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Study on Approach of Static Security Assessment Accounting for Electro-thermal Coupling*

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ABSTRACT

A static security assessment approach considering electro-thermal coupling of transmission lines is proposed in this paper. Combined with the dynamic thermal rating technology and energy forecasting, the approach can track both the electrical variables and transmission lines' temperature varying trajectory under anticipated contingencies. Accordingly, it identifies the serious contingencies by transmission lines' temperature violation rather than its power flow, in this case the time margin of temperature rising under each serious contingency can be provided to operators as warning information and some unnecessary security control can also be avoided. Finally, numerical simulations are carried out to testify the validity of the proposed approach.

Keywords: Power System; Dynamic Thermal Rating; Static Security Assessment; Transmission Line; Electro-thermal Coupling

1. Introduction

As an indispensable technology to guarantee the security operation of power grid, the on-line static security assessment (SSA) has been being focused by both academic and engineering circles [1-3]. It takes charge of screening the anticipated contingencies, identifying serious ones which cause voltage or thermal violation and providing warning information to operators as the important basis for making preventive control decision for the serious contingencies. However, thermal limit (maximum permissible temperature) of transmission line has been being converted into limit on power flow or current in SSA, and the asynchronous between temperature and current of transmission line (thermal inertia) is always ignored, this should be improved under new situation. There are two major reasons motivate the improvement: (1) With the rapid increase of electric power generation & demand, the transfer capability of power grid is being pushed to its thermal limit, therefore, the traditional SSA which ignores the thermal inertia tends to impede the efficient utilization of the existing transfer capability of power grid. (2) As the massive power generated by new energy resource integrates into power grid, the operating state of power grid is becoming more complication and changeful, under this case, the traditional SSA tends to provide warning information frequently by identifying the power flow violation, this correspondingly lead to the unnecessary security control operations.

To address the issues mentioned above, it is essential to realize to consider the electro-thermal coupling relation of transmission lines and regards transmission lines' temperature as their thermal limits in SSA, there are two essential conditions for the goal: (1) Operating temperature & micro meteorological environment of transmission lines are capable of being monitored and the data can be assembled in control center of power grid. (2) The improved power flow calculation which considers transmission lines' temperature as state valuable should be performed fast enough to screen the anticipated contingencies and meet the need of online application. For the first condition, dynamic thermal rating (DTR) can be practicable, it was proposed in 1970s[4-5] and has been widely applied in some developed countries in the end of 1990s[6-7], now its monitoring data (including temperature and meteorological data) is integrated into SCADA, but it has not been combined organically with power system analysis and control. For the second condition, the electro-thermal coupling power flow[8] can be utilized, but it must be simplified to reduce the calculation complication and time consuming.

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In this paper, combined with DTR technology, an on-line security analysis frame considering electro-thermal coupling is firstly formulated to present the precondition & purpose of online security assessment considering electro-thermal coupling. Then the approach is proposed to realize the fast screening of anticipated contingencies with temperature variation calculation.

2. Framework of On-line Electro-thermal Coupling Security Analysis

In this section, a preliminary exploration is performed to combine the DTR technology with power system security analysis, and the framework of electro-thermal coupling security analysis is proposed as **Figure 1** based on the classical security analysis which presented by Dyliyacco in 1970s.

In **Figure 1**, extended state estimation (Block ①) is the foundation for on-line operation of the security analysis considering electro-thermal coupling, it takes advantage data measured by DTR, can not only estimate traditional electric state (such as node voltage amplitude and phase angle) but also the temperature and parameters of HBE[9] (Heat Balance Equation) of transmission lines. As the preliminary research, reference [10] has proposed an extended state estimation based on existing SCADA. The electro-thermal coupling power flow (Block②) technique[8] can be used to simulate the temperature variation trajectory of transmission lines in research time horizon based on the load forecast data. If voltage or temperature violations are found (Block ③), processing corrective control (Block ④) will be activated to eliminate the temperature and electric violations. If initial state is secure (no violation in initial state), the security assessment considering electro-thermal coupling will be activated, it screens every contingency in anticipated contingency set (Block ⑤), picks out serious ones which cause voltage or temperature violation, and provides warning information to operators. According to the information, operators of power system will start the correspondingly preventive control (Block ⑥) to improve the security operation of power system.

