An Real-Time Emergency Control Method Based On Unbalanced Transient Energy Function

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Abstract. In this paper, an emergency control strategy by combining generator tripping and load shedding is presented. Firstly, the unbalanced transient energy function of power system is defined, and its key features are analysed. Then, by combining the unbalanced power characteristics for power system in steady state operation condition, the method for calculating the control quantities of generator tripping and load shedding is proposed. Furthermore, a real-time closed-loop emergency control strategy is proposed. Since the proposed method by only using measurement data is based on the essential of transient instability, the accurate control quantities can be obtained. Compared with single generator tripping control, the low frequency and low voltage problem of system can be improved effectively with the combined emergency control strategy. Simulation results of New England 39-bus system validate the effectiveness of the proposed control strategy.

1. Introduction
Modern power systems are being operated closer to the stability limits due to increasing electricity supply demand and economic factors [1]. The transient stability of power systems is still a serious problem needed to be solved urgently. A large disturbance to a power system may lead to a loss of synchronism for one or more machines and even power outage [2]. In such a condition, the emergency control is vital for preventing transient instability and even avoiding power outage.

The essential of the transient instability is the surplus active power of power system at the sending end or the insufficient active power of power system at the receiving end. This leads to loss of synchronism for the two generator groups of power system at the sending end and receiving end [3]. The emergency control measures of generator tripping and load shedding are most common methods for maintaining the transient stability of power systems, and the two emergency control measures are researched in this paper. The control measure of generator tripping in power grid at the sending end can slow down the leading generator group of the power system, while the control measure of load shedding in power grid at the receiving end can accelerate the lagging generator group of the power system. As a result, the two generator groups of power system can be recovered to a synchronous state. Currently, the transient stability control measures are mainly based on the detailed models and component parameters [4-5], and they are realized by the online or offline simulation and calculation. The effectiveness of control measures depends on the accuracy of the models and parameters which are difficulty to be obtained. The development of wide-area measurement system (WAMS) based on phasor measurement units (PMUs) has made it possible to obtain the real-time dynamic information of power systems so that provides the real-time methods for transient stability analysis and control [6-7].

In this paper, a closed-loop emergency control scheme for avoiding the transient instability of power system by combining generator tripping and load shedding is proposed. The unbalanced
transient energy function of power system is defined based on motion equations of generator, and its key features is analysed based on the corrected energy function. Besides, the equations used to calculate the control quantities of generator tripping and load shedding are derived. Moreover, an over-all closed emergency control strategy which can be applied to real-time is developed. The simulation indicates that the proposed emergency control method is effective.

2. Unbalanced transient energy function

2.1. Definition of unbalanced transient energy function

For a multi-machine power system, suppose that the system can be identified as two generator groups after a disturbance, i.e., the critical generator group and the remaining generator group, which are denoted as S and A, respectively [8]. The dynamic equation of its equivalent SMIB system can be described as

\[
\begin{align*}
\frac{d\delta}{dt} &= \Delta \omega \\
M \frac{d\Delta \omega}{dt} &= P_m - P_e
\end{align*}
\]

where, \(\delta = \delta_S - \delta_A\), \(\Delta \omega = \omega_S - \omega_A\),

\[P_m = \frac{M_r P_{ns} - M_s P_{ead}}{M_s + M_A}, \quad P_e = \frac{M_r P_{es} - M_s P_{ead}}{M_s + M_A}, \quad M = \frac{M_s M_A}{M_s + M_A}, \quad P_m\]

is the equivalent mechanical power and Pe is the equivalent electromagnetic power.

The corrected transient energy function of the system can be defined as [9]

\[
E^{co} = E^{co}_{KE} + E^{co}_{PE} = \frac{1}{2} M \Delta \omega^2 + \int_{\delta_0}^{\delta_t} (P_e - P_m) d\delta
\]

(2)

where, \(E^{co}_{KE}\) and \(E^{co}_{PE}\) are the corrected transient kinetic energy and the corrected transient potential energy, separately. The corrected transient energy is conserved in post-fault process, that is

\[E^{co} = E^{co}_{KE} + E^{co}_{PE} = C\]

(3)

where, C is the constant.

From the view of transient energy and according to the unbalance power in equation (1), the unbalanced transient energy function at time t of the equivalent SMIB system is defined as

\[E_{unb} = \int_{\delta_0}^{\delta_t} (P_m - P_e) d\delta\]

(4)

where, \(\delta_0\) is the equivalent rotor angel of the system for steady state operation, \(\delta_t\) is the equivalent rotor angel of the system at time t.

