ACTUAL LINE AMPACITY RATING USING PMU

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ABSTRACT

Modern technology of synchrophasor measurement allows continuous evaluation of topical line transfer capacity (ampacity) with respect to line load and weather conditions. The following article explains conditions, limitations and principles of methodology and presents results of experimental measurement.

The current secure reserve of line transfer capacity can be used to solve critical situations in the network.

AMPACITY – LINE TRANSFER CAPACITY

The ampacity or line transfer capacity problem started to be topical around the world in connection with power black-outs after 2000 and with the production of large volumes of energy by distant renewable sources (wind and solar power stations). Such power volumes has to be transferred over large distances and local (national) power networks are often used for this task regardless of the fact that the local networks have not been built for such operational conditions. Building and usage of new lines is limited by long building period, unprepared projects and high costs.

Enlargement of transfer capacity or utilization of entire transfer capacity is necessary both in normal conditions and in critical conditions of interconnected networks. These problems drew attention of specialists community already before 2002 when international standards CIGRE and IEEE for mathematical models originated [1].

Definition:

"The ampacity of a conductor is maximal current which will meet the design, security and safety criteria of a particular line on which the conductor is used"

Ampacity of conductor (line) is defined as permitted load by maximum current that can be transferred by conductor without violation of secure and reliable line function. This violation is largely determined by maximum permitted temperature. The definition of maximum permitted temperature has to allow for:

- Electrical and mechanical properties of conductor materials to avoid irreversible changes of quality,
- Minimum line height above ground according to the international and national standards (sag),
- Electrical parameters of connected devices.

The ampacity is not constant value. It depends on weather conditions, namely ambient temperature, solar radiation and wind velocity. The maximum value of current used untill now is defined by rare critical weather conditions (e.g. ambient temperature over 35°C and wind velocity under 0,5m/s at the same time). The following data record of weather conditions in northeast part of the Czech Republic shows that critical operational condition were not achieved at all and the line has enough reserve for increased load in most cases during the year. The red marked area shows conditions close to the critical values.

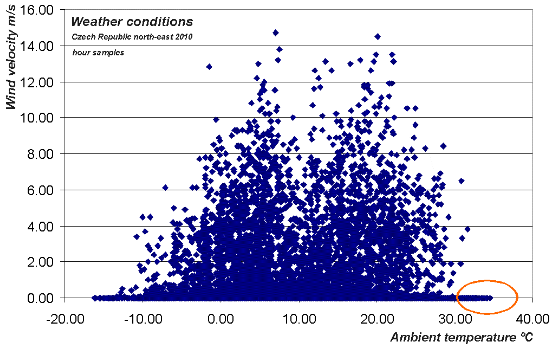

Fig. 1

There are two possibilities how to solve the problems of increased transfer capacity:

1. Constructional modifications of existing lines or construction of new lines
2. Monitoring of current line ampacity and operative usage of reserve

AMPACITY DETECTION

The principle of described method is evaluation of current when conductor achieves the permitted temperature. The method is based on the determination of actual conductor temperature and its reserve for further permitted warming. Simple model allows the calculation of permitted current increment.

Energy and heat balance in the conductor represent a basis for determination of conductor temperature. The methodology for the calculation of conductor temperature and ampacity evaluation is described in standard [1]. Inputs for the calculation are ambient temperature, geographical location of line to determine solar radiation, velocity and direction of wind. Properties of conductor (ability to absorb solar radiation, factor of heat transfer in the conductor surface) represent parameters of calculation.

Energy increasing the conductor temperature and amount of energy that conducts the heat away from conductor has to be balanced:

$$q_s + R * I^2 = q_c + q_r \quad (1)$$

where q_s – energy of warming by solar radiation
R * I2 - energy of warming by flowing current
q_c – energy of heat transfer from conductor to environment dependent on ambient temperature and wind
q_r – energy of heat radiation.