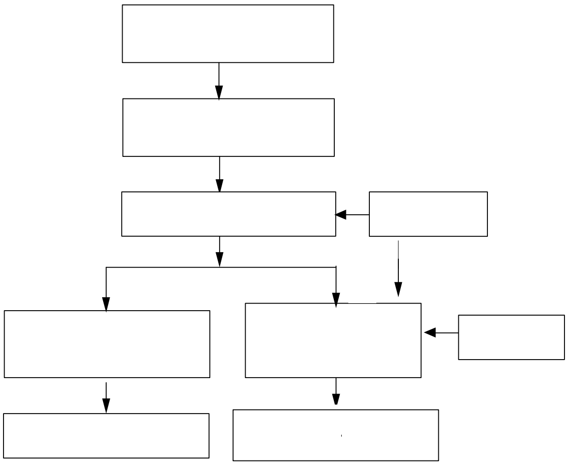

Figure 1. Framework of static state security analysis considering electro-thermal coupling.

From above description, the purpose & precondition of online security assessment considering electro-thermal coupling is clarified: (1) It realizes fast calculation of the temperature variation and considering temperature as transmission lines' thermal limit to identify serious accidents. (2) The initial temperature and parameters of HBE which are needed to perform the security assessment considering electro-thermal coupling can be obtained by means of extended state estimation. Based on this framework, the approach of security assessment considering electro-thermal coupling is proposed in next section.

3. Approach of Security Assessment Considering Electro-thermal Coupling

To track the temperature trajectory under anticipated accident, the electro-thermal coupling power flow technique proposed in [8] is available. The model is as follows:

$$\begin{cases} P_i\left(V(t),\theta(t),T_l(t)\right)=0 & i\in \mathrm{N} \\ Q_i\left(V(t),\theta(t),T_l(t)\right)=0 & i\in \mathrm{N} \\ \dfrac{dT_l(t)}{dt}=H_l\left(t,I_l(t),T_l(t)\right) & l\in L \end{cases} \qquad (1)$$

where, t represents the time of temperature dynamics, $\boldsymbol{V(t)}$, $\boldsymbol{\theta(t)}$ respectively represent the altitude and phase angle vector of voltage, $T_l(t)$ represents the temperature of transmission line l, $I_l(t)$ is the current of transmission line l. The first two equations in equation set (1) represent node power balance equations. Because of the coupling relationship between transmission lines' resistance and temperature, these two equations are not only the functions of voltage but also the function of temperature. The last differential equation represents HBE, it is the function of I_l and T_l when other parameters (such as wind speed, direction, etc) are given by extended state estimation. It can be expressed in detail as follows:

$$m_l C_{pl}\frac{\mathrm{d}T_l(t)}{\mathrm{d}t}=I_l^2(t)R(T_l(t))+q_s-q_c(T_l(t)) - q_r(T_l(t)) \qquad (2)$$

where, $m_l C_{pl}$ is the product of the weight per unit length of transmission line l and its specific heat capacity. The first item on right side of equation (2) represents the resistance heating per unit length of transmission line l. It is the function relates to temperature of lines. q_s represents the heat that produced by the solar heating per unit length. $q_c(T_l(t))$, $q_r(T_l(t))$ represent the heat losses per unit length produced by convection and radiation respectively. They are all the functions relate to temperature of line *l*.

Obviously, model (1) detailedly considers the electro-thermal coupling relationship in power flow, however, it will cost much time for solving differential-algebraic equations for every anticipated contingency which may not appropriate for online application. Fortunately, the coupling between resistance and power flow is weak, that is why the PQ decouple method is effective to the power flow calculation. Meanwhile, the resistance-temperature coefficient is small (always < 0.01). So the coupling between temperature and power flow is weaker. Based on this characteristic, there are two ways to simplify the calculation of temperature dynamics. For one thing, the influence of transmission lines' temperature on power flow can be ignored. For another, the functions that relate to temperature in HBE can be treated approximately through setting a fixed and seemly temperature value. Therefore, the equation (2) can be re-described as follows:

$$m_l C_{pl} \frac{\mathrm{d}T_l(t)}{\mathrm{d}t} = I_l^2(t) R_{\max l} + q_s(t) - q_c(t) - q_r(t) \qquad (3)$$

