General Electric Advanced Technology Manual

Chapter 6.2

Recirculation and Flow Control System

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6.2 RECIRCULATION AND FLOW CONTROL SYSTEMS

Learning Objectives:

1. Explain the three different types of recirculation loops.

2. Explain valve vs. pump flow control.

3. Explain the thermal shock limitation.

4. Explain the power/flow map.

6.2.1 Introduction

The Recirculation System provides variable forced circulation of water through the core, thereby allowing a higher power level to be achieved than with natural circulation alone. The Recirculation System, in conjunction with the Recirculation Flow Control System, provides a relatively rapid means of controlling reactor power over a limited range by adjusting the rate of coolant flow through the core.

Control rod movement and recirculation flow adjustment are the two means of controlling reactor power under normal operating conditions. Control rod motion produces local changes in reactivity and neutron flux, while recirculation flow adjustments produce changes in flux across the core without significantly affecting local to average flux values.

An increase in recirculation flow produces an increase in total core flow, or an increase in mass flow rate of subcooled fluid entering the core. This increase in flow suppresses boiling since additional heating is required to reach saturation. The boiling boundary moves upward and the void volume decreases. The resulting positive reactivity increases core power. Power continues to increase until the boiling boundary and void fraction are restored and core reactivity returns to zero. The reverse mechanism occurs on a recirculation flow decrease. In both cases, void fraction changes are transient and void fraction is eventually returned to near the beginning value. The doppler coefficient produces the slight difference in void fraction because of changes in fuel temperature.

6.2.2 BWR/2

The Recirculation System for BWR/2 product lines, Figure 6.2-1, consists of five parallel piping loops, designated A through E. The pumping loops take suction from the reactor vessel downcomer annulus and discharge to the lower head area beneath the fuel region. The operator adjusts recirculation flow rate by varying the voltage and frequency output of motor generator sets which supply power to the recirculation pump motors.

6.2.2.1 Recirculation System

The five recirculation pumps, arranged in parallel, take suction from the reactor vessel downcomer annulus through individual outlet nozzles and motor operated suction valves. Pump discharge flow passes through individual motor operated discharge isolation valves and reenters the reactor vessel through five inlet nozzles. A 2 inch line containing a motor operated valve bypasses each pump discharge valve. This path allows a minimum flow during pump starting and provides a small backflow to keep an idle loop warm.

All five recirculation loops are normally in operation, with the pumps at the same speed. Under certain conditions, plant operation is permitted with one loop idle, but not isolated.

Various other plant systems that connect to the recirculation system include:

- A 10 inch line joins loop A upstream of the pump suction valve to provide a return flow path to the reactor vessel from isolation condenser A.

- A 3/4 inch line taps off loop A upstream of the pump suction valve to provide a flow path to the sampling system.

- Two 6 inch lines connect to loop B to provide supply and return flow for the Reactor Water Cleanup System.

- Two 14 inch lines connect to loop E to provide supply and return flow for the Shutdown Cooling System.

- A 10 inch line joins the 14 inch shutdown cooling supply line to provide a return flow path to the reactor vessel from isolation condenser B.

The major components of the Recirculation System are discussed in the paragraphs that follow.

Recirculation Pumps

The recirculation pumps provide the driving head for the recirculation system. Each pump is a vertical, single stage, centrifugal pump driven by a 1000 HP, variable speed induction motor. The pumps are powered from individual M/G sets which supply a variable frequency and voltage (11.5 - 57.5 Hz and 460-2300 volts) to change pump speed and flow rate. The flow rate per pump varies from a minimum of 6400 gpm to a maximum of 32,000 gpm.

Each recirculation pump is equipped with a dual seal assembly which contains reactor water within the pump casing and associated controlled leakage lines and allows zero leakage to the primary containment. The assembly consists of two seals built into a cartridge that can be replaced without removing the motor from the pump. Each seal can withstand full pump design pressure so that either will adequately limit leakage if the other fails. A breakdown bushing in the pump casing limits leakage to approximately 60 gpm if both seals fail.

During normal operation, both seals share the sealing work load of the assembly, with approximately a 500 psid pressure drop across each seal. Thus, seal cavity #1 is at reactor pressure and seal cavity #2 is at one half of reactor pressure. This arrangement is maintained by two internal restricting orifices which control the leakage between the seal cavities, and from cavity #2 to the drywell equipment drain tank (DWEDT), at approximately 0.5 gpm. A flow switch in the controlled leakage line actuates an alarm on seal failure (high flow) or orifice plugging (low flow).

