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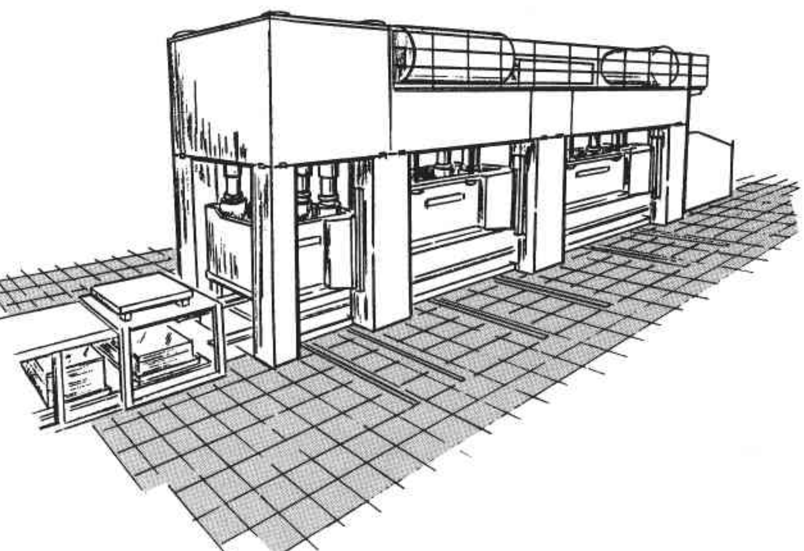
The Care and Feeding of PLC-Controlled* Machinery: Part 2

OR Everything you've ever wanted to know about PLC's and were afraid to ask concerning their relationship to: Products Liability, Safety/Ergonomics, Documentation, Engineering Design, Hi-Tech, Hi-Speed Machinery, The New Industrial Revolution and TRI-AXIS Transfer Presses

by Lawrence K. Bell, P.E.[1]



Abstract

Part 2 of this series on PLC-controlled machinery continues in this issue of The Triodyne Safety Brief, with the third and final part to be published in a future issue.

*In the first part of this series, which appeared in the June 1993 Triodyne Safety Brief, Volume 8, No. 3, the concept of the second industrial revolution, based upon the **mass production-short run** idea, was developed. As a specific example, a large tri-axis transfer press was used as an embodiment, together with a double-action tri-axis transfer press — and all of the necessary ancillary equipment required to support them.*

*The history of the **mass production-long run** basis of American industry, extending back to the Civil War, but coming into its own during World War II, was explored. Additionally, the role of postwar global competitive forces in forming the decision of American business leaders to implement the **mass production-short run** concept, was also discussed.*

* PLC: Programmable Logic Controller
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The Table of Contents for Part 1 of the Article is again listed in Part 2, in order to provide continuity and a ready reference source for the reader as to the detailed nature of the topics discussed in Part 1. Of course, Parts 2 and 3 of the series are also presented in the Table of Contents.

In Part 1 it was seen that its major thrust was on the technical aspects of the tri-axis transfer machine system. Part 2 continues to deal with the rest of the technical parameters of the equipment. Also addressed in Part 2 are questions of engineering documentation, record keeping and software considerations.

Part 3 of this series will conclude the overall discussion of PLC-Controlled Machinery with a very thorough analysis of Product Liability Aspects of the whole subject including the impact of the fact that the tri-axis transfer press system must be considered as a dedicated machine system with respect to guarding the point of operation. Conclusions and recommendations are made for attorneys, insurance companies and manufacturers. Please see the Part 3 Table of Contents for a preview of the subjects.

III. B. TECHNICAL IMPLEMENTATION

1. Control

a. Clutch/Brake Control. In part 1 of this series on PLC-Controlled Machinery Section III.A.12 the importance of very careful design of the control for this critical portion of the press was discussed. Indeed, all other areas must take a lower priority to this circuit. In this particular case it was indicated that a first-order redundant design would be highly appropriate. This was implemented through the use of a dual solenoid valve actuating component, with sensing elements to monitor the status of each valve.

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When applying a PLC to the clutch control, it must be emphasized that the reliability of PLC controllers are not as good as a comparable straight relay control. By employing two separate processors, breaking them out from the rest of the press control system, and timing them properly, the chances of improper clutch activation are almost infinitesimal. A typical block diagram of a dual processor/dual valve clutch/brake control is shown in Fig. 1:

> The press drive itself, when engaged, drives both a resolver and a rotary cam limit switch. As indicated, the resolver, which can be programmed by the PLC, is used for other control functions such as automation requirements, slide position, counterbalance control, etc. The rotary cam limit switch is reserved exclusively for clutch/brake control. The reason that a rotary cam limit switch is recommended rather than a resolver is that by its very design the contacts of the switch are mechanically made and broken. This provides an extra level of safety and reliability for the clutch control circuit.

There are two cams to perform each of the several clutch control functions: Anti-repeat, Takeover, and Top Stop (with high and low ranges if required). Only one cam each is required for brake monitoring and motion detection. The purpose of the brake monitor is to maintain a continual measurement of the effectiveness of the brake; if it wears too much, the control system will be shut down. The objective of the motion detector cam is to detect any breakage in the driving mechanism between the press drive and the rotary cam limit switch. If this does occur, the system would immediately shut down.

As can be seen from Fig. 1 there are two separate CPU* processors. Each PLC receives an input from each of the cams from the rotary cam limit switch. Additionally, each processor receives an instantaneous update on slide position from the resolver, which usually can define the position down to .1 degree. As the slide is given the signal to make a cycle, CPU #1 and CPU #2 compare the start signals, and simultaneously make an internal check of their own status as well as their timing location with respect to the other CPU. If everything checks out okay the electromagnetic contactors are actuated, and the dual solenoid valves are energized. This starts the slide downwards in a controlled fashion. As the slide proceeds to complete the cycle the two PLC's keep a constant check on each other's calculation of instantaneous slide position, speed, as well as a continual internal self-check of their own systems. If this constant comparison does not maintain a balance, or if one PLC starts to get ahead of or behind the other one, the system is shut down immediately. In addition, the cams of the rotary cam limit switch are also used as absolute position markers for the system, so that if anything happens to the resolver outputs, the system will be shut down.

From this very brief description of the clutch control system it is apparent that while the slide is moving it is being continuously checked and monitored, and rechecked again. With this tight surveillance the chances of the equipment malfunctioning or accidentally starting an inadvertent press cycle are very small. In addition, if an emergency stop situation is called for, not only does the PLC systems de-energize the dual valves, but a hard wired stop signal de-energizes the contactors, in essence bypassing the two CPU's. Note that the realization of this clutch control circuit utilizes a hybrid control circuit, or a combination of relays, contactors, and PLC's. As discussed in Part 1, Section II, this is the safest and most reliable control combination for this portion of the press control; indeed, this is the virtual heart of the entire system, and certainly just as critical as a heart.

b. Other Major Control Areas. While the importance and critical nature of the press clutch control circuit cannot be overemphasized, nevertheless there are many other, albeit less critical from a safety standpoint, press functions that must be controlled as well. For these functions, the main PLC is used. Some of the control areas that would fall into this category are listed below:

1. Inch and Microinch
2. Automatic counterbalance control system
3. Lubrication systems
4. Utility systems - hydraulic, pneumatic, water, electrical
5. Manual and automatic slide adjust
6. Moving Bolster Controls
7. Automation, Parts sensors
8. Couplers, fingers, and nests
9. Safety Gate Controls
10. Hydraulic Overloads
11. Tonnage indicating systems
12. Operating Mode Select
13. Line Operation Select
14. Manual and automatic die change
15. Die Identification
16. Transfer Feed Control systems
17. Critical component monitoring: bearings, pressures, voltages, currents, temperatures, accumulator pressures, etc.

Figure 2 is a block diagram of some of these systems as applied to the double-action tri-axis transfer press described in this article. A similar breakdown would be required to describe the single-action tri-axis transfer press. The latter is not shown because of the limited scope of this article.

