2013 IREP Symposium-Bulk Power System Dynamics and Control –IX (IREP), August 25–30, 2013, Rethymnon, Greece

Dimensioning of EHV Series Braking Resistor for Large Thermal Generators

Mikael Wämundson, Sture Lindahl
Gothia Power AB

Jerker Hagman, Daniel Johansson, Fredrik Heyman
OKG AB

Abstract

This paper describes the possibility to improve transient stability for large generators using a series braking resistor. The method of dimensioning the resistor is presented together with results from dynamic simulations done in power system analysis tool PSS/E.

It is found that adding a series braking resistor to a large thermal generator-turbine set results in a greatly increased transient stability when experiencing a close-up three-phase fault. The critical fault clearance time for the studied unit is increased from 150 ms to well above 250 ms. The simulations show that both the braking resistance and braking time influence the stability margin as well as the energy absorbed by the braking resistor. Results also show that the selection of braking resistance and braking time is not very sensitive to changes in the fault clearance time in terms of preserving transient stability.

Introduction

When a fault occurs close to the generator, the low power factor of the fault current reduces the active power delivered from the unit, forcing the generator to accelerate and increase the machine angle. Usually, the protection systems can clear the fault in a few cycles (well under 100 ms) and thus the machine angle can be kept at reasonable levels. However, for faults cleared from breaker-failure protection the clearance time may be prolonged to above 200 ms. A turbine-generator set gaining kinetic energy during this time may be accelerated to a level causing loss of synchronism. The problem of transient stability can be explained using the swing equation, written as

$$\frac{2H}{\omega_0}\frac{d^2\delta}{dt^2} = P_\mathrm{m} - P_\mathrm{max}\sin\delta - P_\mathrm{AL} \tag{1}$$

where P_m is the mechanical power input to the generator, P_max is the maximum electric power output that can be delivered to the network, H is the turbine-generator set inertia constant, δ is the machine angle, ω_0 is the synchronous speed, P_AL is an artificial load and t is the time. [1]

Under stationary and stable conditions P_m and $P_\mathrm{max}\sin\delta$ are equal – the mechanical power input to the generator is equal to the electric power from the generator. The machine angle is kept constant (somewhere between 0 and 90°) and the generator runs at synchronous speed. Upon a fault close to the generator, P_max will be close to zero causing an acceleration of the generator and increase in the machine angle. When the fault is cleared the active power delivered to the network is, usually, increased well over the mechanical power input – since the machine angle has increased and $P_\mathrm{max}\sin\delta$ reaches its maximum at an angle of 90°. This reverse in sign of the right-hand side of (1) forces the generator to decelerate and decreases the machine angle.

Example

The concept of transient stability can be illustrated with the following example. Fig. 1 shows a simplified single-line diagram of the studied system. A generator is connected to the network through a step-up transformer and two outgoing lines. First figure shows the fault inception on one of the outgoing lines ($t = 1$ s). In middle figure the line is disconnected at the remote end ($t = 1.12$ s), but breaker failure prevents disconnection at generator end. The bottom figure shows the line disconnected by breaker-failure protection – fault cleared.

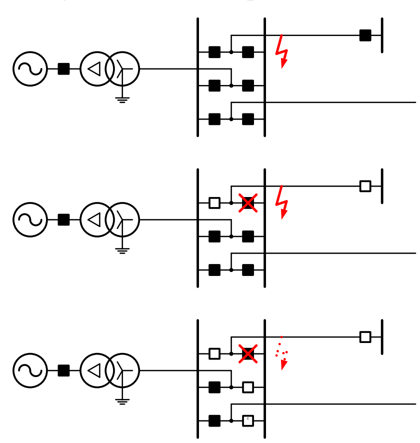

Fig. 1. Sequence of events, from fault inception to fault clearance.

978-1-4799-0199-9/13/$31.00 ©2013 IEEE

Fig. 2 shows the machine angle for two different fault clearance times: 150 and 160 ms. As the fault is applied at $t = 1$ s, the machine angle starts to increase and the generator accelerates. The two curves in the figure show that the critical fault clearance time is 150 ms – for a fault clearance time of 160 ms the generator falls out of step.