Most of equation terms depend on conductor temperature. Characteristics and trend of temperature in temporary state is simulated by model with one time constant:

$$\frac{dT}{dt} = k * [\ q_s + R(T) * I^2 - q_c - q_r\ ] \quad (2)$$

This method is implemented in many programs used for construction and evaluation of lines.
Precision and usability of the method is limited by the amount of estimated parameters and line constants. Therefore methods for direct measurement of line temperature are being sought.
The following text describes the usage of voltage and current synchrophasors in WAM systems for monitoring of line temperature.

LINE PARAMETERS MONITORING IN WAM SYSTEMS

Exact time synchronization by GPS allowed development of devices for simultaneous (synchronous) measurement of electrical quantities. Measurement devices called PMU (Phasor Measurement Units) evaluate voltage and current vectors (vector amplitude and angle) measured in the same instant in various places round the world. Such quantities are called synchrophasors and they form the basis of Wide Area Monitoring Systems (WAMS).
Synchrophasor technology brings exact view of state and behavior of the system and allows realization of many new and more exact functions for support of network development, analysis of network behavior in atypical situations and support of operative network control. On-line evaluation of network stability and recognition of pre-critical and critical states represents also significant benefit.
Voltage and current synchrophasors measured in both line ends allow on-line calculation of line parameters.
Let's use π-cell model:

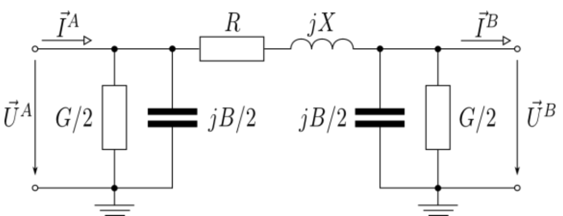

Fig. 2

Series line impedance is

$$Z_{LINE\acute{\imath}} = R + jX = \frac{U_B^2 - U_A^2}{U_A * I_B + U_B * I_A} \quad (3)$$

Voltages and currents in the equation are complex numbers representing synchrophasors of these quantities. The series line impedance R unambiguously defines the topical average line temperature.

$$T = f(R)$$
$$R_1 = R_0 * (1 + \alpha * \Delta T) \quad (4)$$

The temperature coefficient of resistance α is determined by conductor materials and will not change over time. Constant definition for aluminum is used in the following figure. The change of conductor resistance represents approximately 20% for temperature change of 50˚C.
When magnitude and change of resistance is determined, it is also possible to determine the trend of average temperature of the entire line.

CONDITIONS FOR AMPACITY MONITORING

Precision of calculated line parameters depends on precision of synchrophasor measurement. Measuring chain includes PMU devices and instrument transformers of voltage and current.
PMU devices usually measure angles with precision of 0.1˚ and amplitude with precision of 0.2% of nominal value. The Total Vector Error (TVE) can be calculated from error values and its value is usually up to 0.4%. Calibration of PMU can reduce TVE by one accuracy class.

ERROR OF VOLTAGE MEASUREMENT

Voltage Instrument Transformer (VT) mostly measure phase voltage, i.e. voltage between phase conductor and neutral node of switching substation. However, unbalanced currents of all lines and transformers in the substation flow through this node and through the ground resistance. The ground resistance usually represents a value from tenth of ohm to units of ohm.
Error of voltage difference between substations can represent tens of volts or even hundreds of volts in the extreme cases of unbalanced load. Such an error significantly affects precision of calculated impedance.

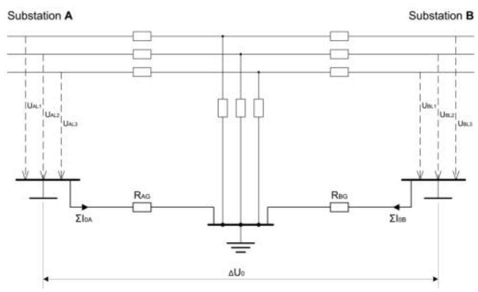

Fig. 3

At present methods for elimination of such errors are being verified.

ERROR OF CURRENT TRANSFORMERS

Maximal amplitude and angle errors of instrument transformers are defined by national standards. Errors correspond to the given accuracy class in the range of 80 to 120% of current nominal value. Errors are larger for smaller values of current.

The following figure shows examples of instrument transformer errors measured in authorized testing laboratory.