2.2. Key features of unbalanced transient energy function

For a multi-machine power system, suppose that: 1) the system can recover to be stable after a large disturbance under its control system; 2) the post-fault system structure change can be ignored; III) the system rotor angels of the steady state operations before and after the disturbance are denoted as \(\delta_-\) and \(\delta_+\), separately, and \(\delta_-= \lim_{t \to -\infty} \delta, \delta_+ = \lim_{t \to +\infty} \delta\). Then the unbalanced transient energy function of the system at full time space \((-\infty, +\infty)\) satisfy the following equation:

\[E_{unb} = \int_{\delta_0}^{\delta_+} (P_m - P_e) d\delta = 0\]

(5)

For a system at the steady state operation, suppose that: I) the system suffers a fault at t0, and the rotor angle and the rotor speed at t0 are \(\delta_0\) and \(\Delta \omega_0\), separately; II) the fault clearing time is tc, and the rotor angle and the rotor speed at tc are \(\delta_c\) and \(\Delta \omega_c\), separately. Then, the unbalanced transient energy function of the system at \(t_0, tc\) satisfy the following equation:

\[E_{unb} = \int_{\delta_0}^{\delta_c} (P_m - P_e) d\delta + \int_{\delta_c}^{\delta_+} (M \frac{d\Delta \omega}{dt}) d\delta = \int_{\delta_0}^{\Delta \omega_{tc}} (M \Delta \omega) d\Delta \omega = \frac{1}{2} M \Delta \omega^2 \int_{\Delta \omega_{tc}}^{\Delta \omega_{tc}} \frac{d\Delta \omega}{\Delta \omega_{tc}}\]

(6)
According to equation (1), there is $\Delta \omega_0 = 0$. Therefore, equation (6) can be rewritten as

$$E_{unb} = \int_{\delta_0}^{\delta_f} (P_m - P_e) \Delta \delta = \frac{1}{2} M \Delta \omega_c^2$$  \hspace{1cm} (7)

Equation (7) denotes the unbalanced transient energy function of the system at the fault clearing time. According to equation (2) and (7), the unbalanced transient energy and the corrected transient energy at the fault clearing time of the system is equal.

For a disturbed power system, suppose that: I) the system can recover to be stable after taking emergency control measures; II) the time of taking the control measures is $t_d$ ($t_0 < t_c < t_d$), and the rotor angle at $t_d$ is $\delta_d$. Then, the unbalanced transient energy function of the system at $(t_0, t_d)$ satisfy the following equation:

$$E_{unb} = \int_{\delta_0}^{\delta_d} (P_m - P_e) \Delta \delta = \frac{1}{2} M \Delta \omega_c^2$$  \hspace{1cm} (8)

By substituting equation (7) into equation (8), the following equation (8) can be rewritten as

$$E_{unb} = \frac{1}{2} M \Delta \omega_c^2 + \int_{\delta_0}^{\delta_d} (P_m - P_e) \Delta \delta$$  \hspace{1cm} (9)

Because the corrected transient energy is conserved, and according to equation (2) and (7), the following equation can be obtained

$$\frac{1}{2} M \Delta \omega_c^2 + \int_{\delta_0}^{\delta_d} (P_m - P_e) \Delta \delta = \frac{1}{2} M \Delta \omega_c^2$$  \hspace{1cm} (10)

Equation (11) can be further rewritten as

$$\frac{1}{2} M \Delta \omega_c^2 = \frac{1}{2} M \Delta \omega_c^2 + \int_{\delta_0}^{\delta_d} (P_m - P_e) \Delta \delta$$  \hspace{1cm} (11)

Combining equation (9) with (11), the unbalanced transient energy function of the system at $t_d$ can be obtained as

$$E_{unb} = \int_{\delta_0}^{\delta_d} (P_m - P_e) \Delta \delta = \frac{1}{2} M \Delta \omega_c^2$$  \hspace{1cm} (12)

According to equation (2) and (12), the unbalanced transient energy and the corrected transient energy at the time of taking the emergency control measures of the system is equal.

