GA–A24468

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MARCH 2004

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This is a preprint of a paper presented at the 20th IEEE/NPSS Symposium on Fusion Engineering, San Diego, California, October 14–17, 2003 and to be published in *Fusion Science and Technology.*

Work supported by
the U.S. Department of Energy
under Contract No. DE-AC03-99ER54463

GENERAL ATOMICS PROJECT 30033
MARCH 2004

Improvements to the Cryogenic Control System on DIII–D

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Abstract. The cryogenic facility that is part of the DIII–D tokamak system supplies liquid nitrogen and liquid helium to the superconducting magnets used for electron cyclotron heating, the D_2 pellet injection system, cryopumps in the DIII–D vessel, and cryopanels in the neutral beam injection system. The liquid helium is liquefied on site using a Sulzer liquefier that has a 150 l/h liquefaction rate. Control of the cryogenic facility at DIII–D was initially accomplished through the use of three different programmable logic controllers (PLCs). Recently, two of those three PLCs, a Sattcon PLC controlling the Sulzer liquefier and a Westinghouse PLC, were removed and all their control logic was merged into the remaining PLC, a Siemens TI555. This replacement was originally undertaken because the removed PLCs were obsolete and unsupported. However, there have been additional benefits from the replacement. The replacement of the RS-232 serial links between the graphical user interface and the PLCs with a high speed Ethernet link allows for real-time display and historical trending of nearly all the cryosystem's data. This has greatly increased the ability to troubleshoot problems with the system, and has permitted optimization of the cryogenic system's performance because of the increased system integration. To move the control logic of the Sattcon control loops into the TI555, an extensive modification of the basic PID control was required. These modifications allow for better control of the control loops and are now being incorporated in other control loops in the system.

I. INTRODUCTION

The DIII–D cryogenic facility is part of a research facility in operation since 1980. The capabilities of the cryogenic system have been repeatedly upgraded to support new equipment and capabilities. The control system upgrades have been representative of the current state of the art at the time of the upgrades and range from simple relays and manual switches to programmable logic controllers (PLCs) and dedicated personal computers (PC).

Before the most recent upgrade, there were a total of three PLCs used in the cryogenic system. These consisted of a Westinghouse Numalogic 1700, a Siemens Simatic TI555 and a Sattcon 31-10. The Westinghouse and Siemens PLCs were used for control of DIII–D systems and their programming was developed by General Atomics personnel. The Sattcon PLC came preprogrammed as part of a helium liquefier assembly supplied by Koch Process (Model 2800R, one of only two ever made). As the equipment has aged, repairs and replacement of parts have become necessary. While there are advantages to using PLCs over relay logic, one unfortunate disadvantage for an older facility is the issue of obsolescence. Westinghouse no longer manufactures PLCs so replacement parts have not been available and there were problems in finding reliable outside repair facilities. There were similar problems with maintaining the Sattcon PLC. The Simatic TI555 is still supported by Siemens. Based upon these concerns it was decided to replace the Westinghouse and Sattcon PLCs. This paper will discuss some of the issues involved in replacing the PLCs and improvements gained from that replacement.

II. PLC HARDWARE

Various upgrade options other than PLCs were studied as replacement candidates including software packages running on PCs. It was decided to stay with PLCs as they are a very mature technology and in our experience have proved very reliable. Various new PLCs from different manufacturers were studied but there appears to have been very little evolution in PLCs over the last twenty years. It was difficult to find any major improvements in the functionality of the new models over the obsolete models. In fact the older Westinghouse PLC had a larger function set than many of the newer PLCs. The main improvement appears to be in communication, *i.e.* Ethernet capability and programming software. Since the TI555 already takes advantage of both these features it was decided to fold the functionality of the other two PLCs into this PLC.

