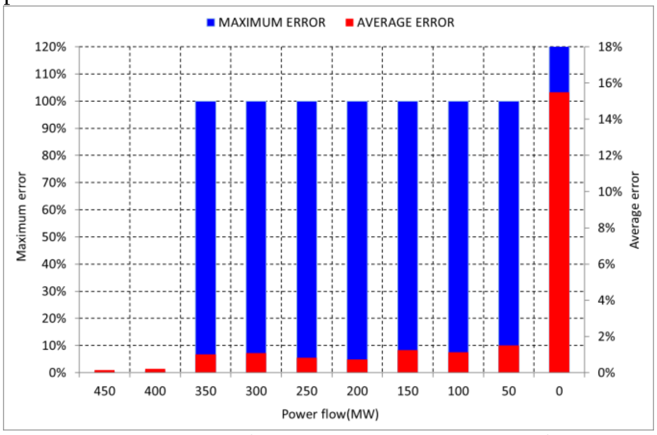

Fig 1. Comparison of measured data and statistics data for winter period for Tumbri - Melina line

The figure 1. and figure 2. shows that there is a significant difference between summer and winter. Since the settings of the measuring devices and other equipment have not changed, it can be considered that one of the important influence is weather condition. It is similar with other observed 400 kV transmission lines.

In order to successfully determine the efficiency of the transmission line and their dependence on the measured data from electricity meter, a comparison was made for the same line in the winter period. The comparison was carried out on 15 minutes measured data from the electricity meter.

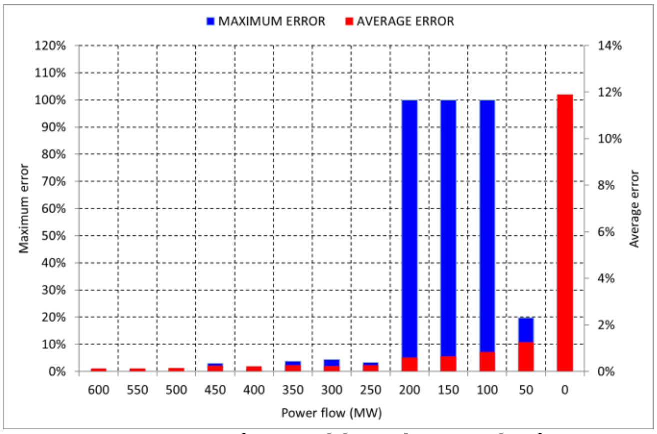

Fig 2. Comparison of measured data and statistics data for summer period for Tumbri - Melina line

Comparison between data from measurement and efficiency of the line is presented on figure 3. Where data index represent measured data from which it is possible to calculate the loss, and the line efficiency is ratio of calculated loss and power flow on the line. The reason for this kind of trend is the limitations in electricity meters and their technology (large constant and energy measurement method). Because of mentioned limitations at lower power data accuracy are poorer.

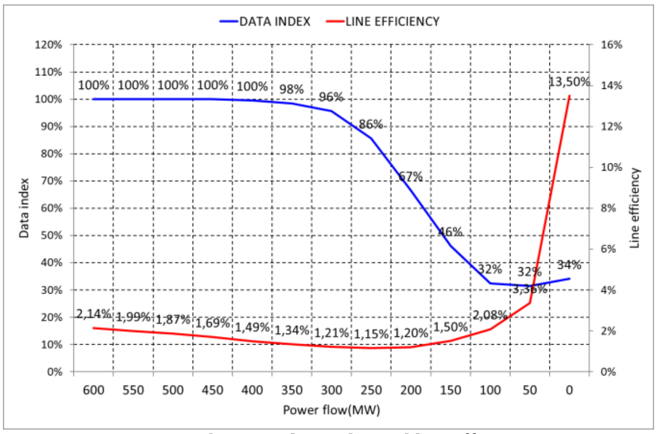

Fig 3. Comparison between data index and line efficiency

Figure 3. shows the difference that occur for power flow under 350 MWh/h for 15-min measurement reading. Under that power flow it can be expected that in some period collected measurement data is unusable, so other techniques must be applied for loss calculation and estimation.

C. Comparison data from ADVANCE and SCADA

As noted before there are some limitations of existing systems and the application itself. To better understand and compare measured data through the year and to better understand the influence of ohmic, corona and leakage losses a measurement source comparison was made for each line. On figure 4. comparison of losses from different source and their dependence to power flow for 400 kV line Tumbri – Melina was taken.

