The Study on Automatic Control Method of Power System Stability

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Keywords: Transient stability. Optimal power flow, trace sensitivity, simulation.

Abstract. In order to control system transient stability and improve TSCOPF's computational efficiency, the paper, based on analyzing the existing problem of multiple faults' transient stability constrained optimal power flow trace sensitivity, introduces strict judgment of transient stability in TSCOPF model and can improve computational efficiency by applying track sensitive technology. The paper adds malfunction screening process in transient stability constraint, which can leave out calculating parts of trace sensitivity, do away with inoperative constraint in time and improve computational efficiency. Meanwhile, for instable malfunction, it has no need to look for critical stable track, so as to save lots of simulation time. It can better control system transient stability and satisfy actual power grid's demands on stability. Simulation results on the system verify effectiveness of algorithm.

Introduction

Stability range probably has a very important role on many engineering fields, especially for electrical power system [1, 2]. Previous literatures have proposed many methods to estimate stability range. However, some of them just estimate a subset of stability range, but have conservative problems. Though some of them describe the constitution of stabile boundary perfectly in mathematics, there are actual computational problems. Alternating current transmission and direct-current transmission have totally different characteristics, but both of them have an extremely closed relation and very complicated interaction in actual power grid operation. The interaction between alternating current transmission and direct-current transmission is an important aspect in the study of power system stability, as well as one of the most concerned problems in power engineering sector. Therefore, it is necessary to carry out an extensive and in-depth study on this topic. In the past ten years, multiple serious power outages happened around the world. These have caused serious consequences for national economy and social life. Scholars at home and abroad introduce advanced theories of complicated system, etc. to the electrical power system, carry out detailed researches on cascading failure and related topics of blackout, and obtain lots of breakthroughs and achievements. Nowadays, researches on cascading failure and blackout exist some problems inevitably, mainly including dynamic behavior, which doesn' t consider system integrity, and few researches aiming at AC and DC system.

Transient Stability Range Simulation and Element Model

Basically, electrical power system is constituted by alternator, excitation system, prime motor, speed controller, network and load. Their interrelation is shown in Fig. 1. □ref is the given rotate speed of electric generator. The meaning of rest variables sees below. When electrical power system is received large-disturbance motion, input mechanical power of electric generator m and output electromagnetic power will lose their balance and cause the alternation of speed □and angle ξ. Meanwhile, units swing relatively. In the large-disturbance motion, the ability to maintain voltage level by this system is called as large-disturbance motion voltage stability. Dynamic behavior of system and load, system continuous and discrete control protective effect determine the voltage stability. Time frame of voltage stability lasts several seconds to tens of minutes. Moreover, different dynamic response time with components has relations with element model. Transient stability often has the interaction and correlation with voltage stability.

Three-phase synchronous generator is the power supply of electrical power system. Its function is to transform mechanical power of prime motor (turbine and water turbine, etc.) transmitted by spindle into electric power. Meanwhile, it is the important power supply to provide reactive power (lag) in electrical power system.

(1) The paper selects four －phase model used by time-domain simulation. Electromagnetic power e of electric generator is:

$$P_{ei} = (V_{qi} I_{qi} + V_{di} I_{di}) + r_{ai} (I_{qi}^2 + I_{di}^3) \quad (1)$$

Voltage equation of generator stator:

$$V_{di} = E_{di}^{'} + X_{qi}^{'} I_{qi} - r_{ai} I_{di} \quad (2)$$

$$V_{qi} = E_{qi}^{'} + X_{di}^{'} I_{di} - r_{ai} I_{qi} \quad (3)$$

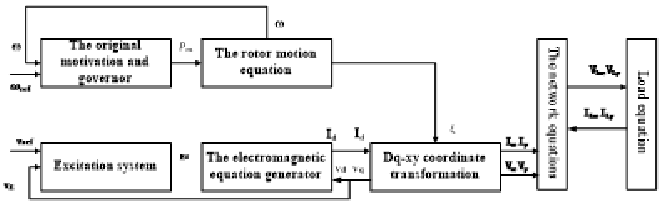


Figure 1 Schematic Diagram of Electrical Power System Basic Composition

d and d′ are d-axle synchronous reactance and transient reactance; q and q′ are q-axle synchronous reactance and transient reactance; ais the resistance of generator stator winding on the ith set; d′ and q′ are the electromotive force on the d and q-axle; d and q are the components on the d and q-axle of alternator terminal voltage fundamental exchange.