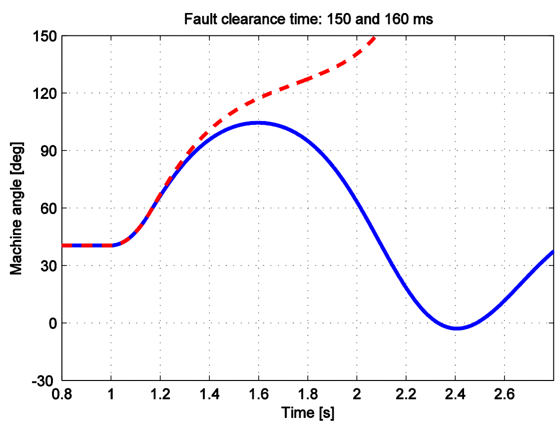

Fig. 2. Machine angle for fault clearance times 150 (solid) and 160 ms (dashed).

An explanation to the difference in success between the two studied cases can be found by examining the mechanical power input to the generator and the electric power output to the network, i.e. the right-hand side of (1) together with the generator speed and machine angle. The values from the simulations are shown in Fig. 3 for a fault clearance time of 150 ms and in Fig. 4 for a fault clearance time of 160 ms.

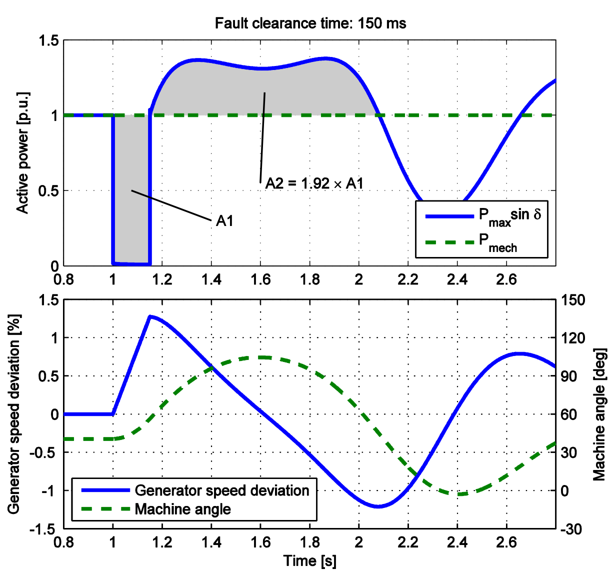

Fig. 3. Mechanical power to the generator and electric power from the generator for a fault clearance time of 150 ms. A1 and A2 indicate the areas (energies) related to acceleration and deceleration, respectively.

As the mechanical power input is greater than the electric power from the generator, indicated by area A1, the generator accelerates. When the fault is cleared the electric power from the generator is greater than the mechanical power input, indicated by area A2 – the generator decelerates.

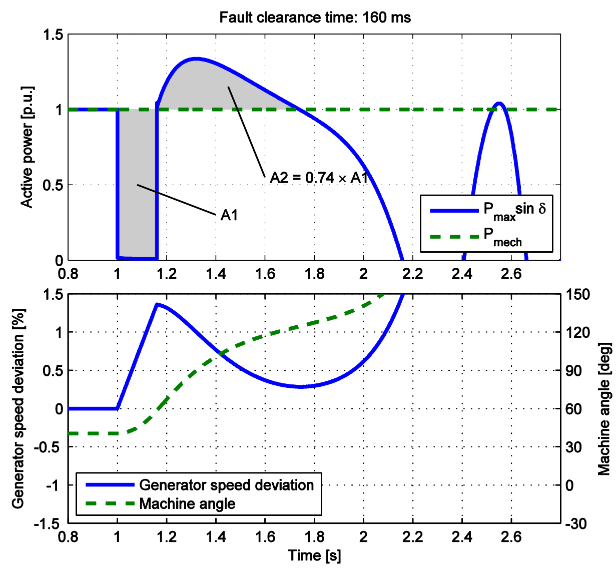

Fig. 4. Mechanical power to the generator and electric power from the generator for a fault clearance time of 160 ms. A1 and A2 indicate the areas (energies) related to acceleration and deceleration, respectively.

