Transient Stability Improvement via Combined Method

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Received: March 2011 Revised: July 2011 Accepted: October 2011

ABSTRACT:
In this article, a combined method is used to improving transient stability. In power systems, the maximum use of existing capacities along with the increased powers transferred through the transition lines make transient stability studies even more important. When the fault occurs, the kinetic energy of system is increased, and if the system kinetic energy exceeds a certain amount, system instability will occur. Generator tripping is one of the most effective methods for improving stability in case of serious faults. In this method tripped a number of units of a certain power plant unit for stabilizing the system. In fact, by removing the generator decrease the kinetic energy of the system so that stability can be achieved. In generator tripping, for the above-mentioned, it should reach stability by tripping the least generator possible. Due to its thermal limitations, fixed place of resistor bank and possibility of back swing, the braking resistor is less efficient than generator tripping. In combined method, system stability against severe turbulence is reached through minimization tripping of generator units. In this method, we first decrease intensity of fault by applying braking resistor, and then, for the purpose of improving transient stability, it try to reduce kinetic energy by removing the least possible amount of producing the desired units at the right time.
Simulations on 9-bus or 3-generator system were conducted, and satisfactory results were obtained.

KEYWORDS: transient stability, generator tripping, braking resistor, energy function.

1. INTRODUCTION

Each dynamic system designed or constructed should operate in stable conditions. Under these circumstances, the system must satisfactorily continue to work and stay stable at all times even during the occurrence of faults with a good safety margin [1].

Assuming the system to be in one of its stable modes, if the system eventually returns to its equilibrium condition after a disturbance, we say the system is stable [2],[3]. If it converges to another equilibrium condition close to the former equilibrium condition, we also call the system stable, and we call the system instable if the variables of the system diverge from the equilibrium point over time.

In short, the stability of power systems consists of tendency of the power system to create recovery forces equal or bigger than disturbance forces applying thereto in order to maintain equilibrium condition of the system.

Transient stability studies involve large and sudden disturbance such as the occurrence of a fault, the sudden disconnection of a line, and sudden entry and exit of charges. Transient stability studies the occurrence of a major disruption is essential. The relay setting system studies are required after a major disturbance. These studies are useful for determining the nature of the required relay setting system, specifying the fault removal critical time, determining the voltage levels of system and specifying intersystem power transfer capability.

Different methods such as controlling the generator's excitation, generator tripping [4], fast valving, braking resistor, eliminating time, removal of charge and series capacitors are used to improve transient stability [1], [5],[6].

The above-mentioned methods try to do one or more of the followings:
a) To reduce the impact of turbulence by minimizing intensity of fault and the period thereof.

b) To increase synchronizer forces of recovery.
c) To reduce the acceleration torque through control of input.
d) To decrease the acceleration torque by applying artificial load.

In reference [7], assuming that production unit $\boldsymbol{i}$ consists of n generators, we trip $\frac{1}{n}$ of production in the first stage of production, and if the system remains instable, we increase the production removal.

In reference [8] assuming that unit $\boldsymbol{i}$, as the most instable unit to trip, we must trip the smallest generator of the unit in the first stage, and if the system remain instable, we will continue this process. For the reasons stated in Section 2, it can't use of these two methods.

In generator tripping, for such reasons, the system has to maintain stability where lest number of units can be possibly blown out. Due to its thermal limitations, fixed place of resistor bank and possibility of back swing, however the braking resistor is less efficient than generator tripping. In our proposed combined method, system stability against severe turbulence is tackled with minimum tripping of generator units. At this proposal, the intensity of fault will be valuably lessen by applying braking resistor, and then, for the purpose of improving transient stability, the kinetic energy is reduced by removing certain unit at the right time.

2. GENERATOR TRIPPING

On account of convenience and fastness [9], this control method is one of the most effective methods of improving transient stability [7]. In removal of the generator, itshed a number of high speed generators so that synchronism difference is eliminated and systems return to stable condition.

