Introduction to Closed-Loop Control
Overview

DC Motor Drive - Simplified Block Diagram

Basics of Closed-Loop Control

In **Open-Loop** control, no feedback loop is employed and system variations which cause the output to deviate from the desired value are not detected or corrected.

A **Closed-Loop** system utilizes feedback to measure the actual system operating parameter being controlled such as temperature, pressure, flow, level, or speed. This feedback signal is sent back to the controller where it is compared with the desired system setpoint. The controller develops an error signal that initiates corrective action and drives the final output device to the desired value. In the DC Motor Drive illustrated above, the tachometer provides a feedback voltage which is proportional to the actual motor speed. Closed-Loop Systems have the following features:

- A **Reference** or **Set Point** that establishes the desired operating point around which the system controls.

- The process variable **Feedback** signal that "tells" the controller at what point the system is actually operating.

- A **Controller** which compares the system **Reference** with the system **Feedback** and generates an **Error** signal that represents the difference between the desired operating point and the actual system operating value.

- A **Final Control Element** or mechanism which responds to the system **Error** to bring the system into balance. This may be a pneumatically controlled valve, an electronic positioner, a positioning motor, an SCR or transistor power inverter, a heating element, or other control device.

- System **Tuning Elements** which modify the control operation by introducing mathematical constants that tailor the control to the specific application, provide system stabilization, and adjust system response time. In process control systems these tuning elements are: Proportional, Integral, and Derivative (PID) functions. In electrical systems, such a generator voltage regulators and motor drives, typical tuning adjustments include:

  - **Gain**, the amplification factor of the controller error amplifier, which affects both system stability and response time;

  - **Stability** which provides a time-delayed response to feedback variations to prevent oscillations and reduce system "hunting";

  - **Feedback** an adjustment which controls the amplitude of the feedback signal that is balanced against the system set-point;

  - **Boost** which is used in AC and DC motor drives to provide extra low-end torque; and

  - **IR Compensation** which provides a control signal that compensates for the IR Drop (Voltage Drop) which occurs in the armature windings in DC machines due to increased current flow through the armature.

Control Systems

Introduction to Closed-Loop Control
Polarity / Safety / Signal Ranges

Feedback Polarity

In closed-loop systems, feedback signals may be either **Regenerative** (in-phase) or **Degenerative** (out-of-phase). Regenerative feedback exists when the feedback polarity or phase relationship acts to aid or boost the main control signal. If the amplitude of the feedback is sufficiently large oscillations will be developed. (This is the principal used in the operation of radio frequency oscillators.) When regenerative feedback is used in control systems, such in the case of IR Compensation, the effect of excessive feedback must limited, otherwise instability will result.

Degenerative feedback, on the other hand, will dampen oscillations and produce system stability. In degenerative feedback, the phase relationship or polarity of the feedback signal acts to cancel or reduce that of the main control signal.

Feedback polarity is critical and proper feedback polarity must be determined when commissioning equipment which consists of separate control and feedback devices. This is not a concern to the installer of a packaged system where the control and feedback devices are pre-wired as a complete system.

In the example DC Motor Drive, shown on the previous page, an operational amplifier configured as a summing inverter is utilized. This configuration requires that the reference and feedback signals be of the *opposite* polarity because the amplifier output (error) will be the mathematical *sum* of the input voltages (here the reference is positive and the feedback is negative). When a differential amplifier is used, the reference and feedback will be of the *same* polarity because the amplifier output (error) will be the mathematical *difference* of the two input voltages.

Safety Considerations

Caution! Care must be taken when troubleshooting any closed loop system to prevent the reversal, disconnection or loss of the feedback signal. Improper feedback may result in system run-away because the control reference is no longer being balanced by the process variable feedback signal, causing the error signal to go to maximum. For example, loss of feedback on a generator voltage regulator may force the field to maximum causing the generator output to rise to a dangerously-high voltage. Loss of feedback on a motor drive may cause the motor to over-speed. In a process control system, loss of feedback could cause a process control valve to close or go to the full-open position and upset the system.

Fail-Safe Position

The position to which a system will revert in the event of a component or other failure is an important consideration for the system design engineer.

For example, pneumatic control valves are designated as air-fail-open or air-fail-closed to define the position to which the valve will move on a loss of control air. This fail-safe position is determined by the arrangement of the spring in the actuator.

