Inputing of electric regime into permissible region in PS security problem

Vladislav P. Oboskalov
Ural Federal University;
ITP of the Ural Branch of the Russian Academy of Science
Yekaterinburg, Russia
e-mail: v.p.oboskalov@urfu.ru

Sergey A. Gusev
Ural Federal University
Yekaterinburg, Russia
email: sergeyalexgusev@gmail.com

Danil A. Ignatiev
Ural Federal University
Yekaterinburg, Russia
email: danil.ignatiev.off@mail.ru>

Irina L. Kirpikova
Ural Federal University
Yekaterinburg, Russia
email: i.l.kirpikova@urfu.ru

Abstract — **Procedures of control actions selection are considered for the purpose of state parameters adjustment to the feasible region. The calculation procedure is divided into two stages – steady state calculation (equality constraints) and state adjustment to the feasible region (inequality constraints).**

Keywords — power systems; security; reliability indices; state adjustment to the feasible region.

I.   INTRODUCTION

The aim of a power system (PS) control is the provision of its reliable operation. Depending on the accepted system of constraints and assumptions, the integral assessment of failure-free operation can be split into three types: structural reliability, adequacy, security. The relatively large number of studies, mentioned in [1-5], were devoted to the first two types of reliability. The problems that were somewhat less covered are ones of security, which comprises post-fault state analysis and selection of optimal control actions (CA) intended for the fullest possible power supply of consumers [3-9].

Largely, it is explained, first, by high complexity and huge time costs of limit and off-limit states calculations, which are typical for simultaneous outage of several PS elements. Secondly, it is explained by the judgement that states, related to outages of two and more PS elements outages, are so improbable, that its analysis makes no sense. Hence, the criteria «n-1», «n-2» [4, 10] are brought to the foreground, with security analysis results in the browsing of the most significant contingency states of a PS [7,9].

 The limitation for number of simultaneous PS elements outages allows taking into account transients and actions of a system automatic control to a fuller extent. As a result, the analysis of PS security is developed in two directions – the static security and the dynamic one [4, 5, 11]. In first case, there is the assumption, concerning ideal system automatic control and instant appropriate reaction of a PS to received CA. In second case, the focus of automatic control actions

(including probabilistic) is taken into account to a fuller extent [6,8] (the second direction is closer to the PS survivability analysis to a certain extent [12]). Consequently, the static security is focused more on solution of the prospective development problems, while the dynamic security is used for solution of the operation control problems [11].

Large blackouts, which occurred in 1970-1980s and recent years, have shown that multiple outages (more than two) are significant. Since the maximally significant depth of PS elements outages is a priori unknown, then, in calculations of static security indices, one should orientate to the analysis of systems with all possible outages combinations ("n-n" criteria). Moreover, the existing methods and algorithms of real PS security analysis do not provide "n-n" criteria calculations. Probably, this is not necessary, because significance of multiple outages in the resultant security indices drastically decreases as far as the number of simultaneous outages grows. Hence, software is to ensure the possibility of the significance verification, with exclusion of redundant calculations. However, the full variety of outages combinations should be a landmark. It allows suggesting necessity of further researches in the field of a PS security. In this study, the research object is the static PS security and its focus on the "n-n" criteria provision.

In security calculations, each random state of a PS is checked for the state feasibility. State is considered feasible, when Ohm's and Kirchhoff's laws hold true, as well as all operational state constraints, which are conditionally divided to bus and branch ones (dynamic constraints are distinctive for the dynamic security).

Bus constraints are related to grid buses. Most often they include minimal and maximal voltage amplitude constraints V_i, along with constraints on variation limits of active P_i and reactive Q_i power, for both generation and load (the class of control variables), in case of the possible additional constraint – inalterability of the power factor, $tg\varphi_i = P_{L,i}/Q_{L,i} = const$.

Branch constraints comprise power flow constraints by the conditions of thermal withstand and static stability:

$$|I_l| \leq I_l^{max}; \quad |P_l| \leq P_l^{max},$$

where I_l, P_l – current and power flow of branch $l = 1,\ldots,m$. respectively.

