THE IMPELA CONTROL SYSTEM

C.B. Lawrence, S.T. Craig, J-P. Labrie, S. Lord and B.F. White

Atomic Energy of Canada Limited, Research Company
Chalk River Nuclear Laboratories
CHALK RIVER, Ontario, Canada K0J 1J0

Summary

The first IMPELA accelerator, a 10 MeV, 50 kW accelerator for industrial irradiation, is under development at the Chalk River Nuclear Laboratories. The control system uses contemporary, industrial control technology to provide an irradiator that is robust, reliable and easy to operate. The conventional controls are augmented with custom-designed electronics to achieve the required performance.

Introduction

IMPELA is a family of electron linear accelerators for application to industrial irradiation that is being developed at the Chalk River Nuclear Laboratories. IMPELA-10/50 is the first member of the family, a 10 MeV, 50 kW, long pulse linac [1]. The control system for the IMPELA-10/50 is engineered to provide simple, reliable operation in a production environment under the supervision of semi-skilled operators.

The IMPELA-10/50 accelerator requires several feedback control loops and has many variables that are interlocked to ensure the sub-systems are in working order. Protection is provided against functional failures, which could occur during accelerator operation, and result either in the product receiving an incorrect radiation dose, or in the equipment being damaged. A major goal for the IMPELA-10/50 control-system design is to provide an irradiator that will operate trouble-free for long periods in a production environment with a minimum of operator training. Automated control sequences assist the operator in getting the irradiator on-line effectively. The target is to have the irradiator available for 97% of the hours in a single-shift five-day week.

The implementation philosophy adopted for the IMPELA control system is to utilize factory automation equipment that will:

- provide a rugged control system, built from proven components,
- ease the learning experience for industry,
- reduce the cost of providing a support infrastructure, and
- simplify the interface to industrial processes.

This philosophy led to the selection of a programmable logic controller (PLC) as the basic building block for the control system. The hardware and software architecture of PLCs have been developed specifically for industrial process control, and are very different from those of conventional computer systems.

The essential outputs of the IMPELA-10/50 irradiator that are controlled by feedback are the electron-beam energy and dose delivered to the product. Since the control loop for the electron-beam energy must act more quickly than the PLC can respond, a closed-loop hard-wired controller has been specially developed. All other feedback control loops are implemented in the PLC.

Although PLCs are widely applied to industrial processes, the IMPELA-10/50 requires special interfaces because it is pulsed to optimize efficiency and capital cost. The electron beam is delivered as a train of pulses, each 200 µs wide, at a pulse repetition frequency (PRF) of 250 Hz. Special interfaces that convert the pulsed parameters to measurements which vary at the PRF, i.e., pulse filters, have been developed.

Another requirement is to protect the klystron, rf windows and accelerator structure from arcs, and the beam-line components from spilled beam. To prevent damage, this protective system must operate within the pulse duration and cannot be implemented directly in the PLC. A high-speed machine protection system has been designed for this purpose. Its operation is supervised and monitored by the PLC.

Industrial Programmable Controller

The PLC selected for the IMPELA accelerator is the General Electric--Fanuc Series Six Plus featuring Genius input/output blocks. The operator's interface consists of two Classicmate II display terminals, a product of Industrial Data Technologies. The prototype accelerator is supplemented with a data logger using a General Electric--Fanuc Cimstar computer (an industrial IBM-AT compatible) with FIX software from Intellution. The data logger performs no control functions: its purpose is to collect data during the commissioning and characterization of the accelerator. Fig. 1 shows the architecture of the control system.