The fail-safe position of control relays is also a consideration. On loss of control power, or in the event that a relay coil fails, the relay will drop-out. By selecting the appropriate contact/s, either Normally Open (NO) or Normally Closed (NC), it may be possible to design a system that will shut-down in an orderly or non-catastrophic manner.

Semiconductor components may fail either shorted or open making fail-safe analysis difficult.

Analog Signal Ranges

Analog Process Control Equipment typically utilizes the following signal ranges:

- 4 - 20 milliamp DC current signals
- 1 - 5 volt DC signals (4 - 20 ma through a 250 ohm resistor provides a 1 - 5 volt drop.)
- 3 - 15 PSI pneumatic pressure signals (Other ranges are also sometimes employed.)

Closed-loop control systems may be either analog or digital. Often, a system will contain a mix of both types of equipment. For these systems to interface properly, circuitry that provides Analog-to-Digital (A/D) and Digital-to-Analog (D/A) signal conversion is employed.

Wind Generator Positioning System
Overview

Author's Note

This wind generator, along with the associated control system, is one that I have designed and built, and with which I am continuing to experiment. There are several closed-loop control systems involved in the operation of this machine and I thought it might be of interest to review the positioning system as an application of closed-loop control. Future Electrician's Notebook articles will focus on more "conventional" control applications.

The basic building construction is patterned after a Dutch-Style post mill where the upper "house" is free to turn a full 360° on a supporting post that runs up through the center of the mill. The pyramid-shaped base is stationery and contains the control system.

The upper story is balanced on a large thrust bearing, and contains the 5 kW DC generator, speed-increasing jack-shaft, electric brake, blade speed and vibration sensors, and the associated generator and brake controls. The house is automatically turned into the wind for maximum blade torque using a DC positioning motor on the tail-pole of the machine. This is an upwind machine (the blades face into the wind). The blades and hub were salvaged from a refinery cooling tower; blade diameter is 19 feet. (As noted below, the blade size/design is inadequate and this set is slated for replacement.)

Flexible cables (SO cord) run between the controls in the base and the generator which is mounted on the revolving frame, so no slip rings are required for power or control. The house rotation is limited to 360° by a travel limit switch. If the travel limit stops the positioning operation before the blades "find" the wind, the positioning motor reverses and the system searches in the opposite direction.

The 5 kV, 125 VDC generator is connected to electric heat loads only; no inverter or battery storage is currently installed. Underground cables run between the generator and the house and shop buildings and a completely redundant set of 125 volt electric heaters has been installed. This eliminates the need for complicated and costly transfer or isolation switches. Electric heat costs represent a major part of our electric utility bill and when this system becomes fully operational some of this expense will be offset.