3. Combined emergency control strategy

3.1. Calculation method of controlled quantities

According to equation (4), the unbalanced power of the system before taking control actions can be defined as follows

$$\Delta P = P_m - P_e$$  \hspace{1cm} (13)

If one multi-machine system loses transient stability after a fault, the emergency control measures combining the generator tripping and load shedding is proposed. The control action of generator tripping is taken in critical generator group $S$, while the control action of load shedding is taken in the remaining generator group $A$. The control quantities for generator tripping and load shedding are denoted as $\Delta P_m$ and $\Delta P_e$, respectively. Supposed that the system can recover to be stable after taking the above control measures, the unbalanced power of the system after taking control measures satisfy the following equation:

$$\Delta P_{eq} = P_m' - P_e' = 0$$  \hspace{1cm} (14)

where, $P_m'$ and $P_e'$ are the equivalent mechanical power and the equivalent electromagnetic power after taking control measures, respectively. According equation (1), the following equation can be obtained as
Combining equation (13) and (15), the following equation can be obtained as

$$\Delta P_m = M_4 (P_m - \Delta P_m) - M_2 P_m$$

$$\Delta P_e = M_4 (P_e - \Delta P_e)$$

(15)

According to the equation (5), the following equation can be obtained as

$$M_4 \Delta P_m + M_2 \Delta P_e = \Delta P$$

(16)

where, $\delta_{max}$ is the maximum rotor angle during the oscillation period which $t_d$ is in.

To further transform equation (17) with area integration formula, it can be obtained as

$$\int_{\delta_0}^{\delta_1} (P_m - P_e) d\delta + \int_{\delta_d}^{\delta_{max}} [(P_m - \Delta P_m) - (P_e - \Delta P_e)] d\delta = 0$$

(17)

where, $n$ can be determined by the following: $\delta^n \geq \delta^{n-1}$ and $\delta^n \geq \delta^{n+1}$.

Therefore, the control quantities of $\Delta P_m$ and $\Delta P_e$ can be calculated by solving two simultaneous equations of (16) and (18).

### 3.2. Selection method for control measures

For ensuring both the maximum load supply and the improvement of low voltage and low frequency caused by transient instability, the unbalanced power of remaining generator group A is considered to be the start condition of the combined emergency control of generator tripping and load shedding. And the corresponding quantitative index denoted as $\tau$ is derived as follows.

According to the generator rotor motion equation, and superpose all rotor differential equations of the remaining generator group A, it can be obtained as

$$\frac{d}{d\tau} (P_m - P_e) = \Delta P$$

(19)

If the effect of the voltage sag on the load is ignored, the above equation at a specific moment can be written as

$$\frac{d}{d\tau} (P_m - P_e) = \Delta P$$

(20)

where, $t_0$ is the time when fault occurs, $U_0$ is the voltage at $t_0$, and $t_n \ (tn > t_0)$ is a specific moment. Suppose that $t_0- \ and \ t_0+$ respectively denote the moment before and after the fault, the initial unbalanced power of system can be defined as

$$\Delta P_{m,t_0-} = P_{m,t_0-} - P_{e,t_0-} \ (21)$$

$$\Delta P_{e,t_0-} = P_{m,t_0-} - P_{e,t_0-} \ (22)$$

Further define the unbalanced power difference before and after fault as follows

$$\xi = \Delta P_{m,t_0} - \Delta P_{e,t_0} = \Delta P_{m} - \Delta P_{e} \ (23)$$

where, $\Delta P_m$ and $\Delta P_e$ are respectively the mechanical power variation and electromagnetic power variation. $\Delta P_m = P_{m,t0} - P_{m,t0+} \ and \ \Delta P_e = P_{e,t0} - P_{e,t0+}$. Because of the inertia effect, $\Delta P_m$ is very small and is almost negligible. Therefore, equation (23) can be rewritten as

$$\xi = \Delta P_{e,t_0} - P_{e,t_0+} \ (24)$$

Because $\xi$ can be considered as the effect of the voltage deviation on the unbalanced power, the unbalanced power of the remaining generator group A at $t_n$ can defined as follows
\[ \Delta P_{e,i} = M_i \frac{d\omega_i}{dt} + \xi \]  

(25)

Therefore, the quantitative index as the start condition of the combined emergency control can be obtained as follows

\[ \tau = \frac{\Delta P_{e,i}}{P_{e,i}} \]  

(26)

If the value of \( \tau \) reaches a set value of \( a \), i.e., \( \tau > a \), the system needs to take the combined emergency control measure of generator tripping and load shedding to enable the system recover to be stable. If \( \tau > a \), the system only needs generator tripping measure to enable the system recover to be stable. In this paper, the value of \( a \) can be selected in the reference range of \([0.2, 0.3]\).