(2) Mathematic model of excitation system transfer function block diagram is: terminal voltage of electrical generator g suffers from measurement through time constant □r and makes a comparison with reference voltage □ref, of voltage regulator. Its deviation will be enlarged after entering into the voltage regulator. Output voltage rof voltage regulator is regarded as exciter exciting voltage, so as to control exciting voltage fof electric generator. V_{ri}^{min} and V_{ri}^{max} are the top and bottom limitation of r.

$$V_{mi} = (V_{gi} - V_{mi}) / T_{ri} \quad (4)$$

$$\dot{V}_{ri} = (K_{ai}(V_{ref,1} - V_{mi} - V_{r2i} - k_{fi} E_{fi} / T_{fi}) - V_{r1i}) / T_{ai} \quad (5)$$

$$V_{ri} = \begin{cases} V_{r1i} & \forall V_{ri}^{min} \le V_{r1i} \le V_{ri}^{max} \\ V_{ri}^{max} & V_{r1i} \ge V_{ri}^{max} \\ V_{ri}^{min} & V_{r1i} \le V_{ri}^{min} \end{cases} \quad (6)$$

(3) In the calculation of transient stability, the load adopts constant impedance model. L+L is the load equivalent admittance of node i; Lx+ Ly is the load absorption current of node i; □Lx+□□Ly is the voltage of node i.

$$(G_{Li} V_{Lxi} - B_{Li} V_{Lyi}) - I_{Lxi} = 0 \quad (7)$$

$$(G_{Li} V_{Lyi} + B_{Li} V_{Lxi}) - I_{Lyi} = 0 \quad (8)$$

(4) Through power balance equation, electric generator can be connected with load, so as to constitute the dynamic model of the whole system and adopt rectangular coordinates to describe network node and power injection. Equation of network node is: in the formula, g and g are power injection of node i electric generator; PLi and QLi are absorbing power of node i load; + and x+y are the voltage of node i and j; x+y is mutual admittance between node i and j.

$$V_{xi}\sum_{j=1}^{n}(G_{ij}V_{xj}-B_{ij}V_{yj})+V_{yi}\sum_{j=1}^{n}(G_{ij}V_{yj}-B_{ij}V_{xj})-(P_{gi}-P_{Li})=0 \quad (9)$$

$$V_{yi}\sum_{j=1}^{n}(G_{ij}V_{xj}-B_{ij}V_{yj})+V_{xi}\sum_{j=1}^{n}(G_{ij}V_{yj}-B_{ij}V_{xj})-(Q_{gi}-Q_{Li})=0 \quad (10)$$

Stability Analysis Based on OMIB Equivalent Model

Electric Generator Equivalent Excitation Model: Electric generator model adopts 3-phase model including excitation dynamics, dynamic process of the model can be expressed as:

$$\begin{cases}\delta=\omega-\omega_0\\ \overset{0}{\omega}=\frac{\omega_0}{M}p_m-\frac{D}{M}(\omega-\omega_0)-\frac{\omega_0}{M}E_q^{'}V_sy_d\sin\delta\\ E_q^{'}=-\frac{1}{T_{d0}^{'}}E_q^{'}+\frac{(x_d-x_d^{'})V_sy_d\cos\delta}{T^{'}_{do}}+\frac{u_f}{T_{do}^{'}}\\ \overset{0}{y_d}=-\frac{1}{T_c}(y_d-y_{d0})+\frac{1}{T_c}u_d\end{cases} \quad (11)$$

Here, w electric generator power angle (rad), …is generator speed(rad/s), w0=314.159 is synchronous speed. Eq is transient potential (p.u.) of generator internal node, x d is d-axle equivalent reactance (p.u.), xd ‘ is subtransient reactance, D is electric generator damping coefficient(p.u.), M is rotational inertia time parameter(s) of electric generator, Vs is infinite node voltage(p.u.), Td0 is d-axle open circuit time constant(s), uf is exciting voltage input(p.u.) of electric generator, ud is virtual control input(p.u.) of system total equivalent electrical susceptance.

Stand-Alone Infinite Generatrix Equivalent Model Constraint Condition: Sensitivity of normalized stability ρ variable can be solved through sensitivity of state variable and algebra variable on control variable, namely:

$$\rho_\lambda=\rho_x x_\lambda+\rho_y y_\lambda \quad (12)$$

Here, corresponding stability ρ of inequality constraints is a malfunction corresponding to an inequation. Constraint quantity is declined n times than power angle constraint, improving computational efficiency. In this way, constraint formula of transient stability is shown as follows:

$$\begin{cases}\phi_{sf}^k=[\phi_1^T,\ldots,\phi_{f1}^T,\phi_{f1+1}^T,\ldots,\phi_{f2}^T,\phi_{f2+1}^T,\ldots\phi_{cn}^{T^T}]\\ \phi_j^k(\rho_{u,j}(t_{u,j},\lambda^k))=\rho_{\min}-\rho_{u,j}^k \quad \mathrm{j}\in S_{f1}\\ \phi_j^k(\rho_{s,j}(t_{r,j},\lambda^k))=\rho_{\min}-\rho_{s,j}^k \quad \mathrm{j}\in S_{f2}\\ \phi_j^k(x(t_j,\lambda^k))=[\delta_j(t_j,\lambda^k)-\delta_{con,j}(t_j,\lambda^k)]^2-\xi^2 \quad \mathrm{j}\in \mathrm{S_{f3}}\end{cases} \quad (13)$$