Although all the wind generator electrical systems are complete and function properly, the present blades do not produce enough torque to drive a loaded generator. Research on longer and improved blades is on-going. Also under consideration is the installation of a low RPM generator (more poles) to permit reducing the gear ratio. The present generator drive ratio (a combination of a chain and belt drives) is 1: 25 to increase the blade speed to the 1725 RPM required for the generator. Since Horsepower = Torque x RPM, this should be a viable solution.
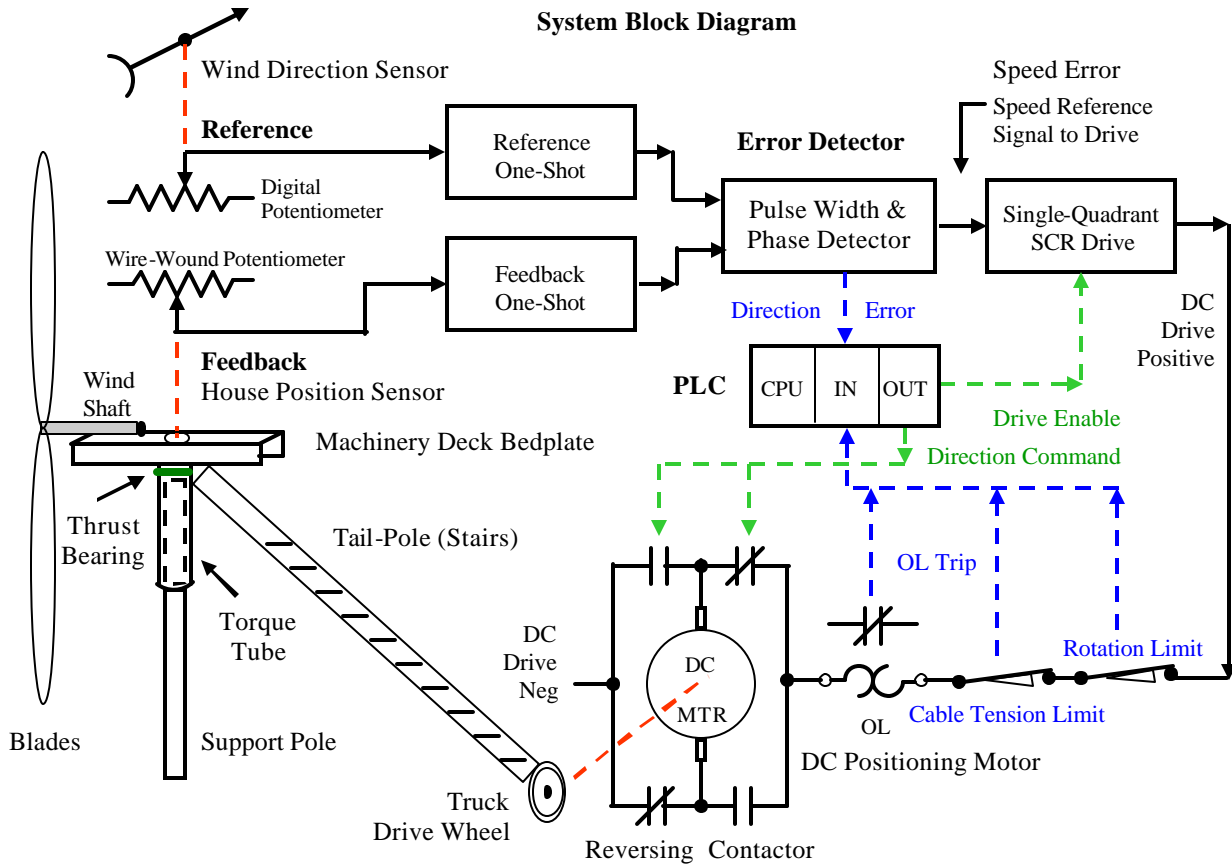

The Seeker II

About the Name

Since this machine will track the wind, we have christened it *The Seeker II.*

The original Seeker is an historic Dutch windmill built early in seventeenth century. It began service as a drainage mill and in 1671 was converted to an oil mill, producing oil from ground nuts. Located in the Zaan region of Holland, it is still operational, an outstanding testament to the skill of the Dutch millwrights.

Wind Generator Positioning System
System Block Diagram & Operation

System Block Diagram

Wind Direction Sensor

Reference

Digital Potentiometer

Reference One-Shot

Error Detector

Speed Error

Speed Reference Signal to Drive

Wire-Wound Potentiometer

Feedback One-Shot

Pulse Width & Phase Detector

Single-Quadrant SCR Drive

Direction   Error

PLC   CPU   IN   OUT

Drive Enable

Direction Command

DC Drive Positive

Feedback
House Position Sensor

Wind Shaft

Machinery Deck Bedplate

Thrust Bearing

Tail-Pole (Stairs)

Torque Tube

OL Trip

Rotation Limit

DC Drive Neg

DC MTR

OL

Cable Tension Limit

DC Positioning Motor

Blades

Support Pole

Truck Drive Wheel

Reversing Contactor

Control Systems

Legend
Red dashed lines - mechanical linkage
Blue dashed lines - Programmable Logic Controller (PLC) input.
Green dashed lines - Programmable Logic Controller (PLC) output.

System Operation

Assume the wind speed is sufficiently high to permit generation.
Assume also that the machine is not facing directly into the wind.

