Journal of Engineering Science and Technology Review
Special Issue on Telecommunications, Informatics, Energy and Management 2019

Conference Article

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

The Advancing Assessment of Power System Stability Using Synchronized Phasor Measurements

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Received 22 September 2019; Accepted 19 February 2020

Abstract

The article presents the advancing assessment method of power system stability and increasing power flow on transmission lines. Electrical energy transmission through power lines of alternating current is limited by the amount of power flows on tie. Limit is determined by the capacity of an electrical network according to regulatory requirements by reliability assurance. Today, calculation programs define margin by search of static stability limits for the worst operating condition scenario. The existing margin on a power flow leads to deviation from an optimal condition of maintaining and, as a result, to decrease in economic indicators of power transmission systems. One of the solutions of this problem is the using the adaptive control method, on the basis of calculation on the design model formed in a controlling circuit. For forecasting of a static stability limit the approximating dependence of the Jacobian matrix determinant is used. Formation of the Jacobian matrix is carried out according to the synchronized phasor measurements data obtained from the WAMS. It makes possible to adapt the prediction of the static stability limit in real time. Approximating dependence is formed from the measurement data continuously and at each measurement the limit and static stability reserve are predicted. With a decrease in the stability reserve below the predetermined value, the conditions for the hazard of breaking static stability are formed. This makes it possible to perform an advanced assessment of power system stability and increasing power flow on tie.
For implementation the presented adaptive control method requires the supplying monitoring of grid condition and creating the software of static stability limit forecasting with hardware complex, which functions in real time using data of the phasor measurement system.

Keywords: stability control, prediction algorithm, Jacobian matrix, phasor measurements.

1. Introduction

Electrical energy transmission through power lines of alternating current is limited by the amount of power flows on tie. Limit is determined by the capacity of an electrical network according to regulatory requirements by reliability assurance. Today, calculation programs define 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 regime area of network functioning.

One of the solutions of this problem is the use of the principles of adaptive control, on the basis of calculation performance on the settlement calculating model formed in a controlling circuit.
Implementation of management principle in electrical power systems requires the solution of the following tasks:

- Supplying observability of a system in the conditions of network of current moment. It carried out by the sufficient number of measurement, equipment placing in controlled nodes of network and the sufficient speed of data collection and transmission.
- Creating the software and hardware complex, which functions in real time using details of the phasor measurement system.

For the organization of a control and management system for a condition of Kazakhstan's National Electrical Network (NEN) use Smart Grid technology basis on a synchronized phasor measurement system of WAMS (Wide Area Monitoring System) [1,2,3]. WAMS gives the chance 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's planned to use WAMS following by creation the system WACS (Wide Area Control System) for inventing adaptive control, identification and damping of low-frequency oscillations (LFO) on «North-South» transit of Kazakhstan's NEN.

Today in China and in the countries of Europe, America use of the WAMS [4-7] system, on the basis of the phasor

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ISSN: 1791-2377

measurement units (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 [8-10].

2. Material and method

2.1. Stability control methods

2.1.1 The existing method of the stability margin calculation

The existing defining stability methods and algorithms 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, is carried out by growth of loading in the PowerFactoryDigSilsent and RastrWin programs. At the same time trajectories of loading representing the sequences of steady-states grid conditions which at change of some group of parameters allow to reach boarder of static stability area are considered. The ways of loading are usually balanced on power where frequency remains almost invariable.

According to Standard of power system stability, the safety factor of static (aperiodic) stability on active power in tie is determined by the following equation:

$$К_{SF} = \frac{P_{cv} - (P + \Delta P_{nro})}{P_{cv}} \quad (1)$$

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.
ΔP_{nro}- amplifier of non-regular oscillations of active power between two area.

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).

