Preventive Maintenance Optimization for Slovak Power Grid Using EOOS Risk Monitor

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Abstract: In recent years, deregulation of the electric industry has resulted in changes to the approach to generation and distribution of power. Previously, one power company would both generate and distribute power. Now these functions are often performed by separate entities. The market has resulted in changes to the way that electric grids are being operated other than those for which they were originally designed, including various configurations and load levels. The deregulated electrical power market has already contributed to conditions that challenge the stability of the grid. The utilization of existing assets is increased. It has resulted in greater power transfers over longer distances. This has increased the loading of the transmission grid and also made local reliability more dependent on distant events. On the other side, the customer expectations of reliability are increasing and the consequences of power outages have never been greater. Even small weak points in the power transmission system might eventually lead to costly outages or trigger cascading failures that affect large regions. The traditional approach to electrical grid reliability is based on deterministic analyses. However, under the changed conditions this approach is not enough. The probabilistic approach (PSA) should be used which can help to identify and correct potential weak points in the power system long before they trigger costly failures. Given a PSA model of the grid constructed, the risk monitor can be developed. This is a specific real-time analysis tool of the grid which can be used to determine the instantaneous risk based on the actual status of its systems and components. The paper describes the risk monitor developed for the Slovak electrical power system.

Keywords: PSA, risk monitor, maintenance, risk profile.

1. INTRODUCTION

The PSA (Probabilistic Safety Assessment) methodology can help to identify and correct potential weak points in the power delivery system long before they trigger costly failures. It helps to system planners to visualize the system reliability and its interaction with neighboring areas. It helps them recognize the critical contingencies that have both high probability and high impact, and develop effective mitigation actions for improving the transmission system reliability. Design weaknesses and low-cost methods to reduce risk can be identified. They enable to quantify risks and thereby place relative values on improvements. This provides a structured method to prioritize projects and determine cost-effective approaches to risk reduction.

This paper describes using of PSA for analysis of the partial and total blackout of the Slovak power grid (400 kV) for different power flows and configuration of the grid given by the preventive maintenance activities. The method uses event and fault tree analysis [2] in combination with the dynamic stability analysis of the grid. The event trees model the grid response to the initiating event of the accident. The fault trees are used to model the reliability of the substation protection systems. Different end states of the event trees are simulated on the basis of dynamic stability analysis, as safe and emergency state, partial and total blackout.

The PSA model has been implemented into the EOOS risk monitor software to analyze the risk for different configurations of the grid and to support the operation and the maintenance activities.

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2. PSA MODEL FOR 400 KV POWER GRID

Within the project for national grid operator (SEPS) the PSA model for 400 kV power grid of Slovakia has been developed [4]. The project has the following objectives:

- assessment of the overall system reliability of the transmission grid,
- identification of the transmission system components most likely to contribute to critical situations,
- identification of the specific branches and busbars most susceptible to interruption,
- quantification of the frequency of partial and total blackout,
- development of a full-scope risk monitor to control the risk in the grid.

The PSA model is developed in RISK SPECTRUM PSA Professional software [3].

2.1 The Initiating Events of the Accident

The accident starts with an initiating event, the continuation of which is then modeled with event trees and fault trees. This approach is suitable also for modeling the power system protection, since the method is developed for analysis of the safety functions after an accident. This analysis of post-fault substation operations is therefore analogous to a nuclear power plant PSA analysis.

Both qualitative and quantitative analyses were made for grid faults during the last 10-year period studied. The causes of the faults and the number of them were analyzed. The faults that occur most often are the initiating events of the event trees.

The following list of initiating events are considered:
1) short connection of the lines,
2) short connection in the substations,
3) outage of power sources,
4) outage of lines
5) outages of consumers.

More precisely, the initiating events are only the short connections of the lines and short connections in the substations. The other initiating events (the outages of lines, power sources and consumers) have only negligible impact on the risk and were screened out.

