Workover Rig Control System Based on AC/DC Hybrid Micro-Grid

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\textbf{Abstract.} In view of the problems encountered in practical application of work-over rig original power "Change from oil to electricity", we propose a scheme for control system of electric work-over rig based on AC/DC hybrid micro-grid. Then take Boost circuit of Bidirectional Buck-Boost DC/DC as an example to design IDA controller. Finally, using the above research results, we design the electric work-over rig control system, and describe control method about energy balance control in this system.

\textbf{Introduction}

Work-over rig, diesel engine as the driving force, is the main equipment in oil field work-over operation. Compared with motor, diesel driven work-over rig has low efficiency and low power utilization rate. With the improvement of environmental protection and energy saving and emission reduction requirements, an electric work-over rig based on AC frequency conversion technology has emerged, power solutions of electric work-over rig are generally two methods: One method, using a large capacity transformer, other method, using the field transformer. These two solutions are not used in large-scale. AC bus electric control system of electric work-over rig. The patent [1], AC bus electric control system of electric work-over rig, gives a good way by using energy compensation technology.

We propose another solution of the electric work-over rig control system based on AC/DC hybrid micro-grid in this paper. Firstly, build the PCH model of the DC/DC converter of the control system, and design the DC/DC IDA-PB control algorithm. Then the effectiveness of the IDA-PB control algorithm is proved by simulation. Finally, using the above research results, we design the electric work-over rig control system, and describe control method about energy balance control in this system.

\textbf{Work-Over Rig Control System Based on AC/DC Hybrid Micro-Grid}

The AC/DC hybrid micro-grid system of work-over rig access to 10KV power system by field transformer, which AC system and DC system connected by PWM rectifier (AC/DC). One side of PWM rectifier is connected by AC bus, the other side by DC bus. DC bus are connected to battery energy storage system and super capacitors energy storage system through DC/DC converter 1, 2, and connected to AC load through the inverter, as shown in Fig.1.
This topology is not a simple one-way flow direction, but bidirectional power interaction. Bidirectional will lead to the fluctuation of bus voltage in AC/DC hybrid micro-grid. The stability of DC bus voltage is the key point of electric work-over rig.

DC/DC converter is the platform of electric energy exchange between two different voltage levels in AC/DC hybrid micro-grid of electric work-over rig, it is an important part of electric work-over rig control, which realizes energy management and controlling. Because DC/DC converters are nonlinear systems and limitations of conventional PID control, we adopt IDA-PBC energy shaping control theory to design state feedback nonlinear controller.

**DC/DC Controller Based on IDA-PBC**

Bidirectional Buck-Boost DC/DC topology structure can achieve two-ways flow of energy between storage system and DC bus. This section will take Boost circuit of Bidirectional Buck-Boost DC/DC as an example to design IDA controller.

**PCHD model for Boost circuit**

Duty cycle ($\mu$) of switching component is the most important parameter of the switching performance of a power converter in a smoothing system, therefore the system can be represented as the following Eq. (1) [2].
\[ x = [J(x) - R(x)] \frac{\partial H(x)}{\partial x} + g(x, \mu) \]  \hspace{1cm} (1)

Where \( J(x, \mu) = -J^T(x, \mu) \)

Establish PWM model of Boost circuit [3]:

\[
\begin{cases}
\frac{di_L}{dt} = -\mu \frac{u_c}{L} + \frac{E}{L} \\
\frac{du_c}{dt} = \mu \frac{i_L}{C} - \frac{u_c}{RC}
\end{cases}
\]  \hspace{1cm} (2)

The capacitance charge and inductance flux are defined as the state vector of the system.

\[ x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} L \frac{i_L}{C} \\ u_c \end{bmatrix} = D \begin{bmatrix} i_L \\ u_c \end{bmatrix} \]  \hspace{1cm} (3)

Where \( D = \text{diag} \{ L, C \} \), \( i_L \) — Inductor current, \( u_c \) — Capacitance voltage, \( \mu \) — Duty cycle