$$\begin{cases}\Delta\phi_{sf}^k=[\Delta\phi_1^T,\ldots,\Delta\phi_{f1}^T,\Delta\phi_{f1+1}^T,\ldots,\Delta\phi_{f2}^T,\Delta\phi_{f2+1}^T,\ldots\Delta\phi_{cn}^{T^T}]\\ \Delta\phi_j^k(\rho_{u,j}(t_{u,j},\lambda^k))=-\Delta\rho_{u,j}^k \quad \mathrm{j}\in S_{f1}\\ \Delta\phi_j^k(\rho_{s,j}(t_{r,j},\lambda^k))=-\Delta\rho_{s,j}^k \quad \mathrm{j}\in S_{f2}\\ \Delta\phi_j^k(x(t_j,\lambda^k))=2[\delta_j(t_j,\lambda^k)-\delta_{con,j}(t_j,\lambda^k)][\Delta\delta_j(t_j,\lambda^k)-\Delta\delta_{con,j}(t_j,\lambda^k)] \quad \mathrm{j}\in \mathrm{S_{f3}}\end{cases} \quad (14)$$

Here, in the formula, f1、f2、f3 are general instable malfunction set [1 ,1], stable malfunction set[1+1 ,2] and extremely stable malfunction set[2+1 ,].

$$\begin{cases}\Delta\rho_{u,j}(t_{u,j},\lambda^k))=(\rho_{u,j})_\lambda\Delta\lambda^{k+1} \quad \mathrm{j}\in S_{f1}\\ \Delta\rho_{s,j}(t_{r,j},\lambda^k))=(\rho_{s,j})_\lambda\Delta\lambda^{k+1} \quad \mathrm{j}\in S_{f2}\\ \Delta\delta_j(t_j,\lambda^k))=(\delta_{\lambda,j})(t_j,\lambda^k)\Delta\lambda^{k+1} \quad \mathrm{j}\in S_{f3}\\ S_f=S_{f1}\cup S_{f2}\cup S_{f3}\end{cases} \quad (15)$$

Calculation Process of Transient Stability Constrained Optimal Power Flow: If power angle deviation of the biggest electric generator is up to 360 degree. Simulating calculation is ended in time t max. Otherwise, it stops at t end. ts refers to calculation ending time of sensibility. Adopt OMIB equivalent to calculate unstable time or power angle regression time is more rigorous than adopting power angle constraint (11). Generally, it is even smaller. When looking for critical stable track, increase simulation time t end suitably. The paper increases 5 tend. Simultaneously, it can ensure the swing stability of the system. System instability mode recognition can be conducted under the system instability state. When power angle deviation of the biggest electric generator is up to 360°, conduct OMIB equivalent in instability mode, according to instability situation.

Generally speaking, because the most serious malfunction stability satisfies the operating point, it also satisfies the malfunction of degree of instability. This paper conducts instable malfunction screening in line with the following principle, so as to improve computational efficiency: set instable malfunction of the kth iteration normalized stability margin least value as ρ min. Normalized stability conforms to the following instability malfunction and makes it eliminate from the iterative stability constraint(case of the paper is selected as 0.5).

$$| \rho_{u,i}^{k} | < \sigma | \rho_{u\min}^{k} |, j \in S_{f1}$$

$$| \rho_{eu,i}^{k} | < \sigma | \rho_{u\min}^{k} |, j \in S_{f3} \qquad (16)$$

Generally speaking, because the least malfunction stability satisfies the operating point, it also satisfies the malfunction of larger degree of instability. This paper screens stability malfunction in line with the following principle, so as to improve computational efficiency: When stability malfunction looks for critical stability trace, if malfunction mute time increases to 0+ .2(c−0), it is still smaller than fault critical clearing time (CCT). It thinks that the system is extremely stable in this malfunction, so this malfunction is eliminated from transient stability. When ending circulation, it only conducts stability margin calculation.

Example Verification Simulation

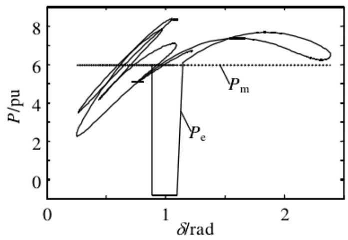
Unchanged system element model, simulation time of system 1 is 1s. Simulation time of system 2 and system 3 is 2s. Simulation step length is about 0.01s. Front 2 system preset malfunction set is the same with Table 5-1 and Table 5-2. On the other hand, malfunction set of system 3 selects corresponding line of system 3 and system 2 in Table 5-2 as fault line. Adopt the same malfunction number, and malfunction mute time of malfunction A and B are 0.16 and 0.27s, respectively. The rest parameters are the same with system 2. ε is 170°. Computer configuration is Intel double core 3.0 GHz CPU, 2G RAM.