2.2 The Accident Simulation

The results of the accident simulations are classified taking into account the stability, the voltage violations, and the thermal limits. Angle stability is classified into the categories: stable and unstable. When the angle stability of the power system is lost in 20 seconds the result is a major disturbance. There is nothing the control centre operation personnel can do to prevent the case. Voltage or frequency stability problems do not occur in this load-flow situation.

The power system states that will be used as consequences in the event trees are safe state, emergency state and system breakdown.

Safe state is a stable in dynamic simulations, no extra generators are tripped, no thermal nor voltage violations occurred. The fault tripped in 100 ms and the rapid automatic reclosing succeeds. Emergency state is a stable case with several lines tripped. Voltages or thermal ratings or both are outside the limits. A trip of the faulted line only cannot lead to an emergency state due to the n-1 principle. A busbar trip, a substation trip and trips of extra generators could be emergency cases if the voltages or thermal ratings are violated. The definition of a partial blackout is that it is an emergency state where one or several extra generators trip due to the extended fault duration. It is worth noting that if a radial line between a generator and the grid is tripped, this is not regarded as an extra trip, since the generator acts as planned after such a fault. The total blackout is any unstable case in dynamic simulations leading to system breakdown.

The power system consequences received from power system simulations are added into the end branches of the event trees.

The grid simulations are made using a power system analysis software package. The grid model in the software is the Slovak interconnected transmission system. The grid models of other countries were not as detailed as that of Slovak grid. Several level of the load flow is simulated to model the power imports from different countries through the Slovak transmission grid. The substation conditions are simulated exactly as they are defined in the event trees. The simulation results are classified to safe state, emergency state, partial and total blackout. The system breakdown can be caused due to different causes. An unstable case in the dynamic simulations is one reason.

The analyses were performed for the short connection of the lines and short connection in the substations. The following end states are defined for the event trees after the occurrence of the initiating event:

- **D1- stable state**
    - No power source is lost
    - No line is overloaded
    - No substation will be without power supply
    - No passive element is lost which can lead to limitation of power supply in Slovak Republic
- **D2 - stable state with limitation**
    - No power source is lost with power higher than 880 MW
    - Two or more substations will not be without power supply (the second substation will not be Krizovany, Levice or V. Dur) and the substation Krizovany will not be without power supply
    - No significant limitation in power supply in Slovak Republic
- **D3 - dangerous state**
    - Power sources are lost with total power higher than 880 MW or
    - Two or more substations will be without power supply (the second station is Krizovany, Levice or V. Dur) or the substation Krizovany will be without power supply or
    - Significant limitation in the power supply in Slovak Republic
- **D4 – unstable state**
    - Power sources are lost with total power higher than 880 MW and
    - Two or more substations will be without power supply (the second station is Krizovany, Levice or V. Dur) or the substation Krizovany will be without power supply and
    - Significant limitation in the power supply in Slovak Republic
- **D5 – total blackout**
    - Blackout is a power system state in which the power system has collapsed. This is a state in which the system has collapsed and operators start the system restoration. The breakdown can be caused due to rotor angle, voltage or frequency instability after the fault. It also can be caused by insufficient operator actions after a fault that occurred during the states D1-D4.

3. THE EOOS RISK MONITOR

The grid risk monitor is developed using the EPRI software EOOS (Equipment Out Of Service) [1]. The software is one of EPRI's Risk and Reliability Analysis Workstation products and is a computer program for monitoring safety. It uses a CAFTA fault tree model but provides an interface that makes the fault tree usable by non-PSA experts. An operator (dispatcher) screen, which can be readily adapted to an individual utility's requirements, allows easy user input to the fault tree.

