Energy Saving Research of Rubber-Tired Container Gantry Hybrid Power Crane

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Abstract: In this paper, a study is done on the rubber-tired container gantry hybrid power crane in order to save energy. Because of the series structure is used in crane hybrid system and working statues of the crane change frequently, a "thermostat + power following "control strategy is used in the hybrid power system based on super capacitor. Based analyzes on the energy flows and system working statues, the super capacitor is adopted different control strategies to avoid the engine starts and stops frequently. The result shows that both the control strategy and the hybrid technology are feasible.

Introduction

Rubber-tired container gantry crane (RTG) is an assembly-equipment in container wharf which is used the most widely at present. It has the advantages of flexibility and generality etc. However, the traditional crane is guzzling, noisy and harmful to the environment which doesn't meet the requirements of energy-saving and the environment protection policy in our country. In order to solve the problems above, many domestic and foreign manufactures have invested a lot of manpower material in its energy-saving's technological transformation, and now it mainly has two ways to achieve the technical transformation: The first way is to completely use the mains supply, that is, "converting oil-drive to electric drive", but it has the disadvantages of large initial investments and complex technical transformations, and due to the old piers' grim infrastructure, it has many factors to be considered for the transformations. What's more, replacing the original diesel generators with a new type generator sets which can automatically adjust with the weights of loads change will result in a waste of original turbines. The second way is to transform the power system of the original diesel generator [1, 2].

The energy of RTG is mainly consumed by accelerating or raising the loads during the loading and unloading process, but this energy will convert into electric energy gradually while the load is dropping, and finally be wasted in energy-dissipation resistance. If this energy can be recycled, the energy consumption of the crane can be reduced significantly. Therefore, on the premise of the second way, a new scheme has been put forward in this article based on the thought above: on the one hand, an energy storage device was added in the original structure of "diesel engine +generator", which could store the electric energy generated during the load's dropping, and then used it to accelerate or rise the load in the next time; on the other hand, a " thermostat+ power following" energy-control strategy had been developed to enable the engine power to be greatly reduced. With the new scheme, the aim of energy-saving and environment protection policy could be achieved.

The system architecture of hybrid power crane

the overall structure of a hybrid power crane

Series-style hybrid architecture was used in the hybrid power system because the multi-mechanism were working simultaneously, its structure is shown as Fig1: [3]

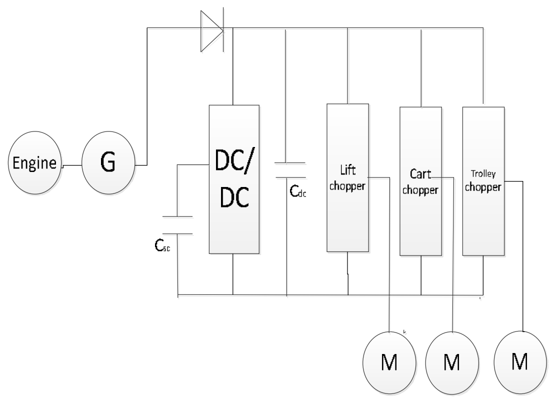

Figure 1 the structure of hybrid power

In the figure, G is a DC generator, G_{sc} is a super capacitor and C_{dc} is a filter capacitor. The motor of the lifting, the trolley and the cart mechanism are all DC motors.

The super capacitor

Crane working mode is intermittent and recurring, meanwhile, its work cycle is short and the engine switches between work and stop frequently. Its dynamic responses to the mechanism must be quick, its starting current is big and its motor power is large——the lifting mechanism motor power is generally between 130-250 Kw, cart and trolley travel agency motor powers are generally less than 40 Kw. Due to these characteristics, we chose a super capacitor as the energy storage element of the system, because the super capacitor has the following characteristics:

The super capacitor is different from ordinary capacitors, its charging and discharging process is complex, generally we adopt the RC equivalent model to analyze it. The structure is shown in Fig.2:

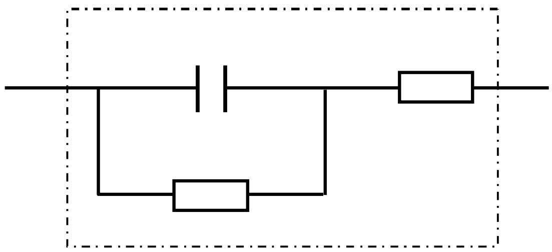
Figure 2 the RC equivalent model of super

The largest effective energy that the super capacitor can store is calculated as:

$$w = \frac{1}{2} C_{SC} (U_{max}^2 - U_{min}^2) \qquad (1)$$

While C_{SC} is capacitance, U_{max} is maximum operating voltages, U_{min} is minimum operating voltage.

Because the super capacitor cannot discharge to 0 V, we define its discharge depth is:

$$q = \frac{U_{max} - U_{min}}{U_{max}} \qquad (2)$$

Integrating the two equations above, we can get:

$$w = \frac{1}{2} C_{SC} U_{max}^2 (1 - q^2) \qquad (3)$$

In general, the super capacitor remains a little energy and a low electrical efficiency when its voltage is low, so we usually take $q = \frac{1}{2}$[4].

