Transient Stability Enhancement of Multi-Machine Power System Based on PID Controlled Dynamic Braking Strategies

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Abstract. The Braking Resistor (BR) or Dynamic Brake known as one of the effective practices to enhance the transient stability of synchronous generators and power systems, following a significant disturbance. In this paper, two methods for calculating the value of BR, one by using a one per unit value of BR, and the other one by using calculating criteria or equation to find the value of BR which will give a cost-wise analysis. Also, by using the Thyristor Controlled Braking Resistor (TCBR) with a PID Controller for the control of the insertion of the braking resistor to enhance the transient stability of the proposed power system, the so-called IEEE9Bus System (or Two Machines to Infinite Bus System). Comparison is made in terms of the speed deviation and load angle of the synchronous generators while using the calculated BR and the one per unit BR which will give us a cost-wise analysis when choosing the brake and the effectiveness of the brake to enhance the transient stability of the proposed power system.

Keywords: Braking Resistor (BR), TCBR, PID, IEEE9Bus System, Transient Stability.

1. Introduction

To make the power grid systems self-sufficient, reliable, and more efficient, plenty of studies executed in different areas of the power grid systems generally called the power system stability. We will take one part of the power system stability and study it, which is known as transient stability. Transient stability is a common term in studying power systems known as the tendency that a power system needs to develop for restoring forces equal to or greater than the disturbing forces to maintain the state of equilibrium [1]. Both the initial state of the system and the severity of the disturbance are affecting the transient stability. A lot of changes and developments are undergoing the power grid systems, and these changes will affect the. Dynamic Braking is one of the powerful methods for transient stability enhancement as per the preliminary studies [2]–[7]. The Braking Resistor (BR) can be viewed as a fast dummy load injection to absorb surplus transient energy of an area that arises due to severe system disturbances. In order to insert BR, the switching time is required, and the value BR is a critical factor for this matter, for that several research papers reported in the previous literatures [7]–[21]. In this paper, a PID controller is proposed for the switching process of the BR, and we are using the equation number one for calculating the value of BR, which is derived by [7]. Also, we will use one per unit value of BR to study the effect and the differences between using minimum value and calculated value. The problem of transient stability is formulated to determine the maximum time through which a fault can be allowed to remain without losing synchronism of the power system. This time is called the critical clearing time (CCT) of the power system, which is a crucial factor for the transient stability of the power system. If the fault duration is less than CCT, the system will remain stable; otherwise, the system will not be stable. Later on in the paper, we will observe how CCT is calculated [7].
\[ P_f = \frac{a + BR^2 + b + BR}{d + BR^2 + c} \]  \hspace{1cm} (1) [7]

**Where:**

- \( P_f \) = Power of the faulted bus
- \( a = (X_1 + X_2) \cdot V_b \cdot \sin \delta \)
- \( b = (X_1 \cdot E)^2 + (X_1 \cdot X_2 \cdot V_b \cdot E \cdot \cos \delta) \)
- \( c = (X_1 \cdot X_2)^2 \)
- \( b = (X_1 + X_2)^2 \)
- \( X_1 = X_t \); Transmission line reactance
- \( X_2 = X_c + X_d \); Transformer reactance + Generator transient reactance
- \( V_b \) = Infinite bus voltage
- \( E \) = Terminal voltage
- \( \delta \) = Load angle

This equation will determine the optimum value of BR that will be inserted and using the MATLAB program to write an m-file to calculate the value of BR automatically for any given system rather than calculating the value of BR manually. This m-file has been given in Appendix – A.

**2. Research Method**

In this work, an IEEE9bus system model has been utilized for the simulation of transient stability enhancement, as shown in Figure 1, using the MATLAB/Simulink program. This model consists of two synchronous generators that are feeding three different loads, also an infinite bus that has been simulated as a synchronous generator as well. The synchronous generators are feeding through step-up transformers and transmission lines, and all the parameters of the proposed system are detailed in Appendix – B. Circuit Breakers (CB) are connected as a protection device to isolate the faulted line.