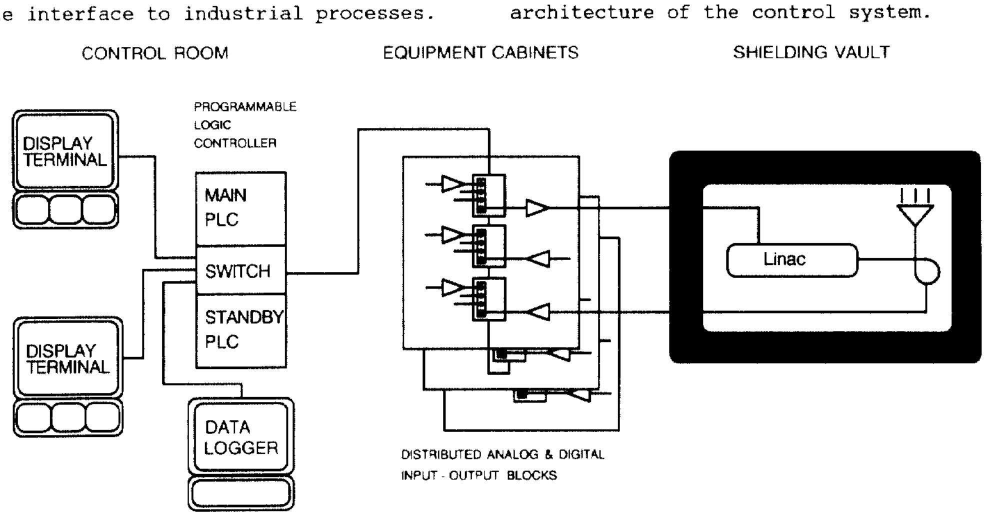

Fig. 1: Control System Architecture

The PLC, located in the control room, is a dual redundant configuration. It consists of two identical processors, each with an identical program, and an automatic switch. The processor that is designated by the switch as the main processor controls the accelerator. A watchdog in each processor monitors its scan time, while the switch monitors other critical performance parameters. If the watchdog or switch detects a failure, control is passed automatically to the standby processor. All input and output data, i.e., to the display terminals, the input/output blocks and to the data logger, are also routed through the switch which transfers all functions when a switch-over occurs. Variables within the PLC, such as timers and counters, are maintained in the standby PLC and switch-over causes no interruption to operation.

The control system's man-machine interface has two display terminals, each consisting of a colour video display and keyboard, to present the accelerator's status to the operator and accept commands. The displays and program are functionally identical in each terminal; however, only one is essential to run the accelerator. The second terminal permits display of additional variables and increases availability through redundancy.

The Genius analog and digital input/output blocks are located in equipment cabinets just outside the accelerator's shielding. Data from the input/output blocks are communicated to the processor, in the control room, via three Genius bus cables. Each bus cable is a shielded twisted pair that provides reliable, bit-serial communication at 150 kbit/s. An advantage of this distributed input/output is the minimal wiring between equipment and the control room.

Feedback Control Loops

Feedback control loops ensure that parameters are maintained within acceptable tolerances without the need for shutdown or complex manual adjustment. In an irradiation facility, product is carried to the scan horn on a conveyor through the shielding maze. The electron beam scans across the conveyor to irradiate product as it passes the horn. The requirement is to provide an absorbed dose uniformity of ±5% at a 2 cm depth in a water phantom. The four important parameters that determine the dose received by the product, all controlled by feedback loops, are the electron-beam energy, the beam current, the scan width and the conveyor speed. The beam currents, emitted from the electron gun, accelerated and delivered to the product, are sensed with toroidal pulse transformers.

Beam current is controlled in the triode geometry electron gun. This voltage control has two functions: it switches the beam on and off, and regulates the current injected into the accelerator by adjustment of the on-state voltage. While the switching is implemented in special hardware, the on-voltage is controlled by the PLC. The electron beam emerges from the scan horn window as a spot, about 10 cm in diameter, and is scanned over the product by means of a deflection magnet. The current in this magnet is cycled to sweep the spots across the product in an overlapping pattern that provides a uniform dose. The width of the scanning pattern is measured by sensors that detect the current at the two extremes of the sweep. The current waveform applied to the deflection magnet is adjusted by the PLC to maintain a constant sweep geometry in the product plane.

The delivered electron-beam energy is determined by the rf electric field in the accelerator. Thus, control of the electron energy requires modulation of the rf drive to maintain the desired rf electric field in the accelerating cavities. Because this feedback control loop is active during the 200 μs pulse, a response bandwidth in excess of 2 MHz is required. A gated, proportional-plus-integral controller modulates the rf drive to regulate the field within ±1.0% of the field setpoint computed by the PLC. Coupling to the structure is optimized at 65% beam loading; consequently, beam is injected prior to the rf pulse to avoid a beam-induced field transient. Fig. 2 shows this high-speed rf field control loop as well as the outer slow loop in which the PLC provides the setpoint to the inner loop.