The Hamiltonian function of the system is defined by the sum of the energy of inductance and capacitance.

\[ H(x) = \frac{1}{2} x^T D^{-1} x = \frac{1}{2} \frac{x_1^2}{L} + \frac{1}{2} \frac{x_2^2}{C} \]  \hspace{1cm} (4)

The PCH model of the Boost converter is Eq. (5).

\[
\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = J(\mu) - R \begin{bmatrix} i_L \\ u_c \end{bmatrix} + gE \\
\begin{bmatrix} 0 & -\mu \\ \mu & 0 \end{bmatrix} R = \begin{bmatrix} 0 & 0 \\ 0 & \frac{1}{R} \end{bmatrix}, g = \begin{bmatrix} 1 \\ 0 \end{bmatrix}
\]  \hspace{1cm} (5)

**IDA Controller for Boost Circuit**

Using the IDA-PBC design technique [4, 5, 6], we design the closed loop system energy function and interconnection of damping matrix in order to control the system. The physical structure of this system was not destroyed in the closed-loop system, and the dynamic equation by using the PCHD can be described as following:

\[ \dot{x} = [J_d(x) - R_d(x)] \frac{\partial H_d(x)}{\partial x} \]  \hspace{1cm} (6)

The purpose of Bidirectional DC/DC converter is to use constant \( V_d \) as voltage output. \( x_0 = CV_d \). According to the working principle of Boost DC/DC converter, its duty cycle \( u_0 = E/V_d \). The desired equilibrium point of system:

\[ x_0 = \begin{bmatrix} LV_d \\ RE \\ CV_d \end{bmatrix} \]  \hspace{1cm} (7)

The Hamiltonian function of the closed-loop system is expected to be
\[ H_d(x) = \frac{1}{2}(x-x_0)^T D^{-1}(x-x_0) \]  \hspace{1cm} (8)

Letting

\[ J_a(\mu) = 0, R = \begin{bmatrix} r_1 & 0 \\ 0 & r_2 \end{bmatrix} \]  \hspace{1cm} (9)

Where \( r_1, r_2 \) are undetermined damping parameters, respectively.

\[ \frac{\partial H(x)}{\partial x} = D^{-1}x, K(x) = \frac{\partial H_a(x)}{\partial x} - \frac{\partial H(x)}{\partial x} \]  \hspace{1cm} (10)

Taking Eq. (7) into Eq. (8), we can get

\[ [-J_d(x) - R_d(x)]D^{-1}x_0 = [-J_d(x) - R_d(x)]D^{-1}x + gE \]  \hspace{1cm} (11)

Now we can obtain

\[ \mu = \frac{1}{\mu_0} (r_1(i_L - i_0) + E), \mu = -\frac{1}{i_0}(r_2(u_c - u_{c0}) - \frac{u_{c0}}{R}) \]  \hspace{1cm} (12)

\( i_0 \) — Inductive current of system balance point  \hspace{1cm} \( u_{c0} \) — Capacitance voltage of system balance point

The two formulas of Eq.(12) are simultaneous, get :

\[ r_2 = \frac{1}{\mu_{c0}(u_c - u_{c0})} + \left[ \frac{u_{c0}^2}{R} - E i_0 \right] - r_1 i_0 (i - i_0) \]  \hspace{1cm} (13)

The range of damping coefficient can be known:

\[ 0 \leq r_1 \leq \frac{E}{i_0 - i_L}, \frac{1}{R} + r_2 \geq 0 \]  \hspace{1cm} (14)

Solution of simultaneous Eq. (14) is:

\[ r_1 \leq \frac{1}{i_0 - i_L} \left( E - \frac{u_{c0}}{R}u_c \right) \]  \hspace{1cm} (15)

It follows that positive definite needs to meet Eq. (15). Thus, the IDA-PBC controller meeting the equilibrium condition is as follow:

\[ \mu = \frac{1}{u_{c0}}[r_1(i_L - i_0) + E] \]  \hspace{1cm} (16)

**Dynamic Simulation Analysis of IDA Controller**

Fig.3 shows the dynamic response process of the IDA controller when the load suddenly increases. Fig.3 (a) shows the inductance current waveform and Fig.3 (b) shows the capacitance voltage output waveform. The system reaches steady state after 0.01s, and the deviation is small. It can be seen that the IDA controller can make the system respond quickly.
Figure 3. Capacitor voltage and inductor current of Boost circuit with IDA controller.