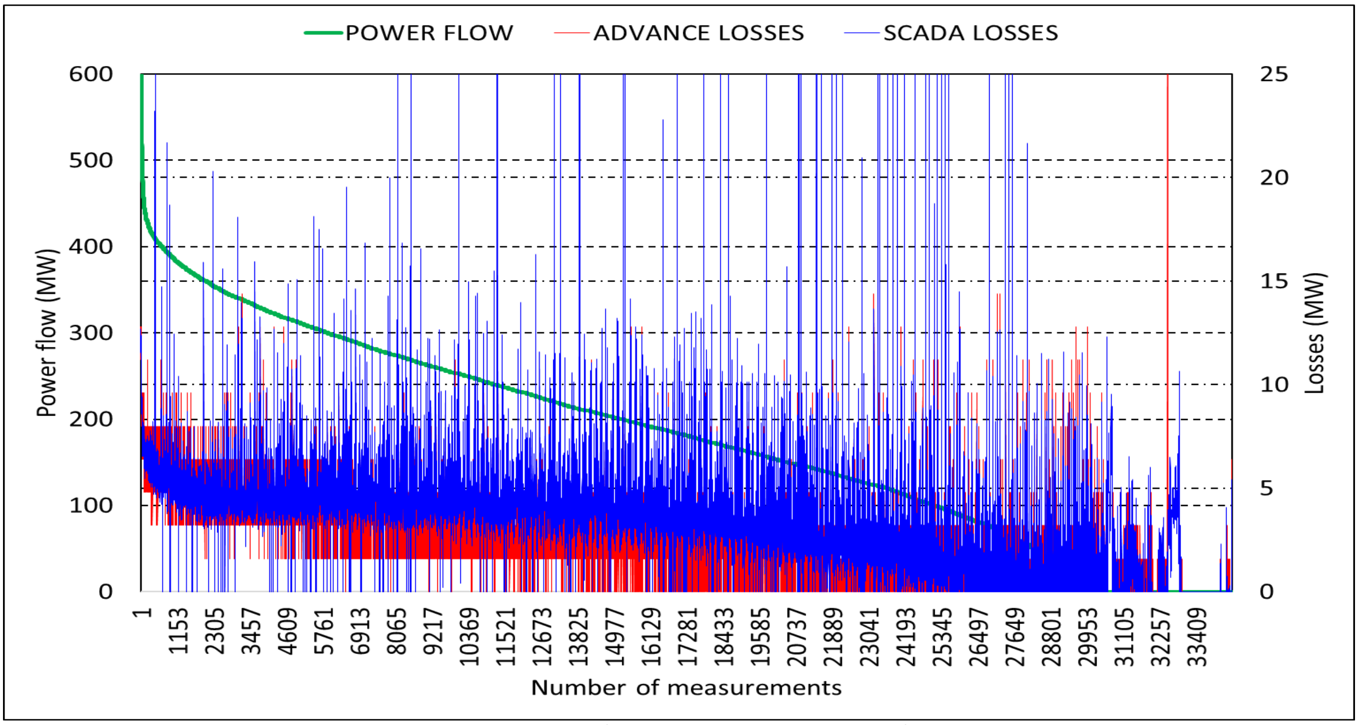

Fig 4. Indications of losses true the year versus power flow

From the figure 4 it is visible difference in the number of spikes appearances. It is also apparent that most of the time there is a good match between the two measurement sources. These spikes in most cases represent losses due to weather conditions, so it is necessary to determine their frequency and amount.

For each 400 kV line the same approach was taken, and the results were similar, although the amount of power losses and number of repetitions is a little bit less comparing to the presented line.

From the figure 5. (400 kV line Tumbri – Melina) it can be seen how much time observed line spend on each power flow thru the year. It can be concluded that line operate most of the time for power flow under 300 MW.

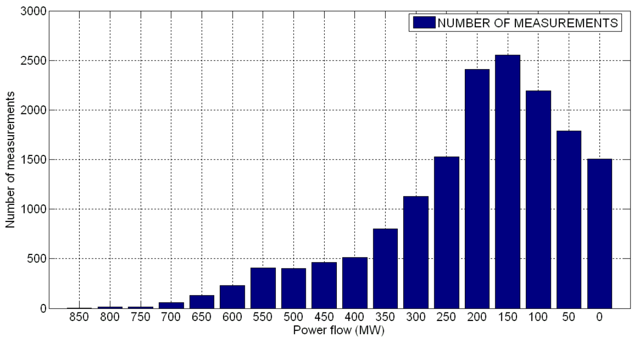

Fig 5. Number of measurement comparing to load flow

D. Influence Corona losses on losses on 400 kV

Given the comparisons of data quality and metrics analysis, a comparison of the realized losses on the observed 400 kV transmission lines and total losses in the transmission network was made. The observed period is six days in February 2018, when there were frequent snowfalls for several days in a row. Based on historical record data, the influence of peak precipitation on the appearance of Corona can be correlated, but the exact amount and its duration is very difficult to determine for many reasons. To approximately determine the amount of corona losses for the observed period the statistical approach of measured losses for the current load flow for each line was taken. In table 2. it's visible that each 400 kV has significant amount of corona losses, and that each of them it has its own characteristics. The biggest difference is on 400 kV line Tumbri – Melina where the efficiency of the line is significantly deteriorated due to corona losses and the appearance of bad weather.