By comparing Fig. 3 and Fig. 4 it can be concluded that the kinetic energy gained by the turbine-generator set (area A1) must be delivered to network as electric energy (area A2) for the generator to stay synchronized. For a fault clearance time of 160 ms this fails – only 74 % of the gained energy is delivered to the network before the generator starts to accelerate again. This approach to analyze the problem is called the *equal area criterion*, indicating that area A2 must be at least equal to area A1 for the generator to stay synchronized.

To keep the generator synchronized it is critical to clear the fault before the generator has gained too much kinetic energy due to the acceleration or to reduce the power imbalance – the right-hand side of (1) – by other means.

The transient stability of the generator (the ability to stay synchronized) is dependent on several factors and can be enhanced by the following means [1]:

1. Reduction in the disturbing influence by minimizing the fault severity and duration.
2. Increase of the restoring synchronizing forces.
3. Reduction of the accelerating torque through control of prime-mover mechanical power (reducing P_m in equation (1), i.e., fast valving).

4. Reduction of the accelerating torque by applying artificial load (increasing P_{AL} in equation (1)).

The series braking resistor, discussed in this paper, is aiming to point 4 in the list above, i.e. to increase the active power delivered from the generator during the fault and thereby reducing the risk of transient instability.

The Series Braking Resistor

As stated above, one way of improving the transient stability is to reduce the accelerating torque by increasing the electric energy delivered from the generator during (and after) the fault. This can be achieved by inserting a shunt braking resistor connected to the EHV bus, a shunt braking resistor connected to the generator terminals or a series braking resistor connected in the path from the generator to the external power system. The idea of inserting a shunt braking resistor between the generator terminals and the step-up transformer has been discarded here, due to the high fault current. The principle of the series braking resistor is described in e.g. [2] and [3]. References to some existing installations of shunt braking resistors are found in [4], [5], [6] and [7]. The principal difference in connection of the shunt and series braking resistor can be seen in Fig. 5.

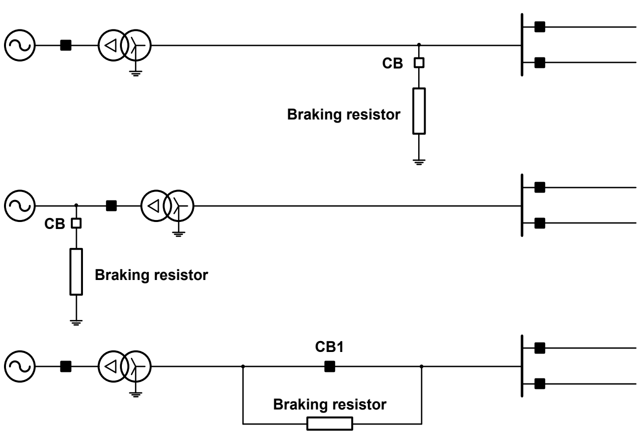

Fig. 5. Principal difference in connection of the shunt braking resistor (top and middle) and series braking resistor (bottom).

Since the improvement in transient stability is related to the active power absorbed by the resistor, an obvious advantage of the series braking resistor can be found by expressing this power. For the shunt braking resistor the power is

$$P_{\mathrm{shunt}} = \frac{U^2}{R} \tag{2}$$

whereas it in the series braking resistor is

$$P_{\mathrm{series}} = I^2 R \tag{3}$$

Since the voltage across the fault is effectively zero the shunt braking resistor will only contribute to the transient stability when the fault has been cleared. One way to improve the effectiveness is to insert the resistor between the generator and the step-up transformer. The series braking resistor, on the other hand, contributes as soon as it is inserted. The remainder of the paper will focus on the series braking resistor.