3.1 Grid Risk Monitor for Operators – Dispatchers

EOOS helps dispatcher to focus on safety and stability. The combined effect of many simultaneous work activities can have a significant impact on grid reliability. With each new task, dispatchers make a complex decision to act based on their perception of how it affects grid reliability. The EOOS operator screen (Fig. 1) helps dispatcher to make these decisions by showing:

- a numerical measure of grid safety that reflects changes in equipment status,
- the maximum time allowed in a particular grid configuration,
- the status of grid systems affected by various test and maintenance activities (providing measures of "defense-in-depth"),
- a list of current activities that affect grid equipment,
- lists of in-service and out-of-service items, ranked by their importance to safety,
- quick recalculating of safety measures for a variety of "what-if" tests (Fig. 2).

For the grid safety measure the Plant Safety index (PSI) was chosen. The value of PSI ranges from 0 – 10 and it is derived from frequency of occurrence of desired end state (D3 or D4). A high PSI value implies a high level of safety: "10" is good, "0" is bad. The analog display is a vertical bar to the left of PSI number. Like a thermometer, this bar fills from the bottom up. The fill color is red, orange, yellow, or green. Red appears with low PSI values, green with high PSI values, and orange and yellow with intermediate values. The boundaries for color change are derived from base-line (no unavailability in the grid) frequency of occurrence of end states D3 and D4.

In the current grid risk monitor the dispatchers can choose one of two transit power flows – 2000 MW or 2700 MW. They are also able to set any configuration of the grid by taking out of service any of 45 400 kV distribution lines, any component within 19 substations or entire substation. Furthermore, dispatchers can model the real situation of the grid also using environmental effects function.

