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SUMO - a system for real-time assessment and short-term forecast of operational limits in the Slovenian transmission network

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SUMMARY

The paper provides an overview of planning and the development of a system for assessing power system operational limits from first ideas to implementation and trail use in the National control centre. SUMO is an answer to the needs in everyday operation due to the surplus generation in north Europe and the Balkans, which require a better insight in the permitted elements loading. Beside this, there are also other factors like difficulties building a new transmission line and the security of operation.
The key goal of a SUMO project was to establish a system for assessing real-time and near future transmission lines capacities based on atmospheric conditions for N and N-1 topology.
One of the key features of SUMO is that the line transmission capacity is determined dynamically based on atmospheric condition along the whole line.
In the planning phase, it was decided that SUMO should be constructed in a way that would allow for seamless integration of different hardware and software solutions from different vendors. For this reason, SUMO is built around the SUMO BUS integration platform that offers integration of different technological solutions. SUMO BUS represents a hub where exchange of current line loading, current and forecasted weather data along the line corridors, line loading forecasts for N and N-1 topology, DTR (DLR) calculations, alarms on exceptional weather conditions and other important data takes place.

KEYWORDS

dynamic line rating, dynamic thermal rating, topology N and N-1

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1. INTRODUCTION

Because of the arduous and long-term process required for the construction of new overhead power lines, increasing the transmission capacity at the existing network is the desire of all advanced transmission network operators. One of the solutions is the use of Dynamic Thermal Rating (DTR), which covers the entire thermal assessment of the elements of a transmission system. A special area of DTR is DTLR (Dynamic Thermal Line Rating) or just DLR (Dynamic Line Rating), which specifically examines the dynamic rating of the transmission capacity of transmission lines. ENTSO-E is also seriously focusing on the problem, which at the time of composing this paper is in the process of issuing an overview of the condition of DLR by individual TSO's, as well as guidelines on the structure of modern systems for the dynamic rating of transmission capacity of power lines.

Slovenia has a long-standing tradition of studying the problem area, from producing several studies to using statistical weather data, which have led to introducing winter and summer settings for over-current protection, the DAMOS system, which is based on measuring atmospheric conditions at certain substations of the transmission network and whose data are also used in the operation of the SUMO system, as well as systematic measurements of the temperature of conductors with OTLM and VALCAP and AdaPro systems.

The main ideas, which have led to the SUMO system, as we know it today, began at the end of 2010. In 2010, the market showed a lack of integral solutions for dynamic rating of transmission capacity of power lines, especially solutions, which would comply with the requirements of Slovenian TSO ELES as the contractor. The perceived deficiencies of commercially available systems on the market encouraged a narrow circle of experts to begin activities in the area of dynamic transmission capacity determination. The reasons for the development of an "in-house" system for transmission capacity determination of power lines and transformers in the company ELES were high-level specifications. These set the basis for the system and to a point determined the specific architectural characteristics. The boundary conditions for the system were determined as follows:

- SUMO is intended for the operator's use at the NCC (National Control Centre of Slovenia). The operator at the NCC apart from information on the current capacity of power lines and transformers (DTR) above all requires a simultaneous N-1 calculation and short-term forecast loading capacity for N-1 topology;
- The uncertainties of SUMO results should be known. By validating individual DTR algorithms and estimated and forecasted atmospheric data, ELES wishes to obtain information on uncertainties, which are brought on by the use of DTR during operation. Only when all the uncertainties will be known SUMO will be ready for regular operational use.

After the start of the SUMO project in 2011 and making the first studies and analyses, the researchers of EIMV and co-workers of ELES defined the strategic guidelines in the concept of developing the SUMO system. This is how in the beginning of 2012 new findings and considerations were made in the SUMO project. The study entitled "The comparison of technical characteristics of selected technologies for the thermal capacity rating of power lines" [1] has among other shown that the SUMO project is an exceptionally daring project, where apart from the first quadrant, where transmission capacity dynamic rating is carried out, commercially available solutions are not available at all.