Design of Control System for Electric Work-Over Rig

Digital Platform of Work-Over Rig Control System Based on Profibus-DP Bus

Using the above research results, we design the electric work-over rig control system adopting modular structure. Each independent electrical module unit communicate through DP field bus. It shows the work-over rig control system digital platform structure based on the Profibus-DP bus in Fig.4, which is a distributed I/O system. S7-300 PLC serves as master station, While PWM rectifier, inverter, bi-directional DC converter as slave station on DP bus. The master station PLC carries on communicate with each slave station, obtaining the operation state of each electrical module unit through the DP Bus.

Energy Balance Control Strategy of Electric Work-Over Rig Control System

According to power capacity of the field and Work-over rig operation, Work-over rig has three kinds of working conditions, each condition can also refine the several modes, which should use different research methods and control strategies.

Work condition 1

Workover rig works in electric light load, the load current is less than or equal to the power capacity of field, the system is powered by the power grid, and PWM rectifier works in controllable constant pressure operation mode.

When the controller determines that the SOC (state of charge) of energy storage system reaches
1.0, the PWM rectifier is operated as a controllable constant voltage source and provides DC power for the inverter. The bidirectional DC/DC converter does not work. Energy flow shown in Fig. 5 (a). When the controller determines that the SOC does not reach 1.0, the PWM rectifier is used as a controllable constant voltage source to supply the DC power to the inverter, at the same time the bidirectional DC/DC converter charge the energy storage system, replenish its energy. Energy flow shown in Fig. 5 (b).

![Diagram](image1)

Figure 5. Energy flow -Work condition 1.

**Work condition 2**

Work-over rig works in electric heavy load, the load current is larger than the power capacity of field. PWM rectifier works in the constant current mode, and bi-directional DC/DC converter operate in constant voltage mode.

When the controller determines the capacity of energy storage system is sufficient, the bidirectional DC/DC converter and PWM rectifier work in paralle. The power grid and the energy storage system compose of hybrid power to provide power for the inverter. PWM rectifier operates in constant current mode, and bi-directional DC/DC converter operates in constant voltage mode. The energy storage system compensates for additional power and energy under heavy load electric state. Energy flow shown in Fig. 6 (a). When the controller determines that the energy storage system can not provide additional energy under the overload electric state, the inverter stops working, while the PWM rectifier operates in a constant voltage mode, charging the energy storage system through the bidirectional DC/DC converter. Energy flow shown in Fig. 6(b).

![Diagram](image2)

Figure 6. Energy flow -Work condition 2.

**Work condition 3**

Work-over rig works in generating state. When lowering pipe, the motor works in the state of power generation and the inverter operates in the fourth quadrant. Potential energy is converted into electrical energy, Store in the energy storage system or field grid, so as to save energy.

When the controller determines that the motor feedback current is less than the energy storage system charging current limit and SOC does not reach 1.0, PWM rectifier does not work, inverter charge the energy storage system through DC/DC converter, Energy flow shown in
Fig. 7(a). When the controller determines the feedback current is greater than the energy storage system of charging current limit and SOC does not reach 1, PWM rectifier works in the inverter state, electrical energy return back to power grid and save to the energy storage. Energy flow shown in Fig. 7(b).

**Concluding Remarks**

We studied deeply the bidirectional DC through theoretical analysis and dynamic simulation, and the study result is applied to the work-over rig control system based on AC/DC hybrid micro-grid. The system better realize the work-over rig driving force "Change from Oil to electricity" using energy balance control strategy.

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