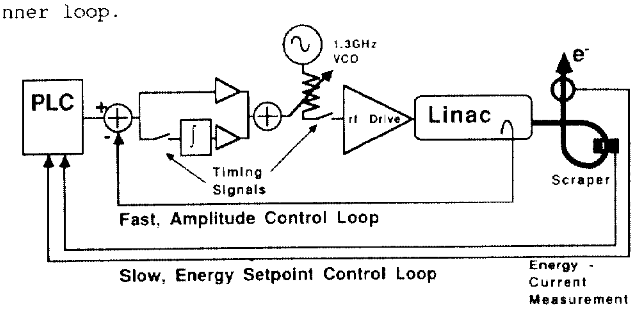

Fig. 2: Energy Control Loop

There are two methods available for calculating the rf field setpoint provided by the outer loop. If a 270° bending magnet is not present, the energy of the electron beam is measured by analytical laboratory methods and the rf detectors are calibrated in terms of energy. For applications where energy is not critical, this is adequate. If the electron beam energy is critical, a 270° bending magnet is used to analyze the beam. The trajectory of the electrons in the bending magnet chamber is determined by the magnetic field intensity and the electron energy. The field is regulated by maintaining a constant current in the magnet. An aperture scrapes a portion of the electron beam and by maintaining a constant fraction of scraped current, the electron-beam energy is assured.

The accelerator is a high Q (about 20 000 unloaded) resonant structure and therefore, tuning is essential to its efficient operation. The main tuning parameters are the physical dimensions of the accelerating cavities and these are carefully controlled during manufacture. Following assembly of the accelerating structure there remain two variables to be controlled: the structure temperature and the frequency of the rf power. The structure temperature is determined by the cooling water and the rf power dissipated in the structure. The IMPELA-10/50 accelerator is cooled with a closed-circuit, de-ionized water loop where the temperature at the heat exchanger outlet is constant at 30°C. This is accomplished by PLC control of the service water flow through the heat exchanger using conventional devices. In spite of the temperature control, variation in the rf power dissipation produces significant changes to the accelerator's resonant frequency.

The mismatch between the driving frequency, generated with a voltage-controlled oscillator (VCO) and the structure resonance, is sensed by measuring the phase difference of the rf field in the structure as compared to its source. This is used by the PLC to adjust the frequency of the VCO to track the stucture resonance, by minimizing the phase difference. A further check of resonance is that the reflected rf power, measured at a directional coupler near the accelerator, is minimized at resonance.

Pulse Filters

The IMPELA-10/50 accelerator is controlled with a PLC which cannot directly read the parameters of a 200 μs pulse. The average scan time of the PLC, i.e., the time for one complete execution of the control program, is about 100 ms, and the execution is asynchronous with the accelerator pulses. A further requirement is to bring the accelerator to full power without damage to components. The electron-beam intensity is sufficient to damage accelerator components if the average power is brought to 50 kW before all parameters are well adjusted. First beam will be established at a low PRF where the average power is insufficient to cause structural damage to the vacuum envelope if the beam impinges where it should not. Thus, the control system must have the ability to read signals and adjust parameters by capturing information from a single pulse.

An essential component for performing measurements on pulsed parameters is a central timing source to coordinate pulsing of the IMPELA-10/50 accelerator and sampling. The master timing generator (MTG), which is controlled by the PLC, synchronizes all pulsed actions. The PLC adjusts the PRF as well as the on-off control of MTG outputs that enable the rf modulator, the electron gun and the pulse measurements.

The sampling of pulsed signals is performed by the digital pulse filter shown in Fig. 3. One of these filters samples the output of each pulse sensor and presents its estimate to the PLC input. The filter consists of a wideband amplifier and other signal conditioning to amplify the input signal to a high level. Next is an analog sample-and-hold circuit that is synchronized to the MTG. Following the analog sample-and-hold, an analog-to-digital and digital-to-analog converter performs a digital sample-and-hold function. An output filter attenuates the high frequency components to match the PLC sampling rate.