One of the main findings was that SUMO needs to be designed to enable the inclusion of different hardware and software suppliers in the system. At the same time with this decision the priorities in implementing the project changed, because the SUMO architecture became much more important than anticipated in the primary start-up proposal. SUMO obtained an additional boundary condition:

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

The consequence of this last condition was that it was necessary to provide a standard way of integrating systems and subsystems into SUMO both in terms of supply of atmospheric data, as well as measured temperatures of conductors or values of the rated thermal flow. This characteristic of the part of SUMO therefore remains open for future upgrades, as well as for increasing competition in product supply (measurements of atmospheric conditions) or service supply (model calculations, DTR algorithm).

It is also worthwhile to mention that at internal discussions of the project group a proposal was made that information on whether there is a storm present near a power line or whether there is gale at a power line route or if there are extreme differences in temperatures is added to the four-quadrant display of results in ODIN-VIS. This is how another boundary condition emerged:

- SUMO has to provide the operator information on extreme atmospheric operating conditions. ELES uses a number of data on atmospheric conditions along the power lines, which can have a significant impact on operating safety in N and N-1 condition.

These results are important in terms of operation, because they enable operators to focus on those power lines, which are operating under more difficult conditions and which are at a higher risk of failure. After the catastrophic ice damage in 2014 the proposed further development of the SUMO system was also in the direction of potentially determining and forecasting ice storms by introducing potential technical measures for their remedial.

By the end of 2013 it was possible to test run SUMO, which enabled the following functionalities:

- exchange of measurements and results of SUMO subsystems via SUMO,
- assessment and forecasting of atmospheric conditions (ONAP),
- power or load-flow studies of transmission network (LF) or forecasts of loads at nodes (NOV),
- power flow studies for N-1 topology, thermal capacity rating for power lines for the II, III and IV quadrant, which is a completely new functionality (LODF and PTDF),
- demonstration of results via the ODIN-VIS visualisation platform, which provides a graphic demonstration of DLR results,
- connection with the SCADA subsystem and other subsystems,
- four-quadrant display of results of DTR calculations for power lines by priority concerning the load in the selected quadrant,
- the possibility of connecting different outer subsystems for DTR with own devices and algorithms.

As of December 2013 SUMO has been trial running at 4 power lines. In December 2015 additional 17 power lines and one phase shift transformer were added to the system. A regular monthly analysis of collected results has been set up.

The individual functionalities of SUMO are roughly presented as follows.

2. INTEGRATION PLATFORM – SUMO BUS

The SUMO BUS is an integration platform, which provides efficient data exchange between SUMO subsystems. It is based on the concept of a service-oriented architecture, which provides developers a quick and permanent method for producing integration interfaces for the integration of their applications in the SUMO system. Integration platform provides the orchestration and data-exchange between subsystems. There are 17 online services implemented with a total of over 120 methods [2].

SUMO BUS is implemented on an application server. Integration between applications takes place with the use of web services. These are described in the WDSL descriptive language, which provides developers automatic generation of required data structures and functions and substantially shortens the time required for the development of integration interfaces.

Because of the needs for scalability we had to choose technologies, which are stable enough to provide the long-term future development of SUMO. SUMO BUS is carried out in the *Spring Framework* programme environment. Its advantage is that it provides quick and simple switching between implementing environments in the event of a need to substantially increase capacity without major corrections in the programming code. For the requirements of the SUMO BUS integration platform the open-code *Apache Tomcat* programme environment has been sufficient for now, which can be upgraded at any time with more demanding and functionally advanced programme environments, such as *iBoss* or *GlassFish.* At the same time in order to provide scalability and independence from one database the *Hibernate* interface was used, which provides a quick replacement of the database without the need to change the programming code. For the requirements of the SUMO BUS platform we are currently using the *MySQL* database, which in its current configuration satisfies the requirements.