The main security indices (SI) include probability q_Σ and flow rate of power supply limitations, connected with the necessity of keeping a system state in the tolerance range (TR); expected values (EV) of the energy are not served (ENS), M(ΔE) and respective damage M(D) (costs of a consumers damage compensation [4] due to power undersupply ΔE). Besides, the calculation of a quite large number of additional indicative factors (probabilities or rates of static stability disturbances, non-convergences, cascading outages, system islanding, etc.) is carried out.

Generally, reference data or redefined rated characteristics for the object under consideration, as well as data concerning failure rate of a grid elements, are initial data. Typically, the failure rate data include failure flow ω, and EV of recovery time, τ, which allow one to determine the probability of the element failure q=$\omega\tau$. Elements failures are considered to be independent events in the static security estimation. Due to small probability of events, connected with the emergency failure of a PS elements:

$$q_\Sigma = \sum_{A_i \in S} q_i; \quad \omega_\Sigma = \sum_{A_i \in S} \omega_i;$$

$$M(\Delta\Theta) = \sum_{A_i \in S} q_i \Delta P_i \tau_i; M(\Delta Y) = \sum_{A_i \in S} q_i \Delta Y_i,$$

where q_i– probability of an event occurrence; S – multitude of those system states, where CA are related to constraint ΔP_i of power supply for the system recovery time τ_i; ΔY_i – respective costs of damage compensation to consumers in case of the A_i occurrence.

In its turn, the SIs of a complex event (simultaneous failure of several elements) are defined through the formulae of independent events probability:

$$q_i = \prod_{j \in A_i} q_j; \quad \mu_i = \sum_{j \in A_i} \mu_j; \quad \tau_i = 1/\mu_i$$

where μ_j – recovery rate of element j.

Hence, all CA, connected with the introduction of electric modes in the admissible domain, are to be defined in order to determine resultant SIs.

II. STATE ADJUSTMENT TO THE FEASIBLE REGION IN THE SECURITY PROBLEM

The identification of a failure, related to the state parameters alterations from maximum permissible ones, is one of the main problems, emerging in the security assessment. Further follows the necessity of CAs determination in the conditions of constrained and non-existing states in case of the simultaneous PS elements failure. Presence of losses and complex functional

relationship of buses voltages with power makes the task of CA selection nonlinear. A CA optimality is generally connected with its implementation costs. Therefore, nonlinear programming methods are more suitable for the security analysis.

The problem of CA selection calculation in its classical form can be presented as the optimization model:

$$\min F(x, y, u) \tag{1}$$

$$g(x, y, u) = 0; \tag{2}$$

$$h(x, y, u) \leq 0; \tag{3}$$

where $F(x, y, u)$ – objective function (OF), for example, the cumulative damage from the energy-not-served; (x, y, u) – vectors of dependent, independent and control variables.

Voltages amplitude and angles, amplitudes of branch currents and power flows are taken as the dependent variables, $x = \{V_i, \delta_i, |I_s|, |P_s|\}$; bus reactive and active power are taken as the independent variables, $y = \{P, Q\}$; generation and load power alterations in buses are taken as the control variables $u = \{ДP, ДQ\}$.

Equality constraints (2) are presented as node voltage equations (NVE) in one form or another [14]. Inequalities (3) define bus and branch state constraints determine nodal and linear security restrictions. They basically include voltage, current and power flow amplitude constraints, also simple constraints regarding load and generation power in grid.

As a result of solving task (1) – (3) optimal Cas $u_{opt} = \{ДP_i, ДQ_i\}$, and state parameters vector x, complying with the system of constraints (2), (3) are calculated. Non-zero CAs are used in the resultant Sis calculation

The real grid calculation practice by means of the mathematical model (1) – (3) shows that use of standard nonlinear programming solvers (for instance, «fmincon» in the MatLab) requires unacceptably high, in the framework of PS security assessment, time costs, nonlinear dependent on the varying variables vector, $z = \{x, u\}$, which is indicative for a large scale PS.