Each of the PLCs had its own proprietary communication fieldbus protocol to link to remote I/O bases. The consolidation to a single main network greatly simplified the network architecture. The chosen fieldbus protocol was Profibus-DP, which is a fieldbus standard that enjoys multiple vendor support. It is believed that the TI-555 will still be available over the remaining life span of the project, approximately ten years. However, this PLC model is not Siemens' flagship product and it often costs more than newer equipment. Using Profibus-DP, I/O equipment from various vendors could be used together. The main CPU and rack is TI555 equipment while the new remote I/O is either newer Siemens or GE Fanuc equipment. If the TI555 PLC becomes obsolete then only the CPU and main rack have to be replaced and whatever replaces the TI-555 CPU would only need to support Profibus-DP, which shouldn't be a severe constraint.

The Westinghouse PLC consisted of 117 digital inputs, 88 analog inputs, 76 digital outputs and 19 analog outputs wired to 44 I/O modules located in 8 different locations. The PLC programming consisted of approximately 400 rungs of logic. The Sattcon PLC consisted of 23 digital inputs, 20 analog inputs, 13 digital outputs and 9 analog outputs wired to 8 I/O modules located in one rack. The Sattcon PLC programming consisted of approximately 300 rungs of logic.

III. PLC PROGRAMMING SOFTWARE

The one great advantage in using the TI555 was not in the TI555 itself but in the programming software. This software allowed for very descriptive tags and descriptions for all programming variables and the ability to easily document every row of logic. The mouse driven graphical user intrface (GUI) interface with cut and paste features greatly eased the writing of large sections of PLC code. Ladder logic, while graphical in nature and fairly easy to follow for a single row, is not ideally suited to complex processes. The ability to document in words the relationship of a single rung, to the process as a whole has proven to be of value; in particular the ability to decode undocumented ladder logic appears to decrease during times of stress such as when the system is malfunctioning.

IV. PLC INTERFACES

The data output from the Sattcon was sent to a local printer to which data was printed out every 10–15 min. Online programming was through a dumb terminal and was accomplished through a control line interface. The Westinghouse was connected to a HMI product but the update time was very slow, e.g. 15–30 s between updates. In contrast, the TI555 connecting to a similar HMI product but using an Ethernet connection has an update time of 1–2 s.

This high-speed access along with the use of a commercial software package that allowed for easy trending and charting of the data has been an "enabling" technology. Graphical user interface (GUI) screens were developed for the cryogenic system PLC. The GUI screes are almost real-time P&I diagrams of the system and give users a better understanding of the process operations. From the helium liquefier overview page the operator can stop and start the liquifier, and observe the current status of the system and associated operational parameters (Fig. 1). Each of the parameters is linked to a data-logging screen, which can be accessed by simply clicking on the value (Fig. 2). The ability to chart the data allowed for quick analysis of problems and has proven invaluable in troubleshooting the system. In addition, there are help screens with information regarding the systems, audible alarms and event logging. Currently, there are 30 main screens and over 300 additional supporting pages used for graphs, help information and expanded control options.

V. PLC RELAY LADDER LOGIC

In addition to replacing the PLC I/O hardware, all the logic and programming in the two replaced PLCs had to be ported to the TI555 system. Porting over the PLC logic from the Westinghouse PLC was a relatively straightforward process. The Westinghouse PLC is programmed using the typical ladder logic format that is very easy to translate to a new system. The only difficulty was that the Westinghouse PLC supported a very rich feature set and not all of the features, *e.g.* one-shot timers and data table manipulation routines such as averaging and sorting were supported in the TI555. However, these functions could be developed, albeit less elegantly in the TI555.

The porting over of the Sattcon PLC logic proved more challenging. The original code itself was available in a statement list format called programmable binary system (PBS). A graphical representation drawn in CAD similar to ladder logic was also provided in the documentation. This representation, while easier to use, had typographical errors that soon required returning to the PBS output.