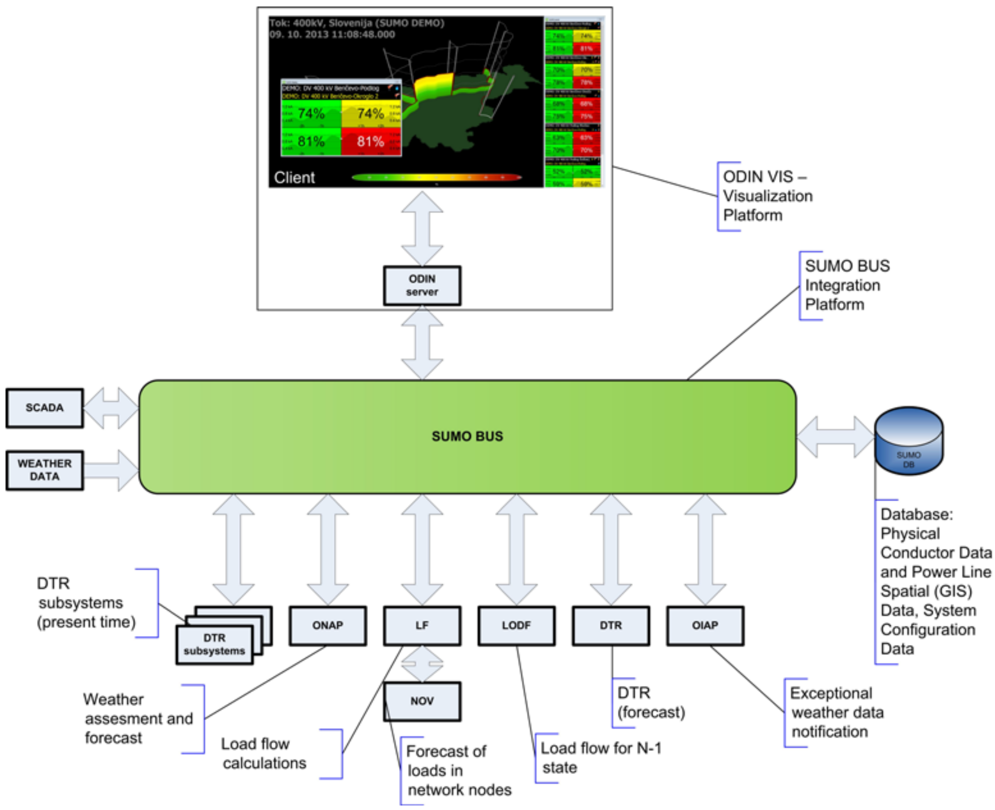

Figure 1 : SUMO system architecture

Figure 1 shows the SUMO system architecture - the SUMO BUS integration platform and individual SUMO subsystems, which exchange data through it.

3. ASSESSMENT AND FORECAST OF WEATHER CONDITIONS - ONAP

The ONAP subsystem enables us to use meteorological models to evaluate weather conditions along the power line routes for t_0 time and forecast weather conditions for $t_0+\Delta t$ time.

The system is composed of two parts:

- Assesment of weather conditions:
  - Weather variables are determined for the fixed geographical resolution grid 500 ×500m from results of the mesoscale meteorological model by using the microscale weather model, which also takes into account the orography of the terrain and some weather measurements (if available).
- Forecast of weather conditions:
  - Weather variable forecast is issued for a period of 15 to 180 minutes in the future based on forecasts of the mesoscale model and the microscale weather model.

4. NODE LOAD FORECASTS AND LODF – NOV AND LODF

The operator in NCC (and the SUMO system itself) require data on current and forecast loads of these elements during normal operating mode and for the N-1 situation. Because this is real-time assessment of the load capacity of power lines and transformers, we need to implement methods, which quickly and accurately offer satisfactory results.

Within LF, NOV and LODF modules (Figure 1) the following tasks are implemented:

