

The power system steady-state stability analysis

Žaneta Eleschová
Anton Beláň

Abstract

In this paper is presented method of steady-state stability analysis according to P. Dimeo and comparison of results with other methods for examination of power system steady-state stability.

Key words: power system, steady-state stability, REI net, Nodal image

Introduction

Transmission system operators, as well as scientific community, pay attention to the power system stability and safety. On the present, questions of the power system stability and safety are high actual. It is necessary to find out such preventive measures to avoid severe contingencies in the power system operation, e.g. blackout. There is effort to find such power system stability margin of which we could say "how stable the power system is" in given steady state.

The power system analyses of blackouts show that main problem is the voltage stability and observance of the "N-1" criterion

1. Steady state stability according to P. Dimeo

Voltage and steady-state stability analysis according to P. Dimeo is based on following conception:

- simplified model of power system creation – REI net (Radial Equivalent and Independent net)
- vectorial expression of the short-circuit currents on the Nodal Image,
- using of criteria for steady state and voltage stability evaluation,
- case worsening procedure - degradation of actual power flow.

1.1 REI net

Simplified model of the power system - REI net makes possible to examine each of generators from point of view any bus in the power system. Radial net of the short-circuit admittances (REI net) is built up for reference (initial) state of the power system.

Generator buses can represent real synchronous machines in analyzed power system or virtual generators – equivalent of other adjacent transmission systems.

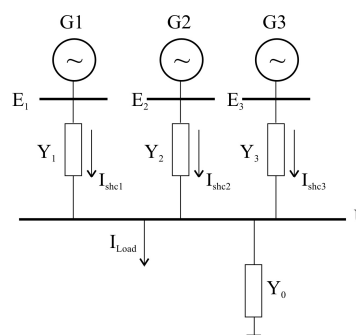


Fig.1 REI net

1.2 Nodal image

The Nodal image of any bus in the power system is diagram that represents the short-circuit currents that flow from generators to given bus through the short-circuit admittances of REI net. Nodal image is vectorial representation of short-circuit currents in a system.

If synchronous generator with internal e.m.f. \bar{E} is connected through impedance \bar{Z} to given (examined) bus with voltage \bar{V} than symmetric three-phase short-circuit current of generator is given

$$\bar{I}_{shc} = \frac{\bar{E}}{\bar{Z}} = \bar{E} \bar{Y} \quad (1)$$

If synchronous machine is no-load before short-circuit than the short-circuit current of generator is given

$$\bar{I}_{shc-0} = \frac{\bar{V}}{\bar{Z}} = \bar{V} \bar{Y} \quad (2)$$

where: $\operatorname{tg} \varphi = \frac{X}{R}$ and $Z \angle \varphi$, $Y \angle -\varphi$.

If voltage phasor \bar{V} is used for references than angle between \bar{V} and \bar{E} is δ . The full-load current of generator can be express:

$$\bar{I} = (E \angle \delta - V) Y \angle -\varphi \quad (3)$$

The Nodal image provides information about currents and powers and also about voltages:

- angles δ_m measure angle between phasors \bar{E}_m and voltage \bar{V} ,
- magnitude of voltage \bar{V} is proportional with the projection of the total full-load short-circuit current on the abscissa axis.