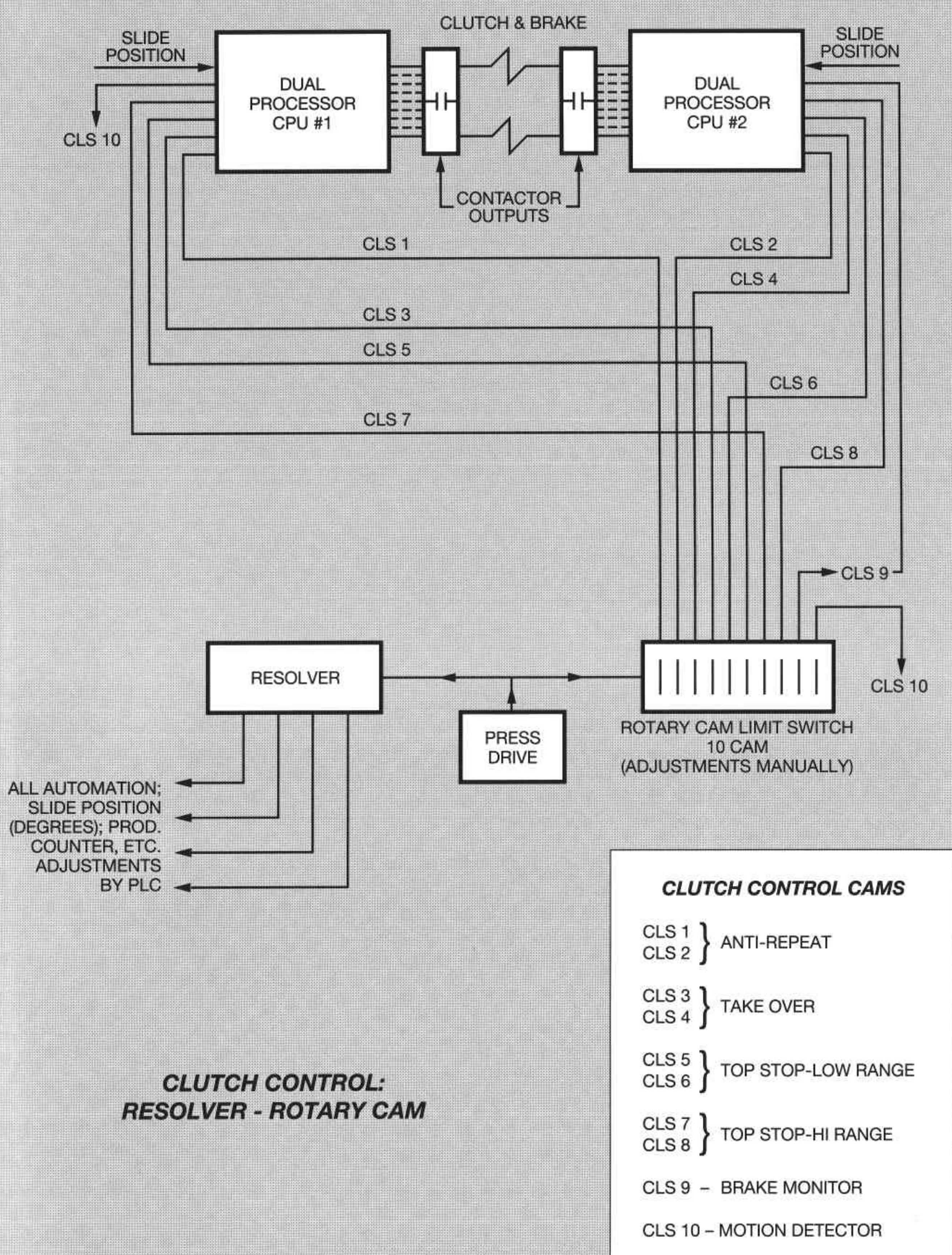
The complexity of the overall system is illustrated by this block diagram. Additionally, there are many subsystems relating to each block that cannot be shown on this block diagram for clarity reasons. For example, under mode select, if the Single mode is selected, there are literally dozens of smaller subsystems that must be called into play in particular sequences to ensure that the press is ready to be adequately operated in single-stroke mode. There are five main areas of operation for the double-action press; these are:

1. Independent press operation (with and without transfer feed)
2. Die Change (manual and automatic)
3. Die Change data entry
4. Line Operation
5. Line Operation-automatic die change

From these five general areas, the rest of the block diagram illustrates what may be controlled under each category. Because of the many combinations involved in the selection process, a separate computer is utilized, with a finger touch interactive screen, that allows these different areas to be brought up. As an example assume that it is desired to make an automatic die change on the double-action press. By touching the "D.A. Press die change" block under the main menu, the suceeding screens displayed will allow the operator to

* CPU: Central Processing Unit

FIGURE 1 – PRESS CLUTCH/BRAKE CONTROL SYSTEM



initiate and complete the automatic die change. Of course, the actual process is completely monitored and checked by the myriad of subsystems and programs required to carry out the die change instructions.

A word on the transfer feed unit is in order, to illustrate the almost completely separate controls required for this equipment. Note that there are nine separate categories of transfer feed control:

1. Torque Releaser
2. Transfer Feed Air Reservoir System
3. Synching feed with press
4. Shot pin and inner distance adjust
5. Clamps lift and shaft stop
6. Height compensator adjust
7. Shift Feed Bars
8. Feed Bar Connectors
9. Turnover operation

No attempt is made here to go into detail on the specific functions of each of these items illustrated in Figure 2. This is regrettable, but to do so would turn this article into a textbook and lose sight of the main objective, which is to address some of the areas of the economy that will be significantly impacted as the short run-mass production industrial revolution kicks in on a high level throughout industry. A good pictorial reference, however, can be found in Part 1, Figure 3, the transfer line block diagram. Many of the components can be identified.

c. Packaging for the Above. Part 2 Sections III.A.2, 3, 4, 5, discuss some of the things required to minimize the effects of electrical noise. The packaging of electrical and electronic equipment for industrial use must be approached with the same care as the actual circuit design and program development. Most of the electronic products developed for home and some commercial uses are not suitable for heavy industrial applications because of the hostile environments in many locations. Some of the negative items are shock, vibration, long cable runs, lubricant sprays, thermal effects and other environmental conditions such as humidity and atmospheric contamination; also electrical noise created by outside sources such as welders, and so-called "dirty power," sometimes caused by thyristor (SCR*) controlled electrical motors.

In order to minimize the deleterious effects of these items, a few general guidelines are listed below:

1. *Component Location.* All of the electrical motor controls should be grouped into separate oil-tight enclosures, high voltage D.C. packages into one (or more as required) enclosures, and high voltage A.C. packages into other separate enclosure(s). All low voltage D.C. power supplies, and other low voltage D.C. components, particularly hard-wired items, should be located in their own separate enclosure(s).

   All PLC's should be mounted in their own separate enclosures, following the manufacturer's assembly instructions. This includes all auxiliary equipment required to support the PLC's, such as remote I/O** transmitters, intercommunication packages, external electronic power supplies, etc.

   The other main category of electrical components used in equipment of this type is standard 120 volt A.C. relays, contactors, and 120 VAC hardwired packages. These items are all located together in their own enclosures. Pushbuttons, stop buttons, selector switches, etc. are all located in oil-tight push button enclosures in the appropriate locations in and around the equipment.

2. *Wiring Configuration.* Because of the electromagnetic and electrostatic radiation that occurs whenever electrical current is flowing, and the possible interference that may be caused, it is necessary to group the wiring originating from the various enclosures and being routed to different locations on the transfer press line into a number of different separate cable and conduit runs. For example, all high-voltage motor runs that are D.C. in nature should be grouped into their own conduits. Similarly, all high-voltage A.C. runs should be isolated in their runs. 120 volt A.C. wiring bundles should be kept separate in their conduits; of particular importance are low-voltage D.C. cable and wiring runs. These include all communication and input runs to and from the PLC's low-voltage D.C power supplies, sensing element runs such as thermistors, thermocouples, pressure and voltage sensors, etc. These too should be grouped together in their own separate conduit(s). This arrangement minimizes the chance of electrical interference among the wiring to and from the press. This becomes very important when the press is of larger tonnage, thus requiring longer cable runs, with a greater susceptibility to noise problems.

3. *Grounding and Shielding.* It is necessary to ground adequately all enclosures, pushbutton boxes, I/O packages, transducers, sensors, motors, etc., to each other as well as to a good ground. A good ground is defined as a low-resistance bond to the press and the building steel and water pipe structure.

4. *Isolation.* A good technique to follow in attempting to keep outside electrical noise from entering the control system is to isolate the main power entrance from the transfer press system. One way this can be done is to use shielded power transformers with special power connections, such as delta to wye primary/grounded secondary. A monitoring of the incoming power is sometimes useful to detect a trend towards any abnormal voltage and current surges, as well as to excess frequency deviations.

   In addition to minimizing the effects of electrical noise, the packaging must be ruggedized and sealed to withstand the effects of shock, vibration, and other environmental conditions commonly found in industry. Because of the nature of the work performed by transfer presses, there are very few industrial processes that can equal the magnitude of the shock, vibration and stress forces that are set up in the transfer press, some of which necessarily transmit themselves into the control hardware.

d. Stopping and Interlocking Levels. The question of safely starting and stopping the complete transfer press/line must be considered with the same careful care used to design the heart of the system, the clutch/brake control design. The stopping systems and subsystems must be considered as a critical item and therefore the use of hybrid relay/PLC controls are highly recommended.

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* SCR: Silicon Controlled Rectifier