The seal cavities require forced cooling to remove heat generated by friction between the sealing surfaces. The Reactor Building Closed Cooling Water System supplies approximately 25 gpm of water to a heat exchanger surrounding the seal cartridge. Reactor water from the pump cavity passes through a hole in the main pump impeller, around the hydrostatic bearing, and through the shaft to casing clearance to an auxiliary impeller located just below the seal cartridge. The auxiliary impeller forces the seal water through the tubes of the heat exchanger.

BWR/2 Recirculation Flow Control System

Each recirculation pump is hardwired to an associated recirculation motor/generator (M/G) set stator. (Figure 6.2-2) Since the pumps are driven by an induction motor, pump speed and resulting recirculation loop flow are determined by generator speed (frequency).

Each M/G set consists of a constant speed drive motor, a fluid coupler, a variable speed generator. The speed of the generator is determined by the generator load and the amount of coupling between the drive motor and generator.

Scoop tubes vary the volume of oil in the hydraulic coupler, and thus the amount of torque transmitted from the drive motors to the generators. As a scoop tube is inserted, the volume of oil in the coupler decreases, and both torque transmission and generator speed decrease. Pump speed also decreases, since the pump operates synchronously with the generator. Likewise, oil volume, generator speed and pump speed all increase as a scoop tube is retracted.

The flow control system contains one speed control loop for each of the five recirculation pumps. Manual speed demand signals are sent to the five controllers from two sources during normal operation:

- In the master/manual mode of operation, a single speed demand signal originating in the master controller passes through each M/A transfer station to the speed controllers. All recirculation pumps operate at approximately the same speed, as determined by the master controller. The automatic position of the master controller is not used and the controller is pinned in the manual position.

- In the loop manual mode of operation, the master controller is disconnected, and pump speed is controlled individually by speed demand signals originating in each M/A transfer station.

The speed controllers compare speed demand signals from the M/A transfer stations to speed feedback from the M/G set tachometers. The resulting error signals are supplied to the Bailey scoop tube positioners, which position the M/G set hydraulic coupler scoop tubes. Feedback signals from the scoop tube actuators and speed tachometers stop motion when scoop tube positions are correct.

6.2.3 BWR/3&4

The recirculation system for BWRs 3&4 (Figure 6.2-3) consists of two piping loops external to the reactor vessel and 20 jet pumps which are internal to the reactor vessel. Each loop has a suction isolation valve, recirculation pump, a discharge isolation valve, instrumentation, and piping connecting to the reactor vessel.

The variable speed recirculation pumps take suction from the reactor vessel annulus region and provide flow to the jet pump riser pipes through the reactor vessel shell. The jet pumps induce additional water from the reactor vessel annulus region into the flow path, increasing system efficiency.

6.2.3.1 Recirculation System

The major parts of the recirculation system are discussed in the paragraphs that follow.

Suction Valve

There is a suction valve in each recirculation loop between the reactor vessel penetration and the recirculation pump. These motor operated suction valves are used for maintenance isolation of each recirculation pump.

Recirculation Pump

The recirculation pumps are vertical, single stage, centrifugal pumps driven by a variable speed electrical motor. The pumps provide a rated flow of 45,200 gallons per minute each. The speed of the recirculation pumps, and hence the system flow rate, is controlled by the recirculation flow control system.

Discharge Valve

Each recirculation loop contains a motor operated discharge valve located between the recirculation pump and the loop flow measurement device. The valve is remotely operated from the control room using a seal-in to close, throttle to open logic. The discharge valves are automatically jogged open on a pump startup by the recirculation flow control system. Additionally, the discharge valves close as part of the automatic initiation sequence for low pressure coolant injection mode logic of the Residual Heat Removal System to provide an emergency core cooling flow path to the reactor vessel. (See Chapter 6.4)

Jet Pumps

There is a bank of 10 jet pumps associated with each of the external recirculation loops. All jet pumps are located in the reactor vessel annulus region between the inner vessel wall and the core shroud. The jet pumps are provided to increase the total core flow while minimizing the flow external to the reactor vessel.