In this section, we study how generator tripping affects improvement of transient stability. According to Atay's energy function [10], [11]:

$$V = \sum_{i=1}^{n} \frac{1}{2} M_i \dot{\theta}_i^2 - \sum_{i=1}^{n} P_{mi}\,(\theta_i - \theta_{is}) + \sum_{i=1}^{n} \int_{\theta_{is}}^{\theta_i} P_{ei}\, d\theta_i \tag{1}$$

Where:

M_i: Inertia constant of generator i
P_{mi}: Mechanical input power of generators
P_{ei} : Electrical power output of generator
δ_0: Vertex
θ_i: Generator's angle to vertex
θ_{is}: The angle at the stable equilibrium point $(s.e.p)$
θ_{ic} : The angle at the instable equilibrium point $(u.e.p)$

$$M_t = \sum_{i=1}^{n} M_i \tag{2}$$

$$\delta_o = (\sum_{i=1}^{n} M_i \delta_i)/M_t \tag{3}$$

$$\dot{\delta_0} = \frac{\left(\sum_{i=1}^{n} M_i \dot{\delta_i}\right)}{M_t} \tag{4}$$

$$\theta_i = \delta_i - \delta_0 \tag{5}$$

The first, second and third terms in energy equation (1) represent the rotor's kinetic energy, rotor's potential energy, and the energy stored in the system, respectively.

Potential energy at instable equilibrium point (V_c)is equal to:

$$V_c = -\sum_{i=1}^{n} P_{mi}\,(\theta_{ic} - \theta_{is}) + \sum_{i=1}^{n} \int_{\theta_{is}}^{\theta_{ic}} P_{ei} d\theta_{\circ} \tag{6}$$

If$V \leq V_c$ then system is stable & if $V > V_c$ then system is instable.

Considering that the fault period is short, variations of angle are small in equation (1). it neglect terms 2 and 3 of equation (1) versus term 1, therefore:

$$V = V_K = \sum_{i=1}^{n} \frac{1}{2} M_i \dot{\theta}_i^2 = \sum_{i=1}^{n} \frac{1}{2} M_i \left(\dot{\delta}_i - \dot{\delta}_0\right)^2 \tag{7}$$

$$\dot{\delta} = \int_0^T \left(\frac{P_{mi} - P_{ei}}{M_i}\right) dt \tag{8}$$

If it assumed T to be small, P_{ei} remains almost constant, therefore:

$$\dot{\delta}_i = \frac{(P_{mi} - P_{ei}).T}{M_i} \tag{9}$$

Itobtain the following relation by substituting equation (9) in equation (7):

$$V_k = \frac{1}{2} T^2 \left[\sum_{i=1}^{n} \frac{(P_{mi} - P_{ei})^2}{M_i} - \left\{\sum_{i=1}^{n} \frac{(P_{mi} - P_{ei})^2}{M_t}\right\}\right] \tag{10}$$

If it assume T to be the fault removal time (t_f), the relation above gives the kinetic energy during the fault removal time.

In case the system is instable, we should reduce its kinetic energy. To this end, we use generator tripping. In this method, after determining the proper production unit, we should shed a number of generators to reduce the kinetic energy aiming to achievedfor the purpose of achieving sustainability.

If we choose production unit $\boldsymbol{i}$ for reducing the kinetic energy, after tripping a number of generators of unit $\boldsymbol{i}$th, relation (7) is transformed as follows:

$$V_K' = \sum_{i=1}^{n} \frac{1}{2} M_i' \dot{\delta}_i^2 - \frac{1}{2} \dot{M}_t \dot{\delta}_0^2 = \frac{1}{2} T^2 \left[\sum_{i=1}^{n} \frac{(P_{mi} - P_{ei})^2 . M_i'}{M_i^2} - \frac{\left\{\sum_{i=1}^{n} \frac{(P_{mi} - P_{ei}) M_i'}{M_i}\right\}^2}{M_t'}\right] \tag{11}$$

$$M_t' = \sum_{i=1}^{n} M_i' \tag{12}$$

$$\dot{\delta}_0' = \frac{\sum_{i=1}^{n} M_i' \dot{\delta}_i}{M_t'} \tag{13}$$

Comparison of relations (10) and (11)brings us to the conclusion that$V_K' < V_K$, in other words, generator tripping has reduced the kinetic energy and thus has contributed to system stability.