** I/O Input and output elements that are routed to and from the PLC

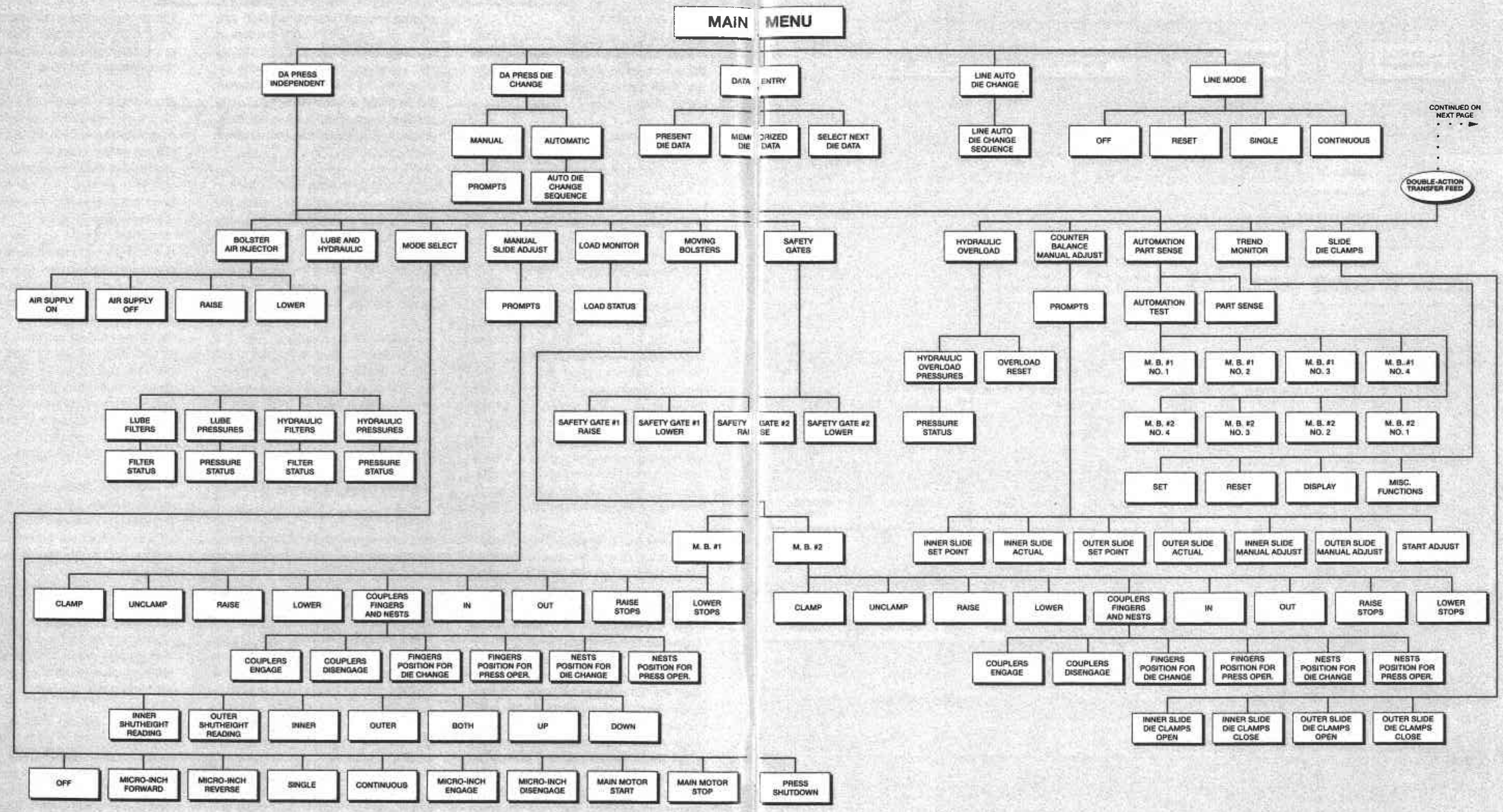


Figure 2a. Other Major Areas of Press Control – Double-Action Press

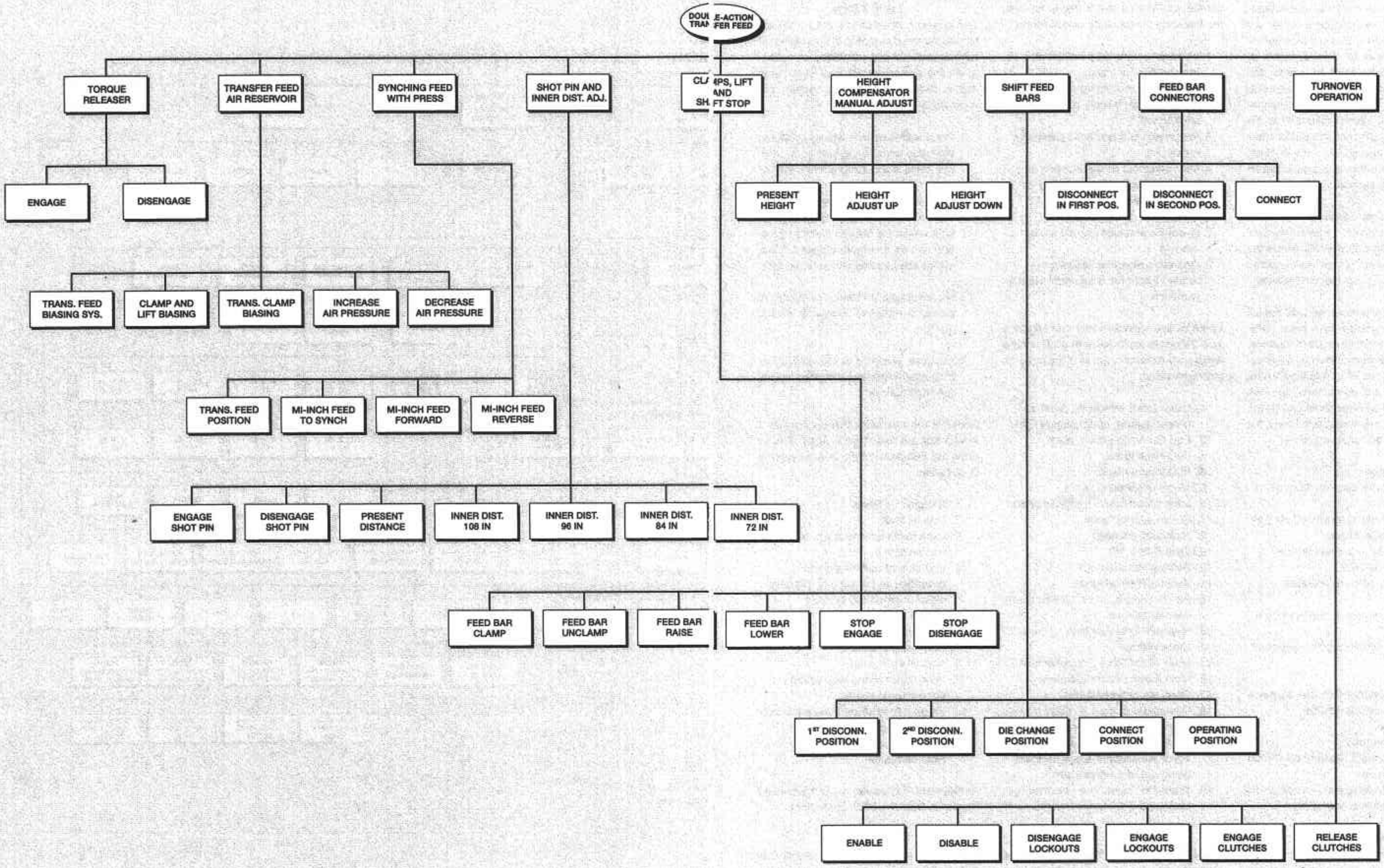


Figure 2b. Other Major Areas of Press Control – Double-Action Press (continued from previous page)

For industrial machinery in general and certainly for the transfer press/line example discussed in this series of articles, the stopping priorities are divided into four categories or levels. These stopping levels are combinations of PLC and relay/contactor stopping mechanisms. The objective of these prioritized levels is to protect the equipment and operator(s) from harm and damage, but at the same time eliminate nuisance tripping which could lead to the possibility of stopping circuits and/or interlocks being jumpered out. Interlocking techniques and requirements are discussed later in this same section.

Level 1 Stop

This stop is considered a true emergency stop as defined by OSHA/ANSI, and is the highest priority level. Under this condition all motions of the press stop immediately.

Operation cannot be resumed until the full "power-up" procedures have been completely carried out in their proper sequence. The stopping is accomplished by a combination of hard-wired MCR (Master Control Relays) relays and contactors, and the emergency stop commands issued by the PLC's. When a Level 1 stop is initiated, the following things occur concurrently:

1. All motors stop
2. Power removed instantly from all PLC outputs
3. All moving parts stop immediately in their present positions
4. Air is dumped to prevent sudden cylinder movement*
5. Hydraulic circuits are pressure relieved.*
6. All electrical power is removed from the systems
7. All auxiliary synchronized equipment is stopped

The specific operators that can trigger a Level 1 stop are as listed below:

1. Die Block Removal
2. Main Disconnect Switch or Circuit Breaker tripped
3. Opening of Safetygates (except for die change or manual operation)

Level 2 Stop

This stopping level is the second highest priority and results in all press motions stopping immediately in their present positions; operation cannot be resumed until the appropriate reset procedures have been carried out. When a level 2 stop is initiated, the following things occur concurrently:

1. All moving parts stop immediately in their present position
2. All clutched motors remain running (e.g., the main motor), but unclutched
3. Pneumatic and hydraulic pressures remain on
4. Main electrical power remains on
5. PLC processor power remains on
6. Power remains applied to all I/O modules
7. Hydraulic and lube pumps remain running
8. Operation resetting sequence is required from the equipment starting positions

Some of the operators that can trigger a level 2 stop are listed below (the following is inclusive but certainly not all of the possible stop operators):

1. Local safety interlocks, such as barrier guards, or curtains of light
2. PLC Communication faults
3. PLC Rack faults
4. PLC Internal faults
5. Motor overload trips
6. Main transmission hydraulic faults
7. Clutch control faults
8. Hydraulic overload
9. Stop Button Hit
10. Bearing vibration fault
11. Various Thermal faults
12. Air pressure loss, particularly counterbalance
13. Hydraulic pressure loss
14. Undervoltage
15. Main motor Drive Controller fault
16. Main motor overtemperature
17. Open die or bed clamps
18. Overspeed of main auxiliary motors (inching, feed inch, etc.)
19. Fault interlocks from either preceding or subsequent line equipment going out of synchronism
20. Transfer feed bar connectors loosening

The above partial list gives an idea of the type of fault and stopping operator that can trigger a level 2 stop. Both PLC and hard-wired contactors are used for stopping.

Level 3 Stop

This level is the third priority stop, and calls for programmed stopping of the press system, as well as any preceding or subsequent line equipment. When a level 3 stop occurs the following things happen (not necessarily concurrently):

1. Press is allowed to finish one cycle and then stop normally; all lube faults, normal cycle stops, programmed stops

2. Press is allowed to continue to run, but after a normal programmed stop all faults must be cleared before operation can be resumed; clogged filters, low oil level, conservation timer, etc.

3. No electrical, hydraulic or electrical power is removed from any control group

4. No basic resetting is required, other than clearing the fault and redepressing the RUN buttons

Some of the operators that can trigger a level 3 stop are listed below. Again, this list does not include all of the level 3 operator possibilities:

1. Clogged oil filters
2. Low oil level
3. Lube faults (unless in the main transmission)
4. One side of control system grounded (in the case of a double-sided ungrounded system)
5. Low air pressure
6. Low hydraulic pressure
7. Low water pressure
8. Normal cycle stop
9. Main motor timed stop (energy conservation timer)
10. Programmed stops from preceding or subsequent line equipment
11. Programmed stops from PLC or Host computer

All stops are PLC generated, with a backup capability from the MCR contactors.