- The evaluation of current conditions in the power system (PS):
  - o the collection of loads at all 110 kV, 220 kV and 400kV nodes of the Slovenian electricity system model, where the module is connected with the SUMO BUS guide, which collects data required for further calculations;
  - o a quick calculation of working power flows at power lines and transformers of the Slovenian PS model in the LF module. The method is based on using PTDF (Power Transfer Distribution Factor), which represents the linearization of the problem, which means that it efficiently speeds up the calculation of power flows, but we can expect a certain error margin in the calculation. PTDF actually presents a gradient of working power flows at power lines and transformers upon changes of injected power at nodes. It is estimated that the error margin does not exceed 5% and therefore does not present a too great risk for the meaningfulness of results. The use of PTDF is explained below;
  - o the calculation of working power flow for a different range of N-1 network topologies based on the use of LODF (Line Outage Distribution Factor). These factors represent a gradient of working power flows at power lines and transformers upon individual failures of elements of the transmission system and provide quick sequential calculations of operating conditions at the power system without respectively calculating the power flow each time. Experience show that by using these factors the N-1 safety analysis for the Slovenian power system is approximately 30-times faster than classical analysis based on calculating power flows. The use of PTDF is explained below;
- The forecast of operating conditions for several hours in advance:

- where a short-term forecast of injected working power at all 110kV, 220kV and 400 kV nodes of the Slovenian power system model is of key importance. The forecasting method is explained below;
- load forecasts at power lines and transformers for several hours in advance using PTDF and load forecasts for these elements at different N-1 network topologies within safety analyses, where LODF is used to speed up the calculation.

4.1 USE OF PTDF AND LODF

In recording and using PTDF and LODF we derive from the one-way model for the calculation of power flows at the network, which means that wattles power is neglected and node voltages are ignored, because we assume the nominal voltage values. Implementation of PTDF and LODF is explained in the study [lit. 5] and the usability of the factors is indicated in the following two equations:

$$P_{ab,1} = P_{ab,0} + PTDF_{ab,c} \cdot \Delta P_c + PTDF_{ab,d} \cdot \Delta P_d \ , \qquad (1)$$

where $P_{ab,0}$ is the working power flow at the overhead power line (or transformer station) *a-b* in its starting operating condition 0 and $P_{ab,1}$ is the working power flow at the same conductor in operating condition 1, which differs from condition 0 in the difference of injected power at nodes *c* and *d*. The essence of PTDF is that the flows in the new operating condition are not calculated by iterative methods, such as the Newton-Raphson Method, but that the calculation is simple and fast.

PTDF is used for operating conditions, which differ only by injected powers, whereas the topology needs to remain unchanged. If the topology changes, LODF would be used for the calculation of working power flows at power lines and transformers and its usability is described by the equation:

$$P_{ab,1} = P_{ab,0} + LODF_{ab,cd} \cdot P_{cd,0} \ , \qquad (2)$$

where $P_{ab,0}$ is again the working power flow at the overhead power line (or transformer) *a-b* at the starting operating condition 0 and $P_{ab,1}$ is the working power flow at the same conductor in operating condition 1, which differs from condition 0 in that in condition 1 the power line *c-d* is switched off. $P_{cd,0}$ is the working power flow at connection *c-d* prior to switching it off.

If the injected working power as well topology changes in the system, it is possible to simultaneously use PTDF and LODF because of the validity of the superposition principle. This combination allows us to calculate the working power flows for all other conditions based on the knowledge of results for one operating condition. The precondition is of course the calculation of PTDF and LODF for the initial operating condition.

4.2 LOAD FORECASTS AT NODES

For forecasting power injections for consumers, production units and limit power flows, there are many methods available for short-term consumption predictions. In the area of short-term forecasting one of the most widespread and accurate methods for very short-term forecasts is the autoregressive method, which is the original time series method. The advantage of such methods is their accuracy, because they take into account the dynamics of consumption during the day and co-dependency of consumption at different times. With time series methods the observed amounts are described as a stochastic process via a chosen time series model. The basic time series models are:

- auto regression models (AR),
- moving average models (MA) and
- integrated models.

Because there was not much information available in forecasting generated power and limit power flows, forecasting is based on observing the fluctuations of amounts of time series and the SUMO system is therefore based on using the AR method. The time schedule forecasts of producers, which Borzen has at disposal, and the forecasts of behaviour of interconnections issued in DACF files (Day Ahead Congestion Forecast), which ELES has at disposal, are of key importance.