3.3. Selection method for control positions

1) Selection for the generator tripping positions: The selection method for generator tripping positions is as follows: Sort the generator units according to the product of the torque and angular velocity of generator \( (M \omega \omega) \), and filter out the generator unit relatively low capacity. Besides, it should be noted that the control quantities of generator tripping obtained by solving equations are generally continuous variables. But in practice the whole generator unit needs to be tripped when taking generator tripping, and the practical control quantities of generator tripping are discrete. Therefore, the control quantities obtained by solving equations need to be rounded up the value that is determined according to the practical capacity of generating set.

2) Selection for the load shedding position: For ensuring the effectiveness of the load shedding measure, the load shedding positions belong to the remaining generator group. In this paper, the load shedding positions are determined according to the magnitudes of the voltage sag during the transient process.

3.4. Flow of the closed-loop combined emergency control strategy

The flowchart of the proposed closed-loop combined emergency control strategy is shown as in Fig. 1. Specifically,

1) Start emergency control when a multi-machine power system is identified as transient instability.

2) Obtain the equivalent SMIB system of the power system by using the measurement data.

3) Calculate the quantitative index \( \tau \) along with calculating the unbalanced transient energy of the power system.

4) Judge whether the value of \( \tau \) is greater than the given threshold \( a \). If \( \tau > a \), start the combined emergency control strategy of generator tripping and load shedding. If \( \tau > a \), just start the generator tripping control, and calculate the control quantity of the generator tripping by solving equation (18) with the control quantity of load shedding \( \Delta P_{e,d} = 0 \).

5) Continue to monitor the operation state of the system after taking an emergency control. If the system is still unstable, continue to start the emergency control procedure until the system recover to be stable.
Determine the index for control measure selection

Take the combined control measure of generator tripping and load shedding

Take the control measure of generator tripping

End

Yes

No

Obtain equivalent SMIB system

Calculate unbalanced transient energy of system

System is stable?

start

Collect measurement data

Figure 1. Flowchart of the closed-loop combined emergency control strategy.

4. Simulation result

To verify the effectiveness of the proposed method, simulations are performed on New England 39-bus system. The diagram and specific parameters about the test system can be found in reference [10]. The loads models are with different proportions of constant resistance and induction motor model. The LLE-based index in [10] for identifying transient instability is used as the criterion for activating the emergency control. The response results to a disturbance by Power System Department Bonneville Power Administration (PSD-BPA) (a China-version BPA software developed by China Electric Power Research Institute) are used as measurement data from WAMS.

A three-phase short-circuit ground fault occurs in the middle of line 4-14 at 0 s, and then the fault is cleared at 0.24 s. The generator rotor angle and the relative rotor angle response curves are shown in Fig.2. According to the LLE-based index, the transient instability can be identified at 0.62 s. By using the proposed control strategy, the active power vacancy $\tau$ is 0.33. Therefore, the combined emergency control measure of generator tripping and load shedding is started. By computing, $\Delta P_mS = 575$ MW, $\Delta P_eA = 90$ MW. The final control strategy is that I) two generator units of 200 MW of G37 and one generator unit of 200 MW of G38 are tripped; II) 16% of the loads on the bus 4 are cut off. Considering the time delay of 100 ms, the control strategy is started at 0.72 s. The relative rotor angle, bus voltage near the fault point and bus frequency after taking the combined emergency control strategy are shown in Fig. 3. For comparison, the simulation results by only using generator tripping measure are shown in Fig.4.
Figure 2. Time domain simulation result.

Figure 3. Simulation results after taking the combined emergency control strategy.
From the simulation results shown as in Fig. 3, it can be seen that the system recovers to be stable after taking the combined emergency control strategy, and there is no issue of low voltage and low frequency. The simulation results shown as in Fig. 4 show that the system recovers to be stable. However, it can be seen from Fig. 4 (c) that the bus frequency is too low by only taking generator tripping measure. The comparison of the two simulation results, the low frequency problem caused by single generator tripping control can be improved effectively with the proposed combined emergency control strategy.

5. Conclusion
In this paper, a closed-loop emergency control strategy based on unbalanced transient energy is proposed for the real-time emergency control. The proposed control strategy combines generator tripping and load shedding, and the accurate control quantities can be obtained by using the unbalanced transient energy and unbalanced power. Besides, the proposed method can improve the problems of low frequency or low voltage. Being different from the traditional equal-area criterion method, the proposed method does not need to calculate the unstable equilibrium points. Therefore, the proposed method can be efficiently used for real-time control.

Acknowledgments
This work was supported in part by the National Natural Science Foundation of China under Grant U1766202.

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