Coordinated control of energy storage electric brake device and generator

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Abstract. The application of Super Capacitor energy storage Brake Device (SCBD) in the electrical braking system of Hydrogenerator can not only assist the rapid shutdown of hydrogenerator, but also significantly provide the ability to resist large disturbance of the system, which is conducive to the improvement of the transient stability of the system. Based on the principle of capacitor energy storage, the differential algebraic model of SCBD and generator excitation and speed regulation system is derived in this paper, and the multi index nonlinear control is used to design the coordinated controller. In order to verify the effect of SCBD on generator system, three-phase short circuit simulation with and without SCBD and voltage regulation disturbance simulation are carried out. The simulation results show that the SCBD braking effect is obvious and the transient stability of the system is improved significantly.

1. Introduction
Because of the short start-up time, hydropower units play the role of frequency modulation and peak load regulation in the power grid, and the number of start / stop is very frequent. During the shutdown of the unit, in order to prevent the thrust bearing from being damaged due to long-term friction, the auxiliary equipment must be used for quick braking [1]. The mechanical switch is used to switch the water resistance at the end of the generator in the traditional hydraulic generator unit braking, and the control of the switching time belongs to the discrete control. The research in this field has made some achievements at home and abroad [2, 3], but this braking mode can not be fast and flexible switching, and can not meet the requirements of ensuring the stable operation of the unit. In reference [4] it is proposed to use thyristor controlled braking resistor to realize electric braking. Although this method can improve the transient stability of the water turbine unit, it will cause unnecessary energy loss of the system because the resistor is an energy consuming element. In reference [5], an energy storage electric braking mode with super capacitor is proposed, as shown in Figure 1, and in this paper, only the coordinated control of generator excitation control, power control and SCBD. Finally, differential algebraic multi index nonlinear control (DAMNC) is designed to coordinate the controller [7], focusing on the analysis of the dynamic and static response effect of the system with or without SCBD.
Fig. 1 Structure of super capacitor energy storage braking device

2. System model

2.1. Mathematical model of SCBD
It can be seen from Figure 1 that according to Kirchhoff’s law and energy conservation theorem, the mathematical model of SCBD in rotating coordinate system can be established as follows

\[
\begin{align*}
\frac{di_d}{dt} &= -Ri_d + \omega q + \frac{U_{gd}}{L} - V_d \\
\frac{di_q}{dt} &= -Ri_q - \omega d + \frac{U_{gq}}{L} - V_q \\
\frac{dt}{dt} &= \frac{3(V_d i_d + V_q i_q)}{2C u_{dc}} - \frac{u_{dc}}{C R_1}
\end{align*}
\]

Where, \(U_{gd}, U_{gq}\) are the DC and AC shaft voltages of the SCBD access point respectively; \(i_d, i_q\) are the DC and AC shaft currents injected into the SCBD system respectively; \(V_d, V_q\) are the DC and AC shaft voltages output from the AC side of the bidirectional converter respectively; \(R\) is various losses; \(R_1\) is the energy dissipation resistance; \(L\) is the output filter inductance; \(C\) is the capacitor bank; \(u_{dc}\) is the DC side voltage.

Without considering the influence of system resistance, the phase relationship between the output voltage of bidirectional converter (\(V\)) and the voltage of access point (\(U_{gq}\)) is shown in Figure 2.

Fig. 2 Relationship between output voltage of converter and system voltage vector

\[
\begin{align*}
V_d &= V \sin(\delta + \alpha) \\
V_q &= V \cos(\delta + \alpha)
\end{align*}
\]
Where: $\delta$ is the power angle of the generator; $\alpha$ is the phase of the output voltage of the bidirectional converter $V$ or the voltage of the lagging access point $U_g$.

According to the reference [8], it can be seen that the exchange relationship between AC and DC voltage of bidirectional converter is as follows:

$$V = 0.3536M u_{dc}$$

(3)

According to formula (1), (2) and (3), the mathematical model of SCBD in rotation coordinate is

$$
\begin{align*}
\frac{d i_d}{dt} &= -\frac{R_i}{L} i_d + \omega i_d + \frac{U_{sy} - u_{a} u_{dc}}{L} \\
\frac{d i_q}{dt} &= -\frac{R_i}{L} i_q - \omega i_q + \frac{U_{sy} - u_{a} u_{dc}}{L} \\
\frac{d u_{dc}}{dt} &= \frac{3(V_d i_d + V_q i_q)}{2Cu_{dc}} - \frac{u_{dc}}{CR_1}
\end{align*}
$$

(4)