The bi-directional DC / DC converter

When using a super capacitor as the energy storage device, the bidirectional DC / DC converter is essential. On the one hand, it can maintain the DC bus voltages and the generator output voltages stable; on the other hand, it can ensure the voltages of super capacitor have a larger space to switch. So a bi-directional DC / DC converter is needed to connect the super capacitor and the DC bus which enable the energy to flow more smoothly.

This paper has used a half bridge bi-director DC/DC converter, which was also called $buck/boost$ bidirectional DC/DC converter, the topology is shown as Fig. 3 [6]:

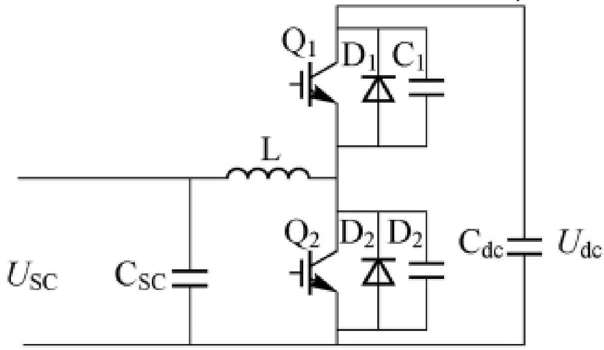

Figure 3 the structure of bidirectional DC / DC converter

When the bidirectional DC / DC converter was in buck mode, the gravitational potential energy was converted to kinetic, energy from the load lifting mechanism flowed to energy storage devices, and the super capacitor was charged; When the bidirectional DC/DC converter is in boost mode, the energy from the energy storage device flowed to the lifting mechanism, and the super capacitor discharged.

the "thermostat + power following" control strategy

Thermostat control strategy means that the generator only charges the super capacitor: the engine stops working when the charge of the super capacitor (SOC) is between SOC_{max} and SOC_{min}, and the electric motor is powered by the super capacitor; When the SOC is less than SOC_{min}, the engine starts to work and the generator charges the super capacitor. This control strategy makes the engine starts and stops frequently which will reduce its lifespan.

The "power following" control strategy means that the output power of the engine follows the change of the load weights. The engine is working all the time, so that it can adapt to the frequent "start and stop" work characteristics of cranes. But the super capacitor only works when the engine is stopped, thus the energy recycle efficiency is not high [3].

Considering the advantages and disadvantages of the two control strategies above, we had developed a "thermostat and power following" control strategy, with which
The current generated by the generator could flow to the super capacitor and the motor at the same time, and the power of the engine could also change in a certain range. We assumed that the maximum optimal engine power was T_{max}, the minimum optimal engine power was T_{min} and between these was the engine optimal working area. When the engine worked in the optimal working range, the engine power changed comply with weights of the loads; when the engine power exceeded the maximum optimal power T_{max}, the super capacitor discharged to meet the load power requirements, so that the engine went back to the optimal working area; when the engine power was less than the minimum power optimization T_{min} (the engine started), the super capacitor should also discharge to compensate the DC bus voltages which could enable the system starts quickly ; when the SOC of the super capacitor was below SOC_{min}, the generator should charge the super capacitor and when it was between SOC_{min} and SOC_{max}, the generator stopped charging.

Analysis of the energy flow of hybrid power crane in working processes

Hybrid power crane's recyclable energy mainly comes from the lifting mechanism when the load is falling, according to the energy conservation law:

$$\text{mgh} = \frac{1}{2}mv^2 + E_{DC} + E_J \qquad (4)$$

The mgh is the gravitational potential energy of loads, $\frac{1}{2}mv^2$ is the kinetic energy of the loads in decreasing process, E_{DC} is the energy absorbed through the bi-directional DC/DC converter in decreasing process, E_J is the mechanical friction loss. We assumed the efficiency of transfer energy of bidirectional DC / DC converter was η_D, so the total energy that the super capacitor can absorb in the dropping process is:

$$E_{SC} = (mgh - \frac{1}{2}mv^2 - E_J) \times \eta_D \qquad (5)$$

It is noteworthy that loads usually drop slowly in the port machineries, so the kinetic energy loss is little, and considering that the factors of the mechanical friction loss and the energy transmission loss is also not big, so the energy recovery efficiency is as high as 50%. Thus, the hybrid power is feasible in theory [4].

Here we have an example of 25T-class tire crane, its original engine was rated at 140Kw and the DC bus voltage of generator was rated at 400V. After transformation, the hybrid engine power could be reduced to 90Kw, meanwhile, the DC bus voltage of generator kept unchanged and ensured the system works normally. Here is the analysis of energy flows and the energy control strategy in hybrid power crane's whole working processes.

The pre-charging process

We should check the voltage of the super capacitor before every organization starts, if the voltage is lower than V_{min}(the system is set to 350V), it should be pre-charged to ensure the system work normally.