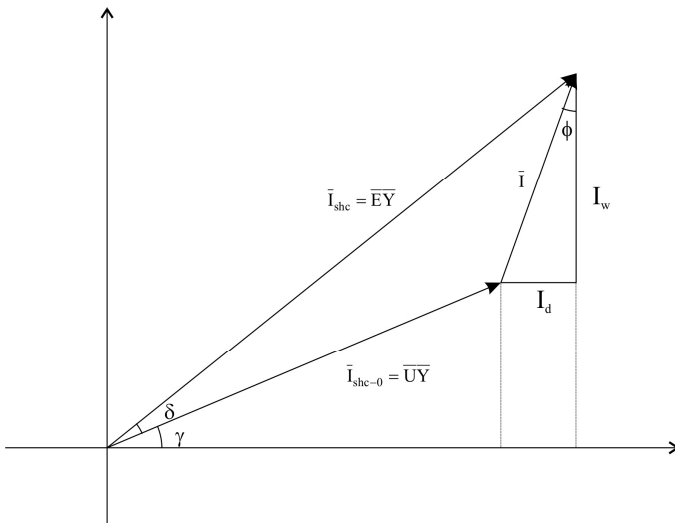


Fig.2 Nodal image for single generator

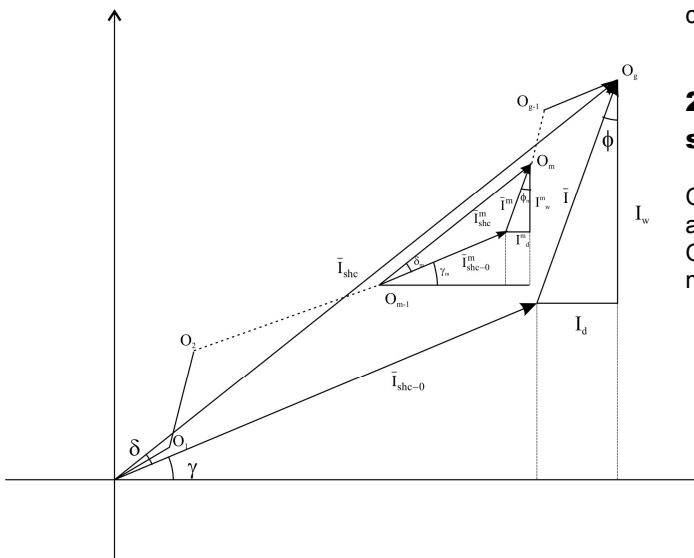


Fig.3 Nodal image for „g“ generators

1.3 Application of dQ/dV stability criterion

Dimo used criterion of steady-state stability $\frac{dQ}{dV} < 0$ in con-

junction with the Nodal image and obtained a simple and efficient steady-state evaluation algorithm.

A critical state is for case of maximum power transfer when $\frac{dQ}{dV} = 0$.

Dimo derived his version of the dQ/dV stability criterion for the Nodal image associated to the REI net reactances when angles γ_m are equal to zero ($\gamma = 90^\circ - \phi$ and $\text{tg}\gamma = \frac{R}{X}$).

$$\frac{dQ}{dV} = \sum_m \frac{Y_m E_m}{\cos \delta_m} - 2V \left(\sum_m Y_m + Y_1 \right) \tag{4}$$

Reactive load is $Q_1 = Y_1 V^2$.

1.4 Distance to Instability. The case worsening Procedure

Voltage and steady-state stability problems are not in the base case, which presumably comes from fully converged load-flow or state-estimate. Base case is stable. To characterize the system state by its “distance” from unstable one is main task of this problem.

In order to find the distance to instability, the steady-state stability calculation must be combined with a “system stressing” or “case worsening” procedure, for example:

- increase the total generated power to supply successively increased load – this is achieved by rotating of the Nodal image vectors anti-clock wise.
- represent the loss of excitation on generator – on the Nodal image, this is done by reducing the length of the short-circuit current of the generator.
- sudden change of operating condition of generator that has reached the reactive power limits – replacing the transient reactance (used for representation of generator in reactive power limit) with the synchronous reactance.

1.4.1 Steady-state stability margin on the nodal image

The nodal image in the power system is designed for base case. Vectors on the Nodal image are rotating while dQ/dV becomes positive.

An angle between the full-load short-circuit current vector in base case and the full-load short-circuit current vector in critical state measures the distance to instability.

2. Simple example of steady-state stability analysis

On a simple system, fig.4, we show the steady-state stability analysis according to P. Dimo.

Obtained results are compared with other methods for examination of the power system steady-state stability.

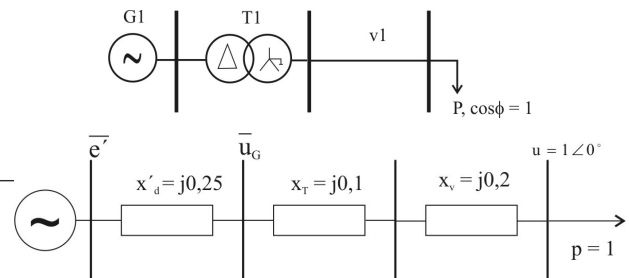


Fig.4 Simple system for steady-state stability analysis (reactances are in p.u.)

Generator internal e.m.f. is $\bar{e}' = 1,1413 \angle 28,81^\circ$.

2.1 The steady-state stability analysis according to Dimo

The full-load short-circuit current:

$$\bar{i}_{shc} = \bar{e}' \bar{y} = 2,0751 \angle -61,19^\circ,$$

where $\bar{y} = \frac{1}{jX} = 1,8182 \angle -90^\circ$.

The no-load short-circuit current:

$$\bar{i}_{shc-0} = \bar{v} \bar{y} = 1,8182 \angle -90^\circ$$

The load current:

$$\bar{i}_{load} = \bar{i}_{shc} - \bar{i}_{shc-0} = 1 \angle 0^\circ$$

Results of case worsening procedure are in table 1.

δ [°]	i_{shc-0} [p.u.]	i_{Load} [p.u.]	v [p.u.]	dQ/dV	p [p.u.]	Case
28,81	1,8182	1	1	-1,268	1	base
36,94	1,659	1,247	0,912	-0,720	1,138	safety
40	1,589	1,334	0,874	-0,470	1,1664	
45	1,467	1,4674	0,807	0	1,1844	critical
50	1,334	1,589	0,734	0,560	1,1664	
80	0,361	2,044	0,1984	11,22	0,405	