Each jet pump has a converging nozzle through which the driving flow passes. This creates a high velocity and relatively low pressure condition at the jet pump suction. This low pressure condition creates additional flow from the vessel annulus, called induced flow, through the jet pumps. The combined flows mix in the mixer section of the jet pumps and then pass through the diffuser section. The diffuser section increases the pressure and decreases the fluid velocity. During full power operation approximately one-third of the total core flow comes from the discharge of the recirculation pumps while the remaining two-thirds is induced by the jet pumps.

6.2.3.2 Recirculation Flow Control

The major components of the recirculation flow control system are discussed in the paragraphs that follow (Figure 6.2-4).

Recirculation Motor Generator Set

The recirculation motor generator set consists of a drive motor, fluid coupler, generator, and the necessary auxiliary components to support motor generator set operation.

The recirculation motor generator set drive motor is a constant speed motor with a horse power rating between 7,000 and 9,000 HP. The drive motor supplies the fluid coupler with motive force through a constant speed input shaft.

The fluid coupler transmits a portion of the drive motor torque to the generator shaft. The amount of torque that is transmitted to the generator is determined by the coupling between the drive motor and generator, which is determined by the amount of oil in the fluid coupler. The quantity of oil in the fluid coupler is regulated by the positioning of a device called a "scoop tube". The greater the quantity of oil in the fluid coupler, the greater the coupling between the generator and drive motor. Therefore, the scoop tube position determines the torque transmitted to the generator.

Recirculation Pump Speed Control Logic

The principle of operation in the flow control logic is to set a desired speed, measure the actual speed, compare these signals and produce a control signal used to position the scoop tube to obtain the desired speed. The components performing this function are discussed in the paragraphs that follow.

Master Flow Controller

The master flow controller provides the means of controlling both recirculation motor generator sets from a single controller. Normal operation of the master controller is in the manual mode of operation. By adjusting the manual potentiometer, a demand signal is developed and transmitted to the manual automatic (M/A) transfer station via a dual limiter.

In the automatic mode of operation the electro-hydraulic control system provides the desired main generator set load demand signal. Only one utility, Commonwealth Edison, has operated in the automatic mode and is licensed to do so.

Manual-Automatic Transfer Station Controllers

The M/A transfer station controllers provide the means of controlling the motor/generator set independently or as a paired unit. Similar to the master controller, the M/A transfer stations contain two modes of operation, manual and automatic. Normal mode of operation is both controllers in automatic.

Speed Limiters

There are two speed limiters used in the control logic to limit the maximum and/or minimum speed demand signal according to plant conditions.

The output of the M/A station controller is routed through two speed limiters. The first of these limiters limits recirculation pump speed to a maximum of 28% with the pump discharge valve not full open or feedwater flow less than 20%. This limiter prevents overheating of the recirculation pumps with the discharge valve not open and cavitation problems for the recirculation pumps and jet pumps at low feedwater flow rates.

The second limiter, operational limiter, limits the maximum recirculation pump speed demand to less than that required for approximately 75% power. This limit ensures a sufficient supply of feedwater to the reactor vessel to maintain the required operating level. This limiter is bypassed whenever level is normal or if all reactor feed pumps are in service. The operational limiter is supplied to plants with turbine driven feed pumps. Plants with motor driven feed pumps and an automatic startup of the standby pump do not require a load reduction to maintain level.

Speed Control Summer

The speed control summer, during normal operation, compares the speed demand signal to the actual generator speed and develops an error signal which is sent to the speed controller. The error signal is limited to about 8% of the control band.

Speed Controller

The speed controller establishes and maintains a speed demand signal in accordance with the error signal received from the speed control summer.

Scoop Tube Positioner

The scoop tube positioner converts the electrical input signal, from the speed controller, to a mechanical scoop tube position.

6.2.3.3 Recirculation Pump Start

Figure 6.2-5 lists the initial requirements and sequence of events occurring on a recirculation motor-generator startup. Briefly, the drive motor starts if all of the permissives are satisfied. If the scoop tube is in the proper position and the pump is not developing any differential pressure, a 7 second time delay is initiated after which the field breaker closes. During this time delay, the drive motor and generator are accelerating to approximately 12% loaded speed; this corresponds to 40% unloaded speed.

Note on Figure 6.2-4 that when the field breaker is open, the speed control system input to the error limiter is replaced by the signal generator and the tachometer feedback by the speed controller output. This serves to position the scoop tube to the 40% unloaded position. Excitation is applied to the motor generator set exciter 5 seconds after the drive motor breaker is closed.