VI. OPTIMIZATION OF SYSTEM PERFORMANCE

The consolidation of the control systems into a single PLC has allowed for a better optimization of the system performance. For example, different operating modes have now been implemented for day and night operation that allow two large He compressors associated with the liquefier to maximize the He liquefaction rate at night while also reducing power consumption. The PLC controls both the compressor loading and the helium liquefaction rate to maintain system stability while maximizing the liquefaction rate. After the liquid He storage dewar is filled the PLC ramps down the liquefaction make rate and gaseous He pressure to a flatline level and then safely offloads an unneeded compressor. The

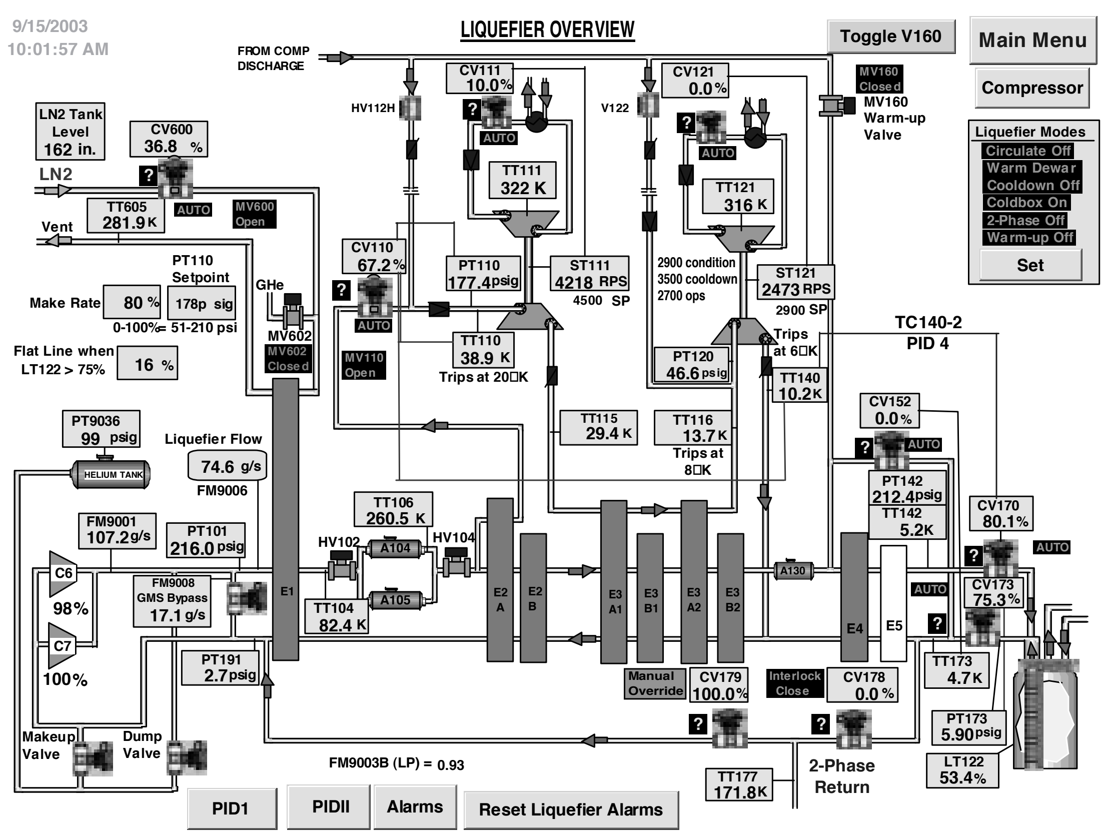

Fig. 1. A GUI screen for the helium liquefier. The user can control the liquefier modes and valves from this page as well as get real-time data on operating parameters.