Without discussing the physical design of the resistor in detail, the connection of the series braking resistor suggested in Fig. 5 has an obvious drawback; during normal operation the braking resistor is energized from the network. A short circuit or ground fault in the resistor will therefore disconnect the entire unit from the network. With a design of the resistor as described in [4], with three single-phase resistors created from several hundred feet of wire strung on towers, the risk of a fault in the resistor is not negligible.

Fig. 6 shows an alternative connection of the series braking resistor, with three circuit breakers; CB1, CB2 and CB3. Under normal conditions CB1 is closed and CB2 and CB3 are open, leaving the braking resistor un-energized. Upon detection of a nearby fault on one of the outgoing lines CB2 and CB3 are closed, energizing the braking resistor. A successful energizing of the braking resistor triggers the opening of CB1, commutating the fault current through the braking resistor.

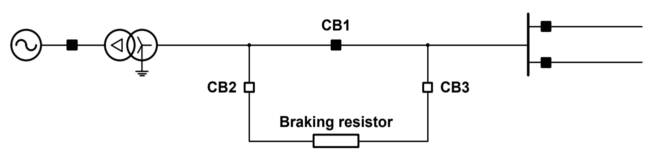

Fig. 6. Connection of the series braking resistor using three circuit breakers.

Comparing the one-breaker to the three-breaker implementation we find, on the other hand that the number of components increases for the three-breaker solution and also the fault rate. In the remainder of the paper the one-breaker implementation will be implied.

Dimensioning of the series braking resistor

In the discussion of simulations and results using the series braking resistor some definitions of the terms used is done in Fig. 7. Note the definition of “braking time”, “activation time” and “deactivation time”.

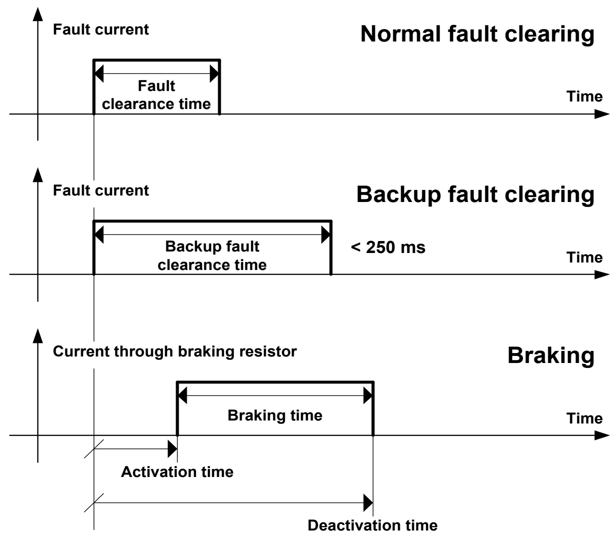

Fig. 7. Definition of terms used in the paper.

In the dimensioning of the braking resistor two parameters are of interest; the braking resistance and the braking time, during which the resistor will absorb and dissipate energy.

It is of importance to choose a braking resistance that will dissipate as much energy as possible during a short period of time, thus minimizing the generator acceleration. Applying the *maximum power transfer theorem* we can conclude that maximum active power delivered from the generator will be found at a resistance of the braking resistor equal to the sum of the generator reactance and the step-up transformer short-circuit reactance. This will be the starting point for further investigations of the resistance. However, the resistive material will have a resistance dependent on the temperature, which will have to be regarded. Also, the generator reactance will change (subtransient to transient reactance) resulting in different optimal resistance values.

The braking resistor needs to be connected in series with the fault as quickly as possible upon fault detection (activation time). Taking into account fault detection time, communication delay and breaker operate time, it is reasonable to assume an activation time around 60 ms.

It is of interest to investigate for how long the braking resistor should optimally be connected (braking time). Some factors play part here; the amount of energy the resistor can absorb/dissipate, limitation in breaker operation cycle speed, and influence on the system stability. In the paper the investigation has been limited to finding the optimal braking resistance and braking time with respect to maximum machine angle.