Excitation is provided from the 120 VAC startup excitation source. Thus, when the field breaker closes 7 seconds after the drive motor breaker closure, the motor generator set is accelerated to approximately 40% unloaded speed and fully excited to provide the necessary pump breakaway torque.

Once the field breaker is closed, excitation will automatically shift back to the generator output following a 20 second time delay. Since the recirculation pump trip breakers are normally closed, the pump motor is directly tied to the generator output and the recirculation pump starts when the generator field breaker closes.

The 15 second incomplete sequence timer allows time for the pump to "breakaway" and generate >4 psid. As soon as the 4 psid is generated, the incomplete sequence timer is de-energized and the timer resets. When the generator field breaker is closed, the speed control circuits are returned to normal and the pump will runback in speed to the limiter value of 28%, with the discharge valve closed. Following the pump start the discharge valve will then automatically jog open.

6.2.3.4 Power/Flow Map

The power/flow map (Figure 6.2-6) is a plot of percent core thermal power versus percent of total core flow for various operating conditions. The power/flow map contains information on expected system performance.

28% Pump Speed Line

Startup operations of the plant are normally carried out with both recirculation pumps at minimum speed. Reactor power and core flow follow this line for the normal control rod withdraw sequence with the recirculation pumps operating at approximately 28%.

Design Flow Control Line

This line is defined by the control rod withdraw pattern which results in being at 100% core thermal power and 100% core flow, assuming equilibrium xenon conditions.

Reactor power should follow this line for recirculation flow changes with a fixed control rod pattern.

6.2.4 BWR/5-6

The recirculation system for BWRs 5&6 (Figure 6.2-7) consists of two piping loops external to the reactor vessel and 20 jet pumps which are internal to the reactor vessel. Each loop has a suction isolation valve, recirculation pump, flow control valve, a discharge isolation valve, instrumentation, and piping connecting to the reactor vessel.

The two speed recirculation pumps take suction from the reactor vessel annulus region and provide flow to the jet pump riser pipes through the reactor vessel shell. The jet pumps induce additional water from the reactor vessel annulus region into the flow path.

6.2.4.1 Recirculation System

The major parts of the recirculation system are discussed in the paragraphs that follow.

Suction Valve

There is a suction isolation valve in each recirculation loop between the reactor vessel penetration and the recirculation pump. These motor operated suction valves are used for maintenance isolation of each recirculation pump.

Recirculation Pump

The recirculation pumps are vertical, single stage, two speed, centrifugal pumps. Each is designed to deliver a rated flow of 35,400 gpm at a discharge pressure head of 865 feet. The pumps motors can receive 60 Hz power from 6.9kV buses or 15 Hz power from the associated low frequency motor generator set (LFMG).

In slow speed, the net positive suction head is supplied by the height of water in the reactor vessel. In fast speed, most of the net positive suction head is provided by the subcooling effect of the cooler feedwater flow entering the annulus region where it mixes with the moisture returning from the steam separation stages.

Flow Control Valve

The flow control valve is a 24 inch, stainless steel, hydraulic operated ball valve. The valve is designed to provide a linear flow response throughout its entire stroke (22 to 100% open). The valve is positioned by a hydraulically actuated ram that receives motive power from an independent hydraulic power unit. The actuator is positioned by the Recirculation Flow Control System.

Discharge Isolation Valve

The discharge isolation valve is a 24 inch, motor operated, stainless steel, gate valve. Valve operation is similar to the suction valve.

6.2.4.2 Recirculation Pump Speed Control

The switchgear in Figure 6.2-8 includes five separate circuit breakers and a low frequency motor generator set. The breakers are interlocked through the pump control logic to prevent supplying the pump motor from both power supplies.

The interlocks provide the proper sequencing of circuit breaker closure during pump startup, speed changes, and shutdown.

The recirculation pump is always started in fast speed because the LFMG does not have the required capacity to supply the necessary breakaway torque.

Recirculation Pump Start Sequencing

To start a recirculation pump in fast or slow, the following permissives (Figures 6.2-9) must be met before the start sequence will initiate:

- Incomplete sequence relay not actuated
- CB-5 racked in
- Flow control valve in manual mode and at the 22% open position
- Suction and discharge valve greater than 90% open
- Vessel thermal shock interlocks satisfied

The incomplete relays activate as a result of the failure to complete the starting sequence. On a slow speed start, the incomplete sequence relay activates if the pump is not operating between 20 and 26% speed or CB-2 does not close within 40 seconds. During a fast speed start, the incomplete sequence relay activates if the pump is not operating at greater than 95% speed after 40 seconds. In addition, loss of logic control power will immediately initiate the incomplete sequence causing CB-1 and CB-5 to trip.