Where $u_{a} = 0.3536M u_{dc} \sin(\delta + \alpha), \ u_{a} = 0.3536M u_{dc} \cos(\delta + \alpha)$

2.2. Differential algebraic model of hydraulic turbine gate, excitation and SCBD

For the control system of hydroelectric generating set, the fifth order differential equation is often used to describe in engineering [9].

$$
\begin{align*}
E'_q &= \frac{-E_q + E_{q0}}{T_{d0}} \\
\dot{\omega} &= \omega - \omega_0 \\
\omega &= \frac{\omega_0 (P_m - P_g)}{T_j} - D(\omega - \omega_0) \\
P_m &= \frac{2[-P_m + (1 + T_w / T_y) \mu] - 2U_w}{T_y} \\
\mu &= \frac{U_w}{T_y}
\end{align*}
$$

(5)

The differential algebraic models of gate, excitation and SCBD can be obtained by combining equations (4) and (5). Among them, $[x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8]^T = [E'_q, \delta, \omega, P_m, \mu, i_d, i_q, u_{dc}]^T$ are the state quantity, namely, the generator transient potential, power angle, angular speed, mechanical power input to the generator, valve opening, DC and AC shaft current injected into SCBD by the system, and DC side voltage of converter; $[u_1, u_2, u_3, u_4]^T = [E_{qe}, U_w, u_{a}, u_{n}]^T$ are the control quantity; $T_j, T_y, T_w$ are the corresponding time constant; are the generator no-load potential and output electromagnetic power respectively; $E_q, T_{d0}$ are the generator no-load potential and output electromagnetic power respectively; $\omega_0, D$ are the synchronous speed and generator respectively. Damping coefficient; in the formula, except that the units of $\omega, \delta$ and time constant are $\text{rad} / \text{s}, \ \text{rad}, \ \text{s}$ respectively, the rest are unit values.

The relationship between constraint variable and state quantity is...
Where \( x_e = x_T + 0.5x_L \); \( P_s \) and \( Q_s \) are the active power and reactive power injected into SCBD respectively. Suppose that the algebraic constraint variables of the system are \( \begin{bmatrix} w_1, w_2, w_3, w_4, w_5, w_6 \end{bmatrix} = \begin{bmatrix} I_{gd}, I_{gy}, U_g, P_s, P_q, Q_q \end{bmatrix} \), then the model composed of formula (4) and formula (5) can be written as the standard form of multi input and multi output nonlinear differential algebraic model.

\[
\begin{align*}
\dot{x} &= f(x, w) + g(x, w)u \\
p(x, w) &= 0 \\
y &= h(x, w)
\end{align*}
\] (7)

3. Design of integrated controller of turbine and SCBD based on DAMNC

3.1. Design principle of DAMNC

All The basic idea of DAMNC is to select the output function containing state quantity (\( x \)) and constraint variable (\( w \)) according to the number of control quantities

\[
y = \begin{bmatrix} h_1(x, w) \\ \vdots \\ h_i(x, w) \end{bmatrix} = C_1x + C_2w
\] (8)

Where, \( C_1 \) and \( C_2 \) are state variable (\( x \)) and algebraic constraint variable (\( w \)) parameter matrix respectively.

The total relative order of the general output function is smaller than the dimension of the system, so the linear subsystem and the nonlinear subsystem of \( i \) space can be obtained by coordinate transformation \( \dot{i} = \Phi(x, w) \) [10].

\[
\begin{align*}
\dot{i}_1 &= i_x, \dot{i}_2 = i_3, \ldots, \dot{i}_{\beta_a} = v_1 \\
\vdots
\dot{i}_{\beta_a + 1} &= i_{\beta_a + 2}, \ldots, \dot{i}_{\beta_a} = v_\sigma \\
\dot{i}_{\beta_a + 1} &= \eta_l(x, w), \ldots, \dot{i}_n = \eta_{n-\beta_a}(x, w)
\end{align*}
\] (9)

In formula (10), \( y = Bu + a \), where \( B = \begin{bmatrix} M_{g1}M_{f1}^{-1}h_1 & \cdots & M_{g1}M_{f1}^{-1}h_n \\ \vdots & \ddots & \vdots \\ M_{g\sigma}M_{f\sigma}^{-1}h_1 & \cdots & M_{g\sigma}M_{f\sigma}^{-1}h_n \end{bmatrix} \), \( a = \begin{bmatrix} M_{f1}h_1 \\ \vdots \\ M_{f\sigma}h_{\sigma} \end{bmatrix} \)

For \( \sigma \) linear subsystems in \( i \) space, based on the quadratic performance index, the control law (\( v \)) is designed and then the control law (\( u \)) is inversely solved shown as
Where $K$ is the feedback coefficient matrix. The final anti disturbance decoupling control law $(u)$ can be obtained by combining formula (8) and formula (10).

$$u = -B^{-1}(a + Ki)$$  \hspace{1cm} (10)

It can be seen from equation (11) that the control law $(u)$ is composed of anti-interference term and initial value, with clear physical meaning.