Level 4 Stop

This stop is used with tri-axis and di-axis transfer feed presses and may not be appli-

* Counterbalance air accumulators and hydraulic overload circuits are excluded

cable to other types of machinery. Many tri-axis feeds are cam driven from a power takeoff attached to the press. Due to the large inertial forces and the masses involved with this type of transfer press feed system, there are certain ranges of slide travel where an instantaneous level 2 stop may damage the press and/or transfer feed. Additionally, such a stop could cause an inadvertent release of the power takeoff torque releaser and/or a breaking of one or more of the feed bar connectors. This in turn could pose a safety hazard to operator personnel.

In order to minimize the effects of such an occurrence, the "window" concept of stopping is used here. Figure 4 will illustrate this concept as well as being useful in the discussion of interlocks. The motion curves for the press and transfer feeds are graphically shown for both types of presses, the double-action and the single-action transfer press. Shaded areas on the figure depict the window concept, showing both window "A" and window "B." In order to avoid the negative consequences of sudden Level 2 stops, the stop circuits are bypassed for certain slide positions and under specific operating conditions. The philosophy is that if the stop is delayed until the transfer feed gets through the shaded window areas, no potential damage will be done to either the equipment or personnel.

Since the window concept does involve bypassing stop operators, the appropriate safeguarding conditions must be followed. With window "A" designating the slide downstroke, and window "B" depicting the upstroke of the press, the following conditions must be met before the windows are actuated:

1. Window "A": (Downstroke)
   - The press is running in the continuous mode at the selected speed
   - All safety gates are closed
   - No level 1 stop has been activated
   - Certain level 2 stops have not been activated (typical examples are the hydraulic overloads, double blank fault, and open slide or bed clamps)
2. Window "B": (Upstroke)
   - Will be activated under all operating modes

If the windows have been activated and a stop occurs outside of the shaded areas, the results are the same as for a normal level 2 stop. If the slide is travelling through one of the shaded areas, the stop will be delayed until the slide has passed through the areas in question. Regarding window "A," if the level 2 stop was a result of one of the special level 2 faults, the stop circuit will NOT be delayed, but will activate immediately. The delayed stop will occur under all level 2 faults for Window "B." Neither window will have any effect upon a level 1 or a level 3 fault.

A study of Figure 4 shows that for both the single-action and the double-action presses, window "A" is roughly between 125 degrees and 195 degrees of slide motion, and window "B" lies between 300 degrees and 10 degrees of travel. It should be emphasized that since the implementation of stopping level 4 involves bypassing stop circuits, this absolutely requires the use of relays and/or contactors, to obtain the maximum reliability of the circuits.

Interlocking

Many of the concepts of interlocking have been dealt with in a previous issue of the Safety Brief, entitled *Safety Interlocks-The Dark Side*, by Frank Hall. When looking at automated transfer press lines, however, such as the one in this series of articles, using PLC-controlled equipment, there are several aspects that need to be addressed in a special manner. Interlocks used in the latter sense may be categorized as follows:

1. Global Interlocking
2. Local Interlocking
3. Self Interlocking
4. The "Over-Interlocking Syndrome"

Items 1, 2, and 3 represent the three major levels of interlocking on the transfer press systems. Item 1 basically represents the interlocking configuration of the line itself. Item 2 represents the interlocking of major transfer press line subassemblies. Item 3 describes self-checking procedures for the major subassemblies. Item 4 represents a very special area of interlocking that could cause both operational and safety problems.

1. *Global Interlocking.* Part 1 of this article, particularly Figure 3, which shows a block diagram of a multi-press transfer press/line, indicates the great amount of equipment involved in an undertaking of this sort. In order to proceed logically with the design of the system, the tasks must be broken down into subareas that can readily be handled by the design teams responsible. Global interlocking is defined as the interlocking required from an overall line perspective so that the major parts of the line, such as both types of presses, and their ancillary support equipment, not only do not interfere with one another mechanically, but that their timing with each other is absolutely correct.

   For example, for proper line operation, the double-action press must lead the single-action press by approximately 180 degrees. If it does not, the parts will not be transferred correctly. Global interlocks make certain that all pieces of equipment are in the right location before line operation can occur. A study of Part 2, Figure 3, in this article, shows some of the mechanical operating sequences, as well as the 180-degree difference between the two presses. Other mechanical timing relationships are shown as well.

   The above interlocks are primarily involved to ensure that the various parts of the transfer press/line all act in a coordinated manner from an operational point of view. Some of these same interlocks, however, can also be used as safety interlocks. Where additional ones are required, they are added where necessary. For line operation, on a global basis, the primary task, although not the only one, of the safety interlocks is to ensure that the safety gates are closed before line operation begins, and that if the gates are opened during running, a level 1 stop will be generated.

2. *Local Interlocking.* This type of interlocking refers to that required by each major subassembly of the overall transfer press/line. In other words, it is the standard interlocking required by each component. For example, the single-action press requires its own interlocking to properly time the press with its feed, the moving bolster synchronization, etc. The single-action press, as also is the case with the double-action press, and other ancillary equipment, has its own local point of operation, which must be guarded independently of the other equipment in the line. This is so since each press must be able to be operated independently of line operation. Further, each press must be able to be operated without its transfer

FIGURE 3 - MECHANICAL OPERATING SEQUENCE

DEGREES ROTATION (RELATIVE TO D.A. PRESS): 280° 300° 320° 340° 360° 0° 20° 40° 60° 80° 100° 120° 140° 160° 180° 200° 220° 240° 260°

EQUIPMENT - FUNCTION		Δ INCREMENT	Start	Time	End
Double-Action Feed (D.A.)	- Clamp	57°	222°	.53 sec.	280°
	- Lift	35°	270°	.32 sec.	305°
	- Feed	110°	285°	1.02 sec.	35°
	- Lower	35°	15°	.32 sec.	50°
	- Unclamp	57°	40°	.53 sec.	97°
	- Return	150°	85°	1.39 sec.	235°
Shuttle	- Lift	35°	270°	.32 sec.	305°
	- Feed	110°	285°	1.02 sec.	35°
	- Lower	35°	15°	.32 sec.	50°
	- Return	130°	85°	1.9 sec.	235°
Turnover	- Rotate Return	110°	285°	1.02 sec.	35°
*	- Grip	50°	35°	.463 sec.	85°
	- Rotate Forward	130°	85°	1.33 sec.	235°
*	- Grip Release	50°	235°	.463 sec.	285°
Height Compensator*	- Vertical Travel	95° (+)	285°	.879 sec.	20°
*	- Vertical Travel	95° (–)	140°	.879 sec.	235°
Single-Action Feed (S.A.)	- Clamp	67°	12°	.625 sec.	80°
	- Lift	45°	80°	.416 sec.	125°
	- Feed	120°	100°	1.11 sec.	220°
	- Lower	45°	195°	.416 sec.	240°
	- Unclamp	67°	240°	.625 sec.	307°
	- Return	120°	280°	1.11 sec.	40°

For line operation, the D.A. press leads the S.A. press by approximately 180°.
The S.A. press and its feed are mechanically independent of the D.A. press and its feed.

*Functions controlled by PLC Program.

feed. Since this is the case, appropriate safety guarding must be furnished.

3. *Self-Interlocking.* This type of interlocking refers to the internal self-checking of various components of the system, as a subset of local interlocking. It is particularly emphasized in PLC control because of the need for very thorough checking and self-checking to insure good reliability. An excellent example of this type of interlocking can be found in the dual processor/dual valve clutch/brake control (See III.B.1.a). In this subsystem it was seen that the two processors not only continually check each other against the rotary cam limit switch and resolver, but they also perform a constant self-check of their own program and firmware structures.

4. *The "Over-Interlocking" Syndrome.* Because of the great need for self and mutual checking, many software and hardware interlocks are required. There is a tremendous design need for exactly balancing the actual number of interlocks with the optimum number required. In that respect it is very much like the four-legged stool of design practice discussed in Part 1.

PRODUCT DESIGN =

ENGINEERING
+
SAFETY ASPECTS
+
ECONOMIC CONSTRAINTS
+
ERGONOMIC CONSIDERATIONS

Obviously, if there are too few interlocks used, much needed protection is lost, and an accident may occur. The other side of the coin, however, presents an equal if not greater problem: where too many interlocks are provided, on the theory that if one order of redundancy is good, five orders are five times better. As everyone knows, this is not a viable theory, and in fact can lead to situations such as too many nuisance shutdowns in production. When this happens, the shop floor people rightly tend to take quick action, such as jumpering out interlocks, so that they can get back into production. When this occurs, without due regard for the ramifications, the baby is often times thrown out with the bath water, and some necessary interlocks could easily end up being jumpered out, creating potential machine damage and safety hazard situations.

It is hoped that this very brief treatment of interlocking and stopping circuits does put the important and critical nature of these items into proper perspective regarding the overall design.

e. Type of Memory: RAM, ROM, PROM. It was indicated in Part 1 Section III.A.6, that the hardware aspect of the PLC represents the physical body of the computer and the software portion represents the brain. In order for the program to be executed properly in sequential fashion, it must be "loaded" or stored in the memory area of the brain. The only limitation to program creativity is that the brain must contain a sufficient number of brain cells, or as it is more properly described, memory capacity. The basic memory cell is an on/off storage device, in which can be stored either an "on" signal, called a "1", or an "off" signal, called a "0". All digital computers operate from a series of "1's" and "0's"; these coded strings form the computer's language, and are known as the binary alphabet, or binary numbering system. As a matter of fact the name digital computer is derived from the fact that it is based on the binary language; "di" means two or double, as does "bi." There are a number of different types of memory, as discussed below:

1. *RAM.* This is an acronym meaning "Random Access Memory". In this type of memory, each memory cell can be accessed by the programmer, usually, but not always, by a keyboard input. Each basic memory cell has a specific and unique address, and can be reached in any random (as opposed to a sequential) manner; hence, its name. Therefore, in this type of memory, program corrections, deletions, additions and modifications can be inputted completely at the discretion of the programmer, and in whatever sequence or manner he/she desires. This gives the programmer a tremendous amount of flexibility in logic design.