2.1.Proper Tripping Time

Generator tripping issupported at risk sudden changes in mechanical and electrical loading, hit the generator, turbine and power supply systems. Although thermal control units withstand such a blow there is also the possibility that the controls do not operate properly. So, removing the generator should not be done recklessly [12].So, thetime to remove the generator affects on transient stability, the amount of production loss [9] and even the generator protection. According to the mentioned cases, the importance of the time was realized ingenerators removal.

It assume t_0 and t_c to denote the fault time, and the critical time, respectively. The two of the followings occur in faulty system:

a) $t_c > t_{cl}$

In this case, the system is stable andgeneratortrippingmaynot contribute to stability, it may even undermine stability. If the aim is to improve transient stability, it would be better to use other methods.

b) $t_c < t_{cl}$

If the fault's type, severity, and location and system's topology, etc. are such that the critical time (t_c) errors is shorter than fault removal time (which is prescheduled and fixed), the system will be instable in the period from critical time through the time when the appropriate action is taken. The generator must not be tripped in the interval $[t_c, t_{cl}]$ considering the importance of economic factor. We suspend generator tripping as long as possible, because the system may recover stability and there would be no need for generator tripping after the protection system started to operate, for example, after occurrence of short circuit in one of transition lines or switching on of one of the line's keys on the time t_{cl}. Therefore, itused generator tripping in the interval $[t_{cl}, t_{reclose}]$. Considering that kinetic energy increases continuously over time, it should generator tripping as soon as possible in this interval so that stabilization could occur with the least power loss. However, it is better for the trip to be conducted a short while after fault clear, because instant variations of transient energy of the system are very high during the fault period, so it should wait for short while before the generator tripping until these variations decrease so that the power loss of more than expected could be prevented.

Considering the economic factor involved in the control method of generator tripping, it should calculate the minimum number of generatortripping in that unit required for reaching transient stability.

2.2. Determining theAmount of Generator Tripping

It is recommended that the following method, which is based on Athay energy function, be used.

Relations (10) and (11) give the kinetic energy of the system at fault time, and after tripping $\frac{m}{l}$ of generators of unit i, respectively. $V_k - V_K'$is equal to the total kinetic energy of generator units required to be shed in power plant unit j to recover the instability. If α denotes the percentage of remaining generators of power plant unit j, the kinetic energy of the generator tripping from the unit j is equal to:

$$V_K^{shed} = \frac{1}{2}(1-\alpha)M_j\dot{\theta}_j^2 = \frac{1}{2}(1-\alpha)M_j(\dot{\delta}_j - \dot{\delta}_0)^2 = \frac{1}{2}T^2\left[\frac{(P_{mj}-P_{ej})^2.M_j''}{M_j^2} - \frac{\{(P_{mj}-P_{ej})M_j''/M_i\}^2}{M_t''}\right] \quad (14)$$

where:

$$M_j'' = (1-\alpha)M_j \quad (15)$$

$$M_t'' = (1-\alpha)M_j + \sum_{\substack{i=1\\ \neq j}}^{n} M_i \quad (16)$$

Finally:

$$V_K^{shed} = \frac{1}{2}T^2\left[\frac{[(P_{mj}-P_{ej})]^2(1-\alpha)}{M_j} - \frac{[(P_{mj}-P_{ej})(1-\alpha)]^2}{(1-\alpha)M_j+\sum_{\substack{i=1\\ \neq j}}^{n} M_i}\right] \quad (17)$$

Therefore:

$$V_K - V_K' = V_k^{shed} \quad (18)$$

In above relation, α is unknown. After obtaining α, $\beta = 100 - \alpha$, which is the percentage of production, the loss of unit j will be specified.

Therefore, having calculated β, considering that the amount ofgenerator tripping is discrete and is equal to $\frac{m}{l}$, it should choose m in a way that$\frac{m}{l}$ is bigger than or equal to β and is the minimum.

3. BRAKING RESISTOR

Brake resistor is a resistor with the ability to absorb high amount of energy a short period of time; when disturbance occurs, this resistor enters in the system like an artificial electrical charge with high speed and increases consumed power. Absorbing the accelerating energy is created as a result of disturbance. According to the standard of equal levels, level of accelerator becomes lower than the level of brake, which results in improved system stability.