In analysing time series an important supposition is the stationariness of the time series of data. Stationary time series imply that the average value, variance and autocorrelation values do not change over time. The time series has to fulfil the conditions noted in (3-5):

$$E(\mathbf{z}_{(h)}) = \mu_z, \quad h = 1, 2, ..., \infty, \tag{3}$$

$$\mathrm{var}(\mathbf{z}_{(h)}) = \sigma_z^2 < \infty, \tag{4}$$

$$\mathrm{cov}(z_h, z_{h-s}) = \mathrm{konst.} \tag{5}$$

$E(\mathbf{z}_{(h)})$, $\mathrm{var}(\mathbf{z}_{(h)})$ and σ_z are expectations, variance and standard deviation of the time series $\mathbf{z}_{(h)}$. Time series $\mathbf{z}_{(h)}$ contains data from the original value in time series z_1 to value z_h, where h is the final observed value. If h equals the last datum in the time series, the time series can be noted as $\mathbf{z}_{(.)}$. In order to satisfy the stationary condition the expectation and variance cannot change over time. The autocovariance is marked with $\mathrm{cov}(z_h,z_{h-s})$, which stands for covariance of the observed value z_h and delayed value for s hours, z_{h-s}. If the time series is stationary, all the covariances between different h and h-s are the same.

In the auto regression model AR(o) the current value of the observed amount is recorded as a linear connection o with past values or o lag and random error. The model order is determined by the oldest past value of observed amount in the time series o. AR model (o) is determined by the following equation (6):

$$z_h = c_z + \phi_1 z_{h-1} + \phi_1 z_{h-1} + ... + \phi_o z_{h-o} + \varepsilon_{iid,h}, \tag{6}$$

where c_z is the conditioned average of the time series $\mathbf{z}_{(.)}$, which is the average of the time series with considered conditions. Symbol z_{h-o} represents the observed amount, delyed from h hour by o hours and φ_o is the auto regression coefficient for lag o. Conditional mean c_z is calculated with the equation (7), where μ_z is the median value of the observed time series $\mathbf{z}_{(.)}$:

$$c_z = \mu_z \left(1 - \phi_1 - \phi_2 - ... - \phi_o\right), \tag{7}$$

where $\varepsilon_{iid,h}$ is random error in the auto regression model for hour h. Auto regression coefficients are determined by using one of the regression analyses, which tries to minimise the random error in the model. The sequence of random errors in the auto regression model namely presents a time series of statistically independent, evenly distributed random variables. The time series of statistically independent and evenly distributed random variables are called the strict white noise and can be mathematically written with the equation (8):

$$E\left(\varepsilon_{iid,i}\varepsilon_{iid,j}\right) = \begin{cases} \sigma_\varepsilon^2 & i = j \\ 0 & i \neq j \end{cases}. \tag{8}$$

The equation notes that the covariance between two random variables equals zero, while at the same time all variables have the same constant variance σ_ε^2.

Equation (6) for AR (o) is written differently with the lag operator L of equations (9), (10) and (11):

$$L\, z_h = z_{h-1}, \quad L^m z_h = z_{h-m}, \tag{9}$$

$$\phi(L) = 1 - \phi_1 L - \phi_2 L^2 - ... - \phi_o L^o, \tag{10}$$

$$\phi(L) z_h = c_z + \varepsilon_{iid,h} \ . \tag{11}$$

5. ALERTS ON EXTREME WEATHER CONDITIONS - OIAP

OIAP is a subsystem, which follows weather conditions along the power line corridors and at exceeded values of weather variables it sends a message (alert) to SUMO BUS for the weather variable, which has been exceeded as well as the identification number of the overhead power line, which the alarm applies to. The list of extreme weather conditions is presented in Table 1. The appropriate symbols display alongside the name of the overhead power line in the four-quadrant SUMO display.

Table 1: Alert symbols for extreme weather conditions

Symbol	*Meaning*
	Thunderstorm – lightning activity on the route.
	High wind speed on the route (gale or storm)
	High air temperatures on the route.
	Low temperatures or frost on the route.
	Heavy rain on the route.
	Danger of glaze ice.