2.1.2 The offered stability control method

One of the solution in the existing disadvantages of stability estimation methods is use of the control principles according to the real time measurements. With information technology development opportunities appear more precisely and in real time to control a 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 to leave from the above described disadvantages of traditional methods of the electric grid conditions monitoring. First of all, identification on the basis of exact 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”. Realization of the ideas, will allow more precisely and in real time to control proximity of the power supply system conditions to stability limit.

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

The offered control system and forecasting of static stability limits with use of the phasor measurements given systems supports group of PMU devices, operational memory devices, group of digital sensors, the block of collecting and data transmission, the block of assessment of a condition of an electrical power system and also consistently connected blocks of definition of the limit conditions, the block of determination of dangerous ties and the block of definition of the maximum allowed power flows.

In the paper the algorithm of a static stability limit forecasting 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 in advance to take measures for prevention of loss of an electrical power system stability. Besides, it allows to create digital active and adaptive control systems, providing and forecasting of regime reliability and stability of grid.

For a static aperiodic stability limit forecasting the property of a matrix Jacobian determinant is used. In the steady operating condition, the determinant has the positive sign, and at loss of stability passes through zero and becomes negative.

2.2 Prediction algorithm

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

$$f = \sum_{i=1}^{n} r_i \cdot [z_i - \bar{z}_i(\dot{u})]^2 \quad (2)$$

where n-number of measurements;
z_i - i value of measurement;
$\bar{z}_i(\dot{u})$is the function reflecting dependence between i measurement and independent parameters – components of complex nodal voltage;
r_i - the weight coefficient characterizing measurement i accuracy.

At the solution of the tasks connected with calculations of the electric conditions as independent parameters modules and phases of voltage are used, as a rule. 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. Earlier given parameter was not available.

For formation of a system settlement model (formation of a Jacobian matrix and calculation of determinant) using the operating condition estimates given the block, forms settlement model of network and Jacobian matrix. According to the system of phasor measurements parameters of the network condition are read out:

1. Voltage in bus of an electrical network ($V_1 \dots V_n$);

2. Angle δ between phasor of voltage in buses;
3. Power flows on Pij lines.

Jacobian's matrix is formed in the form of [11]:

$$\frac{\partial W}{\partial \delta} = \begin{bmatrix} \frac{\partial w_1}{\partial \delta_1} & \cdots & \frac{\partial w_1}{\partial \delta_{m-1}} \\ \cdots & \cdots & \cdots \\ \frac{\partial w_{m-1}}{\partial \delta_1} & \cdots & \frac{\partial w_{m-1}}{\partial \delta_{m-1}} \end{bmatrix} \quad (3)$$

Here the equation of the steady state grid condition (W) in the form of capacities balance is leveled:

$$W_i = P_i - U_i^2 Y_i sin\delta_i + \sum_{\substack{j=1 \\ j\neq i}}^{m} U_i U_j Y_{ij} \sin(\delta_i - \delta_j) = 0 \quad (4)$$

Respectively Jacobian is called the determinant of a matrix (3)

$$J = \begin{vmatrix} \frac{\partial w_1}{\partial \delta_1} & \cdots & \frac{\partial w_1}{\partial \delta_{m-1}} \\ \cdots & \cdots & \cdots \\ \frac{\partial w_{m-1}}{\partial \delta_1} & \cdots & \frac{\partial w_{m-1}}{\partial \delta_{m-1}} \end{vmatrix} \quad (5)$$

where Ui and δi values get out of synchronized phasor measurements data, conduction (Yij) 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:

$$J<0 \quad (6)$$

For determination of the approximating function parameters, the stability indicator in the form of a Jacobian matrix determinant allows to construct a certain dependence of determinant on measured by change of the condition, for example from the generation power. This approximating surface can be used for forecasting of a static stability limit if to use to conditions (6) and property of continuity and concavity of a boundary surface of stability (or curve dependence of a stability indicator on parameter independent change).