2. *ROM.* This also is an acronym meaning "Read Only Memory." This memory type was developed to limit the RAM memory's flexibility. For example, in the dual clutch control system, once the control design has been debugged and is satisfactory, it *MUST* not be changed, because of the critical nature of the machine function it controls. The only way that this could be achieved was to eliminate its random access capability. The ROM does this by loading the program into the memory in a permanent manner, so that it cannot be changed; hence the name Read Only–. There are two general types of ROM; one is as described above where the entire program is permanently loaded into memory. The other type is of a firmware configuration: i.e., the basic program is loaded into ROM, but there is some flexibility in entering data, such as different numbers, lengths of time, etc. The data entered is different, but the program processing is the same.

3. *PROM.* This memory type is halfway between the RAM and the ROM; in many instances, particularly in field applications, it was found necessary to "fine tune" the ROM program. In most cases of this type, the ROM memory either cannot be changed or cannot be changed conveniently. The PROM memory, which was developed in response to this problem, can be programmed to make additional changes at the field site, via a special portable programming machine. The acronym means "Programmable Read Only Memory."

In general, ROM memory is used in very critical areas of the press control, such as the clutch/brake control, the stopping systems, the interlocking arrangements, certain repetitive subroutines, firmware devices, etc., where the program cannot be changed because of safety reasons or programming requirements. RAM is used in other areas of the control system where the safety, stopping, and interlocking requirements are not quite as stringent. PROM memories are used as interim devices during the final development stages of a system design, as well as in certain firmware devices.

There are a number of other memory types used, all of which are derivatives of the three types mentioned above. Some of these are mentioned below and briefly described:

1. *d-RAM.* This memory type is called a "dynamic-RAM," and must be con-

tinually "refreshed," or updated to retain its memory data. It is, however, a RAM-type memory.

3. *Bubble Memory.* A specific embodiment of a RAM-type memory.

2. *E-PROM.* This memory type is actually a PROM memory that may be erased and reprogrammed electrically, using the appropriate device. The acronym means "erasable-programmable read only memory."

f. The "Muscle" Components. In Part 1, Section III.A.8, the output elements of a system were defined as those devices whose job it was to carry out the commands of the PLC(s) in an ordered and sequential manner. These elements are the so-called muscle components of the system, and provide the power and energy to perform the tasks assigned to them by the program. The major types of output devices found on the transfer press/line discussed in this series are briefly outlined below:

1. *Hydraulic and Pneumatic Cylinders.* These output components provide rectilinear motion, and are used for various purposes. In the transfer press/line used as an example in this series of articles, there are dozens upon dozens of cylinders used; they perform functions ranging from counterbalance purposes to transfer feed system biasing cylinders, and various clamping purposes.

2. *Solenoid Valves, Hydraulic and Pneumatic.* These components, while considered as output elements in their own right, in most cases when used in the transfer press lines, actually act as the intermediary between the actuating cylinders and the electrical command signals. When The PLC furnishes the command to move the cylinder, the signal actually goes to the solenoid valve; the valve itself is the direct controlling link to the cylinder.

3. *Electric Motors, A.C. and D.C.* These output devices are rotating devices which furnish the majority of the high power requirements of the transfer press/lines. For example, the main motor of the single-action press for a line that size (See Part 1) could be over 600 horsepower. It is a D.C. motor, which lends itself better to speed and instantaneous position control than does the A.C. motor.

4. *Contactors/Relays, Starters.* These output devices not only provide the extra reliability required for critical circuits but they can and do serve as the electrical equivalent of solenoid valves. Just as the latter provides the control for rectilinear cylinders, so do the electrical starters provide for the control of electric motors. If the motor requires more than simple starting and stopping, in many cases a separate and more sophisticated motor control package is then required. For this line, there are dozens of motor starters and control packages required.

5. *Mechanical, Pneumatic, Hydraulic Clutches.* These devices provide the coupling requirements between rotating high energy devices such as flywheels, and drive components that must be clutched in and driven in a completely controlled manner. The clutch/brake system of the press is a good example; when the proper moment for slide motion is at hand, the clutch connects the rotating flywheel to it. Other examples are the use of a mechanical torque limiter between the power takeoff of the press and the cam driven transfer feed, and the clutching required to connect the separate inch drive to the press slide(s).

6. *Control Outputs.* These are defined as output elements that are used for adjustments of various things, that do not require much muscle. Typical examples would be:

- Linear motors
- Electrical solenoids, not used in valves
- Motor adjusted potentiometers
- Motor adjusted pressure, flow, and temperature commands
- Electrically adjusted pressure, flow, and temperature commands
- Electrically adjusted dynamic resistance for control purposes
- Electromechanical throttling devices.

All of these elements are used to adjust various other higher muscle outputs, such as water valves, air regulators, tonnage meters, height compensators, etc.

7. *Non-control Display and Monitoring Outputs.* The following output devices, while classified as "low-muscle" elements, are different from control outputs in that they do not control anything, and hence are not susceptible to crosschecking and feedback checking. Their purpose is only to display data for visual information, and/or to warn of faults in a visual, audio, or graphical manner. Some of these devices are as listed below:

- Display Monitors (CRT's)
- Pilot Lights
- Printers
- Scoreboard Displays
- Horns
- Bells and Whistles
- Fault and Other Message Displays

None of these elements furnish any control to any output component; their sole purpose is to provide display and monitoring information to the operator(s).

g. Control as Implemented by Software, Firmware, Hardware. The purpose of this section is to list the major areas of control, and to discuss the various combinations used (i.e., software, firmware, hardware). It must again be emphasized that to go into design detail would be outside the scope of this series of articles. The major control areas involved are as follows:

1. *Overall Transfer Press/Line Control (Global)*

Software

Communication between PLC's, especially when processing line commands, such as automatic die changes and operating speed changes and control. Primarily on a global level. Safety gate control and checking.

Firmware

Some specialized devices, such as tonnage meters, and double blank detectors. Also, many subroutines that are called up on line operation that also perform the same function for local operation.

Hardware

The primary piece of hardware on line operation is the line control console. It not only houses all of the selector switches, pilot lights, and PLC communication remote transmitters, but many of the non-control devices, and line meters, etc. Of course, the myriad of local hardware items that operate on either line or local operation are also programmed to operate on line commands, when that mode is selected. Safety gate control and checking is also included.

2. *Subassembly (Local Control).* This category takes into account single-action and double-action presses, and all the ancillary equipment required to support them. Each such subassembly must be capable of running in proper line synchronization, where useful production is obtained, as well as local operation. The latter mode, while not required for line operation, is necessary for maintenance purposes, die and other subcomponent adjustments and checks, and local manual or automatic die changes where necessary.

Software

Provides the overall control program for the subassembly involved. One main PLC is required for most of the program, but specialized and critical areas of control need separate PLC's. For the presses, of course, the dual clutch/brake control is the prime example. The other major subassemblies, comprising the ancillary equipment (See Part 1 section III.A.1) all have their own PLC's, which must be connected to one another for communication purposes, and line operation.

Firmware

There are many examples of firmware devices on local equipment, such as load tonnage monitors, height compensators, resolvers, double blank detectors, motor control packages, bearing temperature transmitters, PLC internal timers, up/down counters, arithmetical calculation subroutines, counterbalance pressure control sensors, unit conversion devices, etc.

Hardware

Each local subassembly has many different types of hardware, such as output elements, input elements, muscle components such as cylinders, motors, etc., power supplies, motor control units, contactors, relays, starters, push buttons, control enclosures, control pushbutton units, emergency stop buttons, rotary cam limit switches, resolvers, transducers, sensors of all types, transformers, PLC hardware, etc.

Naturally each circuit of the local assembly is a combination of software, firmware, and hardware. The right mix of each is dependent upon the specific function of each portion of the design.

3. *Interlocking Techniques for Personnel and Machine Guarding.* This area has been adequately covered in Part 2, Section III.B.d of this article, and needs no further discussion. Additionally, Part 1, Section II, Engineering Factors, and Section III.A.14, discusses in some detail some of the safety aspects involved. The main areas of emphasis are on the four prioritized stopping levels, and the three levels of interlocking.

2. Programs (Non-control Areas)

The last section of this article (Part 2, Section III.B.1) described the circuits involved directly and indirectly in the actual control of the movement of the transfer press/line and its major subassemblies. Both global and local control areas were defined and analyzed. However, the actual control portion of the programs and hardware represents only a small part of the memory required to adequately process the total requirements of the overall system. This section deals with the non-control areas of the transfer press system, and while not involved in the control of machine movements and safety interlocking, nevertheless are vital to the smooth operation of the line. These items are categorized into a number of areas, which are:

1. Monitoring
2. Displays
3. Job Menus
4. Production Data Collection
5. Identification
6. Instructional
7. Trending

The items involved together with a brief functional description, are listed below:

a. Messages. Informational messages play a critical role in the operation of the entire system. Part 1, Section III.A.9, 10, 11 discusses the various types of messages generated, and their roles. These are fault messages, diagnostic messages, and tutorial/instructional messages. Prompts are a subset of the latter group. No matter what type of message it is, there is a commonality among the groups. For example, whether a message is fault, diagnostic, tutorial or prompt, it has the characteristics of displaying the message from a suitably addressed trigger, it is monitored, and it can be used for identification, and it is instructional in nature (See items 1, 2, 5 and 6 above):

1. *Fault Messages.* This type of message displays an abnormal, incorrect, or out-of-sequence condition. In some low priority cases, monitoring and recording the fault is all that is required. If it is a serious situation, however, such as one of the PLC's getting out of synchronism, or in the case of a low voltage condition that is outside of tolerance, the fault not only is displayed and recorded, but it also breaks into the control portion of the machine, and generates a level 1, 2 or 3 stop, whatever the case might be.