The flow control valve in manual prevents valve cycling during flow changes when the pump starts.

Requiring the flow control valve to be at the 22% position minimizes flow increase during pump start. This reduced flow during pump starts limits thermal stresses on vessel internals, limits power excursions, and allows the pump to reach desired speed faster.

The suction and discharge valves are required to be open during all pump operation for pump protection.

There are three reactor vessel thermal shock interlocks which prevent large changes in water temperature, both in the vessel and recirculation loops. The first of the three interlocks limits the temperature difference between the vessel bottom head drain and the steam dome temperature from exceeding 100 °F. This limit prevents rapid changes in bottom head region water temperature. During periods of low core flow, a stagnant layer of cold water can form in the bottom head region because of the cold control rod drive water. Large changes in recirculation flow (pump start) could sweep away the cold layer, replacing it with hot water creating large temperature gradients on the reactor vessel and its internals. The second temperature interlock limits the difference between the steam dome and the applicable loop suction temperature to less than 50 °F. The 50 °F limit further restricts operation to avoid high thermal stresses on the pump and piping. The third interlock limits the difference between the two loops to less than 50 °F. This limit protects the pump against damage resulting from excessive heatups.

Slow Speed Start Sequence

The recirculation pumps are always started in fast speed. If after the initial start permissive are satisfied, total feedwater flow is greater than 30% and the power level interlock is bypassed, the slow speed start sequence is actuated.

In the slow speed start sequence CB-5 closes, accelerating the pump to 95% speed. At 95% speed CB-5 trips, allowing the pump to coast down. Simultaneously, CB-1 closes, starting the LFMG. When the pump reaches 20-26% speed, CB-2 closes holding the pump at 450 rpm (25% speed, 15 Hz).

Fast to Slow Speed Transfer

Fast to slow speed transfer can be accomplished manually or automatically. Manual transfer from fast to slow is accomplished by depressing both recirculation pump transfer to slow pushbuttons simultaneously. Automatic transfer from fast to slow is accomplished if any of the following conditions are met:

- Feedwater flow less than 30%
- Delta T between steam line and recirculation suction temperature is less than 7 °F.
- Reactor vessel water level 3
- EOC-RPT

6.2.4.3 Recirculation Flow Control

The recirculation flow control system, Figure 6.2-10 and 6.2-11, is capable of varying recirculation flow over a range of 35 to 100% with the recirculation pumps in fast speed or 30 to 40% in slow speed. The major components of the recirculation flow control system include:

- Master Controller
- Neutron Flux Controller
- Flow Controller
- Operational Limiter
- Hydraulic Power Unit
- Valve Actuator

Master Controller

The master controller provides a means of controlling both recirculation flow control valves from a single controller. Controller operation is accomplished in manual or automatic. When in the manual mode, a power demand signal is manually established by the operator with a slide switch on the front of the controller. In automatic mode of operation the controller accepts a load demand signal from the Electro-Hydraulic Control System This signal is then processed throughout the remaining RFC System circuitry to adjust recirculation flow and hence reactor power to balance the load demand. The normal mode of operation on the Master Controller is *MANUAL* mode.

Neutron Flux Controller

The neutron flux controller provides a second means of controlling both recirculation flow control valves from a single controller. In addition, it also provides a stabilizing effect on plant operation by virtue of its power feedback signal. When in manual mode, a flow demand signal is established by the operator. In automatic mode of operation the controller receives a neutron flux demand signal from the master controller which is compared to the reference APRM signal. These two signals are compared to produce an output signal in terms of a flow demand signal. The normal mode of operation for this controller is *MANUAL*.

Flow Controller

The loop flow controllers, one for each loop, provide a means of individually controlling the flow control valves. These controllers can also be operated in manual or automatic. In the automatic mode the controllers receive a flow demand signal from the flux controller and also a flow feedback from the flow element in its recirculation loop suction piping. These two signals are compared and produce an output signal in terms of a flow error signal which is transmitted to its respective hydraulic power unit. Normal mode of operation is automatic.

Operational Limiter

The flow controller output signal is processed through a loop flow limiter. When the recirculation pumps are in ***fast*** speed the flow limiter limits the signal to a maximum of 48% loop flow (38% FCV position) in the event there is a loss of one reactor feed pump and level cannot be controlled above the low level alarm point.

