A Fast Clustering and Transient Stability Assessment Method Based on the Generator Energy Transfer Function

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Abstract: Based on the port energy structure and transient energy function, this paper proposed the generator energy transfer function (GETF) of generator port to analysis power system transient stability issue. By calculating the energy transferred between generators, generator port energy and its changing rate, it can quickly identify the critical generator cluster in a short time after the fault cleared and assess transient stability of the power system, also take control measures. Finally, this method was verified through IEEE-140 node system and it proved the effectiveness of the method.

1. Introduction
By viewing accident happened in these years among the whole world [1,2], we can find that the transient stability issue is particularly important. There are mainly two methods to study it. One is the time domain simulation method based on the accurate system model and parameters, and the other is the transient energy function (TEF) based on the Lyapunov stability theory [3,4]. The former could obtain accurate results but the speed is slow. While the latter can quickly assess the stability through system energy calculated by TEF. Since the energy in the power system comes from generators, focusing on the energy variation in generators is a better way to study the power system transient issue [5,6]. Therefore, this paper defined the GETF, based on the energy structure theory and the transient energy function. By collecting information of generators buses and network parameters and calculating the energy transferred between any two generators, we could quickly identify the critical generator cluster. Meanwhile, through port energy changing rate of every generator, we evaluated the transient stability and taken control measures. Finally, the effectiveness is verified by the IEEE 140-node system.

2. Generator Energy Transfer Function

2.1 Definition and Construction of the GETF
The TEF is mainly used to describe the transient energy and its distribution of the whole power system or some parts in it. The energy structure theory is to describe the energy flowing through interfaces between the system and the external [7-9]. Here we combine two theories to define the GETF, which represents the energy transferred between any two generators. In this function, every generator is an energy sub-system, while transmission network is simplified into interconnection lines among sub-systems. All energy transmitted on interconnection lines is the energy which is delivered by generators to the network and loads, as Figure 1 shows.
After the fault is eliminated, there is a linear relationship between the time step and the voltage phase angle variation on the generator bus at each moment, and the slope is the bus frequency deviation at each moment, which is as follows:

$$\Delta \theta_{ij} = \theta_{ij} - \theta_{ij-1} = \Delta \omega_{ij} \ast dt = 2\pi \Delta f_{ij} \ast dt \quad (1)$$

In this equation, $\Delta \theta_{ij}$ is the voltage phase angle variation, $\Delta \omega_{ij}$ is the angular speed deviation, $\Delta f_{ij}$ is the bus frequency deviation.

In the power system, the branch active power transmission equation is:

$$P = \frac{U_i U_j}{X_{ij}} \sin(\theta_i - \theta_j) \quad (2)$$

Assuming the generator bus voltage is $U_i$, the bus voltage phase angle is $\theta_i$, and the frequency deviation is $\Delta f_i$. Considering that we just focus on the transient energy after the fault cleared, the stable component before the fault occurs should be subtracted. Therefore, in equation (2), $P$ is replaced by $\Delta P$ and then the GETF is obtained:

$$E_{\rho i} = \int \Delta P d\theta = \int \frac{U_i U_j}{X_{ij}} \sin(\theta_i - \theta_j) \sin(\theta_j - \theta_i) d\theta_i \quad (3)$$

$$E_{\rho i} = \int \frac{U_i U_j}{X_{ij}} \sin(\theta_i - \theta_j) \sin(\theta_j - \theta_i) (\Delta \omega_i - \Delta \omega_j) d\theta_i$$

$$E_{\rho i} = 2\pi \int \frac{U_i U_j}{X_{ij}} \sin(\theta_i - \theta_j) \sin(\theta_j - \theta_i) (\Delta f_i - \Delta f_j) d\theta_i \quad (3)$$

This function represents the amount of energy transmitted on the interconnection line of any two generators during $[t_i, t_i]$. $X_{ij}$ is equivalent reactance of the interconnection line.

We have mentioned that this function also represents the energy flowing on any interconnection lines, so from equation (3) we can get equation (4), it means the whole transient potential energy of the power system:

$$E_{\rho i} = \sum_{j=1}^{n(n-1)} E_{\rho ij} = \frac{1}{2} \sum_{j=1,j \neq i}^{n} |E_{\rho ij}| \quad (4)$$

### 2.2 Identification of the critical generator cluster and Assessment of the Transient Stability by the GETF

From equation (3), we expressed the sum of the energy transmitted by a generator to other generators as:

$$E_{\rho i} = \sum_{j=1,j \neq i}^{n} E_{\rho ij} \quad (5)$$
We call $E_{gi}$ as the generator port energy sum, which represents the amount of energy transmitted by a generator to other generators in the power system. Those generators of which $E_{gi}$ are positive are in a relatively accelerated state, we call them “source generators”, which increase the transient potential energy and drive other generators to have an accelerating trend, and those generators are divided into the critical generator cluster. The rest generators of which $E_{gi}$ are negative, are in a relatively decelerating state, by absorbing energy to give source generators a deceleration trend and eventually achieve synchronization; we call these generators as “depletion generators”, which are grouped to the non-critical generator cluster. Therefore, according to the positive and negative values of $E_{gi}$, we complete the identification of critical generator cluster. Then we define the energy changing rate of generator port as $P_{gi}$ shown in equation (6) to assess the transient stability of the power system.

$$P_{gi} = \frac{dE_{gi}}{dt}$$

If $P_{gi}$ of source generators stays positive, it means source generators will transfer more energy to the power system, which leads to instability; if $P_{gi}$ of source generators decrease to zero, even to negative, it means the transient status is stable.

