Development and deployment of a control system for energy storage

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ABSTRACT

Power systems are coming under close scrutiny as the fossil fuel and global warming issues become more evident around the globe. In the interests of reducing fuel consumption and by extension carbon emissions industry are developing methods for increasing the efficiency of power systems and generation. One method for doing this is Energy Storage, this tool is used in many ways, one powerful implementation is to store energy in a system and use this to avoid drawing power from a generator unit. A prime example of this is onboard a Diesel Rubber Tyred Gantry (DRTG) Crane, a large plant unit used in ports around the world to move transport containers on site. The crane could be considered an islanded power system, with its own generator unit and power network. During operation large quantities of energy are regenerated by the system, this energy is currently wasted as heat in resistors. The intent of this paper is to demonstrate methods by which a Flywheel Energy Storage System (FESS) may be controlled to optimise the energy saving potential of the system. The control strategies will be evaluated on a computer model and the practical implementation on a test rig will be explained.

Keywords:
RTG Crane; Control; SimPowerSystems; Simulation; Power;

1. INTRODUCTION

Diesel Rubber Tyred Gantry (DRTG) cranes operate as an islanded power system; this means that they have no mains connection [9]. As such a local power source is required for these systems; a DRTG crane employs a diesel generator to supply power to the motors onboard. Diesel generators systems are comprised of two coupled units, an electrical machine and an engine [6, 7]. These systems are typically operated at constant speed as this is the most efficient use of a diesel engine. The constant speed of rotation also sets the frequency of the resultant voltage from the generator. An excitation system controls the generator to ensure the correct voltage amplitude is always available to the loads. This form of local generation has its benefits; the crane is completely free to move around its working environment. It also means that facilities don’t have to have large transformer stations and increased capacity from the grid. The problem with this method however is that the operational costs are fully subject to the cost of diesel and the operational tempo of the facility; the more the plant is used the
greater the fuel consumption [9]. As such methods of reducing the fuel consumption are being sought by facilities with a high operation tempo [1, 2, 4]. The high tempo makes energy management systems cost effective, for low tempo operations the payback time would be too large. Energy storage has been used in many applications ranging from voltage sag correction to UPS systems. In systems such as this however the store is required to introduce as little load on the generator as possible, while UPS and voltage sag systems are charged from the source. The store needs to reduce the load on the diesel generator across the duty cycle in order to reduce the fuel used in the system [3, 5]. There are many strategies to do this. This paper will briefly look at various energy storage systems and their advantages and then discuss the control methods that have been employed to operate them.

2. STORAGE DEVICES

There are a number of energy storage devices available today, battery, supercapacitor and flywheels are some of the most common and understood. Batteries store energy in chemical form and are a well known method of energy storage. Supercapacitors are a relatively new technology that shows great promise; they store energy in an electric field across the plates that comprise their structure. Flywheels are an old technology that store energy in kinetic form, unlike the previous two devices flywheels require a transducer to allow them to function. This transducer is one of the electrical machine types available in industry, these being Permanent Magnet Synchronous Machine (PMSM), Induction or Switched Reluctance (SR). No one energy store is suitable in all applications due to their characteristics [1]. Batteries have a large energy density but a small power density; this means that while they can hold large quantities of energy the speed at which this can be used is very low, if damage to the cells is to be avoided. At the opposite end of the spectrum is the supercapacitor, which has a very low energy density but a large power density, so energy can transfer very quickly but not much energy can be stored. Sitting between these two devices is the flywheel technology, which has a large power density and a medium energy density [1]. The limits on each device are due to their characteristics drawn from their composition. It has long been known that drawing high power from batteries can break down the battery and reduce its lifetime and ability to hold energy.

![Figure 1: Depth of Discharge vs. Expected Life for Battery](image)

Supercapacitors energy is based on the surface area between the positive and negative components within, as such physical size limits them [8]. They also have a charge/discharge lifetime like batteries, after repeated cycles their components will break down. They are currently rated into the 100, 000’s of charge/discharge cycles. Energy on a flywheel is determined by the inertia of the mass and the square of the speed at which it rotates, as shown in Eq. 1.
Where $E$ is the stored energy, $I$ is the Inertia of the mass and $\omega_s$ is the speed in radians per second. Unlike the other two they do not break down under repeated cycles of charge and discharge, only being limited by the service life of the bearing mechanism used in their construction. Their limitations come from the trade off between speed and inertia and how this relates to the materials used. Some materials cannot tolerate the forces at high speed, while those that can are usually light and so lose the energy derived from the inertia. In this application significant power is seen on the system, this would make batteries an undesirable method of storage [8]. Supercapacitor banks would grant the energy required and the power however control over such systems is very difficult and balancing the voltages across the capacitors themselves is very difficult. In this application the authors have decided that a flywheel energy storage system would be most appropriate.