It is necessary for the OF to be quadratic, and for constraints to be linear, in order to significantly reduce calculation time. In addition, the problem (1) – (3) is written in the following form:

$$\min_z \left\{ F(z) = \frac{1}{2} z^t \mathbf{H} z + v^t z \right\} \tag{4}$$

$$\mathbf{A}z = \mathbf{B}; \quad \mathbf{C}z \leq \mathbf{D}. \tag{5}$$

where $\mathbf{H}, v$ – quadratic form parameters; in the iteration calculations process matrices A,C and vectors $\mathbf{B}, \mathbf{D}$ are defined by means of constraints (2), (3) linearization in the point $z^{(k)} = \{x^{(k)}, u^{(k)}\}$ for the variables {x,u}.

One approach of speeding up calculations is the decomposition of the state adjustment problem with division of the calculation procedure into two relatively independent stages – solving a system of non-linear steady state equations (SSE) and choosing the optimal CA [13]. The second stage, in its turn, can represent a sequential set of independent calculation procedures.

Problem decomposition to two stages requires the stepwise solution refinement organization of an iteration process. The SSE $g\left(x^{(k+1)}, y^{(k)}\right) = 0$ calculation is carried out at each iteration k of solving the optimization problem (1) for the fixed CA vector at hand $\left(u^{(k)}, u^{(0)} = 0\right)$. The obtained values of state parameters $x^{(k+1)}$ may not satisfy constraints (3). CA $u^{(k+1)}$, $y^{(k+1)} = y^{(k)} + u^{(k+1)}$ are required for the vector x to enter the feasible region $h\left(x^{(k+1)}, y^{(k+1)}\right) \le 0$. The iteration process of the $x^{(k+1)}$ correction is finished when the iteration process of vector x calculation is converged and its location is in the feasible region. This procedure can be described by the following algorithm:

1. Steady state calculation.
2. If there is a convergence, then move to the p.4.
3. Do state parameters belong to the feasible region? If yes, then move to the p.5.
4. The CA selection in order to move a state point to the feasible region. Move to the p.1.
5. The procedure is over.

The suggested algorithm is equivalent to the Gauss-Zeidel method, where groups of variables are alternately varied. The calculations speeding-up is expected due to the reduction of varying variables vector dimension – only the vector x is being varied at the first stage, and only the vector u – at the second stage. In addition, the second stage may not be required for a relatively large number of states related to grid elements failure, if all state parameters are in the feasible region.

The suggested decomposition of the calculation procedure is physically substantiated – CAs are accepted or not depending on the values of bus voltages and branch currents.

Additionally, decomposition allows one to either simplify OF - only the OF component part that depends on the varying variables is considered at each stage – or to completely change the mathematical model. In particular, at the first stage, the problem can come down to the solving of nonlinear equations system $g(x, y) = 0$ with the possibility to apply quite a large number of specific software packages (RastrWin3 [16], MatPower [17] etc.). And the second one, – OF can be presented in the linear or quadratic form, making the CA selection problem under consideration of linear or quadratic programming.

Among other things, if active and reactive components of load power, $u = (\Delta P, \Delta Q)$, which are of great interest in the security assessment, are considered as CAs, then cumulative costs of energy-not-served damage compensation are generally accepted as the OF:

$$F(\Delta P) = \sum Y_i = \sum y_i(\Delta P_i) \cdot \Delta P_i, \qquad (9)$$

where $y_i(\Delta P_i)$ – per unit damage of a consumer i with the power supply limitation to the value ΔP_i. If the per unit damage curve $y_i\left(\Delta P_i\right) = \beta_i + \alpha_i\left(\Delta P_i / P_{\text{н},i}\right)$ is linear, then the OF (9) have a quadratic form:

$$F(\text{ДР}) = \sum_{i \in L}\left(\beta_i + \alpha_i \frac{\Delta P_i}{P_{\text{н},i}}\right)\Delta P_i = \text{ДР}^t\text{НДР} + \text{в}^t\text{ДР}, \qquad (7)$$

where $\mathbf{H}$ – diagonal matrix $\mathbf{H} = diag\left(\alpha_i / P_{\text{н},i}\right)$.

Often, in the practice of SI calculation, the assumption concerning constancy of per unit damage, $\alpha_i = 0$ is used, which makes the OF linear, $F(\Delta P) = \text{в}^T\Delta P$ with more efficient (time-wise) linear programming solvers being able to be used as the main mathematical tool.