2. *Diagnostic Messages.* This message couples the basic fault condition with diagnostic statements that aid in quickly determining the location and nature of the fault. Thus, if it was a level 2 fault, once the nature of it has been found, the chances are that it can be fairly quickly corrected, and production resumed.

3. *Tutorial/Instructional Messages.* These types of messages, while similar to each other, are different in emphasis. The tutorial message is meant to educate an operator in some aspect of the system. For example, if the operator wishes to become more familiar with the die change process, particularly the automatic die change, the tutorial group of messages concerning that operation could be called up as a group, and the operator could proceed scrolling them on the screen at his own pace. The thrust of the messages would be that of familiarization.

Instructional messages, on the other hand, give exact instructions on how to proceed through a given situation; for example, if it is desired to know how to set the automatic correcting counterbalance air system at different levels, the instructional messages would point out how this is to be done, and what conditions must precede as well as what subsequent conditions must be in order to complete that particular step.

4. *Prompts.* Prompt messages are very similar to instructional messages, as far as their objectives are concerned. The difference between the two is that prompts are woven into the fabric of the control such that if a prompt message is not adequately fulfilled, it will not allow the operator to proceed to the next step.

b. Production Data Collection and Printouts. This type of message combines the features of monitoring, display, recording, printouts, data collection, identification, and instructional (See items this section 1, 2, 4, 5 and 6). Part 1 of this series, Section III.A.15, discusses the function of this part of the overall system. The main thing to realize here is that while the information gathered by this system is very useful for determining efficiencies, preventive maintainance procedures, scheduling, etc., it is not crucial to the actual operation of the system. For this reason, the data collection system has its own computer, and may be disconnected from the rest of the system control units, so that production may continue, in the event it has problems.

The data collection unit is programmed to record all messages and faults during a particular time period generated by the transfer press/line, and collate them as to various types of faults. This includes press faults, line stops, bearing and lubrication conditions, etc. It has no ability to start or stop the line, since the faults generated do have that ability. It is simply an information and data collection device. Some of the information collected is as follows:

- Part Count, and accumulated totals
- Downtime
- Uptime
- Average Line Speed
- Scrap pieces made, and at what point in the cycle
- Pieces left to go in current run
- Next job - description
- Estimated time, day, and shift to start new job
- Primary cause of downtime - planned or unplanned
- Printout of computer analysis of faults that occurred, that might indicate a trend towards specific problems

There is another group of data collection that comes under the category of "trending," which is item 7 of this section. Every critical bearing in the overall transfer press/line has a sensor that monitors its temperature. Additionally, there are shock and vibration sensors mounted at strategic points throughout the system. The information is obtained in an analog fashion and also on a continuous basis. All of these points of data are fed into the main data collection system, as well as fault points. This data is monitored and printed out daily, and points to trends that might become major problems down the road, so that corrective action can be taken before serious damage occurs. If the point in question changes too rapidly for the trend monitoring, it will be caught as a fault, and shut the system down immediately.

c. Job Menu for Auto Die Change

d. Die Identification. One of the things that has contributed in a large way to the creation of the mass production-short run concept is the fact that a die change on the transfer press/line can be cut from hours to minutes. In fact, for a system of the size discussed in this article, a twenty-minute die change for the whole line is not unusual. The following description of the automatic change procedure is given so that the method may be understood. The manual die change is similar except that each step is governed by prompts that must be followed by the operator:

1. For each press (D/A and S/A) there are two complete sets of moving bolsters. In the case of the double-action press, there are two bolsters, and for the single-action press four bolsters.

2. One set of moving bolsters is locked in place underneath the presses, with the dies mounted and attached to each station of the bolster. Production is running from this set of dies.

3. During the production run the unused or idle sets of moving bolsters are fitted with the next job to be run; this includes the complete upper/lower die for each station. In the embodiment of the transfer press/line given in this series of articles, there is one set of dies on the D/A bolster, and three sets of dies on each S/A bolster. Thus there are a total of six dies for the S/A press, and one die for the D/A press.

4. When the current production job is completed, an automatic die change is set in motion. This consists of unclamping the upper dies from the press slides, moving the slides to the top, and moving the bolsters out of the press area on a set of tracks. Each bolster is self-powered by its own motor.

5. While the first set of dies and bolsters are moving out of the press area, the second set, with the new dies mounted, are moving into the press area, located exactly, and then clamped in place under the bed area. The press slides move down to make contact, and the upper dies are clamped to the slides. The transfer press is then ready to start again with the new job.

This whole automatic die change operation takes less than twenty minutes to achieve. The interlocking and safety requirements can be seen to be fairly complex and the manufacturer's instructions must be followed exactly.

As an illustration of some of these problems, it must be remembered that each of these seven die sets has to be placed in precisely the proper sequence and die position (i.e., not turned the wrong way). It must also be confirmed that all of the dies belong to the same job, and are placed in the right station. Obviously, a thorough job and die identification procedure must be done. Further, since the new dies can be set up days ahead of time, the job confirmation check must be made again at the time of the auto die change, in order to avoid any possibility of any of the dies being changed or moved out of position.

A complete set of dies and jobs that can be run on the particular transfer press/line are loaded into the line computer. The next job to be run is retrieved from the menu and loaded into the proper buffers. This information contains all of the details of the new job, including the die serial numbers and positions. Then when the auto die change is commanded to take place, the job menu provides the proper reference check for the dies coming in on the moving bolsters. If there is any discrepancy, the die change aborts, and the proper fault messages appear.

e. PLC Communications. When the overall line (global) is considered, there are

STOPPING AND INTERLOCKING LEVELS AND PRESS MOTION CURVES

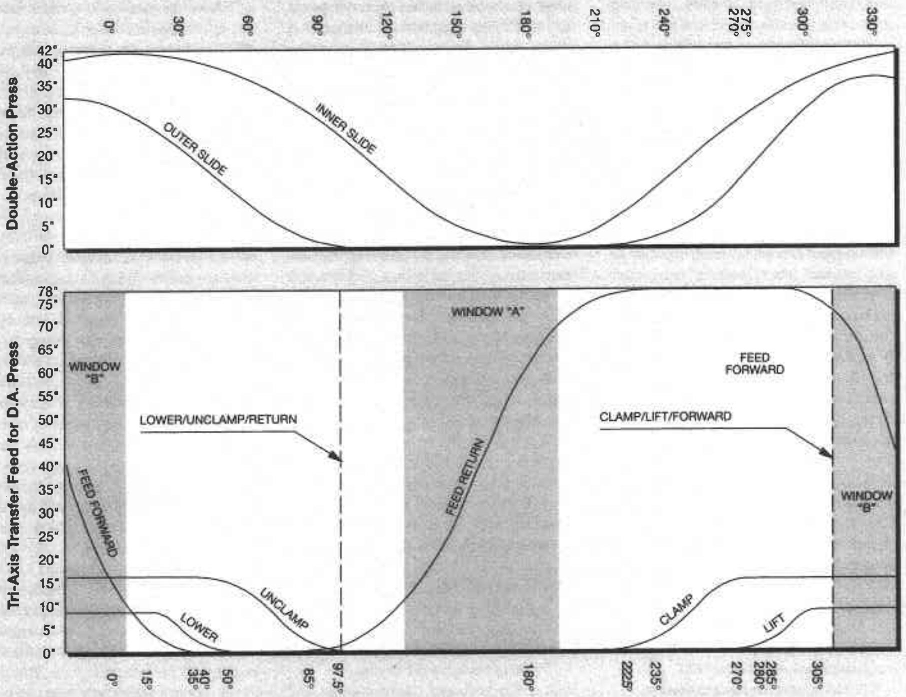
WINDOWS FOR E-STOP BY-PASS:

Window "A" is enabled only when the press is running in continuous mode, and all safety gates are closed.

Window "B" is enabled any time the press is running.

Shaded areas indicate emergency stop by-pass

NOTE: When windows "A" and/or "B" are enabled, the E-Stops are by-passed as indicated.