Where, the R_{maxl} is the resistance under the maximum permissible temperature ($T_{\max l}$) of transmission line *l*. note that items on the right side of equation (3) no longer relate to temperature. There are two approximations for this expression. Firstly, the influence of changing temperature of transmission line on power flow is ignored, which makes the current quadratic term unrelated to temperature. Secondly, the resistance of transmission line is set as a conservative constant value (the resistance under the maximum permissible temperature). For the cooling items, the same approximation is implemented, using the conservative constant temperature value

$$\frac{T_{\max l} + T_{0l}}{2}$$

to ensure the relatively conservative outcome, where the T_{0l} represents the initial temperature of transmission line *l*, it can be obtained by DTR or extended stat estimation . After the above approximate treatment, the meteorology-related items in HBE, q_s, q_c and q_r are all constants under a certain meteorological condition. Then make definite integral over t_0-t_f to both sides of equation (3), and obtain:

$$T_l \Big|_{t_0}^{t_f} = \frac{1}{m_l C_{pl}} \int_{t_0}^{t_f} \left[I_l^2(t) R_{\max l} + q_s(t) - q_c(t) - q_r(t) \right] dt \qquad (4)$$

Supposing that the environmental parameters are constant during the whole research time horizon, then the q_s, q_c and q_r are all constant in equation (4), and equation (4) can be expressed as:

$$T_l \Big|_{t_0}^{t_f} = \frac{1}{m_l C_{pl}} \int_{t_0}^{t_f} \left[f(I_l^2(t)) \right] dt \qquad (5)$$

where, $f(I_l^2(t)) = I_l^2(t) R_{\max l} + C$ $\quad C = q_s - q_c - q_r$

Equation (5) indicates that the variation of temperature of transmission lines during t_0-t_f can be expressed by an integrating function of current quadratic term. Supposing that t_0-t_f is divided into *n* time period with $\triangle t$ time step, equation (5) can be discretized as followed:

$$T_l(t_f) - T_l(t_0) = \frac{\Delta t}{m_l C_{pl}} \sum_{t=1}^{n} f(I_l^2(t)) \qquad (6)$$

Therefore, if power flow at *t=1…n* are calculated then substitute the I_l (t) into equation (6), the temperature variation value from t_0 to t_f can be fast obtained. If the temperature difference meet the followed equation, the transmission line is identified to be safe under certain contingency.

$$\frac{\Delta t}{m_l C_{pl}} \sum_{t=1}^{n} f(I_l^2(t)) \le T_{\max l} - T_{0l} \qquad (7)$$

If detailed temperature trajectory is required during t_0-t_f, equation (6) can be calculated after every power flow calculation at *t=1…n* without solving differential-algebraic equations. Moreover, the resistance, HBE parameters of transmission lines can also be updated under new temperature value, the calculation accuracy will be improved.

4. Case Study

To demonstrate the validity of proposed security assessment approach in this paper, the modified six-node power system is adopted as the test system. Its structure is shown in **Figure 2**, and the electric power grid parameters are shown in **Table 1**. In **Table 1**, the transmission lines' initial temperature is obtained by solving a

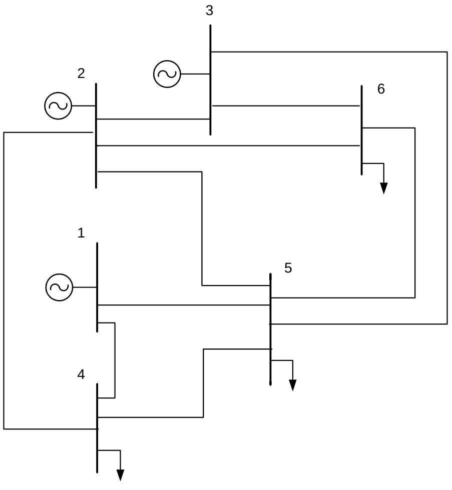

Figure 2. Six nodes power system.

static HBE, whose differential item is set to be zero under initial operating state and under a normal meteorological condition described by [8]. Under online operating circumstance, it also can be obtained by extended state estimation. The thermal ratings are also calculated under the environmental parameters given by [8], and transmission lines' maximum permissible temperature is 70℃. They are regarded as the thermal limit of transmission lines in conventional static security assessment.

In followed two scenes, suppose that transmission lines' maximum permissible temperature are 70℃, the initial time point(t_0) is 0, research time horizon is 30 minutes ($t_f = 30$) and the time step is 5 minutes, so the whole research horizon is divided into 6 time periods. The initial nodes' input power is given in **Table 2**.

4.1. Scene 1

Under the given condition above, suppose that the anticipated accident set includes the outage of all transmission lines in **Figure 2**, and occur at t_0. The traditional static security assessment has been firstly carried out, and the outage of transmission line 1-4 which caused line 2-4's current (1.00 p.u) over its thermal rating (0.98 p.u) is screened out as serious contingency. According to this result, corresponding preventive control have to be activated to answer this contingency.

