The advancing assessment of power system stability using smart grid technology

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Abstract. The paper proposes new method for assessment of power system stability. New method based on advancing approach to determination of stability limits. The paper represents more accurate and reliable ways to determine limits for power transmission through the grid. Nowadays, the static stability limits formed by using special software which solves nonlinear equations of the electrical system. Power systems control power flows through the power lines for avoiding black outs by using automated control systems. Automation thresholds depend on the maximum power transmitted through the line or section, and the maximum transmitted power is calculated using the iterative methods. But the calculations in this way are not sufficiently accurate and flexible, since the calculations are done for the entire system, and not for each section individually. And it means the limits on certain sections and lines can vary. The proposed method differs from the existing one in a way it determines the limits using the angle shift between the voltage phasors in the nodes in real time. It makes possible to more deeply and adaptively manage. Also proposed new control algorithms which determines stability boundaries in advance. Algorithm was verified through experimental studies on physical model of the power system.

Keywords: Jacobian matrix, WAMS, predicting algorithm, Smart Grid, stability control.

1. Introduction

Electrical energy transmission through alternating current (AC) power lines is limited by the amount of power flows on tie. Limit is determined by the capacity of an electrical grid according to regulatory requirements by reliability assurance. Today, calculation software defines restriction by search of static stability limits of electrical power system for the worst operating conditions. This does not allow to use transfer capacity fully in a wide range of scheme and mode of grid functioning. The existing restriction on a power flow leads to derogation from optimal conditions of maintaining the grid conditions and, as a result, to decrease in economic indicators of power supply systems. The calculations are usually made for the worst scenario because while using calculation software it is impossible to define power flow restrictions in advance.

One of the solutions of this problem is the use of the principles of Smart Grid, on the basis of calculation performance on the computational model formed in a controlling circuit. Implementation of management principle in electrical power systems require the solution of the following tasks:

- supplying observability of a system in the conditions of grid at current moment. It carried out by the sufficient number of measurements, equipment placing in controlled nodes of grid and the sufficient speed of data collection and transmission.
• development of software and hardware complex, which function is using details of the phasor measurement system in real time.

For the organization of a control and management system in case of Kazakhstan’s National Electrical Grid (NEG) Smart Grid technology based synchronized phasor measurement system or Wide Area Monitoring System (WAMS) is used [1], [2]. WAMS gives the possibility not only to organize passive monitoring of power system parameters, but also to create adaptive control systems of the power supply system operating condition, to predict the dangerous conditions leading to stability violation. It is planned to use WAMS following by creation the system Wide Area Control System (WACS) for inventing adaptive control, identification and damping of low-frequency oscillations (LFO) on «North-South» transit of Kazakhstan’s NEG.

Today in China and in the countries of Europe, America use of the WAMS [3]-[5] system, on the basis of the phasor measurement unit (PMU) devices allows to carry out identification of the different operating conditions parameter fluctuations, which are relate to energy power system, such as mutual angles, frequencies, power flows through inter-area lines and identifications of LFO [6],[7],[11].

2. Stability control methods

2.1 The existing method of the stability margin calculation

The existing methods and algorithms of defining stability are based on the principles of using model out of a controlling circuit. This method excludes adaptability of management to the real grid conditions.

Today, calculation of electrical power flow limited by static stability conditions in tie, it is carried out by changing of loading in the software as RastrWIN, Digsilent, ETAP and etc. At the same time trajectories of loading representing the sequences of steady-state grid conditions which at change of some group of parameters allow reaching edge of static stability area are considered. The ways of loading are usually balanced on power where frequency remains almost invariable. According to standards [8] of power system stability, the safety factor of static (aperiodic) stability on active power in tie is determined by the following equation:

\[
K_{sf} = \frac{P_{cv} - (P + \Delta P_{noe})}{P_{cv}}
\]  

(1)

Where: 

- \( P_{cv} \) - calculated critical value of active power flow by static stability in consideration tie;
- \( P \) – operating electrical power flow in tie , \( P > 0 \);
- \( \Delta P_{noe} \) - amplifier of non-regular oscillations of active power between two area.