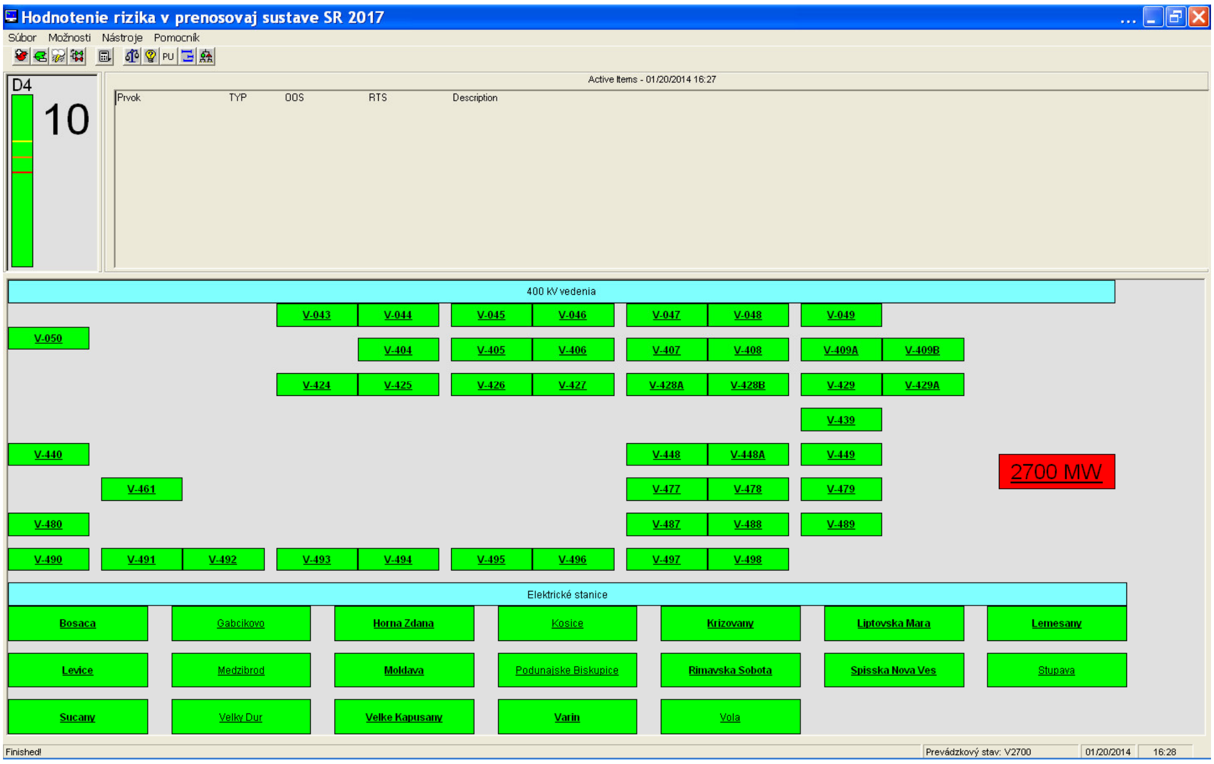

Figure 1: Operator – Dispatcher Screen for D4 End State

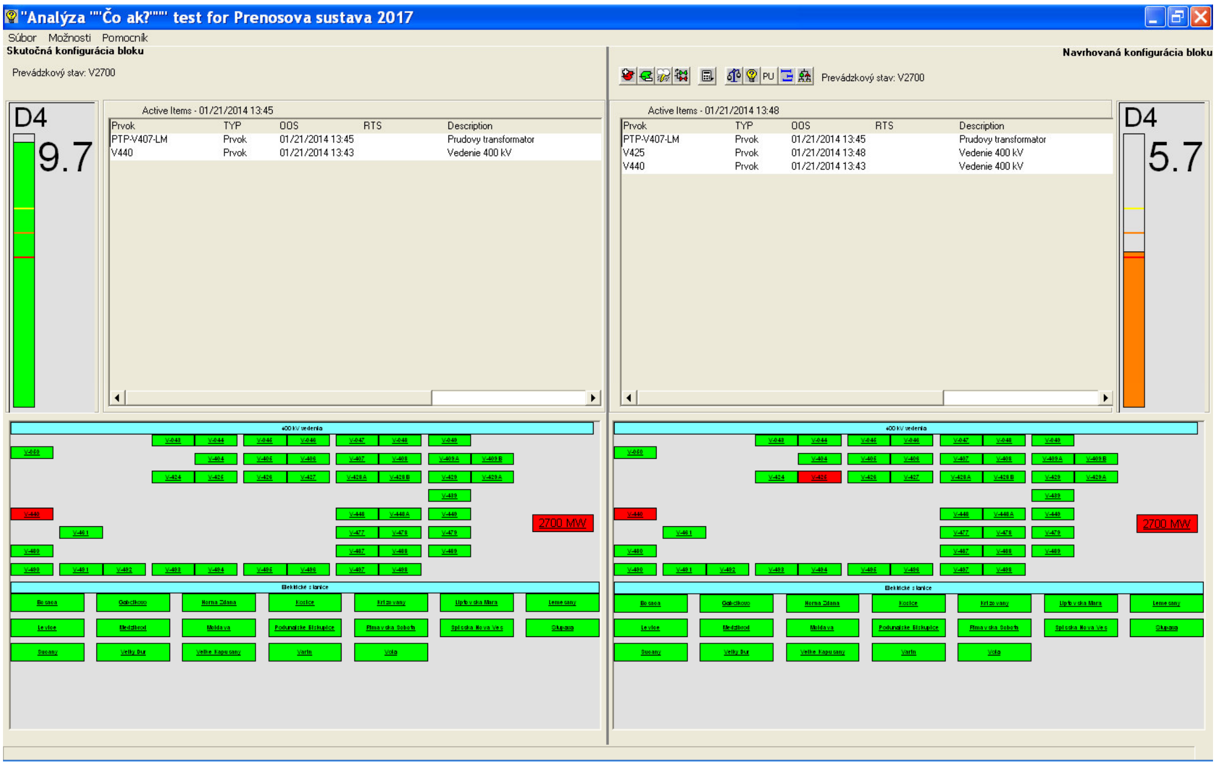

Figure 2: Operator - Dispatcher Screen With "What-If" Function

3.2 Grid Risk Monitor for Scheduler - Planner

The EOOS scheduler's screen shows how grid operations affect safety over a period of time. A typical user would be a maintenance activities scheduler who makes decisions about when to perform maintenance on grid equipment over periods of several weeks or months.