1. The Reference One-Shot develops a pulse which is proportional to the wind vane position (wind direction).
2. The Feedback One-Shot develops a pulse which is proportional to the position of the machine.
3. The Error Detector Circuit determines the phase relationship of the pulses, calculates the error of the loop, and determines the direction in which the machine must move to correct the error.
4. The Programmable Logic Controller (PLC) detects the error, selects the appropriate direction, picks the motor direction contactor, and, after programmed time delay, issues a Drive Enable command to the SCR Drive. This programmable time delay is the main tuning adjustment of the loop and provides stability by ignoring rapid fluctuations in the wind direction sensor and eliminates "hunting".
5. When the SCR Drive receives the Drive Enable command from the PLC, it looks at the Speed Reference Signal from the Error Detector and sets the speed of the position motor based on the amount of system error. In this way a large error is corrected quickly and then the motor is slowed down as it approaches the final position. (This concept is used in NC and CNC machine tools in X-Y axis positioning.)
6. The positioning motor drives the house around toward the wind and as it moves it changes the position of the feedback potentiometer reducing the system error. When the feedback signal matches the reference signal, the positioning motor stops with the blades facing directly into the wind.

Wind Generator Positioning System
Reference / Feedback / PLC Equipment

Wind Vane
Positioning system reference input.
A permanent magnet on vane closes
reed switches located in base of the
sensor. These switches input a digi-
tal display on the operator control
panel and the digital potentiometer
(D/A converter) on the Wind Direc-
tion Card.

This is an old Heathkit Weather
Station that was modified for the
application.

Anemometer (wind speed
indicator)
Permanent magnets on cup
assembly close a reed switch
that inputs the Wind Speed
Card and the digital display
on the operator control panel.

Wind Sensors
Located on nearby building.

House Position Sensor
Positioning system feedback input.
Unit is a 360 degree rotation, wire-
wound potentiometer which is at-
tached to the channel iron bedplate of
the revolving house. The shaft of the
pot is driven by a toothed timing belt
that is held in a fixed position by a
rod that passes through a hole in the
bedplate and attaches to the top of the
support pole. (The shaft of the poten-
tiometer is stationary and the case
turns as the house revolves.)
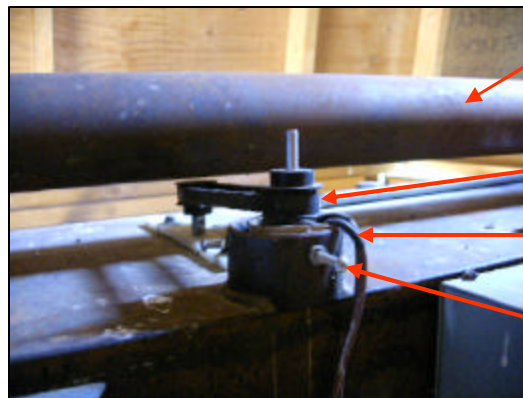
Wind Shaft
3 inch diameter 10 foot
long stress-proof steel.

Timing Belt

Potentiometer leads to control.

Potentiometer housing locking
screw permits position zero
adjustment.

Feedback Potentiometer

Electronic Controls Card Cage
    Opto Isolators
    Power Supply
    Wind Speed Card
    Digital Potentiometer
    Wind Direction Card
    House Position Card
    Position Error Logic
    Blade Speed Control Logic
    Metering and Misc. Logic
    Generator Control Logic

Control Panel Door
Operator interface metering
and controls. Both manual
and automatic operation are
possible.

Hand-Held Programmer
Displays ladder logic on a
four-rung LCD display.
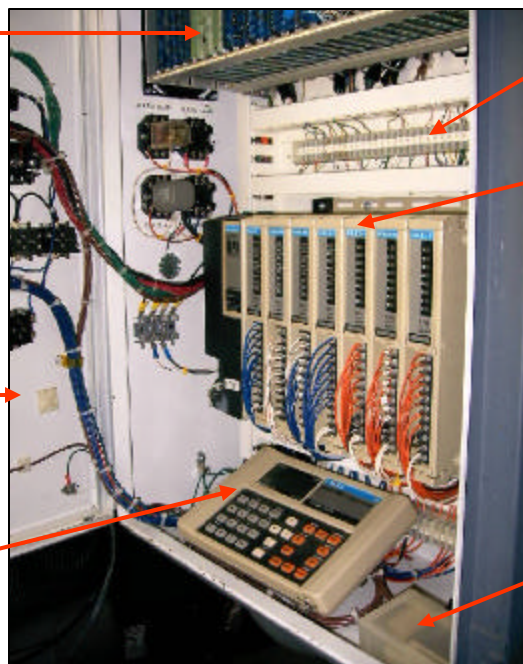
Sensor Termination Strip

PLC
Modicon Micro 84. One of the
first Programmable Logic Con-
trollers. A low-cost, highly reli-
able, and very easy-to-program
system, but physically large by
today's standards. It has only 2
kB of memory but is quite satis-
factory for this application. The
windmill control uses 32 inputs
and 24 outputs.