The value of non-regular oscillations identified for each ties according to measurements. In absence of the measurements data the value of non-regular oscillations can be calculated by the following equation:

\[
\Delta P_{noe} = K \sqrt{\frac{P_{d1} P_{d2}}{P_{d1} + P_{d2}}}
\]  

(2)

Where: \( P_{d1}, P_{d2} \) – summary demanding in each area connected by consideration tie, MW.

Coefficient \( K \), accepted - 1.5 at manual regulation and 0.75 at automatic control of output power flow in power plants.

Under the condition of power system stability, the minimum safety factor of static aperiodic stability on active power in ties are normalized. For normal grid operating condition the safety factor (minimum margin factor) is 0.2 or 20% and for post-emergency condition the minimum margin factor is 0.08 or 8% calculated by the equation (1).

At the same time the margin in 20% is defined as the maximum allowed power flow (MAPF). MAPF determined by the dispatching center of each national grid, providing admissible parameters in the different operating conditions. The margin in 8% is defined as the emergency allowed power flow (EAPF) and determined by the dispatching center for 20 minutes after black.
There are several issues of existing stability control method:

- huge amount calculations by loadings for each type of operating conditions;
- Calculations are carried out for the worst scenario that leads to the overestimated stability margin.
- at computational loading there are unaccountable factors which happen in real power system at the rate of process that affects quality of calculations;
- the grid parameters input are entered by personnel, that means there are subjective factors.

2.2 The offered stability control method

One of the solutions for the existing disadvantages of stability estimation methods is use of the control principles according to the real time measurements. With information technology development there appear new opportunities for more precisely and in real time control of the condition of an electrical power system. A perspective scope of synchronized phasor measurements is identification of model of the power supply system reflecting the main properties of grid in real time, and further application of this equivalent of a system for the analysis of its properties. Identification of an equivalent in real time allows avoid the above described disadvantages of traditional methods of the electric grid conditions monitoring. First of all, identification on the basis of accurate synchronized measurements, comprises properties of a real system unlike predetermined model. Secondly, due to identification in real time there is an opportunity to analyze the current situation, but not “the worst scenario”. Development of the ideas, will allow more precisely and in real time control of the power supply system conditions to stability limit.

For electrical grid the idea of management according to synchronized measurements is methodized by calculations of stability in the conditions of real time by means of the control unit with use of computational model. This model is formed in a controlling circuit for determination of dangerous ties in systemically important grid and capacity at adaptive reaction to changes of the scheme and the condition of an electrical power system.

In the paper the algorithm of a static stability limit predicting on the current measurements of parameters of the grid condition in real time without procedure of performance of calculations with loading for the chosen tie is offered. It will give the chance to operation personnel to take actions for prevention of loss of electrical power system stability in advance. Besides, it allows to create digital active and adaptive control system, providing and predicting of mode reliability and stability of grid.

The tasks for developing the new stability control method:

1. Justification of a static overloads forecasting method on inter-area connections with use of the adaptive grid parameters identification when loading the conditions at sets of power on tie;
2. Use of approximation methods by search of the operating condition limit;
3. Development of an identification algorithm of the operating condition limit with use of a matrix of Jacobian;
4. Formation of a Jacobian matrix according to synchronized phasor measurements in a controlling circuit;
5. Calculation of coefficients of the approximating function by the least-squares method;
6. Determination of a static stability limit and reserve in real time;
7. Development of algorithms in the WAMS software.

3. Prediction algorithm

The base of the steady-state stability prediction algorithm is the method of weighted least-squares. The balanced electric operating condition is defined as a result of minimization of the following criterion function:

\[ f = \sum_{i} r_i (z_i - z_i(u))^2 \]  

(3)
where \( n \) - number of measurements;
\( z_i \) - i value of measurement
\( \zeta_i(\hat{u}) \) - function reflecting dependence between i measurement and independent parameters – components of complex nodal voltage;
\( r_i \) - weight coefficient characterizing measurement i accuracy.

The technology of phasor measurement of the grid parameters conditions, allows to expand the list of the parameters received for estimation of a state due to accounting of voltage phases in various nodal points of power supply system. Previously such parameters were not available.