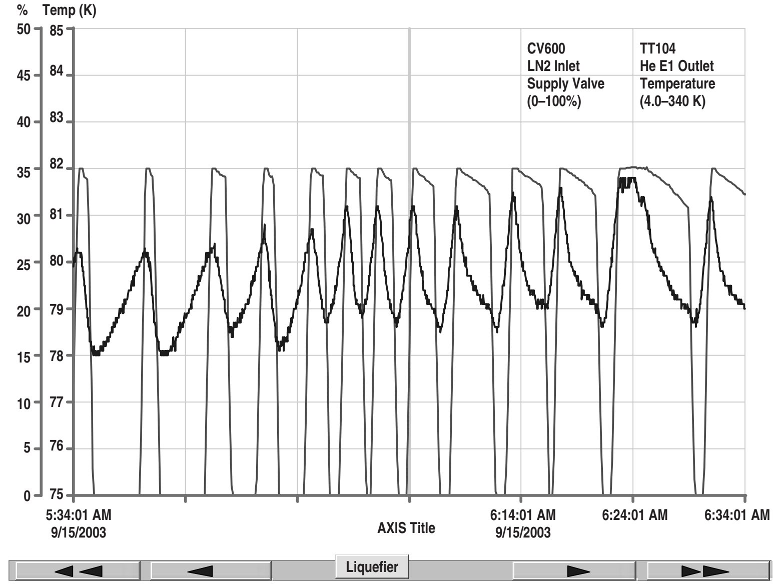

Fig. 2 A typical screen charting values of the liquefier. In this case the output temperature of the first heat exchanger, TT104, is shown along with the output of control valve CV600. The PID terms controlling CV600 are unable to respond quickly enough and the override terms of the extended control loop are opening and closing the valve to keep the temperature within limit.

cost savings for this automated mode is estimated at $2,500 per operating week.

The consolidation of all the PLCs has allowed for a higher overall system stability. For example, the liquefier supplies liquid He for a varying number of users. If the liquefier doesn't have adequate compressor loading or if its liquefaction rate is set too high the operating limits on the liquefier can be exceeded and the liquefier will shut down. Restarting of the liquefier can take several hours. Now the PLC monitors the compressor loading, inlet temperatures and pressures, shuts down users and issues alarms to the operators before the liquefier trips.

VII. PLC PID FUNCTIONS

Both the Westinghouse and Sattcon PLC had built-in feedback control functions using proportional integral and derivative (PID) control loops. The use of these PID functions is very similar. The user supplies parameters such as the gain terms, sample rate, and a setpoint and control variable and the PID function calculates and returns an output, which can be used for control [Fig. 3(a)]. The Sattcon also included an interlock open and interlock closed functionality, which was not present in the TI555. Instead the TI555 PID loops allow you to run special function programs, which are programmed, in a simple basic-like language, which the PID function will automatically execute at various points in the loop cycle and allows for modification of the loop parameters.

The liquefier system consists of nine closely interrelated control loops, six of which utilize PID control. The output from one loop will adjust a valve that can have an affect on all the other loops on the system. Needless to say this makes tuning control loops very difficult. The original designers of the system had used many conditional ladder logic statements to limit the PID loop outputs especially during transient conditions. As this was ported over to the TI555 it became easiest to incorporate these features into a construct which utilizes the PID control loop calling the special function program. Eventually, a generic template for an extended PID control was developed [Fig. 3(b)].

An example of this extended PID control is the loop used to maintain the gaseous He output temperature, TT104, at 82 K on the He Liquefier. The primary control of this temperature is by varying the amount of cold gaseous N2 flowing through the first heat exchanger E1. A cascaded PID loop construct is used to accomplish this. The first control loop, outputs a value from 260 to 340 K based upon the He outlet temperature, TT104. As TT104 increases the loop output value decreases. This outlet value is used as the setpoint for the next control loop which will then adjust the liquid N_2 control valve CV600 to match this setpoint value to the N_2 gaseous N2 outlet temperature. TT605 high temperature setpoint will result in CV600 closing, decreasing the liquid N_2 flow and warming the system. However, TT104 is also affected by flow from compressors C6 and C7 that is a function of the adjustable liquefaction rate and from the return flow through the system that is a function of an adjustable number of loads on the system. There was a considerable effort to tune the proportional, integral, and derivative parts of the loops. However, since both the gaseous He inlet and return flow can vary widely it has not proven possible to select proportional, integral, and derivative parameters that maintain smooth control over all time periods. Fig. 2 shows an example where the PID control is continually overridden by manual open and close requests, which minimizes the overshoot, and undershoots to acceptable levels.