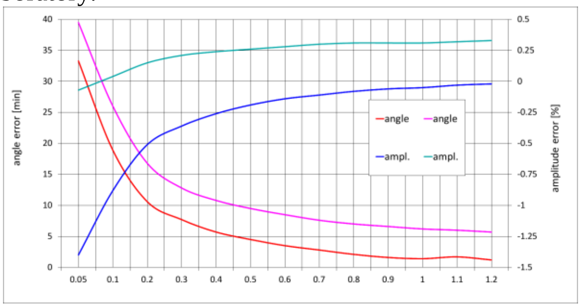

Fig. 4

Voltage is usually measured between phase and neutral conductors, i.e. in the zone about 58% of nominal value. The VT error is constant during operation, because operational voltage stays close to this value.

However, there is a different situation in the case of current transformers. Input ranges of instrument transformers are rated with reserve above the expected maximal line current. The operation line load can be in the range of 0 to 80% of maximal line current. Permanent line load of 20% of nominal current transformer value represents quite a common case. It is apparent that the correction of measurements from current transformers is necessary for synchrophasors usable for precision calculation of line resistance.

Estimation of calculation error trend in various operational conditions was used for the correction of errors. The basis for the correct estimation is long lasting measurement of voltage and current synchrophasors in both line ends. Mathematical model results from systematic measurement of error in dependency on amplitude. The following equation represents model with best results:

$$e = a + b * A + \frac{c}{d + A} \qquad (5)$$

where a, b, c, d are correction constants

A is current amplitude

MONITORING OF TEMPERATURE AND AMPACITY

The following figure shows trend of line resistance and current during the 6-hour experimental measurement in 110kV line. Voltage and current synchrophasors represent the basis of series resistance calculation with correction according to the formula (5). The figure is completed by trends of temperature and wind.

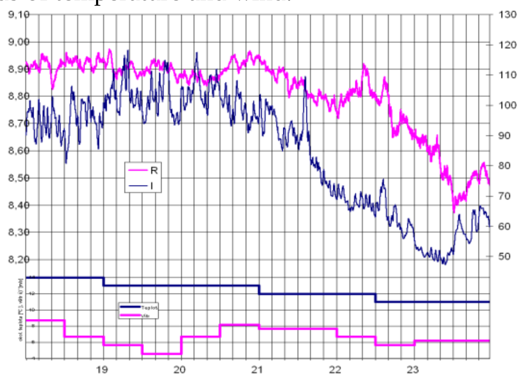

Fig. 5

The following model was suggested for analysis of dynamic temperature response

$$T \approx R = f(I, T_{okolí}, v_w) \qquad (6)$$

where v_w is wind velocity in the direction perpendicular to the line.

The influence of solar radiation was not included in the model because corresponding data was not available. Time constants and influence were evaluated separately for each variable.

The trend of resistance calculated from synchrophasors can be seen in the following figure.

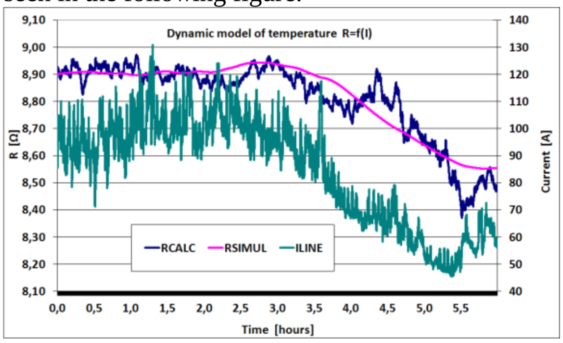

Fig. 6

Values measured in the larger range of ambient temperatures and currents are necessary for the correct setting of model. Permanent measurement of synchrophasors in several lines is being prepared at present, corresponding results will be available after data evaluation.

STATIC AMPACITY

The following figures expect limit conductor temperature $T_{max} = 80°C$.

The current magnitude that causes warming to T_{max} in the steady state is called static ampacity.