For model the brake resistor in the system, at first consider the system to be without resistance; its admittance matrix will be as follows:

$$\begin{bmatrix} I_G^0 \\ 0 \end{bmatrix} = \begin{bmatrix} Y_{GG} Y_{GK} \\ Y_{GK} Y_{KK} \end{bmatrix} \begin{bmatrix} E_G \\ V_K^0 \end{bmatrix} \quad (19)$$

where:

E_G^i: Voltage behind the transient reactance of straight shaft of ith generator.

$V_K = |V_K|e^{j\theta_K}$: voltage of ***kth*** bus bar without generator.

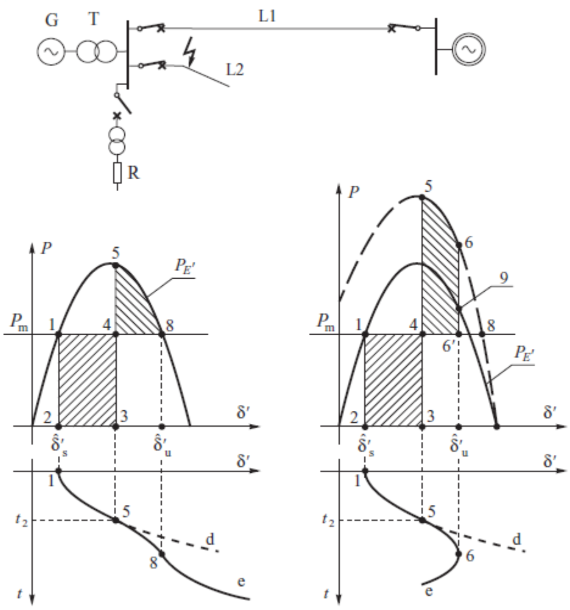

Fig.1. Effect of brake resistoron transient stability [9].

Ithas from relation (19):

$$I_G^0 = Y_G E_G \tag{20}$$

$$Y_G = Y_{GG} - Y_{GK} Y_{KK}^{-1} Y_{GK} \tag{21}$$

where:

Y_G: Matrix of reduced reactance with elimination of all nodes except for the generator's internal nodes.

ith element of ***jth*** column of matrix Y_G regardless of conductance is as follows:

$$Y_{ij} = jB_{ij} \tag{22}$$

For the system with n machine, real output power of ***ith*** generator is as follows:

$$\begin{aligned} P_i &= \mathrm{Re}(E_i I_i^*) = \mathrm{Re}(E_i \sum_{j=1}^{n} Y_{ij}^* E_j^*) \\ &= E_i^2 G_{ii} + \sum_{\substack{j=1 \\ \neq i}}^{n} E_i E_j \{B_{ij} \sin(\delta_i - \delta_j)\} \\ &= P_{oi} + \sum_{j=1}^{n} b_{ij} \sin\delta_{ij} \end{aligned} \tag{23}$$

Conductivity of braking resistor that is connected in parallel to bus is equal to $G_s(t) = \frac{P_s(t)}{|V_k|^2}$,

where:

$P_s(t)$:power absorbed by the resistor

$|V_K|$: Size of voltage of the bus bar on which the brake resistor is installed.

After connecting the braking resistor, the kth element of admittance matrix changes from $Y_{kk}$to $Y_{kk} + G_s$, therefore, relation (21) is rewritten as follows:

$$I_G = Y_G E_G \tag{24}$$

$$Y_G = Y_{GG} - Y_{GK}[Y_{KK} + G_s]^{-1} Y_{KG} \tag{25}$$

$$V_K = K_G E_G \tag{26}$$

$$K_G = -[Y_{KK} + G_s]^{-1} Y_{KG} \tag{27}$$

Since admittance of a busbar is equal to thévenin of k-th bus bar, and assuming$G_{kk} \ll B_{kk}$, ithas:

$$Y_{KK} = G_{KK} + jB_{KK} \cong jB_{KK} = \frac{1}{jX_{Th}} \tag{28}$$

According to equation (28), ithas:

$$\begin{aligned} [Y_{KK} + G_s]^{-1} &= \frac{1}{Y_{KK} + G_s} = \frac{1}{Y_{KK}} \frac{1}{1 + Y_{KK}^{-1} G_s} \\ &\cong Y_{kk}^{-1} \frac{1}{1 + jX_{Th} G_s} \end{aligned} \tag{29}$$