TABLE II. MEASURED AND ESTIMATE LOSSES FOR:

A) 400 KV ERNESTINOVO - ŽERJAVINEC

DAY	POWER FLOW*	ELECTRICITY METER*	EST-SUM*	EST-WIN*	WIN/SUM	LOSSES [kWh/100km]	EFFICIENCY
2.2.2018	28.203.200	396.800	270.628	298.145	10,2%	1.723	1,4%
3.2.2018	35.366.400	806.400	448.662	481.336	7,3%	3.502	2,3%
4.2.2018	37.998.400	491.200	514.668	532.164	3,4%	2.133	1,3%
5.2.2018	37.574.400	465.600	510.622	536.695	5,1%	2.022	1,2%
6.2.2018	43.769.600	657.600	685.603	714.525	4,2%	2.855	1,5%
7.2.2018	45.142.400	891.200	743.106	773.085	4,0%	3.870	2,0%

* [kWh]

B) 400 KV TUMBRI - MELINA

DAY	POWER FLOW*	ELECTRICITY METER*	EST-SUM*	EST-WIN*	WIN/SUM	LOSSES [kWh/100	EFFIC IENCY
2.2.2018	10.168.000	556.800	102.382	209.024	104,2%	4.367	5,5%
3.2.2018	9.544.000	604.800	100.222	202.598	102,2%	4.744	6,3%
4.2.2018	10.014.400	174.400	105.041	199.848	90,3%	1.368	1,7%
5.2.2018	13.940.800	200.000	145.545	232.516	59,8%	1.569	1,4%
6.2.2018	4.355.200	272.000	52.807	142.912	170,6%	2.133	6,2%
7.2.2018	4.939.200	467.200	53.540	137.644	157,1%	3.664	9,5%

* [kWh]

C) 400 KV MELINA - VELEBIT

DAY	POWER FLOW*	ELECTRICITY METER*	EST-SUM*	EST-WIN*	WIN/SUM	LOSSES [kWh/100km	EFFIC IENCY
2.2.2018	36.208.000	916.800	649.610	741.013	14,1%	5.128	2,5%
3.2.2018	45.532.800	1.422.400	941.540	1.065.543	13,2%	7.955	3,1%
4.2.2018	43.832.000	972.800	883.181	983.239	11,3%	5.441	2,2%
5.2.2018	43.483.200	907.200	870.178	965.921	11,0%	5.074	2,1%
6.2.2018	54.048.000	1.419.200	1.295.895	1.362.247	5,1%	7.937	2,6%
7.2.2018	55.363.200	1.729.600	1.353.727	1.439.858	6,4%	9.673	3,1%

* [kWh] EST-SUM – estimation on summer data
EST-WIN – estimation on winter data

Figure 6 shows the trend of losses compared to load flow on 400 kV Tumbri – Melina. In the figure 6 x-axis represent number of measurement for observed period, and y-axis represent power flow on left and losses on right. Time periods where losses are higher comparing to power flow match to presented values in Table II B).

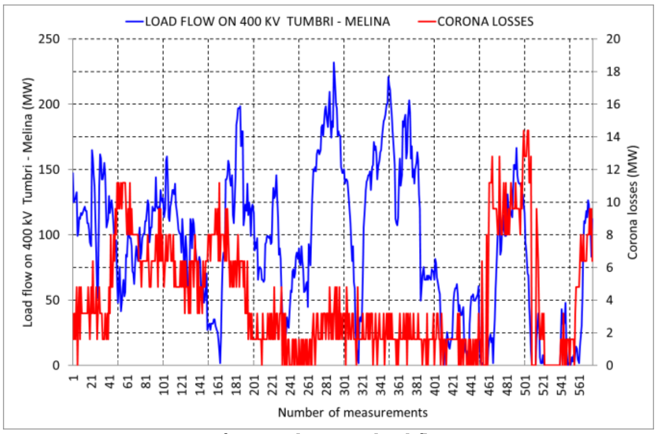

Fig 6. Comparison of corona losses to load flow

To approximately determine the amount of corona losses in the total losses comparison was made. For an observed period losses on observed 400 kV lines comparing to total losses in the transmission network are presented in figure 7. Amount of corona losses can be up to 20 MWh/h for observed 400 kV lines, or up to 20% of total losses.