3.2. Design of coordinated controller for excitation speed control system and SCBD of hydraulic turbine

According to the design principle of DAMNC, the key of controller design is to select the appropriate output function and determine the coordinate mapping relationship [11]. According to the control target corresponding to the control quantity, the output function can be expressed as

$$h_i(x, y) = c_{i1} \Delta U_g + c_{i2} \Delta \omega$$
$$h_2(x, y) = c_{21} \Delta P_+ + c_{22} \Delta \omega + c_{23} \Delta \mu$$
$$h_3(x, y) = c_{31} \Delta P_+ + c_{32} \Delta i_d$$
$$h_4(x, y) = c_{41} \Delta U_g + c_{42} \Delta Q_+ + c_{43} \Delta i_q$$  \hspace{1cm} (12)

Where, $C_1$ and $C_2$ are respectively expressed as follows

$$C_1 = \begin{bmatrix} 0 & 0 & c_{i3} & 0 & 0 & 0 & 0 \\ 0 & 0 & c_{i4} & 0 & c_{i5} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{i6} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{i7} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & c_{i8} \end{bmatrix}, \quad C_2 = \begin{bmatrix} c_{i1} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & c_{i3} & 0 \\ 0 & 0 & 0 & c_{i4} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

After calculating $\frac{\partial p}{\partial w}$ and $\frac{\partial p}{\partial x}$, substitute them into matrix $B$, and arrange them as follows

$$B = \begin{bmatrix} M_{s1}^\phi h_1 & M_{s2}^\phi h_2 & M_{s3}^\phi h_3 & M_{s4}^\phi h_4 \\ M_{s5}^\phi h_1 & M_{s6}^\phi h_2 & M_{s7}^\phi h_3 & M_{s8}^\phi h_4 \\ M_{s9}^\phi h_1 & M_{s10}^\phi h_2 & M_{s11}^\phi h_3 & M_{s12}^\phi h_4 \\ M_{s13}^\phi h_1 & M_{s14}^\phi h_2 & M_{s15}^\phi h_3 & M_{s16}^\phi h_4 \end{bmatrix}, \quad M_{g1}^\phi M_{g2}^\phi h_{i,j} = \left(\frac{\partial h_j}{\partial x} - \frac{\partial h_j}{\partial w} \left(\frac{\partial p}{\partial w}\right)^{-1} \frac{\partial h_j}{\partial w}\right) g_{ij}, (i, j = 1, 2, 3, 4)$$

By substituting the initial operating point of the system into $B$, we can know that the matrix is full rank. Because of relative order $r = 4 < 8$, it is still necessary to construct four smooth functions that satisfy the relation formula $M_{g1}^\phi \phi_j(x, w) = 0 (i, j = 1, 2, 3, 4)$. After observation, they can be taken as

$$\phi_1(x, w) = \Delta \delta, \phi_2(x, w) = \Delta \omega, \phi_3(x, w) = \Delta P_+, \phi_4(x, w) = \Delta i_d + \Delta i_q + 0.75 \Delta \mu / (CL)$$

Then the nonlinear coordinate transformation that satisfies the following relations can be constructed, shown as follows:

$$i = \begin{bmatrix} i_1, i_2, i_3, i_4, i_5, i_6, i_7, i_8 \end{bmatrix}^T = \begin{bmatrix} h_1(x, w), h_2(x, w), h_3(x, w), h_4(x, w), \phi_1(x, w), \phi_2(x, w), \phi_3(x, w), \phi_4(x, w) \end{bmatrix}^T$$

Finally, the control law $(u)$ of DAMNC can be obtained from equation (11).
4. Digital simulation

4.1. Introduction to simulation system

With the help of MATLAB simulation system, this paper compares DAMNC control method with linear optimal control (LOC) to verify the superiority of DAMNC method in controller design. The three-phase short circuit simulation of the system is carried out, and the dynamic response of the system with and without SCBD is analyzed. Taking a hydropower station in Guangxi as an example, the basic operation parameters of the system are as follows: \( x_d = 1.09 \text{ pu}; x_q = 0.728 \text{ pu}; \)

\[
x'_d = 0.42 \text{ pu}; x_T = 0.169 \text{ pu}; x_L = 0.242 \text{ pu}; T_{d0} = 6.2s; T_j = 7s; T_w = 1s; T_y = 0.5s; \]

Basic parameters of SCBD: \( R = 0.05 \text{ pu}; L = 0.1 \text{ pu}; C = 0.6 \text{ pu}; R_l = 0.3 \text{ pu} \).