Here we take the fault removal time as the start point and 10-time steps later as the end point of integration in equation (3), then calculating the equation (5) to divide generators into source generators and depletion generators, in order to identify the critical generator cluster. After identifying, we set a period (2 to 5-time steps) to observe the energy changing rate of generator port, in order to assess whether the power system is stable.

2.3 Safety Control Measure Based on Generator Energy Function
If we find that the power system will lose stability, we will take the generators tripping measure to stabilize the power system. Taking into account the tripping instruction delay and the generator operating time, the tripping time is set to 7-time steps after the fault cleared. The tripping sequence is to trip the source generator with the highest port energy, then the second one, until to the last source generator or meet the tripping amount of active power. For the tripping amount, it can be calculated through EEAC method.

3. Examples Verification

3.1 Rationality verification of GETF
We take the IEEE 39-node system to verify the rationality of the GETF. By calculating the transient energy through the TEF and equation (4), we get results shown in Figure 2.

![Figure 2. System potential energy calculated by two functions](image)

In Figure 2, the amount and vary tendency are very similar, the difference is due to the different
power system models used. Furthermore, the correlation coefficient between two results is 0.9809, which means that the transient potential energy from GETF is very high correlation with the TEF. Therefore, the GETF proposed in this paper is consistent with the transient energy function theory both in physical and mathematics.

3.2 Simulation Results

3.2.1 Critical Generator Cluster Identification and Transient Stability Assessment. Here we use IEEE 140-node system shown in appendix, to do simulation analysis, the system model is shown in appendix. The fault set as a three-phase short circuit occurred at time 0 on line 8-9, and it was cleared at 0.3s, the simulation step length is 0.01s.

Through calculating equation (3) and (5), we got the generator port energy sum shown in Figure 3(a). We can find that after the fault cleared, the eight generators gen21 to gen36 transmitted energy to other generators through interconnections lines while the rest absorbed the energy via their ports. Therefore, the eight generators were divided into source generators, which is grouped to the critical generator cluster; the remaining were depletion generators, which is grouped to non-critical generator cluster. Then we calculated the energy changing rate of generator port during the setting period, as Figure 3(b) shows, $P_g$ of gen21 to gen36 were positive during the period, while the other were negative, which means the transient energy of the power system continues to increase, thus we assessed that the transient status is unstable. From the fault cleared to assessment done, we just took 0.05s.

![Graph](image)

(a) the generator port energy sum  (b) the energy changing rate of generator port

**Figure 3.** The GETF calculating results after the line 8-9 fault cleared

Combined the time domain simulation result, the power angle difference and unbalanced power calculated by the EEAC method, we find that the power angle of the former group (gen21-gen36) leads the other group, and the difference continued increase, so we determined that the former group is critical generator cluster. We know the time the unbounded position gap (UPG) equals $180^\circ$ is 0.61s from Figure 4(a) through traditional heuristic judgment method. Also, we can find that the unbalanced power first decreased to zero (dynamic saddle point, DSP) when the transient kinetic energy is not zero, thus the transient status is unstable, and the dynamic saddle point occurs at 0.46s in Figure 4(b).

![Graph](image)

(a) power angle difference between two clusters and UPG   (b) unbalanced power and DSP

**Figure 4.** Parameters in the line 8-9 fault

Comparing the above three methods, we can see that the GETF is superior to the traditional
observing UPG method and the EEAC method, as Table 1 shows.

|                  | GETF | Observing UPG method | EEAC method |
|------------------|------|-----------------------|-------------|
| Time (sec.)      | 0.05 | 0.31                  | 0.16        |

3.2.2 Safety Control Measure. We calculated the generator port energy sum and sorted them by absolute value. As Figure 5 shows that the gen23 is the first generator to be tripped, then is the gen26, the gen22 and so on. According to the EEAC method, we calculated the amount of tripped active power is 158.72MW, which was the sum of active power of critical generator cluster at tripping time. After taking the measure, we can see from Figure 6 that the maximum generator power angle difference fell from 200° to 60°, and then remained stable at about 70°, indicating that the power system returned to stability. Therefore, the GETF has significance to the power system safety control measure.

![Figure 5](image5.png)

**Figure 5. The absolute value of generator port energy sum at cutting time**

![Figure 6](image6.png)

**Figure 6. Curve of the max generator power angle difference after the measure taken**

4. Conclusion
In this paper, we defined the GETF based on the transient energy function and energy structure theory. The advantages of this method including: 1) It combines the network parameters without too much simplify, only needs a little amount of electrical information to do calculation. 2) The generator port energy sum and the changing rate can effectively and quickly identify the critical generator cluster and assess the transient stability after faults cleared, also provides a new method for control measures. However, since DC transmission lines are not the same as AC transmission lines, this function needs to be improved in DC or AC-DC hybrid system, and how to identify several clusters is the future research direction.
Appendix

IEEE 140-node system

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