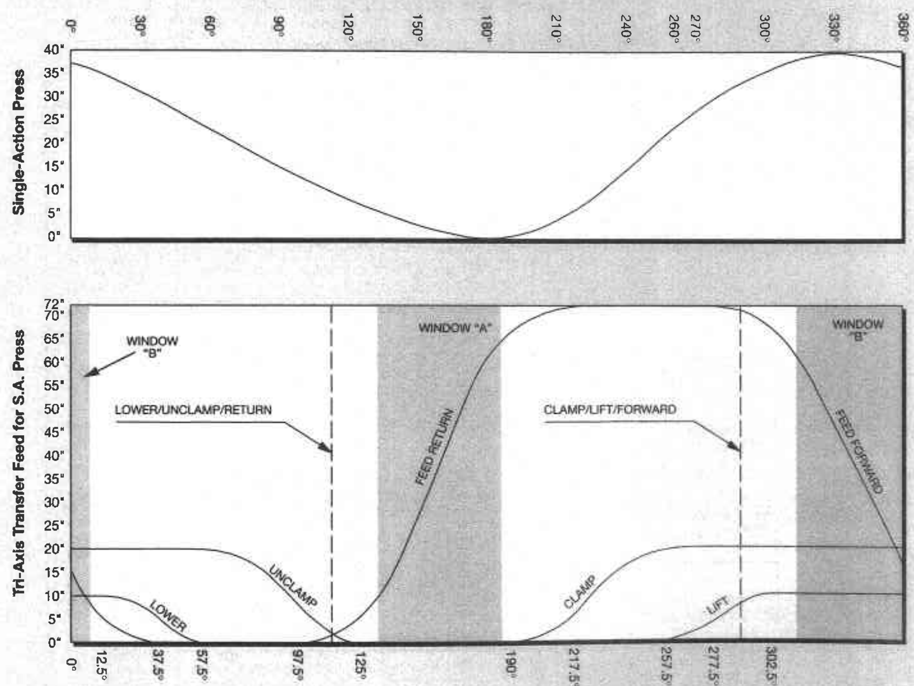
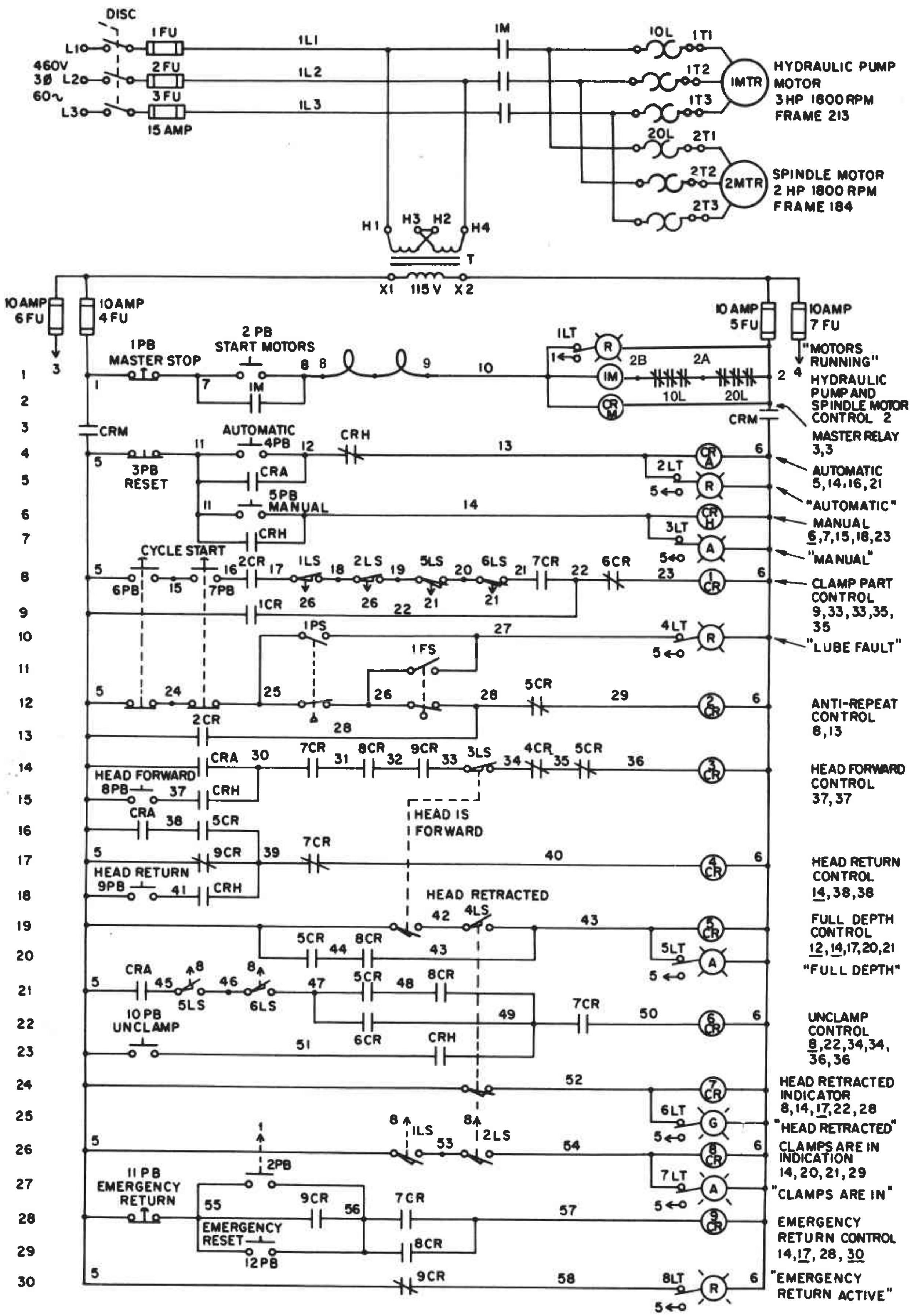
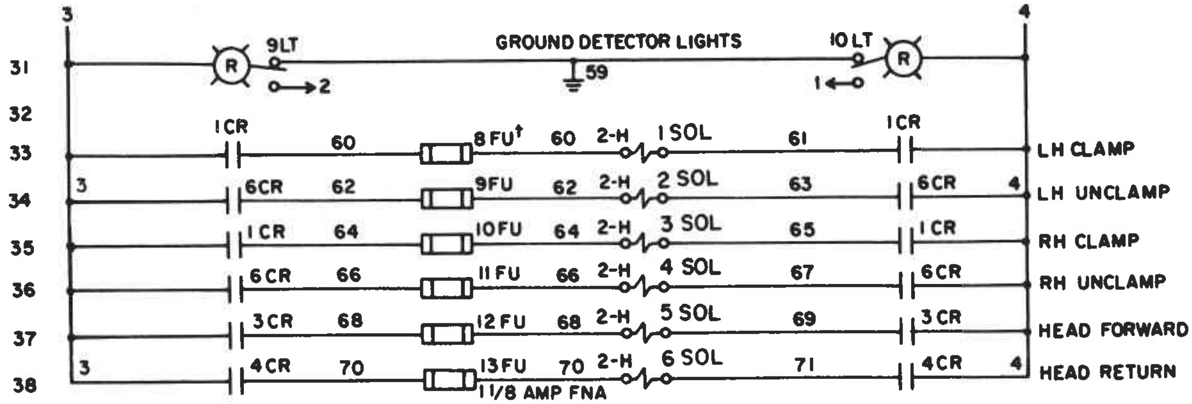


Figure 4. Stopping and Interlocking Levels and Press Motion Curves

FIGURE 5 – TYPICAL SEQUENCE OF OPERATION





† WHERE SOLENOID FUSE IS PART OF TERMINAL STRIP ASSEMBLY, CONDUCTOR NUMBER DOES NOT CHANGE

SEQUENCE OF OPERATION

A. PRESS "START MOTORS" PUSHBUTTON "2PB." MOTORS START. "MOTORS RUNNING" LAMP "1LT" AND "CRM" ARE ENERGIZED.

B. PRESS EITHER AUTOMATIC "4PB" OR MANUAL "5PB" PUSHBUTTON. CORRESPONDING RELAY AND LAMP ARE ENERGIZED. *NOTE:* TO SWITCH FROM MANUAL TO AUTOMATIC, OPERATOR MUST PRESS "RESET" PUSHBUTTON "3PB" BEFORE PRESSING AUTOMATIC PUSHBUTTON "4PB."

C. ***AUTOMATIC CYCLE:*** WITH MOTORS RUNNING AND "CRA" ENERGIZED, MACHINE IS SET FOR AUTOMATIC CYCLE. HEAD MUST BE RETRACTED AND PART UNCLAMPED TO START CYCLE.

1. OPERATOR LOADS PART IN FIXTURE AND PRESSES BOTH "CYCLE START" PUSHBUTTONS "6PB" AND "7PB," ENERGIZING "1CR" (SOL A AND SOL C) TO CLAMP PART.
2. CLAMPED PART TRIPS "1LS" AND "2LS," ENERGIZING "8CR." RELAY "3CR" (SOL E) IS ENERGIZED MOMENTARILY, STARTING HEAD FORWARD IN RAPID ADVANCE. HEAD CAMS VALVE INTO FEED.
3. WHEN HEAD IS IN FORWARD POSITION, "3LS" IS TRIPPED, ENERGIZING RELAY "5CR."
4. "5CR" CONTACT ENERGIZES RELAY "4CR" (SOL F) AND HEAD RETURNS.
5. WHEN HEAD IS FULLY RETRACTED, "4LS" IS TRIPPED, DE-ENERGIZING "4CR" AND ENERGIZING "7CR" WHICH ENERGIZES "6CR" (SOL B AND SOL D) UNCLAMPING PART.
6. WHEN PART IS UNCLAMPED, "5LS" AND "6LS" ARE TRIPPED, DE-ENERGIZING RELAY "6CR."
7. "2CR" RELAY PREVENTS MACHINE RECYCLING IF BOTH "CYCLE START" PUSHBUTTONS ARE NOT RELEASED.

D. ***MANUAL CYCLE:***

1. WITH HEAD RETRACTED AND PART UNCLAMPED, PRESS "CYCLE START" PUSHBUTTONS "6PB" AND "7PB," ENERGIZING RELAY "1CR" (SOL A AND SOL C) TO CLAMP PART.
2. PRESS "HEAD FORWARD" PUSHBUTTON "8PB," ENERGIZING "3CR" (SOL E) TO START HEAD FORWARD.
3. TO RETURN HEAD TO RETRACTED POSITION, PRESS "HEAD RETURN" PUSHBUTTON "9PB," ENERGIZING "4CR" (SOL F).
4. WITH HEAD RETRACTED, PRESS "UNCLAMP" PUSHBUTTON "10PB," ENERGIZING "6CR" (SOL B AND SOL D) TO UNCLAMP PART.

E. ***EMERGENCY RETURN:*** IF "EMERGENCY RETURN" PUSHBUTTON "11PB" IS PRESSED ON EITHER "AUTOMATIC" OR "MANUAL" CYCLE, THE HEAD WILL RETURN AND REMAIN IN THE RETRACTED POSITION. IN ORDER TO START CYCLE, THE "EMERGENCY RESET" PUSHBUTTON "12PB" OR "START MOTORS" PUSHBUTTON "2PB" MUST BE PRESSED.