Table 1. Parameters of electic power grid.

Node number of transmission line		R_l p.u	X_l p.u	$B_l/2$ p.u	$m_l cp_l$ J/kg ℃	Initial temperature ℃	Thermal rating p.u
1	4	0.065	0.2	0.01	711.3	39.6	1.22
1	5	0.08	0.3	0.016	853	36.5	1.31
2	3	0.05	0.25	0.014	1127	33.6	1.60
2	4	0.05	0.1	0.005	444.5	47.4	0.98
2	5	0.1	0.3	0.016	711.3	35.4	1.20
2	6	0.07	0.2	0.011	711.3	34.9	1.22
3	5	0.12	0.26	0.012	1127	37.9	0.97
3	6	0.02	0.1	0.005	1127	39.1	1.55
4	5	0.2	0.4	0.02	444.5	33.6	0.98
5	6	0.1	0.3	0.016	711.3	33.9	1.20

Table 2. Initial active power of nodes (p.u).

Node	Active power
1	0.88
2	1
3	1
4	-1.05
5	-1.08
6	-0.7

For the approach proposed in this paper, this scene supposes load node 4 and corresponding generator node power variation during t_0-t_f are given in **Table 3**.The power of generator nodes are obtained by the participation factors which decided by economic dispatch.

As seen in **Table 3**, load node 4's power tends to increase. The warning information provided by the proposed approach is given in **Table 4**. With the proposed approach, temperature is considered to be thermal limit of transmission lines, and the temperature of line 2-4 will violate 70℃ between 10min and 15min after the outage of line 1-4. It can be seen that the proposed approach screened out the outage of line 1-4 as serious contingency, meanwhile, the detailed temperature trajectory can be tracked and the time margin (> 10 min, < 15 min) before the temperature violation can also be provided to operators for the preventive control decision.

4.2. Scene 2

In this scene, the load node 4 and corresponding generator node power variation during t_0-t_f is given in **Table 5**. Conversely, the load power of node 4 tends to decrease.

Under this case, the temperature violation is avoided because of the downtrend of power generation and load after the outage of 1-4, so the initial state of power system is identified to be security by the proposed security assessment approach and the superfluous preventive control can be avoided.

The temperature and current trajectory of line 2-4 under the outage of line 1-4 are given as **Table 6**.

Table 3. Active power of node 1-4 (p.u).

Time period	Node 4	Node 1	Node 2	Node 3
1	-1.07	0.885	1.010	1.005
2	-1.09	0.890	1.020	1.010
3	-1.11	0.895	1.030	1.015
4	-1.13	0.901	1.040	1.020
5	-1.15	0.907	1.050	1.025
6	-1.17	0.914	1.060	1.030

Table 4. Result of static security assessment (p.u).

Serious accident	Time period	Temperature of line 2-4	Current of line 2-4
Outage of line 1-4	1	62.7	1.00
	2	69.6	1.02
	3	72.9	1.04
	4	75.1	1.05
	5	76.8	1.07
	6	78.5	1.09
Time margin	>10 min, <15 min		

Table 5. Active power of node 1-4 (p.u).

Time period	Node 4	Node 1	Node 2	Node 3
1	-1.03	0.875	0.990	0.995
2	-1.01	0.870	0.980	0.990
3	-0.99	0.865	0.970	0.985
4	-0.97	0.860	0.960	0.980
5	-0.95	0.855	0.950	0.975
6	-0.93	0.850	0.940	0.970

Table 6. Result of static security assessment (p.u).

Time period	Temperature of line 2-4	Current of line 2-4
1	62.7	1.00
2	67.8	0.99
3	68.8	0.97
4	68.2	0.95
5	67.2	0.94
6	66.1	0.92

5. Conclusions

In this paper, the framework of on-line static security analysis considering electro-thermal coupling is presented, and the corresponding security assessment approach is further proposed. The conclusions are as follows:

1) The proposed framework of on-line static security analysis is the organic combination of DTR technology and static security analysis.

2) The proposed security assessment approach is a kind of simplified electro-thermal coupling power flow, it is capable of calculating the temperature dynamics of transmission lines after contingency with less computation amount.

3) The proposed security assessment approach considers temperature as transmission lines' thermal limit which can make the security assessment more actually. Moreover, the time margin can be provided as warning information and some unnecessary preventive control can also be avoided.

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