For formation of a system computational model (formation of a Jacobian matrix and calculation of determinant) it needs to determine several parameters According to the system of phasor measurements following parameters of the grid condition are identified:

- Voltage in bus of an electrical grid (\( U_1 \ldots U_n \));
- Angle \( \delta \) between phasor of voltage in buses;
- Power flows on \( P_{ij} \) lines;

Jacobian's matrix is formed in next way [9-10]:

\[
\begin{bmatrix}
\frac{\partial W_1}{\partial \delta_1} & \ldots & \frac{\partial W_1}{\partial \delta_{n-1}} \\
\frac{\partial W_1}{\partial \delta_{m-1}} & \ldots & \frac{\partial W_1}{\partial \delta_{n-1}} \\
\frac{\partial W_{m-1}}{\partial \delta_1} & \ldots & \frac{\partial W_{m-1}}{\partial \delta_{n-1}} \\
\end{bmatrix}
\]

(4)

Here the equation of the steady state grid condition (W) shown in the form of power balance:

\[
W_i = P_i - U_i^2 \sin \delta_i + \sum_{j=1}^{n} U_j Y_{ij} \sin(\delta_i - \delta_j) = 0
\]

(5)

Respectively Jacobian is called the determinant of a matrix (4)

\[
J = \begin{bmatrix}
\frac{\partial W_1}{\partial \delta_1} & \ldots & \frac{\partial W_1}{\partial \delta_{m-1}} \\
\frac{\partial W_1}{\partial \delta_{m-1}} & \ldots & \frac{\partial W_1}{\partial \delta_{m-1}} \\
\frac{\partial W_{m-1}}{\partial \delta_1} & \ldots & \frac{\partial W_{m-1}}{\partial \delta_{m-1}} \\
\end{bmatrix}
\]

(6)

Where \( U_i \) and \( \delta_i \) values come from synchronized phasor measurements data, conduction (\( Y_{ij} \)) parameters are determined by data of the equivalent circuit of the working model.

Necessary condition of static instability with use of a Jacobian matrix is transition through zero of Jacobian:

\[ J < 0 \]

(7)

For determination of the approximating function parameters, the stability indicator in the form of a Jacobian matrix determinant allows to build a certain dependence of determinant from measured variable of the mode from the generated power. This approximating surface can be used for forecasting of a static stability limit by using the condition (7) and property of continuity and concavity of a boundary surface of stability (or curve dependence of a stability indicator from parameter of independent variable).

Coefficients of the approximating function or indicator of stability in the form of Jacobian are defined by method of the least-squares.

The mean of the least-squares method when determining coefficients of the approximating function is as follows. Let set \( n \) of unknown variables, \( f_j(x_i) , \ i = 1, \ldots, m \ m > n \) - set of functions from this set of variables. The task consists in selection of such values \( x \) that values of these functions were closest to
some \( y_i \) values. In essence the specified sense of the maximum proximity of the left and right parts of a system is about the solution of the redefined system of the equations \( f_i(x) = y_i, i = 1,..., m \). Thus, the essence of the least-squares method can be expressed as follows:

\[
\sum_i e_i^2 = \sum_i (y_i - f_i(x))^2 \rightarrow \min
\]

(8)

Approximation accuracy in limits function existence, obviously, depends on quantity or the amount of measurements and also the measurements frequency. In this case approximation is carried out periodically in process of the new measurements receipt. If measurements are made for the steady state conditions, then intervals of determination of dependence remain in the same ranges that are not provided with conditions of dependence specification.

For determining of a static stability limit, maximum allowed power flow and abnormally allowable limits, according to a condition (7) for dependence of an indicator of stability from the measured parameter (power flow) needs to monitor when Jacobian passes through zero and to become negative. The found value of variable power at which the system will pass into the unstable condition is a limit of static stability. For definition of stability limit the safety factor of static stability is entered (1).

When determining of the approximating function within existence of this dependence the accuracy of approximation depends on the measurements scope. The most accurate approximation becomes at approach of a system to extreme values. As shown below at approach of a system to a limit of \( K_{SF} \) decreases and becomes less, than a standard limit in 20%.