F. ***LUBRICATION FAULT:*** IF OVER-PRESSURE OR INADEQUATE SUPPLY IS INDICATED BY THE OPERATION OF PRESSURE SWITCH "1PS" OR FLOAT SWITCH "1FS," "LUBE FAULT" LAMP "4LT" IS LIGHTED AND RELAY "2CR" WILLL REMAIN DE-ENERGIZED AT THE END OF THE MACHINE CYCLE. WHEN THE FAULT IS CORRECTED, "2CR" WILL BE ENERGIZED WHICH ALLOWS THE OPERATOR TO RESUME NORMAL OPERATION OF THE MACHINE.

LIMIT SWITCHES

1LS (8,26) TRIPPED WHEN PART IS CLAMPED
2LS (8,26) TRIPPED WHEN PART IS CLAMPED
3LS (14,19) TRIPPED WHEN HEAD IS FORWARD
4LS (19,24) TRIPPED WHEN HEAD IS RETRACTED
5LS (8,21) TRIPPED WHEN PART IS UNCLAMPED
6LS (8,21) TRIPPED WHEN PART IS UNCLAMPED
1PS (10,12) OPERATED BY LUBE SYSTEM OVER-PRESSURE
1FS (11,12) OPERATED BY ADEQUATE LUBE SUPPLY

probably more than two dozen PLC's of various memory sizes being utilized for the system. Consequently, the communications task of tieing in all of these CPU's into a common data highway and intercommunications link becomes a significant job. It is necessary to do this in order to tie in all of the equipment subassemblies so that line operation can be achieved. The communications link has been discussed earlier, and will not be repeated here.

f. Implementation Techniques. The implementation procedures for the non-control area of the design are very similar to the control areas as discussed in the previous section. There are, however, several major differences. In the non-control sector, there are no muscle output elements to consider, since the primary job of the non-control area is to provide and collect information and data. Secondly, the non-control area has many, many inputs as opposed to the control areas. This is because most of the inputs to the non-control area are sensors and transducers of one type or another. Lastly, the circuits involved in message generation are very similar to one another, so that a great deal of repetition is necessary. This means that a lot of pre-programmed subroutines and firmware can be used here.

The non-control programs are stored in the same PLC's as the control portion of the program, and are almost exclusively RAM software. There are no hybrid relay/contactors in these areas, and firmware is used in the large number of subroutines, as well as in many of the sensors and transducers.

g. Load Tonnage Monitor. Both presses have quick-acting hydraulic overloads, that relieve the slide in case of an overload due to a double blank or a stuck part. This is a catastrophic type of protection device, however, and there is a need for monitoring the instantaneous loads developed after each stroke of the press. The load monitor measures the forces by means of strain gauges mounted on the press columns. This allows the load monitor to measure the reaction forces after a hit by the slide on the workpiece.

By recording or observing the loads, a trend can be spotted if the loading keeps creeping up, which might mean that the dies may have to be worked on. It could also mean that there is not enough lubrication on the workpiece, thus causing a heavier load in forming the piece. In any event, this is yet another piece of data that can be used by the production facility to help maintain a high efficiency rate of production.

3. The 2/3 - 1/3 Rule of Memory

The following empirical rule is broken out from the other sections because of its importance and usefulness in estimating the amount of memory required for a particular job. It has been this author's experience that for an average PLC-controlled piece of industrial machinery, for a given size of memory, and an average amount of diagnostic and fault/prompt capability, about 1/3 of the memory is taken up by the program for the direct control of the equipment and about 2/3 of the memory is taken up by the non-control portion of the program. The reason for this disparity is that storing the messages require a great deal of memory. For example, most processors are set-up in such a way that one word of memory is used to represent one character, be it a letter, a number, or a logic symbol. It is therefore fairly easy to see why the non-control portion of the program is such a memory hog.

The usefulness of this rule lies in the fact that it is relatively easy to judge the memory size required to develop the control program. By using the 1/3 - 2/3 rule, it is then simple to judge the approximate amount of total memory needed, and it can be ordered at the beginning of the project without fear of running short. For example, assume that the memory requirements for a specific machine controlled by PLC will use approximately 60K words of memory. By invoking the 1/3 - 2/3 rule of memory, the diagnostic and non-control portion of the program will take approximately 120K of memory. Therefore, a 64K memory and a 128K memory will be ordered, to accommodate the 180K memory requirements.

C. DOCUMENTATION/RECORD KEEPING

1. Importance

To an engineer, the part of an engineering project with the least amount of fun and appeal is undoubtedly the necessity for keeping good records and documentation of the project. Unfortunately, the unappealing portions of the project must be given as much attention as the appealing parts. Certainly, the necessity for keeping good records has never been disputed, and most engineers swallow the pill with resignation, and complete the job the way it should be. It is almost certain that this has been the case since the dawn of history.

With the advent of computers, ushering in the "information age," and the proliferation of government agencies, the importance of keeping good records and documentation is even more critical than ever. In addition, the continuing development of high-tech engineering, mostly in the form of software programming, poses an additional factor to be considered. Years ago, when most industrial control circuits were either all relays and contactors, or transistorised solid state, the good service engineer could almost always find his way through the circuit even if the schematics weren't available, simply by tracing through the wiring of the electrical/electronic panel. This option has been eliminated by the PLC since it is impossible to determine the details of the program merely by observing the equipment; one must have a printout of the logic circuit in order to troubleshoot it. In many cases, even calling up the program on the monitor screen will not suffice, since it has only a limited capacity to show what the overall logic sequence is. Good record keeping, therefore, is not only necessary for the standard reasons, it is mandatory in order to be able to service and maintain the equipment.

One of the problems that arises in connection with a piece of equipment such as the transfer press/line discussed in this series of articles is that in addition to the normal engineering drawings to be considered, how should the software tapes and disks be stored, so that they will be a significant and accurate record? This is essential when these records are to be used for product liability reasons, as well as with the customer if there are questions down the road.

2. Engineering Records

For industrial machinery, there are standard drawings that are made in connection with the project, some of which are also sent to the customer for his records, and all of which are stored in a suitable storage area. Additionally, microfilm records are also sometimes kept as a record backup.

The types of drawings involved are as follows:

- *Schematics.* These drawings illustrate the formation of the various electrical, electronic, hydraulic and pneumatic circuit and logic structures. Where PLC control is involved, that portion of the schematic is called the I/O schematic, they show where in the PLC all of the inputs and outputs are connected. The PLC individual addresses are also shown on these schematics.

- *Wiring Diagrams.* These drawings, sometimes called connection drawings, show how the schematic circuits are actually assembled and wired together.

- *Conduit Layouts.* These drawings illustrate how the wires and cables are actually routed on the equipment. It specifies the number of conduits involved, their sizes, the control enclosures, the push button panels, the sensor and transducer locations, etc.

- *Parts Drawings.* Each part and component in the system has a drawing and a part number assigned to it. All parts are either made in-house from these drawings, or the drawings are used to purchase parts from an outside vendor.

- *Bills of Material.* It is standard practice to develop a complete materials list of the product. This list is numbered in sequence, and has its part number listed, a brief description of it, and whether or not it is being ordered from an outside vendor or made in-house.

The above drawings are all in draft form, and stored in the drawing area. They represent a complete engineering record of how the product was built.

3. Program Disks, Tapes, and Printouts

Instead of on drawings the computer programs are usually stored on magnetic tapes and/or hard disks. Of course, a hard copy printout is made of the total program once it has been completely debugged. There are four separate time periods when the program should be stored, in order to protect the manufacturer; the storage area should be of limited access, and in many cases an outside disinterested party performs the storage service; these are:

- *As Shipped.* This period represents the initial approval of the equipment by the customer. It is essential to have a record of the program as it was initially shipped with the machine, and approved by the customer.

- *After Initial Installation.* The program at this stage represents the structure of the program at the customer's site, and after he has given preproduction approval. Another set of tapes, etc., should be stored along with the as shipped group.

- *After Customer Approval.* After the customer has approved the equipment for production, another set of tapes are made and stored with the others.

- *Periodic Program Changes.* During the course of operation of the equipment, or through government-mandated changes, there may be periodic modifications required in the program. When this occurs, and after the changes are made, another set of tapes, etc., must be made and stored.

Additional discussion of documentation is continued in Part 3, Section IV.A, with emphasis on the legal aspects of documentation.

4. Service and Operating Manuals

In addition to standard manuals, which should include schematics, maintenance instructions, safety manuals, parts lists for spares, etc., the program should be included as a printout and a tape. Suitable cautionary statements should be made as to the use of these tapes. The tapes should not be distributed to the customer until after phase 3, customer approval for production. A disclaimer should be attached cautioning the customer against changing the program without notifying the manufacturer. If the control/non-control programs are very complex, special servicing programs/routines should be considered to aid in troubleshooting the system.

5. Sequences of Operation

This subject was introduced in Part 1 Section III.A.8, and stated that the logic program could not really be developed until the sequence of operation was determined. The sequence of operations should be considered as an integral part of the engineering documentation. If a mechanical design change is made, this will in many cases necessitate a modification in the sequence of operation and therefore the software. The sequence of operation for this transfer press/line is many pages long, involving hundreds of input and output elements, together with all of their operating interconditions and constraints. To present even a portion of this sequence would obscure the theory of construction of it by its own ponderous weight. Consequently, in order to illustrate the concept, a rather simple sequence is shown in Figure 5. An electrical schematic is presented along with the sequence of operation. The latter is seen to be a verbal description of the operation of the electrical schematic; the control schematic is based on the sequential operation of the machine equipment. There are also many other sequences to be determined other than the logic required to fulfill the basic machine sequence. This involves safety interlocking, remote operation capability, sequences to accommodate specific machine peculiarities, stopping and starting circuits, power up/power down, etc., etc.

Part 3 of this series will appear in a future issue of the Triodyne Safety Brief.

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