Results from Simulations

Dynamic simulations have been performed in PSS/E on a system including an 850 MVA synchronous generator experiencing a nearby fault, as in Fig. 5 (bottom). The generator is connected to the bulk network by a 21/420 kV step-up transformer. The generator reactance plus the transformer short-circuit reactance, reflected to the 400-kV side, varies between 93 and 111 Ω in the subtransient to transient range. Applying the *maximum power transfer theorem* we have a reasonable guess of the optimal braking resistance around 100 Ω.

The backup fault clearance time 250 ms (without the series braking resistor the critical clearance time is 150 ms, as illustrated in Fig. 2). The activation time of the braking resistor is 60 ms (implemented by opening CB1). The resistor deactivation time is varied between 160 and 480 ms in steps of 20 ms (braking time 100–420 ms). The resistor deactivation is implemented by closing CB1. For each value of deactivation time, the resistance value is varied between 0 and 320 Ω in steps of 10 Ω.

Thus, in total 17×33 = 561 dynamic simulations have been performed. For each simulation the maximum machine angle (during the first swing) is registered together with the energy absorbed by the braking resistor. From this information Fig. 8 and Fig. 9 are created, showing the maximum machine angle and absorbed energy, respectively.

In Fig. 8 the colored “iso-angles” correspond to different combinations of braking times (*x*-axis) and braking resistance values (*y*-axis) resulting in the same maximum machine angle. From the figure it can be found that the smallest machine angles (around 60°) are found for combinations near 200 ms and 120 Ω.

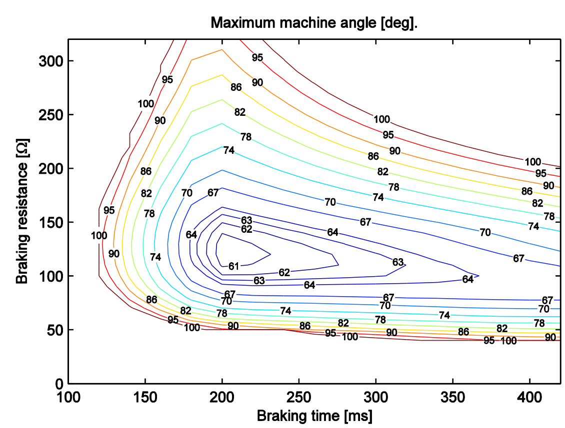

Fig. 8. The maximum machine angle as function of braking time and braking resistance.

In the same way as shown in Fig. 8, a plot of "iso-energies" can be created, shown in Fig. 9, where each curve corresponds to different combinations of braking times (x-axis) and braking resistance values (y-axis) resulting in the same absorbed energy.

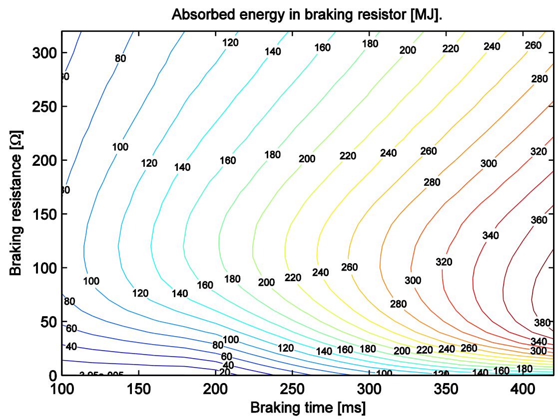

Fig. 9. The energy absorbed by the braking resistor as function of braking time and braking resistance.

From Fig. 8 a braking time of 200 ms and a braking resistance of 120 Ω are selected as "optimal" parameters for the series braking resistor. From Fig. 9 it is seen that the energy absorbed by the resistor during the braking is around 180 MJ.

A sensitivity analysis can be performed around this optimal parameter selection by studying how the maximum machine angle and absorbed energy will depend on changes in the braking time and braking resistance, respectively. The result is shown in Fig. 10 for variations of the braking resistance and in Fig. 11 for variations of the braking time.