For definition of the actual limit static stability of a system the following algorithm shown on figure 1 is used.

4 Experimental studies

The algorithm was tested in the physical model of the power supply system consisting of two generators (Figure 2 & 3) and the infinitive bus which connected with power lines (Fig 3). For experimental studies on physical model \( \text{МГ-5} \) (G1) generators and \( \text{МК-3} \) (G2) were used.

Figure 1. The control flow chart of static stability prediction in real time.

Figure 2. Generator model МГ5-1500
All calculations was given to 500 kV system parameters, to show as close as possible to real system. The limit of static aperiodic stability of the system shown in figure 4 was defined by an experiment. For definition of a limit of static aperiodic stability the operating condition was made heavier by increase in power of generation on the G1 generator.

### Figure 3. Generator model MK3-1500

### Figure 4. Three-phase element of the power line model

### Figure 5. Equivalent circuit of model

### Table 1. Parameters of synchronous generators

| # | Symbol | Parameter                  | Generator MK-3 | Generator МГ-5 |
|---|--------|----------------------------|----------------|----------------|
| 1 | S      | Apparent power [kVA]      | 3              | 5              |
| 2 | P      | Active power [kW]         | -              | 4              |
| 3 | $U_r$  | Rated voltage [V]         | 230            | 230            |
| 4 | $I_r$  | Rated current [A]         | 7,52           | 12,6           |
| 5 | $\cos\phi$ | Power coefficient | 0              | 0,8            |
| 6 | n      | Rated rotation [rot/min]  | 1500           | 1500           |
| 7 | $i_{foc}$ | Excitation current o.c. U=U_r [A] | 0,56          | 0,88           |
| 8 | $i_{fsc}$ | Excitation current s.c. I=I_r [A] | 0,4           |                |
| 9 | $x_p$  | Peltier reactive impedance [r.u] | 0,02          | 0,07           |
| x_d | d axis reactance [r.u.] | 1.24 | 1.17 |
|-----|------------------------|------|------|
| x_q | q axis reactance [r.u.] | 0.66 | 1.04 |
| x_2 | Negative sequence reactance [r.u.] | 0.07 | 0.06 |
| x_0 | Zero sequence reactance [r.u.] | 0.02 | 0.03 |
| x_d | d axis transient reactance [r.u.] | 0.17 | 0.14 |
| x_d | d axis sub-transient reactance [r.u.] | 0.07 | 0.08 |
| x_q | q axis sub-transient reactance [r.u.] | 0.09 |
| T_d0 | Time constant of excitation circuit for open stator circuit [s] | 2.8 | 1.56 |
| T_d | Time constant of transient component of stator current [s] | 0.39 | 0.09 |
| T_d | Time constant of sub-transient component of stator current [s] | 0.01 |
| r_0 | Resistance of stator [ohm] | 0.08 | 0.07 |
| GD^2 | Centrifugal moment of machine without disk [kg·m^2] | 2.44 | 8.92 |
| GD^2 | Centrifugal moment of machine with disk [kg·m^2] | 25.7 |
| T_jmin | Time constant of machine without disk [s] | 5.0 | 10.9 |
| T_jmax | Time constant of machine with disk [s] | 31.5 |

**Table 2. Parameters of line model**

| Parameter | Line 1 | Line 2 | Line 3 |
|-----------|--------|--------|--------|
| X_a [ohm] | 18.73  | 16.2   | 16.32  |
| X_b [ohm] | 17.56  | 16.2   | 16.00  |
| X_c [ohm] | 18.13  | 16.17  | 16.20  |
| C_bc [µF] | 8.0    | 8.61   | 8.12   |
| C_ac [µF] | 8.16   | 8.61   | 7.96   |
| C_ab [µF] | 8.16   | 8.45   | 8.04   |
| C_ag [µF] | 4.00   | 4.03   | 4.06   |
| C_bg [µF] | 4.08   | 4.03   | 3.98   |
| C_eg [µF] | 4.08   | 4.02   | 4.03   |
| R_a [ohm] | 1.87   | 1.62   | 1.63   |
| R_b [ohm] | 1.76   | 1.62   | 1.6    |
| R_c [ohm] | 1.81   | 1.62   | 1.62   |

Increasing the power of generation on the G1 generator, three Jacobian values for each step of loading (table 3) were calculated.