The purpose of the limiter is to reduce reactor power to within the capacity of one reactor feed pump by closing the FCVs.

Hydraulic Power Unit

The hydraulic power unit is a self contained hydraulic oil system for each recirculation flow control valve. The HPU receives an electric flow signal from the flow controller and converts it into a hydraulic oil pressure signal which then positions the FCV via the valve actuator. FCV position cannot be changed without the HPU in operation.

6.2.4.4 Power/Flow Map

A tool used to monitor BWR performance is a power/flow map (Figure 6.2-12). The power/flow map is a plot of core thermal power (in percent of rated) versus core flow rate (also in percent of rated) for various operating conditions. The power/flow map contains information on expected system performance and limits on the recirculation system for operation of the recirculation pumps, jet pumps, and flow control valve.

6.2.5 Summary

The Recirculation System evolved from a 5 loop, with variable speed pumps, system for the BWR/2 to an internal jet pump two loop system for BWRs 3 through 6. The BWR/3 and 4 utilize two variable speed pumps and 20 internal jet pumps to obtain the necessary core flow while minimizing the vessel penetrations. BWRs 5 and 6 also have two independent recirculation loops like the BWR/3 and 4, but vary core flow by throttling flow with a flow control valve.

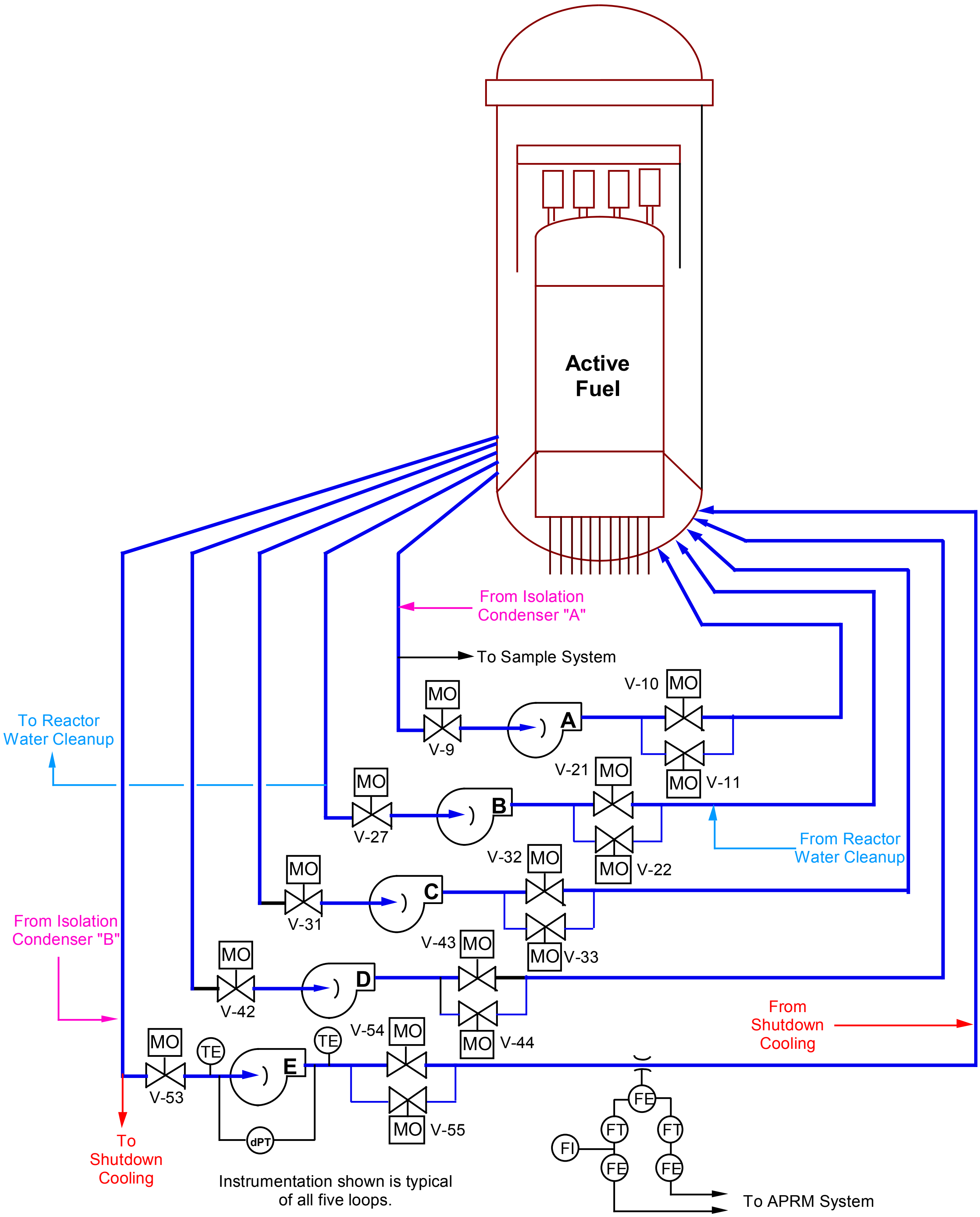

Figure 6.2-1 BWR/2 Recirculation System

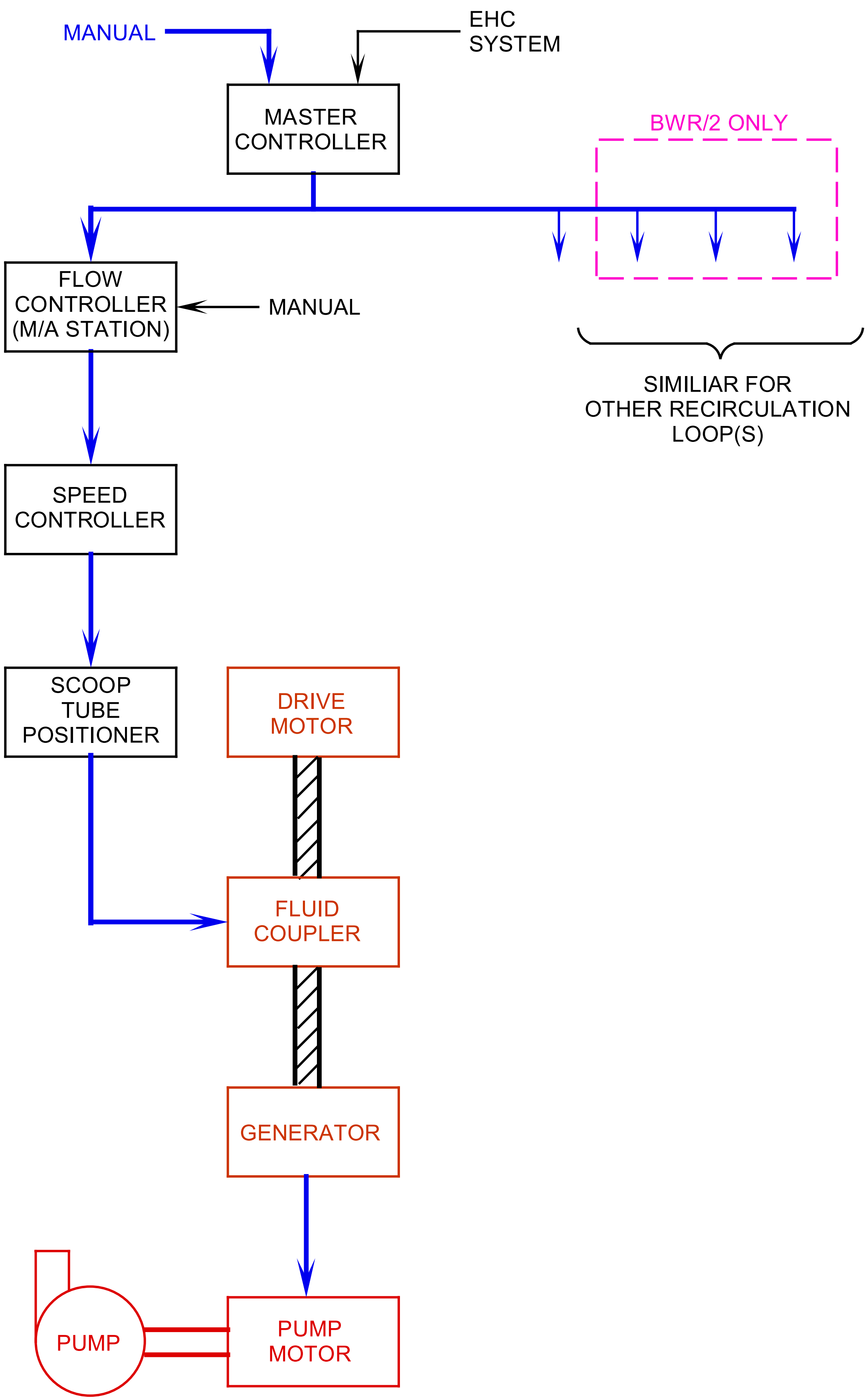

Figure 6.2-2 RFC System (BWR/2,3 & 4)