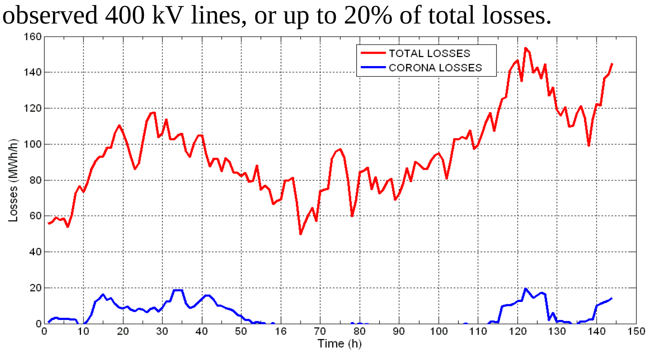

Fig 7. Comparison of corona losses to total losses

E. Intraday prediction of total losses on 400 kV level

For the conducted analysis it was concluded that occurrences of corona effect are very difficult to predict in the day ahead planning, so the proposed model for forecasting the amount of corona losses must be within the day. The figure 8. shows a delayed model of 15 min and 1 h compared to the measurement readings. Due to the characteristics of the storm and the geographical area it will affect, it is difficult to determine the rate of increase in the amount of loss for the observed power line. It can be seen that for the period where the weather is nice (sunny and dry) EST-STAT (green line) follows the measured (blue line). EST-STAT is statistical estimator that takes into account all measurements and predicts losses depending on the historical data for the current power flow on the line. For most of the period, the hourly error is small, but during the period of bad weather the hourly error is significant. For that period EST-STAT is not sufficient so the EST-MODEL 15-min or EST-MODEL 1-h has to be used (which is currently available). EST-MODEL 15-min or EST-MODEL 1-h are dynamic models that take into account previous measurements and determine the increase in losses in 15-min or 1-h resolution. Based on these measurements a prediction of losses is made for the observed line.

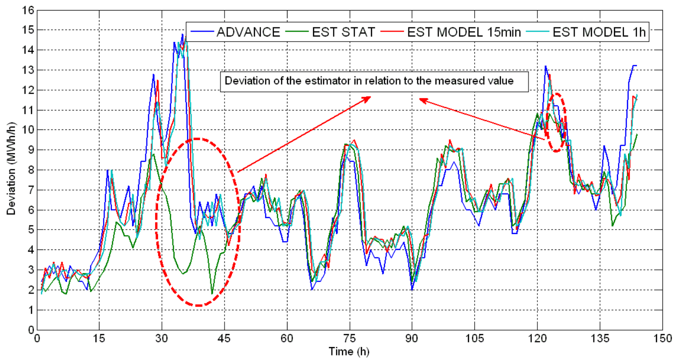

Fig 8. Intraday prediction on losses during bad weather

The trigger to switch from one model to another is zero sequence component of the current from PMU measurement. Soon as the a certain amount of zero component of the current occurs, the estimation of the losses is no longer monitored based on statistical data, but on the basis of corona and leakage losses estimation. The basis for estimation would be the amount of the zero sequence component of current. Zero sequence component should be fixedly added to the estimated statistics amounts, and the value would be from approximately 1MW/100km to 7MW/100km. This values are empirically evaluated from historical data. EST-MODEL is enabled to have prompt response to detection of losses due to Corona's on observed single transmission lines and for all of them together. The proposed model significantly reduced the deviation of the loss plans compared to the accrued losses for the observed period. Comparing to planning losses for the day before, the accuracy of around 5% loss planning and much less deviation for the hourly planning for the given period is given. Scheduling within the day is actually significantly improved, where a 15-min and hour could significantly reduce the deviation. Overall, within the day the error is several percent, while the hourly error rate is higher. Compared to existing method, the EST-STAT is significantly better and it can contribute to the improvement of loss planning on daily basis. The main drawback of the proposed method showed at the beginning and end of the storm. In that period the error is maximum, so for this time period the prediction might be challenging. .

VII. CONCLUSION

The model proposed in this paper is a logical step in the desire for better understanding losses and calculation of technical losses on transmission lines. Based on available measurements from different sources, comparing data, and comparing previous databases using predictive functions, it is possible to determine technical losses in each transmission line for the current state. Determination of losses on transmission lines has practical meaning in forecast of the grid losses on daily and intraday planning of all losses in transmission grid.

The proposed model of real-time losses calculations based on the above-mentioned business systems would help to improve the planning and procurement of losses. From the economic and technical point of view it will improve today's process and, in the future, will optimize the procuring and achieving losses. This process would be integrated into the control system of the transmission system operator and monitoring the efficiency of the system itself from the point of losses on transmission lines/transformers/regions.

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