**Table 3. Increasing power in 3 step**

| Power flow, [MW] | Jacobian determinant value, [r.u.] |
|------------------|-----------------------------------|
| 276              | 1.04                              |
| 793              | 0.88                              |
| 899              | 0.61                              |

Increasing the power of generation on the G1 generator, three Jacobian values for each step of loading (table 3) were calculated.
Jacobian values was taken concerning the condition at which there will be a theoretical maximum (U1=Ur=500 kV, U2=Ur=500 kV, U3=Ur=500 kV, δU1- δU2=0º, δU3- δU2=0º, δU3- δU4=0º).

On these three points linear approximation (figure 6) was made, and the predicted point of transition of Jacobian through zero was found. Power at which Jacobian crossed zero corresponds to a limit on static aperiodic stability:

\[ P_{pf} = 2100 MW \]

\[ K_{sf} = 52\% > 20\% \]

![Figure 6. Approximation of Jacobian values by three calculations](image)

As safety factor more than 20% the loading proceeded. At the following stage Jacobian calculated for 6 loadings (table 4).

| Power flow, MW | Jacobian determinant value, [r.u.] |
|---------------|-----------------------------------|
| 276           | 1.04                              |
| 793           | 0.88                              |
| 899           | 0.61                              |
| 1114          | 0.55                              |
| 1196          | 0.39                              |
| 1298          | 0.36                              |

After approximations of data (figure 7) predicted limit was received:

\[ P_{pf} = 1842 MW \]

\[ K_{sf} = 24\% > 20\% \]

![Figure 7. Approximation of Jacobian values by six calculations](image)

Safety factor equals 24%, the limit was not reach. Further the system continued to loading. Jacobian was calculated for additional two values of the power (table 5).
| Power flow, [MW] | Jacobian determinant value, [r.u.] |
|-----------------|-----------------------------------|
| 276             | 1.04                              |
| 793             | 0.88                              |
| 899             | 0.61                              |
| 1114            | 0.55                              |
| 1196            | 0.39                              |
| 1298            | 0.36                              |
| 1402            | 0.23                              |
| 1446            | 0.22                              |

Approximation of these values (figure 8) showed that the predicted limit is:

\[ P_{PF} = 1771 \text{MW} \]

\[ K_{SF} = 13\% < 20\% \]

**Figure 8.** Approximation of Jacobian values by eight calculations

Safety factor shall be under control and monitored. And in cases when safety factor decreases until 20% appropriate actions shall be taken to keep stable condition.

**5. Conclusions**

Nowadays, in order to identify the conditions of stability violation, numerous variant calculations of normal and abnormal grid modes are performed. In practice, when performing calculations, the conditions for violation of static stability are determined by the limiting values of power flows over controlled tie. This method of monitoring stability by the observed parameters of the mode is the simplest and most feasible in connection with the ability to measure the value of power flows. However, the use of this method has several disadvantages:

- ambiguity of stability control by indirect parameters of the mode, by power flows;
- inability to maximize the use of bandwidth in connection with the calculation of limit modes for the most severe grid conditions;
- to control the maximum load of the cross-section for the transmitted power between the nodes, the automation devices (Automatic Power Loose) must be installed on all power lines included in this section;
- the automation devices settings are dependent on the grid circuit; in post-emergency (or repair) schemes with shutdowns of sections of parallel overhead transmission lines in transit, it becomes necessary to change the settings.

Today with development of IT technologies, and integration it to the power system controls new opportunities are appearing. Proposed method for predictive determination of stability limits can reduce the issues above. By using WAMS system it is possible to solve problems of power transmission adaptively in real time.
The expected results of an adaptive control system development are:

- Predicting of static stability limit with using the approximating function;
- Identification dangerous power surge according to phasor measurements;
- Maximum using of transmission capacity;
- Development of control system for dangerous overload values;
- Development of the dispatcher adviser with using WAMS technologies.

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