These activities affect grid safety and often involve disconnecting of 400 kV lines or realignment of substations so that workers can safely gain access to the equipment.

EOOS helps schedulers focus on safety. The combined effect of many simultaneous maintenance activities occasionally has an unexpected impact grid safety. To avoid this, schedulers spend a good deal of time performing safety reviews. EOOS helps schedulers perform these safety reviews by:

- Generating timelines showing the changing status of grid safety.
- Identifying the specific equipment and activities that have the strongest influence on safety.

This information helps schedulers decide whether and how to change a schedule to optimize grid risk.

The typical EOOS scheduler screen representing risk profile for grid maintenance activities planned for one year is shown in Fig. 3.

All maintenance activities are presented in the upper part of the scheduler screen. The middle part of the scheduler screen indicates the status of the grid components (e.g. 400 kV lines, transformers, etc.). The lowest part of the operator screen presents the annual risk profile for end state D4.

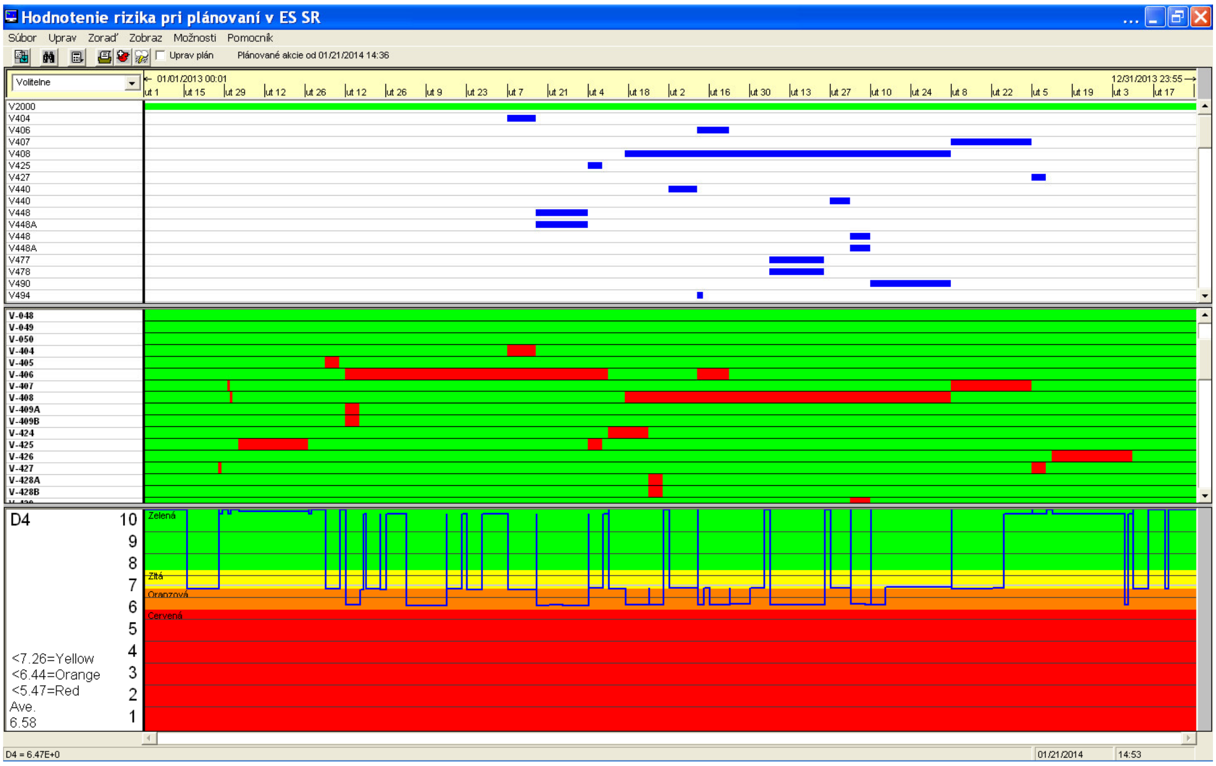

Figure 3: Scheduler Screen for One Year Maintenance Plan

The typical scheduler tasks sequence is explained using figures 4 and 5.