**Figure 1.** IEEE9Bus System Model \[25\]
The Automatic Voltage Regulator (AVR) is shown in Figure 2, and the Governor (GOV) is fixed to mechanical power with a value that equals the power factor of the related generator. Both AVR and GOV control the system model and are presented in the simulation. In the simulation, a three-line to ground fault (3LG Fault) occurs one time at the bus No. 7, and one time at bus No. 9 near the related generator, respectively, in order to simulate the sever case that a power system can handle and face, the simulated fault is permanent and chosen to occur at one second of the simulation time that equals to ten seconds. The simulation of the proposed system is executed using a 100 MVA as a base MVA and 529 ohms as a base impedance.

3. Critical Clearing Time (CCT) Measurement:
The simulation procedure executed using the MATLAB/Simulink environment with a simulation time of ten seconds and a step time of fifty microseconds (50μs). The three-line to ground fault (3LG Fault) is simulated at one second by giving the MATLAB program a value of one in the workspace and expressed as "FT," fault time. After that, the clearing time of the fault is chosen and expressed as "CT," clearing time. With the condition that CT is bigger than FT, by using the bisection method [22], a CCT is measured using the simulating for each time until reaching a clearing time (CT) at which the system keeps synchronism. After several trials and errors, the CCTs for the IEEE9Bus model were measured, and it is 65ms for bus No. 7 and 150ms for bus No. 9.

The purpose of the study is to enhance the transient stability limit by using BR units, and after doing so, the CCT of the model is enhanced, and the results will be shown later in this paper.

4. Thyristor Controlled Braking Resistor (TCBR):
The BR units were inserted using the Thyristors with the PID controller, for that it is called Thyristor Controlled Braking Resistor (TCBR) as shown in Figure 3; this controlling is a combination of six (6) thyristors connected as three sets, each consists of two thyristors, namely T1 and T2, connected back-to-back in series with the BR unit. Each one of the sets is for one of the phases of the power system.

5. PID Controller:
The PID controller, shown in Figure 5, is designed to generate respective triggering signals for each model. It consists of a classical proportional integral derivative (PID) controller, a limiter, and a mathematical block with a constant entry of 180 named "K." The PID controller, shown in Figure 6, designed to use the speed deviation, Δω, of the generator used as the input of the PID, and the output α fed to the limiter block that is used to limit the output of the PID controller within the range of L-min equals zero, and L-max equals 180 as required for the
operation of the TCBR. The parameters of the PID controller are $K_P = 3$ and $T_I = 0.0000003$; these parameters are determined using trial and error, and the procedure to determine these parameters is based on the Ziegler-Nichols tuning method [23].

![PID Control Diagram](image1)

**Figure 4. PID Control Diagram**

![PID Controller](image2)

**Figure 5. PID Controller**

6. Simulation Procedure:
Using the MATLAB/Simulink program to construct the model, as shown in Fig. (5) then running the program with a simulation of three-line to ground fault (3LG fault), CCT is measured and after a clearing time (CT) that is beyond CCT the system lost synchronism, at that CT, the BR is inserted, and simulation is executed for both calculated BR and one per unit BR. For both values of BR, the system restores its equilibrium and runs in synchronism. The simulation shows the responses of the speed deviation, load angle, and the current values running through the BR unit.

7. Simulation Results and Discussion:
The simulation results, shown in Figures (6 – 15), showed the speed deviation and load angle of the synchronous generators for both one (1) per unit of BR and calculated value of BR. The maximum absorbed power by the BR units and the maximum currents passing through the BR units are shown in Table 1 and Table 2.

| BR Per Units | CCT (ms) | Enhanced CCT (ms) | Max. Power (MW/Phase) | Max. Current (Amps/Phase) |
|--------------|----------|-------------------|-----------------------|--------------------------|
| 1.0          | 65       | 130               | 367.74                | 1,715.2                  |
| 1.75         | 65       | 130               | 162.05                | 1,138.6                  |

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| 1.0          | 150      | 180               | 367.74                | 1,715.2                  |
| 1.51         | 150      | 180               | 162.05                | 1,138.6                  |
**Figure 6.** Relative Load Angle Buses 7&9

**Figure 7.** Speed Deviation With & Without BR, Bus 7 & BR = 1 pu
Figure 6. Relative Load Angles with BR, Bus 7 & BR = 1 pu

Figure 7. Speed Deviation With & Without BR, Bus 7 & BR = 1.75 pu
Figure 8. Relative Load Angles with BR, Bus 7 & BR = 1.75 pu

Figure 9. Speed Deviation With & Without BR, Bus 9 & BR = 1 pu
Figure 10. Relative Load Angles with BR, Bus 9 & BR = 1 pu

Figure 11. Speed Deviation With & Without BR, Bus 9 & BR = 1.51 pu
8. Conclusion:
The power system has been enhanced by improving the CCT of the power system. CCT improved from 65 ms to 130 ms at bus No. 7 utilizing the braking resistor with values of 1 pu and 1.51 pu, respectively. Also, CCT improved from 150 ms to 180 ms at bus No. 9 utilizing the braking resistor with values of 1 pu and 1.75 pu, respectively.