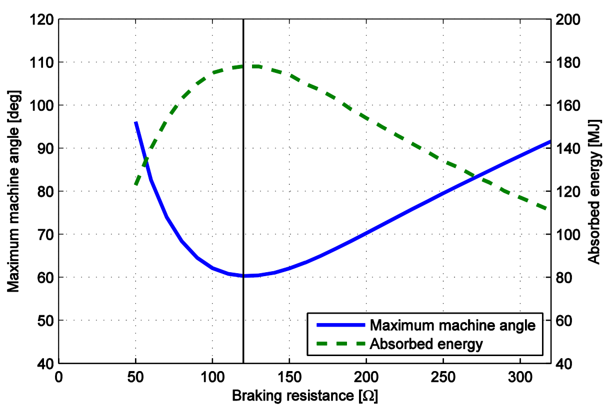

Fig. 10. Maximum machine angle and energy absorbed by the braking resistor as functions of the braking resistance. A braking time of 200 ms is chosen. The braking resistance 120 Ω is indicated.

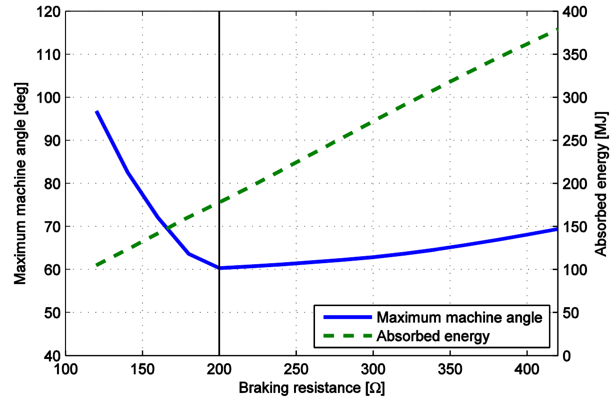

Fig. 11. Maximum machine angle and energy absorbed by the braking resistor as functions of the braking time. A braking resistance of 120 Ω is chosen. The braking time 200 ms is indicated.

From Fig. 11 it can be concluded that the maximum machine angle is not very sensitive to an increase in the braking time from 200 ms. The energy absorbed by the resistor is linearly dependent on the braking time.

In Fig. 12 the transient event is shown in the time domain for a braking time of 200 ms and a braking resistance of 120 Ω. The kinetic energy gained by the generator-turbine set is very moderate and also the increase in machine angle. The unit remains synchronized to the network with sufficient margin.

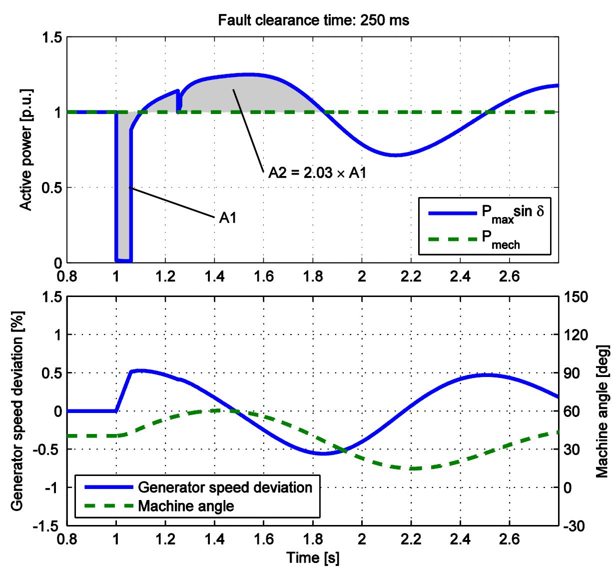

Fig. 12. Mechanical power to the generator and electric power from the generator for a fault clearance time of 250 ms. A1 and A2 indicate the areas (energies) related to acceleration and deceleration, respectively.