6. VISUALISATION - ODIN-VIS

ODIN-VIS is an independent visualisation platform for advanced visualisation of the electricity network, such as for example the visualisation of voltage and voltage angles at network nodes, loads at power lines and reactive power flows. Within the platform is also a module for the visualisation of SUMO results, which provides the visualisation of:

- dynamic thermal ratings (current values and forecasts),
- current loads and forecast of loads at overhead power lines,
- results of N-1 analyses,
- weather conditions and
- alerting of extreme weather conditions along overhead power line routes.

It also provides an insight in the archive of network conditions for all display sets.

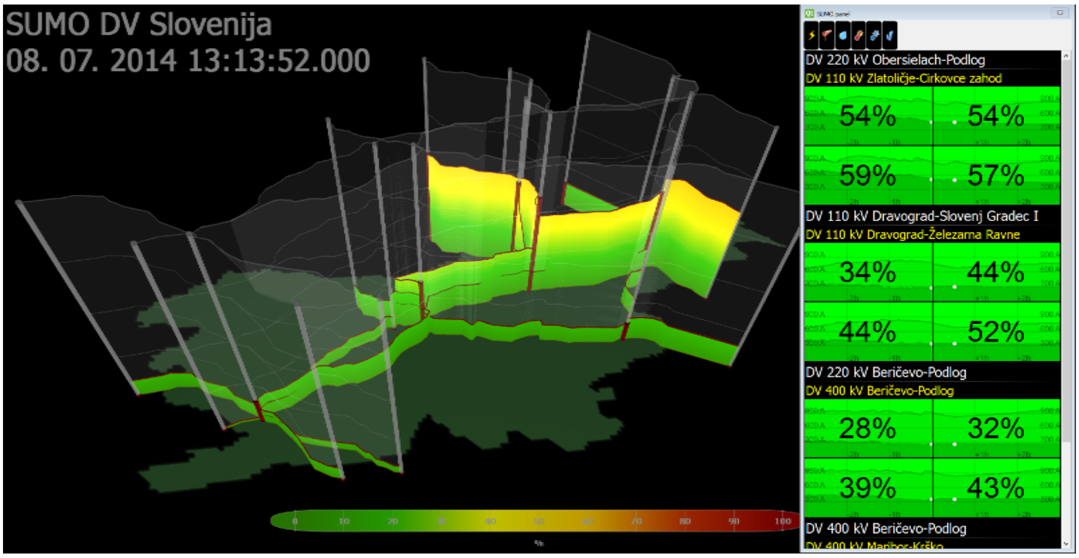

Figure 2 : Visualisation application ODIN-VIS

Quickly responsive and graphic presentation of the results of the SUMO system is very important for an operator and this is why extensive effort was put in developing an appropriate display. This is how the so-called four-quadrant display was produced as shown in Figure 3.

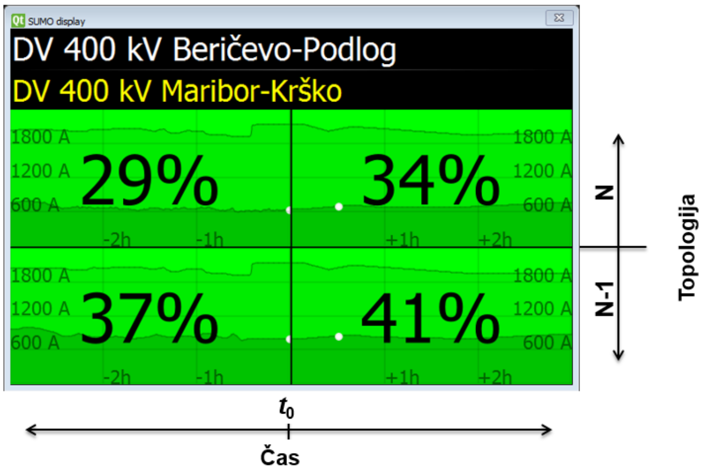

Figure 3 : Four-quadrant SUMO display

The name of the overhead power line (PL 400kV Beričevo-Podlog) is displayed at the top of the window, below is the name of the overhead power line where outage would be the most inconvenient according to N-1 analysis (in this case the PL 400kV Maribor – Krško). Every display is divided into four quadrants. Each quadrant contains power line load curves and thermal flow in terms of time and load percentage (for the left quadrants in current time, for the right quadrants in future time, which is adjustable – in this case it is set to half an hour). The border between the left and right quadrant is current time; at left of the border time is three hours behind, whereas at the right three hours in advance – in this case we are talking about load forecasts and thermal flow ratings based on meteorological forecasts. The upper two quadrants apply for the observed power line for N topology, whereas the bottom two for topology N-1, which in practice means that they pass each other the load of the observed power line in the event of outage of the least favourable overhead power line.