The controlling method was a PID controller that has been used to have the triggering angles for the system as per the speed deviation of the generators and has shown good responses. The results in CCT using different values of BR are indicating a cost-wise concerning choosing the right and the proper BR value. Different fault locations have been studied in this work, and the dynamic braking resistor showed a good performance in enhancing the transient stability of the proposed power system.

Appendix – 1
The m – file programmed by the MATLAB program to calculate the optimal value of the braking resistor (BR).

% Braking Resistor Calculating Program
syms Rb P_Rb % Defining Variables.
XL = input ('Enter reactance value of the transmission line. 
');
Xt = input ('Enter reactance value of the transformer. 
');
Xdash = input ('Enter transient reactance value of the synchronous generator. 
');
E = input ('Enter the value of the terminal voltage. 
');
Vb = input ('Enter the voltage value of the infinite bus. 
');
P_Rb = input ('Enter the power value of the faulted system. 
');
X = Xdash + Xt + (XL/2);
Pmax = (E*Vb)/X;
delta = asin(P_Rb/Pmax);
X1 = XL;
X2 = Xt + Xdash;
A = (X1+X2) * E * Vb * sin(delta);
B = (X1^2+E^2)+(X1*X2*E*Vb*cos(delta));
C = (X1 * X2)^2;
D = (X1 + X2)^2;
Num = (A*Rb^2)+(B*Rb);
Den = (D*Rb^2)+(C);
S1 = (Num)/Den==P_Rb; % S1 = Arbitrary Variable
delta = delta * (180/pi);
BR = round(double(solve(S1,Rb)),2)
Appendix – 2
The parameters of the IEEE9Bus Power System Model [24]

Table 3. Transmission Line Parameters

| Transmission Line | R (pu) | X (pu) | B (pu) |
|-------------------|--------|--------|--------|
| 1 – 4             | 0      | 0.0576 | 0      |
| 2 – 7             | 0      | 0.0625 | 0      |
| 3 – 9             | 0      | 0.0586 | 0      |
| 4 – 5             | 0.0100 | 0.0850 | 0.176  |
| 4 – 6             | 0.0170 | 0.0920 | 0.158  |
| 7 – 5             | 0.0320 | 0.1610 | 0.306  |
| 7 – 8             | 0.0085 | 0.0720 | 0.149  |
| 9 – 6             | 0.0390 | 0.1700 | 0.358  |
| 9 – 8             | 0.0119 | 0.1008 | 0.209  |

Table 4. Synchronous Generators Data

| Synchronous Generator | No. 1 (Slag Bus) | No. 2 (PV Bus) | No. 3 (PV Bus) |
|------------------------|------------------|----------------|----------------|
| Rated MVA              | 247.5            | 192.0          | 128.0          |
| MW                     |                  | 163.0          | 85.00          |
| Rated KV               | 16.50            | 18.00          | 13.80          |
| X_d                    | 0.361            | 1.720          | 1.680          |
| X_d'                   | 0.150            | 0.230          | 0.232          |
| X_q                    | 0.239            | 1.650          | 1.610          |
| X_q'                   | 0.100            | 0.230          | 0.232          |
| T_{d0}                 | 8.960            | 6.000          | 5.890          |
| T_{q0}                 | 0.001            | 0.530          | 0.600          |
| X_l                    | 0.062            | 0.422          | 0.314          |
| H                      | 9.550            | 3.330          | 2.350          |
| R_a                    | 0.000            | 0.000          | 0.000          |

Table 5. Load Data

| Load Bus | Real Power (MW) | Reactive Power (MVAR) |
|----------|-----------------|-----------------------|
| 5        | 125.0           | 50.0                  |
| 6        | 90.0            | 30.0                  |
| 8        | 100.0           | 35.0                  |

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