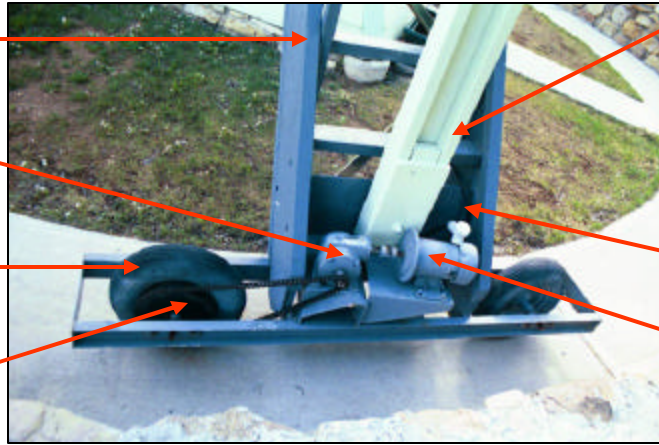Spare Program Pack

PLC Control Cabinet

Control Systems

Control Systems

Stairs to Revolving Frame

Right-Angle Gearbox
18:1 Ratio

Drive Wheel

Drive Chain and Sprocket

Wooden Slip-Joint
Enables Truck to move
up and down as
required for slight
variations in sidewalk
elevation.

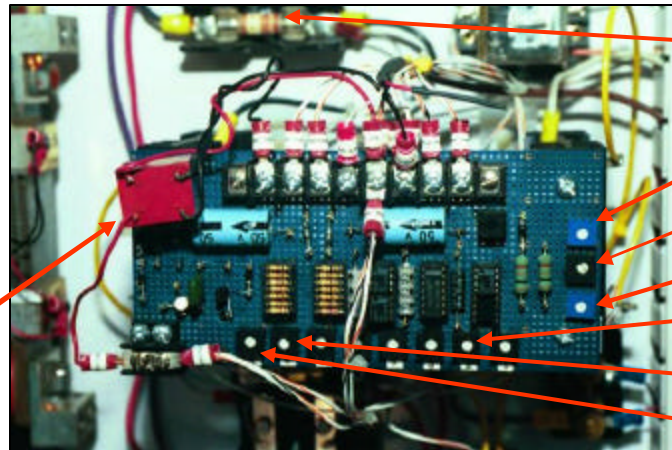Drive Motor Power Cable
Attached to stairway.

1/4 HP 90 VDC
Positioning Motor

Windmill Truck

This SCR DC Drive is itself a
closed-loop system. The
speed reference signal is com-
pared to the counter-emf of the
motor to hold the speed of the
motor constant under varying
load conditions.

SCR Pulse Transformer

High Speed Rectifier Fuse

Adjustment Potentiometers

Max Speed

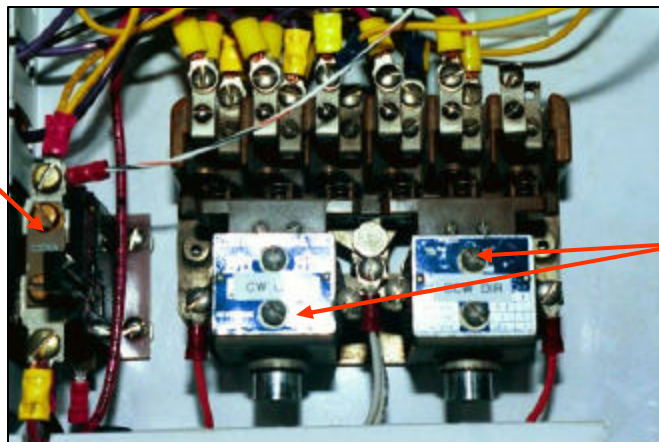Main Speed

Min Speed

Feedback

Gain

Current Limit

Position Motor SCR Drive Control Board

Drive Motor Thermal
Overload Heater

DC Drive also has electronic
current limit protection. The
OL heater is used as a current
shunt - the voltage drop across
the heater element is an input
to the current limit circuitry on
the drive board above.

Direction Contactors
Energized by PLC

Drive Motor Reversing Contactor