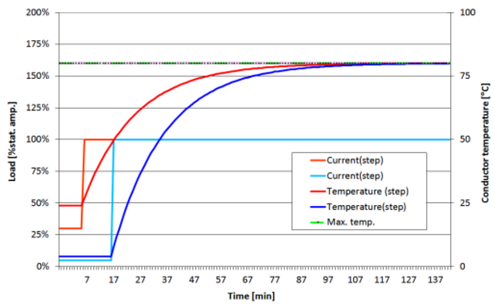

Fig. 7

There are two jumping changes of current shown in the figure. The currents begin at different values and jump to the static ampacity value. The line temperature gradually reaches the maximum limit. Time constants lie in the interval of tens of minutes. Static ampacity is calculated from ratio of limit resistance to the line resistance and from the value of current. Weather conditions were taken into consideration in the topical line temperature. It is not necessary to measure weather conditions in the case of their small changes.

Line ampacity was evaluated from the experimental measurement. Previous fixed limit is 290A, the calculated ampacity ranges is from 330 to 350A. Results can be seen in the following figure:

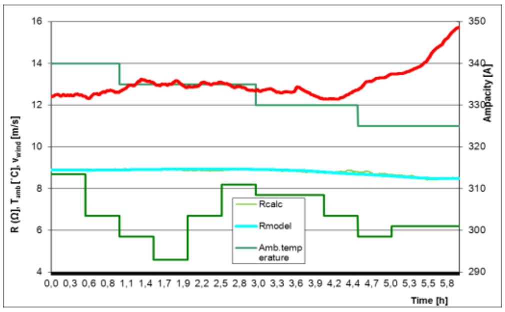

Fig. 8

DYNAMIC AMPACITY

Temperature capacity of line can be utilized for short-time line overload so that the line temperature must not exceed the permitted limit. Permitted overload time depends on initial current value and actual time constant of warming.

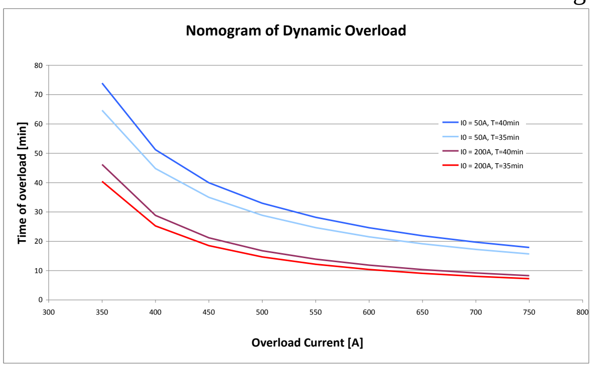

Fig. 9

Trend of line current and temperature created by model can be seen in the following figure. Short-time overload to 150% of static ampacity for 18 minutes is presented. The temperature doesn't reach the permitted limit.

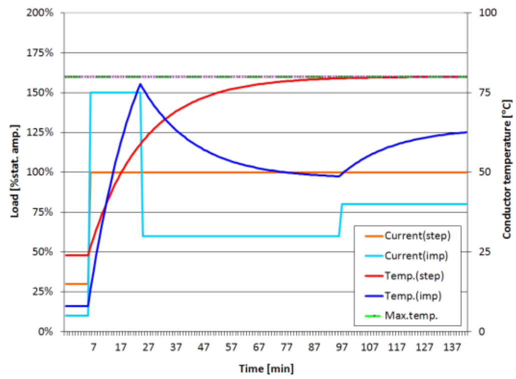

Fig. 10

SUMMARY

Wide Area Monitoring systems allow continuous evaluation of static and dynamic ampacity. The correct setting of model requires long-period measurement in the range of 0 to 100% of line load and monitoring of weather conditions. The benefits of described method:

- Direct measurement of line resistance
- On-line calculation of static ampacity.
- Evaluation of short-time line overloads usable for solution of critical situations.
- Continual supervision topical line temperature.

The above stated results have been obtained by short-time experimental measurement in 110kV network.

The measurement of synchrophasors in several 110kV lines is being prepared at the moment. Measured data will be used for further development and verification of methodology for calculation of line parameters, static and dynamic ampacity.

Research of WAMS and methods of ampacity calculation is performed within the RAD project (#FR-TI1/46) supported by Ministry of Industry and Trade of the Czech Republic.

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