It is planned to use this extended PID control in other parts of the cryosystems where complications similar to that in the liquefier exist. These include multiple closely coupled control loops where the output of one loop affects the control of other loops and vice versa. Also, this can be applied to processes where large step-function changes occur or where there are sudden disruptions in the control variables. The increased functionality of the extended PID control allows for solutions other than tuning the loop gain parameters, which often is not sufficient.

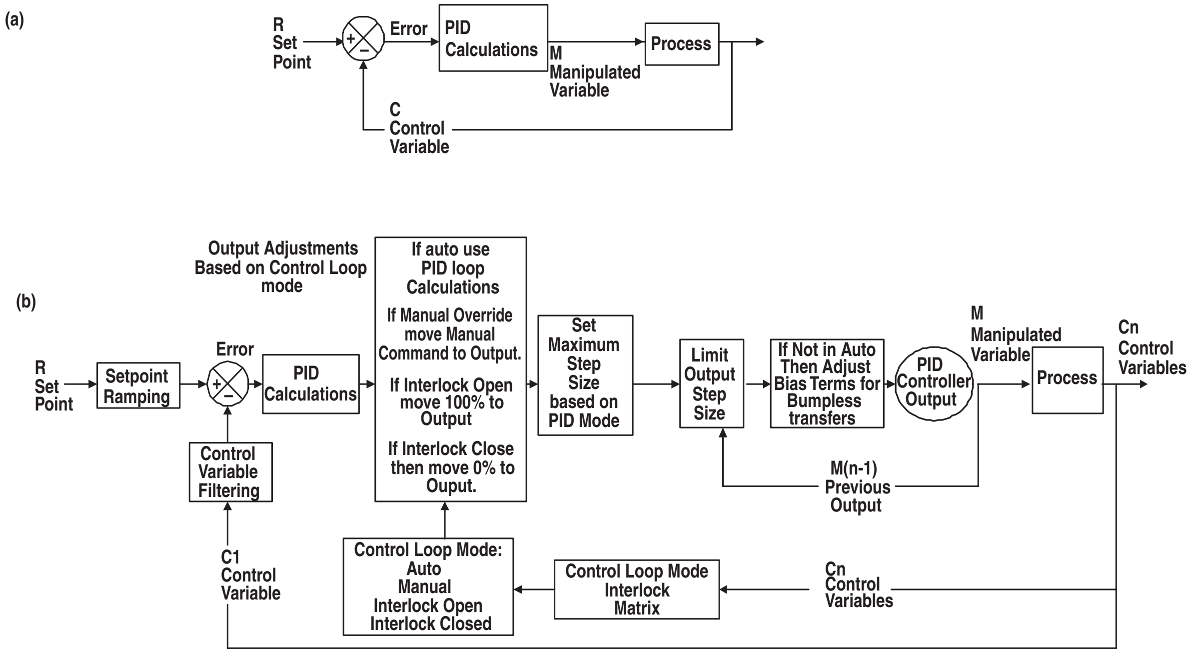

Fig. 3. (a) A schematic for a typical control loop is shown in part. (b) An extended control loop that was developed which has additional control parameters.

VIII. CONCLUSIONS

It became necessary to replace two of the three PLCs in the DIII–D cryogenics control system due to the obsolescence of the equipment. Interestingly, newer PLCs supplied very little improvement in functionality, with the notable exception being in Ethernet connectivity which allows for high speed transfer of the data into PCs where it can be displayed with GUI packages and data historians. The ability to display real-time data in its proper contextual relationship to the system and the ability to easily log and display historical data has been a large improvement to the system. The ability to display and manipulate the data has greatly increased the understanding of the system by both the designers and the users of the system. Extended PID control loops were developed that have additional functionality and allow for more involved control than just adjusting gain terms, which has proved insufficient in many cases.

ACKNOWLEDGMENT

Work supported by the U.S. Department of Energy under Contract DE-AC03-99ER54463.