Therefore, because $X_{Th} \ll 1$, it can write:

$$\frac{1}{1+\alpha} \cong 1 - \alpha \tag{30}$$

Therefore, the relation (28) will be written as:

$$[Y_{KK} + G_s]^{-1} \cong Y_{KK}^{-1}(1 - jX_{Th} G_s) \tag{31}$$

Assuming Y_G^0 ،V_G^0،$I_G^0$to denote quantities of the network in the absence of braking resistor, based on relation (31) relations, relations (24) to (26) can be simplified as follows:

$$Y_G \cong Y_G^0 - \Delta Y_G[-jX_{Th} G_s] \tag{32}$$

$$I_G \cong I_G^0 - \Delta Y_G E_G[-jX_{Th} G_s] \tag{33}$$

$$V_K \cong V_K^0 - Y_{KK}^{-1} Y_{KG} E_G[-jX_{Th} G_s] \tag{34}$$

where:

$$\Delta Y_G = Y_{GK} Y_{KK}^{-1} Y_{KG} \tag{35}$$

Equations (32) to (34) give the effect of braking resistor on variables of bus bar.

According to relation (33), current of generator i is as follows:

$$I_i \cong I_i^0 - \Delta I_i[-jX_{Th} G_s] \tag{36}$$

where:

$$\Delta I_i = \sum_{j=1}^{n} \Delta Y_{ij} E_j \tag{37}$$

Therefore, the generators' output power after applying the braking resistor is:

$$P_i = P_i^0 - \Delta P_i[X_{Th} G_s(t)] \tag{38}$$

It is observed that applying of braking resistor results in reduced output power of generators, in other words, it contributes to transient stability by reducing output power of generators.

Installing the resistance bank in the system, regardless of its location, results in recovery of stability to the system by reducing floating accelerating energy in the system. However, the most proper place to install the resistance bank is the low-voltage side of the power transformer connected to generator.

4. COMBINED METHOD OF GENERATOR TRIPPING AND BRAKING RESISTOR

As noted earlier, among advantages of generator tripping are fastness, effectiveness and convenience. This method is used in case of severe incidents in transmission system [12]. At present, private power companies try to make optimization with respect to economic issues. In generator tripping method, the generator's produced power is wasted as the generator produces a power which is not delivered to the customer, therefore, company incurs losses due to wastage of its production on the one hand, and should bear the damages inflicted on the customer due to power cutoff on the other hand.

Braking resistor method has limitations in severe disturbances. Considering that the resistance bank is fixed in its place, this method is less effective in case of faults far away from bank's location. On the other hand, if the resistance bank stay connected for a long time, instability will be likely to occur in the back swing mode [12].

Considering the limitations of resistance bank, resistor braking is ineffective in improving instability in the event of serious fault. Generator tripping must be practiced to improve transient stability due to serious faults. To minimize the number of generator units to be tripped, using the combined method is recommended.

In combined method, first, the resistance bank is switched in the system, which would result in stability through reducing seriousness of the fault. In case the system remains instable, it will practice generator tripping.

According to relation (10), the kinetic energy of generator is directly proportional to generator's output power (P_{ei}). On the other hand, after applying the brake resistor, generator's output power decreases according to relation (41). In other words, it decreases the kinetic energy of the system.

According to relation (21), number of trip,V_k^{sh},decreases as the system's kinetic energy (V_{k}) decreases. As result, braking resistor helps to minimize generator tripping by reducing the effect of fault.

Combined approach has the following advantages:
1) it can be used in the event of serious faults;
2) It reduces the number of generator tripping and as a result reduces fatigue life of generator's shaft;
3) It reduces economic costs;
4) It resolves the back swing problem;
5) It lowers dependence on location of disturbance

5. RESULTS OF SIMULATION

Studies were conducted on 9-bus, 3-genrator unit and 6-line system, simulations were conducted using DIgSILENT software.

It consider unit 1 as slack with voltage of $1.04 < 0^0$. Powers of units 2 and 3 are 163 and 85 MW, respectively.In simulations,it assume the fault to be three-phase error, bus 7, andthe occurrence time to be 0.02 and clearing time to be 0.25 seconds.