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

The essence of the least-squares method when determining coefficients of the approximating function is as follows. Let - set n of unknown variables, $f_i(x)$, $i = 1, \dots, mm > n$ -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 $f_i(x) = y_i$, $= 1, \dots, m$.Thus, the essence of the least-squares method can be expressed as follows:

$$\sum_i e_i^2 = \sum_i (y_i - f_i(x))^2 \to min_x \quad (7)$$

Approximation accuracy in limits function existence, obviously, depends on quantity or the measurements scope 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 definition of a static stability limit, the maximum allowed power flows and abnormally allowable limits, according to a condition (6) for dependence of an indicator of stability on the measured parameter there is a value the measured change at which 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 (formula 1).

When determining of the approximating function within existence of this dependence the accuracy of approximation depends on the measurements scope. The most exact 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%.

3. Results and discussion

Experimental studies

The algorithm was tested in the physical model of the power supply system consisting of two generators and the infinitive bus which connected with by power lines. For experimental studies on physical model MG-5 (G1) generators and MK-3 (G2) are used.

The limit of static aperiodic stability of the system shown in figure 1 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.

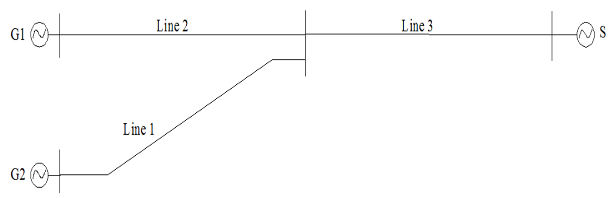

Fig 1. Equivalent circuit of model

Increasing the power of generation on the G1 generator, eight Jacobian values for each step of loading (table 1) were calculated.

Table1. Jacobian values

P, MW	J, 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

Jacobian values are taken concerning the condition at which there will be a theoretical maximum (U_1=U_r=500 kV, U_2=U_r=500 kV, U_3=U_r=500 kV, δ_{U1}- δ_{U2}=0º, δ_{U3}- δ_{U2}=0º, δ_{U3}- δ_{U4}=0º).

On these eight points linear approximation (figure 2) was made, and the predicted point of transition of Jacobian through zero was found. Power at which Jacobian is leveled zero corresponds to a limit on static periodic stability:

$$P_{PF} = 1771\ MW$$

$$k_{SF} = 13\% < 20\%$$

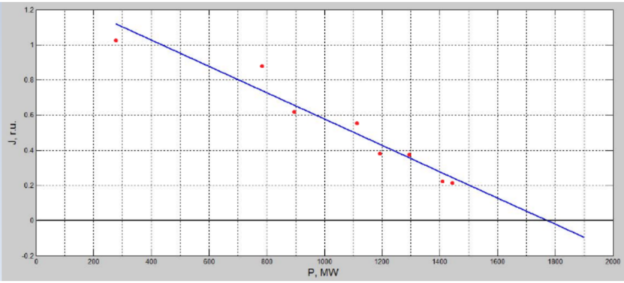

Fig 2. Approximation of Jacobian values by eight calculations

When safety factor becomes less than 20%, it is necessary to take operations for damping oscillations and prevention of stability loss.

4. Conclusions

At operation of power grid in real time, the most relevant are points of using the principles and algorithms of adaptive assessment, control and forecasting of operating conditions reliability indicators. In addition, the important point is identification of a system approach conditions to stability limit before unsteady moment with using the phasor measurements system.

Weaknesses of the existing static stability assessment methods of the steady state operating condition the based on calculations of iterative process of balance search in nodes do not provide sufficient conditions and a guarantee of a necessary stability limit search.

Alternative technique of the operating conditions limit search is the method of static stability limits forecasting offered in article with using the approximating dependence of static stability criterion on controlled parameters of the grid condition.

The expected results of an adaptive control system realization are:

• The static stability limit forecasting with using the approximating function;
• Identification dangerous power surge according to phasor measurements;
• Maximum using of transmission capacity;
• Creation of dangerous overload values digital control system;
• Creation of the dispatcher adviser with using WACS technologies.

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