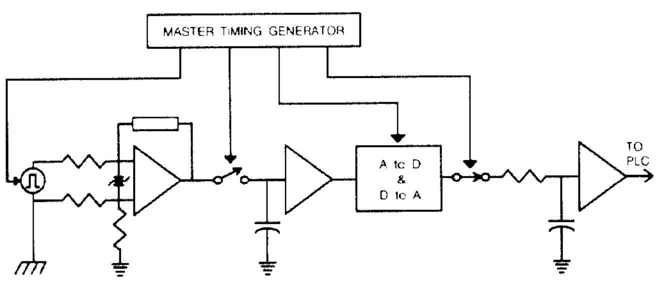

Fig. 3: Pulse Filter

The digital pulse-filter retains a measurement from a single pulse for an indefinite period. The control algorithms in the PLC are executed continuously and are not required to be pulsed in synchronism with the accelerator. Tuning of control parameters that may change with PRF is performed automatically by the PLC as it adjusts the PRF to control average power.

High-Speed Machine Protection

The three types of high-speed machine protection required for the IMPELA-10/50 accelerator are:

- triggering the high-voltage crowbar if an arc develops in the klystron or its modulator,
- stopping rf drive to the klystron if an arc develops in the waveguide or structure, and
- disabling the electron gun current if the beam impinges on specific components.

The scheme developed for this protection function is illustrated in Fig. 4. A current source, located in a head end module in the control room, establishes a current loop through a distributed set of protection modules. As long as current flows in the loop, the high-speed actuator, e.g., the high-voltage crowbar, is prevented from operating. When a protection threshold is exceeded, the current flow is interrupted, activating the crowbar. Coupling of each protection module to the loop is performed optically which permits the modules to be located in different equipment cabinets with high immunity to electromagnetic interference.

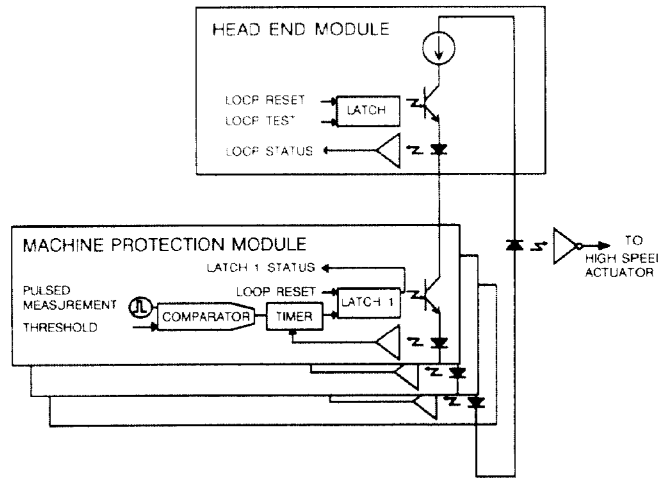

Fig. 4: High-Speed Machine Protection Loop

Each of the three head end modules has an input from the PLC to allow testing of the loop and an output to indicate the loop status. Each protection module also senses the loop status to allow only the first protection event to be latched by any module on the loop. Subsequent events are locked out when the loop opens so that, when the PLC examines each module status following the protective measure, it will be able to identify the initiating event. If multiple events occur within the loop signalling time (typically 3 μs), each will be latched. Each protection module also includes a timer to prevent short duration events from causing a spurious protection action. The PLC controls some thresholds, reads the loop status and resets the loop, but does not actuate the protective device.

A watchdog timer on the PLC is connected to the three protective loops so that if the PLC fails, the high speed protection actions are carried out automatically, ensuring a safe shutdown.

Development Experience

With program design and implementation well advanced, the strengths and limitations of PLCs have become more apparent. PLC programs, as we expected, are not difficult to write or understand and there is a low overhead in housekeeping software to implement a control system. The limitations inherent in the PLC are the lack of precise timing in a real-time response, the lack of a high-level language and a limited ability to carry out information processing. One consequence is that the control program must be simple. The advantage is that the control program contains only the essentials. This forces the program to be strictly functional and aids in providing a high-quality program, permitting very high standards of quality control. It also follows that the architecture of the control system is near optimum, with the PLC handling only the vital accelerator controls, and information being sent to another computer for data logging, quality assurance recording or other information processing which is application dependent.

References

[1] J. Ungrin et al., "IMPELA: An Industrial Accelerator Family", presented at the 1988 EPAC conference, published in a special edition of Nuovo Cimento.