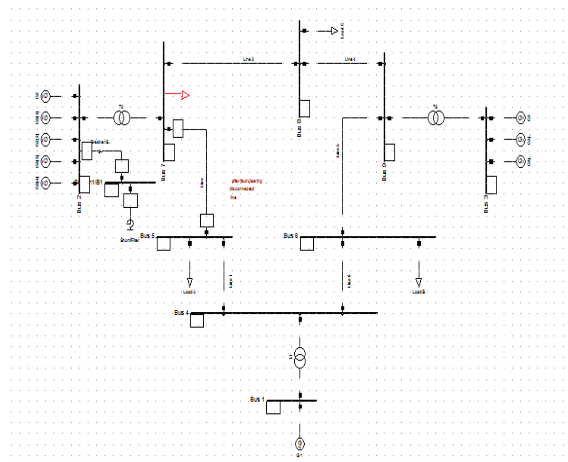

Fig. 2. Singleline diagram of studied network

System's specifications are as table (1):

Table 1. Constant values of generators

Unit Number	Number of parallel machine	H(s)	X'_d (P.U)
1	1	4.775	0.15
2	5	5×0.354	$\frac{1}{5}\times 1.15$
3	3	3×0.583	$\frac{1}{3}\times 0.69$

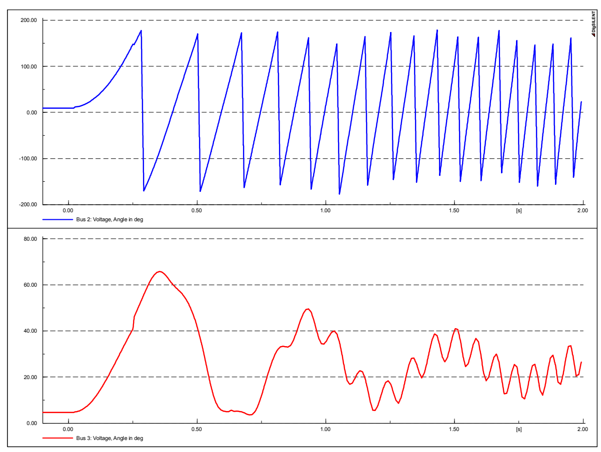

Fig. 3. Respective bus voltage angle of generators before control action

To take due action to improve stability, it should make sure of the instability of system. Fluctuations of the respective bus voltage angle of generators are used to make sure of necessity of applying of production loss method. In this case, oscillation of bus voltage angle in figure (3) show both of generator will be instable.

Use Braking Resistor:

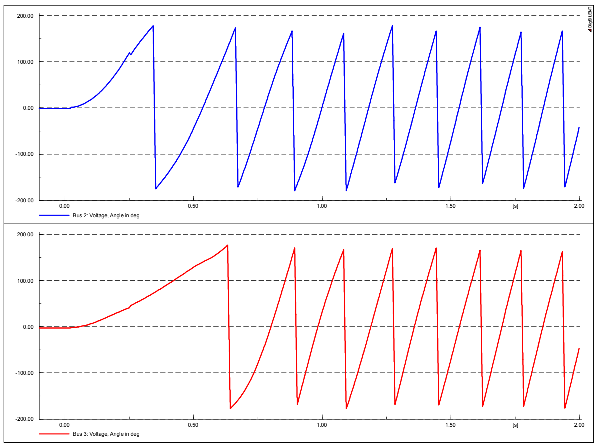

Fig. 4. Respective bus voltage angle of generators after application of brake resistor

The results of simulations show that braking resistor is unable to improve stability in the event of severe fault.

Tripping one generator in power plant 2:

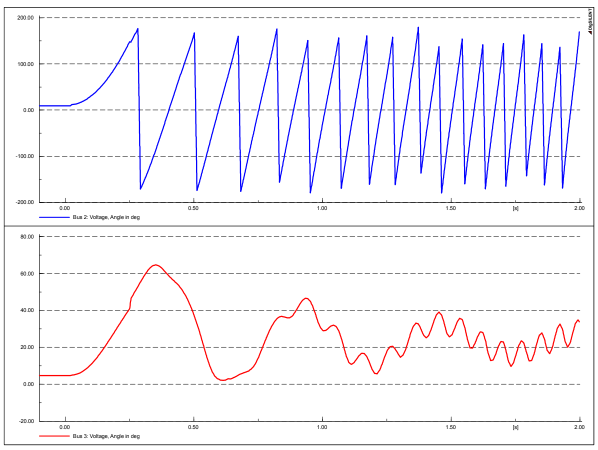

Fig. 5. Respective bus voltage angle of generators after tripof one generator

Tripping one generator is unable to prevent of instability.