It was previously mentioned that a set of control variables comprises quite a wide range of state parameters, which can be divided into three classes, implemented in the hierarchical order:

- conditionally not connected with any costs (tap ratio changing, switching on and switching off reactors or static compensation banks, switching commutations in a grid, etc.);

- reallocation of generation power, which can be a result of the additional re-optimization task of parallel unit power allocation with the costs, connected with transition to the new state;

- partial or complete load shedding with relatively huge costs of energy-not-served damage compensation.

The presented CA types are implemented by means of algorithms with different OFs. In particular, the tap ratio alteration is carried out automatically in case of inacceptable voltage alteration at the transformer secondary winding, and solution of the second class CA task can be carried out by using efficient specialized software packages («MatPower» [17] etc.). The third CA class can be united with the second one. However, a large number of additional variables (dispatchable load) result in a sharp increase of calculations time. Hence, this CA class requires its own specific software.

As a result, p.4 in the mentioned above algorithm is to be split into three steps of CA selection according to its class. Moreover, the next step is performed if CAs of the previous step are insufficient.

In the security problem, specificity of the steady state calculation lies in the fact that this calculation is carried out along with CA selection, which include generation and load power alterations. Therefore, the prevailing form of presentation is the node voltage equations in the power balance form with calculation procedures based on the Newton-Raphson's method [15].

III. INEQUALITY CONSTRAINTS.

In the iteration cycle "SS calculation – CA selection", the CAs are chosen for the purpose of satisfying inequality constraints, which can be violated with the new vector $x^{(k+1)} = x\left(y^{(k)}\right)$, satisfying the following equality constraints system at the "SS calculation" stage:

$$h\left(x^{(k+1)}, y^{(k)}, u\right) = h\left(x^{(k)}, y^{(k)}, u\right) + \Delta h\left(x^{(k+1)}, y^{(k)}, u\right) > 0.$$

Consequently CA can be directed to less as meeting conditions (3) than as a compensation of broken constraints values. And the new vector of independent variables is changed to the CA value:

$$y^{(k+1)} = y^{(k)} + u.$$

The main function of an OF is to move parameters, forming the independent variables vector $x = \{V, \partial\}$ in the feasible region, i.e. to obtain inequality:

$$h\left(x^{(k+1)} + \Delta x\left(u^{(k+1)}\right), y^{(k+1)}\right) \leq 0.$$

If the amplitude and angles of voltages are considered as the dependent variables, then CA $u = \{\Delta P_i, \Delta Q_i\}$ lead to alterations $\Delta \partial(u); \Delta V(u)$. Hence, in case of linear approximation $h(x, y)$ at the point $\left(x^{(k)}, y^{(k)}\right)$:

$$h(x, y) = h\left(x^{(k)}, y^{(k)}\right) + \frac{\partial h}{\partial \delta}\Delta\delta + \frac{\partial h}{\partial V}\Delta V + \frac{\partial h}{\partial P}\Delta P + \frac{\partial h}{\partial Q}\Delta Q \leq 0.$$

With certain assumptions, this expression is additive parameter-wise – one part of the constraints is determined by the voltages amplitudes alteration (initially ΔQ), and the other part – by the angles alteration (branch power flows, ΔP).

First CA class. Such CA as alteration of tap ratios or grid elements parameters result in re-calculation of the admittance matrix and they are defined through combinatorial mathematics methods. However, taking into account real physical properties of a grid generally allows one to construct CA hierarchy and to obtain solution using the method of sequential CA implementation. Indeed, it is appropriate to change tap ratios in direction from supply centers to load buses. Firstly, it allows one to limit the number of transformers with controllable tap ratios, and, secondly, to exclude oscillatory nature of the parameter adjustment process.

For the second CA class, it is appropriate to use specialized software (optimal power flow). Voltage constraint is one of many forming feasible regions.

The third CA class is characterized by the supply limitation. It is connected not only with an active power reduction, but also with a proportional reactive power reduction. Therefore, less active $\{\Delta P_i\}$ than reactive $ДQ_i = ДP_i tg(\varphi_i)$, power alteration is to be considered. In

addition, as a rule, the assumption is made regarding constancy of power factor $\{tg(\varphi_i) = Q_{L,i} / P_{L,i} = \text{const}\}$. OF (10), representing costs of energy-not-served damage compensation, can be presented in a quadratic form, expressed through the $ДQ_i$ CAs, which are the basic in the voltage control.