Tab.1 Results of case worsening procedure

2.2 Distance to instability

In base case projection of the full-load short-circuit current on the vertical axis:

$$i_{shc}(y) = \bar{i}_{shc} \sin \delta_{zakl.} = 1.$$

In critical case projection of the full-load short-circuit current on the vertical axis:

$$i_{shc}(y) = \bar{i}_{shc} \sin \delta_{krit} = 1,467.$$

In safety case (safety margin is given for example 15%):

$$i_{shc}(y) = 1,247 \Rightarrow \delta_{bezp} = 36,94^\circ$$

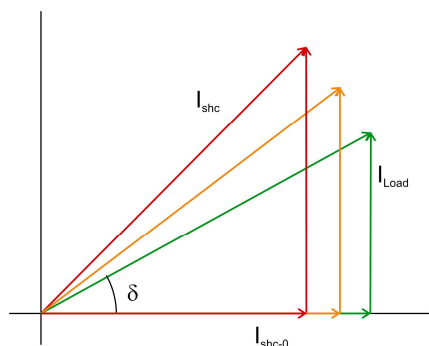


Fig.5 Nodal Image

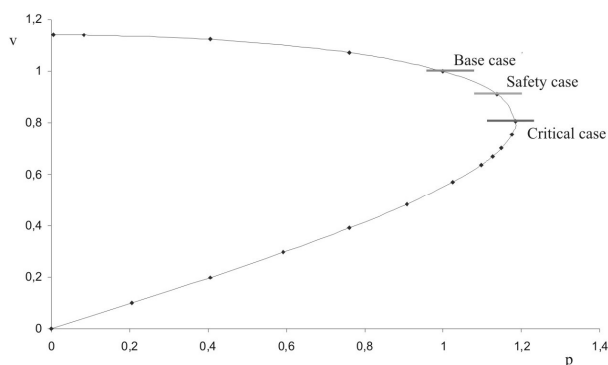


Fig.6 P-V curve

2.3 The steady-state stability analysis according to "conventional" method

We present results of steady-state stability analysis according to "conventional" method using $P = f(\delta)$, where stability margin is for angle $\delta = 90^\circ$.

Maximum power of curve $P = f(\delta)$:

$$P_{max} = \frac{e'v}{X} = 2,075 \text{ p.u.}$$

Coefficient of power reserve:

$$k_p = \frac{P_{max} - P_0}{P_0} \cdot 100\% = 107,51\%$$

High value of this coefficient is caused using transient reactance in generator model.

Replacing transient reactance with synchronous (1,8 p.u.) generator internal e.m.f. will be:

$$e = 2,326 \angle 64,54^\circ.$$

Then maximum power of curve $P = f(\delta)$ will be 1,1076 p.u. and coefficient of power reserve 10,76%, this value is too low.

Obtained results using "conventional" method are showed in table 2.

Case	Transient reactance in generator model (e'=const.)				Synchronous reactance in generator model		
	v [p.u.]	p0 [p.u.]	pmax [p.u.]	kp [%]	e [p.u.]	pmax [p.u.]	kp [%]
Base	1	1	2,075	107,5%	2,326	1,1076	10,76%
Safety	0,912	1,138	1,895	66,3%	2,775	1,205	5,9%
Critical	0,807	1,1844	1,675	41,39%	3,185	1,224	3,43%

Tab.2 Results of stability analysis using "conventional" method

These two methods are not relevant from the point of view of results because the methods are based on different pre-suppositions.

"Conventional" method assumes that generator works to infinite bus, where $v = \text{const.}$

Method according to Dimo contrariwise assumes "soft" voltage at bus and generator internal e.m.f. is constant.

2.4 The steady-state stability analysis of using modal analysis

We also present results of steady-state stability analysis by modal analysis, using the eigen values λ of the reduced Jacoby matrix.

When $\lambda_i > 0$, the power system is under stable condition, when $\lambda_i < 0$ the system is unstable.

Critical state is when the eigen value is equal to zero.

Case	δ [°]	v [p.u.]	Criterion dQ/dV	p [p.u.]	Eigen value λ
base	28,81	1	-1,26818	1	1,56134067
safety	36,94	0,912	-0,72083	1,138	1,04220663
critical	45	0,807	0	1,184091	0,36325395
unstable	48,56	0,755	0,388611	1,17496	-0,0005135

Tab.3 Results of steady-state stability analysis by modal analysis

From obtained results we can see that critical state defined by using Dimo's method ($\delta = 45^\circ$) and modal analysis ($\delta = 48,56^\circ$) are approximated equal.

Conclusion

To ensure stability and safety in the power system operation is main task in the power system.

Steady-state stability analysis according to P. Dimo can be used within preparation of the power system operation as another tool for safety and reliability control of transmission system or can be also used in development study of the transmission system.

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Žaneta Eleschová

Slovak University of Technology in Bratislava
 Faculty of Electrical Engineering
 and Information Technology
 Department of Electrical Power Engineering
 Ilkovičova 3
 812 19 Bratislava
 Tel.: 02 602 91 477
 E-mail: zaneta.eleschova@stuba.sk

Anton Beláň

Slovak University of Technology in Bratislava
 Faculty of Electrical Engineering
 and Information Technology
 Department of Electrical Power Engineering
 Ilkovičova 3
 812 19 Bratislava
 Tel.: 02 602 91 249
 E-mail: anton.belan@stuba.sk