Tripping three generators in power plant 2:

Figure (6) show event tripping 3 generators aren't enough to improving transient stability.

It should trip 4 generator units of power plant 2.

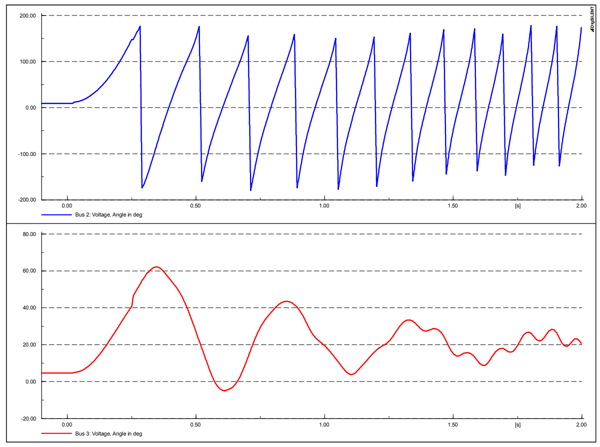

Fig. 6. Respective bus voltage angle of generators after trip of three generators

Application of Combination Method:

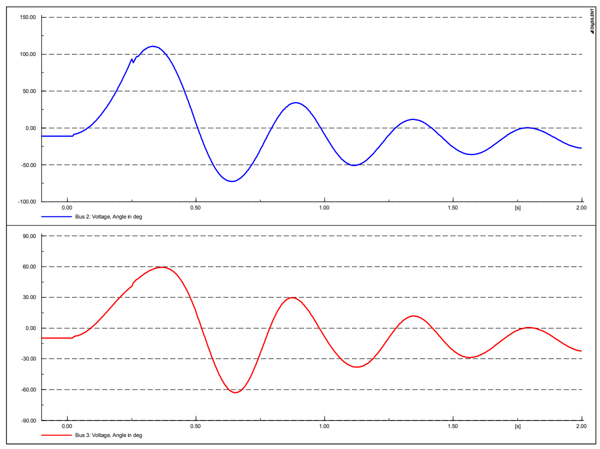

Fig. 7. Respective bus voltage angle of generators after application of combined method

Combined method result to improving transient stability. In this method tripped only one generator after switched braking resistor.

In this section, It use maximum oscillation, critical time and settling of bus voltage angle for evaluate effect different method of improving stability transient.

The results of simulations show that braking resistor is unable to improve stability in the event of severe fault. Control method of generator tripping must be used to recover stability. In case only generatortripping is considered in simulation, it should trip 4 generator units of power plant 2.This number of trip has high economic cost and has negative effect on fatigue life of the shaft if the considerations regarding tripping time of generators are not observed.

If the combined method is used, system will recover stability after tripping only one generator in power plant 2.

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Table 2. Results of comparison between methods

Method	t_{cr} (s)	t_S (s)	M_P
Before control action	0.18 0.18	Unstable 1.75	--- 69
Braking Resistor	0.25 0.25	Unstable Unstable	--- ---
Tripping one generator	0.31 0.31	Unstable 1.62	--- 68
Tripping three generator	0.35 0.35	Unstable 1.54	--- 62
Combined Method	0.38 0.38	1.78 1.5	118 60

If the combined method is used, system will recover stability after tripping only one generator in power plant 2.

6. CONCLUSION

Considering limitations of resistance bank, resistor braking may be ineffective in improving in the event of a serious fault. Generator tripping must be practiced to improve transient stability due to serious faults. In this case, it should trip more than one generator unit to recover stability. To minimize the number of generator units to be tripped out, using the combined method is recommended.

Combined method designed for large fault that need the tripping many generator. In this method there is improving stability transient for far resistor bank.

In this article, production loss values were calculated considering two economic and stability factors.

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