3. CONTROL SYSTEMS

The topic of control theory is well established; however the use of electronic controllers has significantly advanced the field. There are two categories of control system, open and closed loop, shown in Figure 2. The difference between the two is the presence of a feedback path in the closed loop system; this feedback gives the control access to its affect on the system.

![Figure 2: A] closed loop, [B] open loop control topology](image)

The advantage of this feedback line is that error in output can be corrected using the controller, it also adds stability and robustness to the system. Simple processes may only require an open loop control; however in this study much more controllability is required. As such closed loop methods have been exhaustively investigated. These are systems that take the form shown in Figure 2 [A], it shows how a process output is fed back into the controller, this allows the setting of a desired value for the output and the production of an error signal. The controller then uses this to set the process input to a value that will achieve the desired output from the process. There are a number of topologies of closed loop control; simple Proportional (P), Figure 3, Proportional-Integral (PI), Figure 4, and Proportional-Integral-Differential (PID), Figure 5, techniques form the most common group. Beyond that are rule based, optimal and learning techniques; learning techniques include neural network control methods. Over time these learn behaviour for systems, these are very difficult to apply and not greatly used in industry. Optimal control techniques are widely explored in academia and used in some high tech applications, the main issue with this method is the difficulty with operation of complex equations in real time.
Optimal control is a recursive method of establishing control parameters; as such multiple operations need to be made every control cycle. Rule based controls operate based on a set of laws determined by the designer; these laws set the input to the process and can be based on any number of inputs [3, 5]. These systems are coming into use in industry in the form of fuzzy logic and gain scheduled control types. This project focuses on P, PI, PID and fuzzy logic control types. The topologies of these schemes are shown in Figures 3-6.

**Figure 3: Proportional Control Topology**

**Figure 4: Proportional-Integral Control Topology**

**Figure 5: Proportional-Integral-Derivative Control Topology**

**Figure 6: Fuzzy Logic Control Topology**
The P, PI and PID controls accept a single input from the system; this is typically an output from the system we seek to control. It is fed back and subtracted from a desired value; this gives the e[n] or error demand. This error is then multiplied by a gain value, in the integral paths this is cumulative, in the differential path it is based on rate of change. The fuzzy logic system can accept multiple inputs; it then checks these against the rule base established and derives an output to control the process. These 3 systems were trialled on a model of the RTG crane developed by the authors in Matlab/Simulink [9].

4. RESULTS

The results are taken in response to real data taken from an RTG crane under operating conditions at the Port of Felixstowe. The actions for the validation data were taken from a set of known operations of the crane. A run of 4 lift operations was done with a crane using test loads of various weights, the current and voltage across the AC and DC power lines were measured during these operations. Once the model, developed in matlab/simulink, was validated using this data, the energy storage model was added. The four controllers described above were implemented to control the energy store the P, PI and PID took their input from the DC voltage on the system. Figure 7-8 shows the crane validation data plotted with the model data, a close correspondence can be seen between them over the range of loads used. By subtracting the model value from the maximum value seen in the validation data we can obtain a percentage error for the model, under these data sets the model was accurate to within 5% in steady state conditions. Figures 9-11 show the effect of a flywheel energy store using P, PI and PID control respectively.

![Figure 7: Model Data (Blue) vs. Real Test Data (Red), 0 Tonne Load Duty Cycle](image7.png)

![Figure 8: Model Data (Blue) vs. Real Test Data (Red), 25 Tonne Load Duty Cycle](image8.png)
CONCLUSION

In conclusion the test results show that, in such a well defined demonstration duty cycle the 3 closed loop topologies have a very similar performance. Indeed the variation between them over the cycle is only a few percent. It is not surprising that this would be the case; there is no high frequency component to the action of the crane that would cause instability in the P control, while the usual advantages of the PI and PID over P are negated due to this slow system action. The results show that the PID and the PI respond slightly faster than the P, but this does not translate into any significant difference in the energy saving. This could also be explained by the practice of maintaining the gains across all three topologies. Future work will look at other tuning methods for these 3 topologies, the Ziegler-Nichols being one of these methods.
With this paper a baseline saving for a controlled energy storage has been set, a fuzzy logic system will now be implemented that will attempt to provide greater savings than these 3 systems. It is evident that while the controls in their current condition do not present a clear best option, it can be seen that the effect of energy storage on a system can be profound. The current required to provide the motor action is greatly reduced, such a reduction represents a large saving in fuel which can be directly related to the current. The future of the project will be to adapt these controllers to achieve the greatest possible reduction in energy use. The best control will then be used to regulate a flywheel energy storage system on a DRTG crane for real hardware testing.

REFERENCES