Once the maintenance plan has been entered into grid risk monitor and the risk profile has been recalculated, the unacceptable risk (red color for PSI) is identified for some time period in the plan (yellow ellipse in Fig. 4). After that the scheduler has identified the problematic maintenance activity – line protection maintenance in substation 400 kV Krizovany (red ellipse in Fig. 4). In the next step the scheduler has moved the critical maintenance activity to a different time period and recalculated the risk profile.

The result is shown in the Fig. 5. The problematic maintenance activity has been moved to a new time period (red ellipse in Fig. 5), while the risk in this time period remained acceptable (yellow ellipse in Fig. 5) and risk in previous time period returned to acceptable level (black ellipse in Fig. 5). Finally, the new maintenance plan can be recommended for agreement.

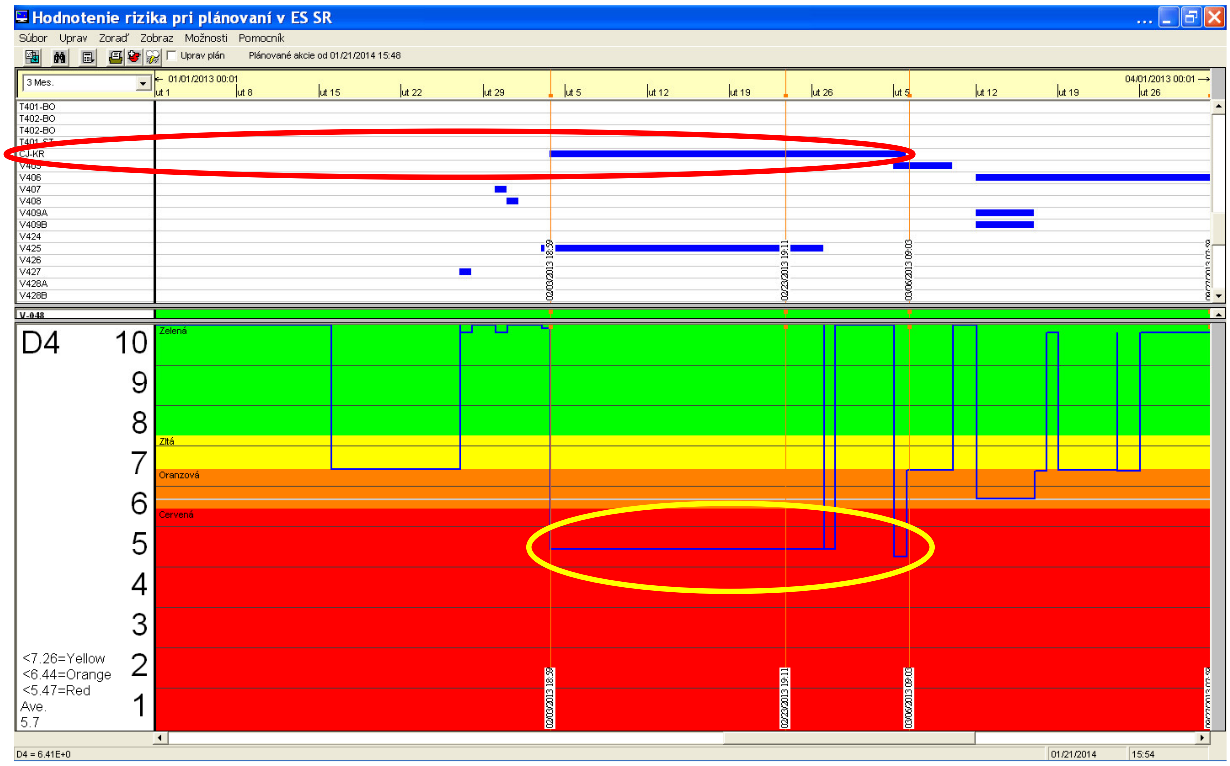

Figure 4: Scheduler Screen for New Maintenance Plan with Unacceptable Risk

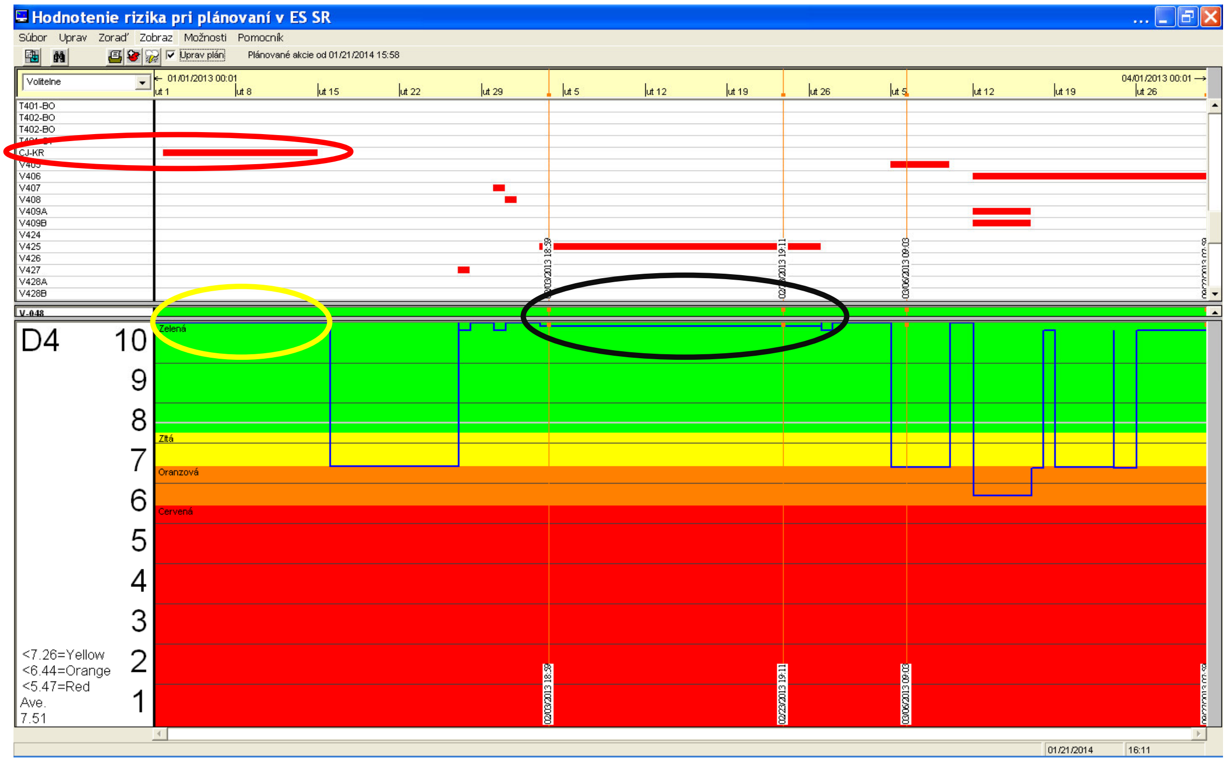

Figure 5: Scheduler Screen for Fixed Maintenance Plan

4. CONCLUSION

In particular, the use of a risk monitor will:

- allow the grid operators the controlling the grid configurations, thus ensuring that the overall risk from the grid will be lower,
- provide risk information in a form that is readily understandable and can be used to demonstrate the level of safety of the grid,
- make it easier to address the maintenance activities, to assess the risk prior to entering a planned maintenance configuration and immediately after entering a non-voluntary configuration for all the modes of operation of the grid and
- provide a basis for a wide range of risk-informed applications.

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