As shown in Table 1, it indicates calculation results comparison in different constraint conditions. Through adjusting ρ min, lowest stability degree of system can be promoted to 1.26% from 0 of malfunction A. The lowest stability is promoted to 1.5% from 0 of malfunction A.

Table 1 Calculation Results Comparison in Different Constraint Conditions

ρ min/ pu	τ /pu	Cost Time/s	Cycle Index	Cost/($/h)	Malfunction	CCT/s	ρ s
3	0	480.33	14	71586.39	A	0.160	0.000
					B	0.298	0.138
8	5	264.41	6	71598.66	A	0.165	0.015
					B	0.302	0.168

As shown in Figure 3 and 4, after promotion, regression angle of power angle is advanced. Accelerating power absolute value of regression time is increased. In this way, it can select stability floor ρ min in line with actual power grid stability requirement, so as to make stability satisfy safety economy requirements of power grid and adjust the balance between power grid economy and safety reasonably.



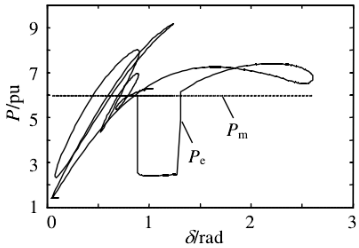
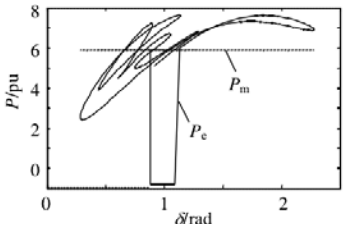


Figure 2 The 1st Constraint Condition(Malfunction 1)   Figure 3 The 1st Constraint Condition(Malfunction 2)



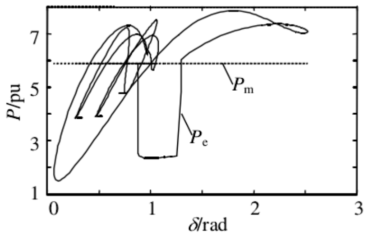


Figure 4 The 2nd Constraint Condition(Malfunction 1)   Figure 5 The 2nd Constraint Condition(Malfunction 2)

Comparison of system transient stability constraint quantity is shown in Table 2. Because procedure cycle can screen and process different malfunctions, transient stability quantity is smaller than the number of malfunction . In 5 cycles of the 2nd constraint conditions of the system 1 include 1 constraint for once, 2 constraints for once and 4 constraints for 4 times. It greatly improves computational efficiency. From the table 1, it can see that malfunction C and D belong to extremely stable malfunction and are inoperative in multiple iterations. The procedure only controls stability of malfunction C in the second cycle. In literature [10], every cycle transient stability constraint quantity only can be equal to the multiply between number of defect and number of electric number.

Table 2 Comparison of Transient Stability Constraint Quantity

System		n	Transient Stability Constraint Quantity of this Paper	Transient Stability Constraint Quantity in Literature[10]
1	6	3	≤6	18
2	2	10	≤2	20
3	2	20	≤2	40

Table 3 gives comparison of results obtained in the method of this paper and track sensibility method of literature[10] presented in system 2. It can be observed that method in this paper is superior to the method of literature[10] in computational accuracy and combination property indicator. Stability trace use angle for reference to confirm and judge top and bottom limitation. Iteration needs to look for critical stability track. On the other hand, method in this paper has no need to look for critical stability track because of normalized stability and instability malfunction. Thus, it saves lots of simulation time.

Table 3 Comparison of Results in System Obtained by Two Methods

Optimization Method	Malfunction	Cycle Time	Cost Time /s	Cost/($/h)	Indicator of Stability
Method in this paper	A, B	6	54.64	36 135.36	135.36
Literature Method		1	31.09	36145.30	145.30

Conclusions

According to equivalent model, it can introduce strict transient stability judgment in TSCOPF model, and can apply track sensibility technology to improve computational efficiency. Moreover, in TSCOPF model, there is a malfunction corresponding to transient stable constraint, reducing transient quantity of transient stable constraint. Malfunction can be divided into stable malfunction, extremely stable malfunction, generally stable malfunction and extremely instable malfunction. All of them are added with malfunction screen processing in transient stable constraint, leaving out calculation of parts of tract sensibility and getting rid of inoperative constraint. Meanwhile, for instable malfunction, it has no need to look for critical stable track. Thus, it saves lots of simulation time and improves computational efficiency.

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