The second step (CA selection) is based on the estimation of the state parameters alterations $x = \{V, \partial\}$ in varying CA $\{ДP, ДQ\}$. The Linear approximation (6) of NVE, defining equality constraints, can be used in order to reveal interconnection of the dependent (x) and control (u) variables.

IV. DOMINANCE CONSTRAINTS METHOD

One of the most significant state constraints is that of voltage amplitudes, which can be represented in the following linearized form:

$$\mathbf{V}^{(k+1)} - \mathbf{V}_{\max} \leq \mathbf{J}_{QV}^{-1}Д\mathbf{Q}^{(k+1)} \leq \mathbf{V}^{(k+1)} - \mathbf{V}_{\min}. \tag{8}$$

where $\mathbf{J}_{QV}$ – Jacobian matrix.

$$\mathbf{J} = \begin{pmatrix} \mathbf{J}_{P\delta} & \mathbf{J}_{PV} \\ \mathbf{J}_{Q\delta} & \mathbf{J}_{QV} \end{pmatrix} = \begin{pmatrix} \dfrac{\partial \varphi}{\partial \delta} & \dfrac{\partial \varphi}{\partial V} \\ \dfrac{\partial \psi}{\partial \delta} & \dfrac{\partial \psi}{\partial V} \end{pmatrix}$$

for NVE in the power balance form:

$$\varphi(V, \partial) = \text{Re}\left(diag\left(\mathbf{U}^*\right)\mathbf{Y}\mathbf{U}\right) = P + ДP;$$
$$\psi(\mathbf{V}, д) = \text{Im}\left(diag\left(\mathbf{U}^*\right)\mathbf{Y}\mathbf{U}\right) = -(Q + ДQ).$$

Inverse matrix $\left(\partial\varphi / \partial V\right)^{-1}$ is involved in the constraints (8). If the Jacobian itself is sparse and the mathematical apparatus of sparse matrices can be used, the inverse matrices are completely fulfilled, which requires a huge amount of computer memory and its operation increases calculations time. The method of preemptive consideration of active (dominant) constraints allows avoiding necessity of working with full large-scale matrices.

Generally, CAs, accepted with the aim to adjust certain parameters to the feasible region, are appropriate for the other parameters as well. Particularly, reactive power increase, intended for the unacceptably low voltage increase in some load bus, leads to the voltage increase in other buses as well. Consequently, adjusting minimally low voltage to the feasible region will most probably be sufficient for other PS buses with unacceptably low voltage. Similarly, CAs, accepted with the aim to decrease maximally high voltage in remaining buses. As a result, if constraints are of the same type (voltages of all grid buses have relatively low values), the procedure of only one constraint consideration repeated few times (if one step is not sufficient) can be more efficient.

At the same time, alternative state constraints violations can take place - a PS includes both unacceptably low and high voltage buses. CAs, accepted for the purpose of the one

constraint consideration, can become inappropriate for the other. In this case, the problem solution is the procedure (conditionally called as the active dipole method) of CAs selection for two (maximum) alternative constraints provision, for example, adjusting minimally low and maximally high voltages to the feasible region.

Limitation of the simultaneously considered constraints number can lead to the possibility of using more efficient calculation procedures, for example, Lagrange method. Constraints classes (bus voltages, branch currents and power flows) also have their own consideration hierarchy – adjustment of voltages into tolerance range results in the reduction of the voltage control range, and, consequently, in the reduction of voltage amplitudes differences for adjacent buses, and, in the end, to the branch current decrease. CAs, intended for decrease of the unacceptably high currents, lead to the power flow decrease as well. As a result, CAs, intended for the voltage adjustment to the feasible region, are to precede current CAs, and power CAs are to be considered in last turn.

The main idea behind decomposition of the CA selection procedure lies in the dimension reduction and structuring of the varying variables vector, and in the consequential OF simplification, and this gives opportunity to use "faster" solvers.