The four-quadrant displays are organised in the so-called SUMO panel, which is a list of four-quadrant displays in the SUMO included overhead power lines, organised by priority concerning the load in the selected quadrant (right part of Figure 2). By changing the background colour, the operator is further warned of the danger of a critical situation. In the event of load over 100%, the quadrant turns red and also issues a permissible operating time under such load.

Another module was made within the visualisation platform to display weather with an outlined sheet of air temperatures at the geographical area of Slovenia in accordance with a certain colour scale. In addition to temperatures, the sheet also displays:

- ELES overhead power lines for easier orientation in space,
- at locations of 400 kV substations wind indicators are also displayed with additional information on wind speed, and
- wind indicators along PL routes included in SUMO are also displayed in enlarged view.

7. LESSONS LEARNED

The decision for the pilot project has proved to be the correct course of action, because during the project we have encountered a number of questions and problems we had not expected.

Experiences gained on the topic of uncertainties of individual subsystems were exceptionally important. Although much insecurity is brought on by weather models, without them the DTR simply cannot exist. There is still a lot of work to be done in this area, especially in terms of location and the number of required weather stations, which would complete the weather model and reduce its uncertainty. Currently we are analysing the uncertainties of DTR algorithms, which are showing interesting results and this analysis is much needed, if we wish to use SUMO during operation.

Experiences so far have shown that the permissible load at transmission lines is higher than that stipulated by standards. This experience has given us additional encouragement, because it proved that an investment in DTR consequently implies a later need for investments in a new infrastructure, which are too often unrealisable. On the other hand, we can be truly thankful for those, although rare moments, when SUMO has alerted us of critical conditions and accordingly about the transmission capacity, lower than predicted static capacity. In this situation the operator can reduce the load at the power line and prevent potential damage of the power line or an excessive hanging of the conductor.

8. CONCLUSIONS

SUMO starts a new chapter in the operation of the power system. This chapter dictates a better utilisation of the existing infrastructure and a higher level of awareness of the state of the transmission network. DTR complies with the two requirements and with accurate visualisation; it provides the operator also other information, which could have a major impact on network operation. This includes extreme weather conditions, because they can quickly lead to failures. Consequently, the operator places more importance on more exposed power lines. Apart from DTR and its key components, the knowledge about weather conditions along the power line routes, SUMO also includes important analytical elements, N-1 analyses and short-term forecasts. Most power lines achieve peak load only in N-1 condition and this is why DTR is sensible for use only in combination with N-1 analysis. We should not forget about the uncertainties. An operator has to have confidence in every newly implemented system, before they start using it. It is the latter that has driven us to produce a trustworthy integral DTR system, which includes N-1 analytics and short-term forecasts, which provide the operator with all the relevant information so that they can use the existing transmission capacities to their fullest potential and never beyond it.

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BIBLIOGRAPHY

[1] G. Lakota Jeriček, A. Souvent, G. Milev, in J. Kosmač, *Primerjava tehničnih značilnosti izbranih tehnologij za ocenjevanje termične zmogljivosti daljnovodov : študija št. 2136*. Ljubljana: Elektroinštitut Milan Vidmar, 2012.
[2] A. Souvent, G. Lakota Jeriček, J. Kosmač, J. Stojanović, M. Naglič, G. Milev, V. Djurica, in G. Zlatarev, *Vzpostavitev programske platforme SUMO BUS in nadgradnja programske opreme ODIN-VIS : študija št. 2168*. Ljubljana: Elektroinštitut Milan Vidmar, 2013.