Using the same braking resistance, 120 Ω, and the same braking time, 200 ms, the transient stability at a fault clearance time of 150 ms is examined. As stated above, this is the critical fault clearance time for the studied unit without series braking resistor (see Fig. 3). In Fig. 13 the mechanical and electric power is shown together with the machine angle and speed deviation. Compared to a fault clearance time of 250 ms the difference is very small in generator behavior. Compared to the scenario without braking resistor there is a substantial improvement.

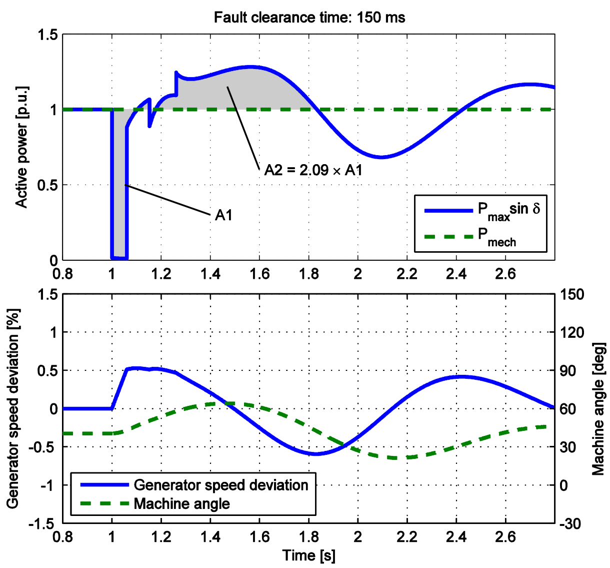

Fig. 13. Mechanical power to the generator and electric power from the generator for a fault clearance time of 150 ms. A1 and A2 indicate the areas (energies) related to acceleration and deceleration, respectively.

Conclusions

Adding a series braking resistor to a large thermal generator-turbine set shows, using dynamic simulations, a greatly increased transient stability when experiencing a close-up three-phase fault. The critical fault clearance time is increased from 150 ms to well above 250 ms. The simulations show that both the braking resistance and the braking time influence the stability margin as well as the energy absorbed by the braking resistor. Results also show that the selection of braking resistance and braking time is not very sensitive to changes in the fault clearance time, in terms of preserving transient stability.

References

[1] Kundur, P., *Power System Stability and Control*, 1994, McGraw-Hill, Inc., USA.

[2] Bergvall, R.C., "Series Resistance Method of Increasing Transient Stability Limit Series Resistance Inserted into Generator Circuit Loads Machines During Fault and Retards Subsequent Overswing", *Transactions of the American Institute of Electrical Engineers*, vol. 50, no. 2, pp. 490–494, June 1931.

[3] Tumilty, R.M., Bright, C.G., Burt, G.M., Anya-Lara, O. and McDonald, J.R., "Applying Series Braking Resistors to Improve the Transient Stability of Low Inertia Synchronous Distributed Generators", *CIRED, 19th International Conference on Electricity Distribution*, Paper No. 0045, Vienna, 21–24 May 2007.

[4] Shelton, M.L., Winkelman, P.F., Mittelstadt, W.A. and Bellerby, W.J., "Bonneville Power Administration's 1400 MW Braking Resistor", *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-94, no. 2, pp. 602–611, March/April 1975.

[5] Ellis, H.M., Hardy, J.E., Blythe, A.L. and Skooglund, J.W., "Dynamic Stability of the Peace River Transmission System", *IEEE Transactions on Power Systems*, PAS-85, no. 6, pp. 586–600, June 1966.

[6] Grobovoy, A.A. and Lizalek, N.N., "Multiple Dynamic Brake and Power System Emergency Control", *Proceedings of the International Conference on Power System Technology*, POWERCON '98, vol. 2, pp. 1351–1355, 1998.

[7] Peelo, D.F., Hein, D.W. and Peretti, F., "Application of a 138 kV 200 MW braking resistor", *Power Engineering Journal*, vol. 8, no. 4, pp. 188–192, 1994.