The alterations of buses reactive power are generally considered as the prevailing CAs in order to adjust voltages to the feasible region. Active power alterations also influence voltage amplitudes allocation, though to a smaller extent. Hence, the procedure of optimal parallel units' generation allocation (second CA class) should precede to the load shedding. And only in case when generation power reserves are not enough, load active power alterations are to become CA (outage of grid elements, third CA class). In this case, both active and reactive load power reduction occurs (proportional reduction). In addition, reactive power is the primary one, but OF is defined, basically, by active power alteration (costs of energy-not-served damage compensation).

V. TEST CALCULATIONS.

Calculation of the 14-bus IEEE scheme (case-14) was performed in order to examine suggested algorithms in the Matpower framework [16] in the computer: Intel(R) Core(TM) i3-2100 CPU @ 3.10GHz. Duration of the n-3 criterion calculation was 71 seconds, while that of OPF calculation (Optimal Power Flow, Dispatchable Load) with interior point optimization was 230 seconds, which confirms the efficiency of the suggested method.

VI. CONCLUSION

Static PS security is the object of the presented analysis. It was shown that the most time-consuming operation is that of CA selection, which, in common case, presents the nonlinear programming problem. The decomposition of constraints of the consideration task is proposed for the purpose of a quite high time costs reduction. The calculation procedure is divided into two stages – steady state calculation (equality constraints) and adjusting a state to the feasible region (inequality constraints). In its turn, state constraints are differentiated functionality-wise and taken into account separately. The accepted assumptions allow one to linearize the constraints system, simplify the task to that of quadratic programming and, finally, to speed-up calculations.

References

[1] Rudenko, M.B. Cheltsov, "Reliability and redundancy in power systems", Nauka, Novosibirsk, 1974.

[2] J. Endreni, Modeling for reliability calculations in power systems, M.: Energoatomisdat, 1983.

[3] R. Billinton, R.N. Allan 'Reliability evaluation of power systems Pitman Books, New York and London, 1984.

[4] Yu.N. Rudenko, Reliability of Power systems and their equipments, Vol.2. Reliability of electric power systems. Reference book, M.: Energoatomisdat, 2000.

[5] N.A. Manov, M.V. Hohlov, Y.J. Chukreev, "Meshed power system reliability estimation models and approaches," Komi science center of Uro RAN, Russia, 2010.

[6] M.N. Rozanov, "Reliability of energy system and equipment", Energoatomizdat, Moscow, 2000.

[7] Yu.N. Kucherov, O.M. Kucherova, N.G. Kasimov and others, The state and direction of the development of the PC analysis of the regime and reliability of the AC / DC PS for IBM PC – ANARES, Proc. RAS. Power engineering, Vol. 4, pp. 24-44, 1992.

[8] Fam Chung Shon, N.I. Voropai, Investigation of the regime reliability of power supply systems with distributed generation and cascade accidents, Electricity, Vol. 12, pp. 13-21, 2013.

[9] A.V. Domyshev, D.S. Krupenev, Estimation of the regime reliability of electric power systems based on the Monte_Carlo method, "Electricity", Vol.2, pp.4-12, 2015.

[10] G.F. Kovalev, L.M. Lebedeva, Areas of using of applicability of the criterion N-1 in the formation of the structure and the choice of parameters of PS elements, Irkutsk: ISEM, 1999.

[11] D.V. Polubotko, Yu.Ya. Chukreev, Methodological approaches to the analysis of static regime reliability of regional power plants using parallel computing tools, ELECTRO, Vol. 2, pp. 9-13, 2010.

[12] N.I. Voropai, Security of Electric Power Systems: Methodological Principles and Methods of Research, Energy and Transport, Vol. 6, pp. 52-59, 1991.

[13] V.M. Gornstein, B.P. Miroshnichenko, A.V. Ponomarev et al, Methods for optimizing of the power systems modes, Moscow: Energia, 1981.

[14] B.I. Ayuyev, V.V. Davydov, P.M. Erokhin, V.G. Neuimin, Computational models of power flow distribution in electrical systems, Moscow: Flint: Science, 2008.

[15] «RastrWin3» Software Complex. User Manual. Retrieved from: http://www.rastrwin.ru

[16] Retrieved from: http://www.pserc.cornell.edu/matpower/