Initial operation condition of the combined system: \( P_{g0} = 0.9 \text{ pu}; Q_{g0} = 0.06 \text{ pu}; U_{g0} = 1.05 \text{ pu}; U_0 = 1.0 \text{ pu}; \delta_0 = 43.6^\circ \).

The parameter matrix \( C \) and feedback coefficient matrix \( K \) of DAMNC method are configured as follows:

\[
C_1 = \begin{bmatrix}
0 & 0 & 3 & 0 & 0 & 0 & 0 \\
0 & 0 & 4 & 0 & -8 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.5 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.5
\end{bmatrix},
C_2 = \begin{bmatrix}
-5 & 0 & 0 & 0 \\
0 & 0 & 0 & -2 \\
0 & 0 & 4 & 0 \\
0 & -24 & 0 & 0
\end{bmatrix}, \quad K = \begin{bmatrix}
10 & 0 & 0 & 0 \\
0 & 10 & 0 & 0 \\
0 & 0 & 20 & 0 \\
0 & 0 & 0 & 10
\end{bmatrix}
\]

The control law of LOC design is

\[
\rho = \begin{bmatrix}
r_1 \Delta \omega + r_{12} \Delta U_g \\
r_21 \Delta P_g + r_{22} \Delta \mu \\
r_31 \Delta P_s + r_{32} \Delta i_d \\
r_41 \Delta Q_s + r_{42} \Delta i_q + r_{43} \Delta U_g
\end{bmatrix} + \begin{bmatrix}
E_{q e0} \\
U_{w0} \\
u_{a0} \\
u_{b0}
\end{bmatrix}
\]

4.2. Introduction to simulation system

In order to verify the effect of SCBD on system stability, this section starts from whether the system is connected to SCBD, and carries out three-phase short-circuit fault simulation for the system. When \( t = 1s \), the system has a short-circuit fault. After 0.1s, the fault is removed and reclosing is successful. The response curves of various state variables of the system are shown in Figure 3 (a) to Figure 3 (d). It can be seen from Figure 3 (a), figure 3 (b), figure 3 (c) and figure 3 (d) that in case of three-phase short circuit fault of the system, the system equipped with SCBD can well calm down the system oscillation, and all state variables of the system can be well controlled, with rapid dynamic response; while in the system without SCBD, the power angle, speed, terminal voltage and electromagnetic power of the system fluctuate greatly in case of three-phase short circuit. It is not conducive to the stable operation of the system, and after the short-circuit fault is removed, the stable time is longer. It can be seen that the controller designed with multiple indexes can well coordinate the excitation and speed regulation system of the generator, so that SCBD can not only give full play to the effect of electrical braking, but also provide certain power support for the system, which significantly improves the ability of the system to resist large disturbances.
(a) Response curve of speed
(b) Response curve of power angle
(c) Response curve of terminal voltage
(d) Response curve of electromagnetic power

Figure 3. Three phase short circuit response curve

In addition, through repeated time-domain simulation, the allowable limit clearing time of three-phase short circuit fault is obtained, as shown in Table 1. It can be seen that SCBD can improve the limit removal time of the system. Although it is impossible to have such a long-term short-circuit fault in practice, this extreme phenomenon can be studied through simulation experiments to get the ultimate removal time, which reflects the value of simulation experiments.

Table 1. Fault limit removal time

|                | With SCBD | Without SCBD |
|----------------|-----------|--------------|
| Ultimate removal time(t/s) | 0.13      | 0.236        |

5. Conclusion
In this paper, the differential algebraic model of SCBD and generator excitation and speed regulation system is established. By comparing the controller designed by DAMNC and LOC, the simulation results show that DAMNC method can effectively solve the nonlinear control problem of differential algebraic model of complex power system; SCBD can well coordinate the control of generator excitation and speed regulation system, and the dynamic and static performance of the system can be effectively improved. The transient stability of the system is obviously improved.

Acknowledgments
This research is supported by the National Natural Science Foundation of China (51267001), Guangxi Natural Science Foundation (2014GXNSFAA118338), Guangxi scientific research and technical development project (14122006-29) and Nanning scientific research and technical development project (20165186)
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