The engine starting process

After receiving a start command, the engine should start before any other mechanisms, and we will find the voltage of generator gradually increases. At this time, the super capacitor should discharge in a constant voltage discharge mode to supply the DC bus with voltage and make the motor starts quickly.

As shown, when the engine was starting, the voltage of generator was 360V, and at this time, the super capacitor discharged to compensate DC bus voltage to enable the voltage of motor was maintained at 400V, so the motor could start quickly. After about 5s, the engine power reached to the rated power, the DC bus voltage was stable at 400V, while the super capacitor stopped discharging [3].

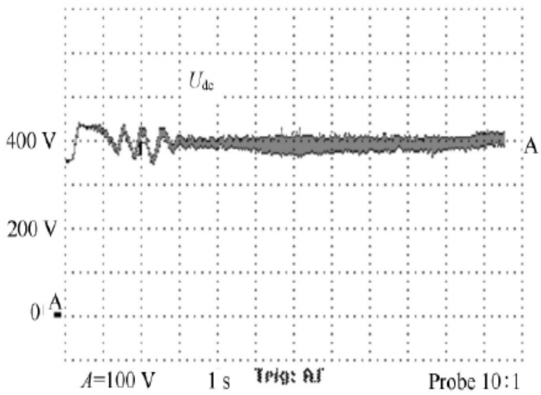

Figure 4 the starting process of hybrid crane

The lifting mechanism rising process

There are two cases in the lifting mechanism rising process: firstly, the engine works in the optimal working range (the load is light), the super capacitor will not discharge in this case. And during this time, if the voltage of the super capacitor is lower than V_{min}, it should be charged; secondly, the engine power exceeds the maximum optimal power V_{max} (the load is heavy), the super capacitor should discharge in constant power discharge mode to enable the power of engine go back to the optimal working area. Here are the current and voltage of the hybrid crane with 25T load during rising process:

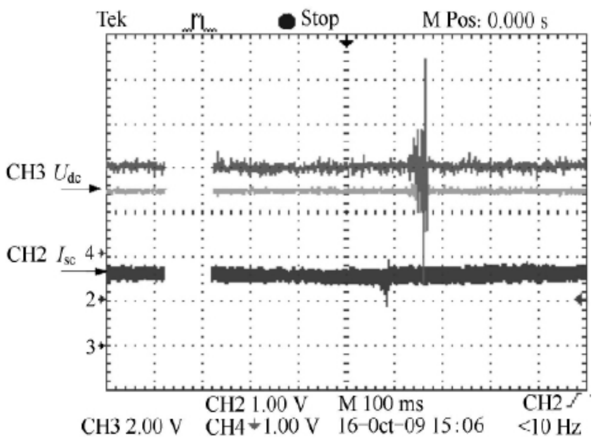

Figure 5 the lifting mechanism rising process of hybrid crane

As shown in the diagram, CH3 is the DC bus voltage, which was maintained at 400V, CH2 is the super capacitor discharge current, which was in constant power discharge mode and the current discharged was stable[3].

The lifting mechanism decline process

When the lifting mechanism is declining, the motor begins to generate electricity, and the current flows into the super capacitor through the bi-directional DC/DC converter, thus the super capacitor is in charging mode. During the time, we should pay attention to the feedback energy, if it's so large that make the voltage of super capacitor higher than V_{max} (the system is set at 400V), we should let the energy consumption resistances work to protect the voltage from exceeding V_{max}. Here is the figure about the current and voltage of the hybrid crane with 25T load in decline process:

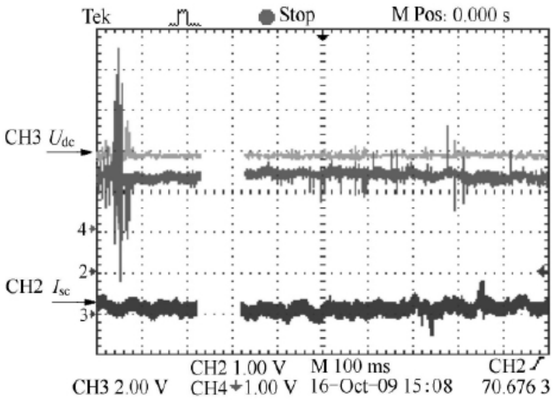

Figure 6 the lifting mechanism decline process of hybrid crane

As it is shown in the diagram, CH3 is the DC bus voltage, which was maintained at 400V, CH2 is the super capacitor discharge current, which was in constant current charge mode and the charge current was stable[3].

Conclusions

Through the experiments we have demonstrated the feasibility of the hybrid power system and the control strategy: the engine power had been reduced to 90Kw compared with which was 140Kw before it was transformed by the hybrid power technology. The efficiency of the energy saving, which could reach（140-90）/140=35% , was obvious, and it was accord with the current development trend of cranes. With the further research of the hybrid power crane system and the continual improvement of the super capacitor, the hybrid power crane’s far more wide application is predictable.

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