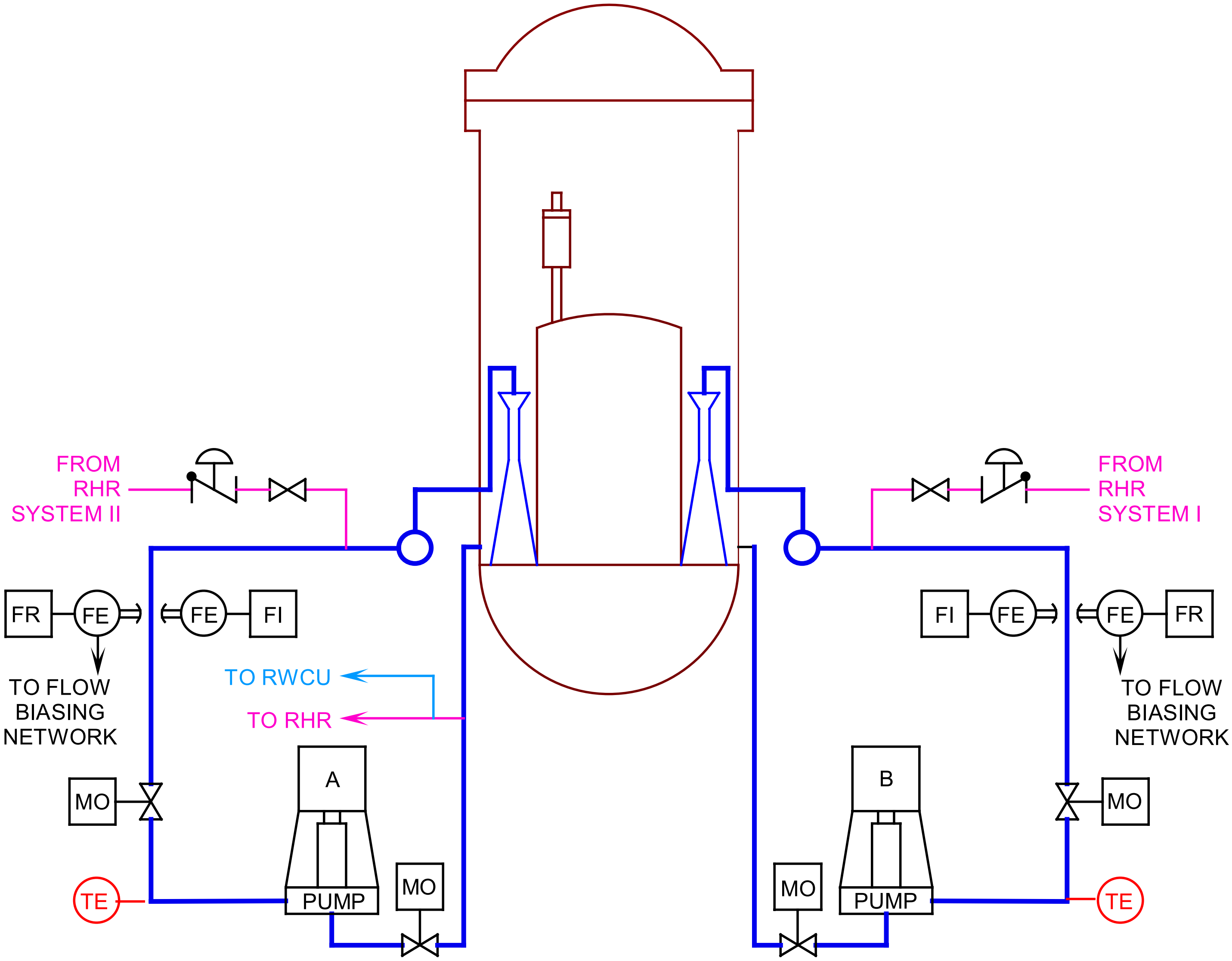

Figure 6.2-3 Recirculation System (BWR/3 & 4)

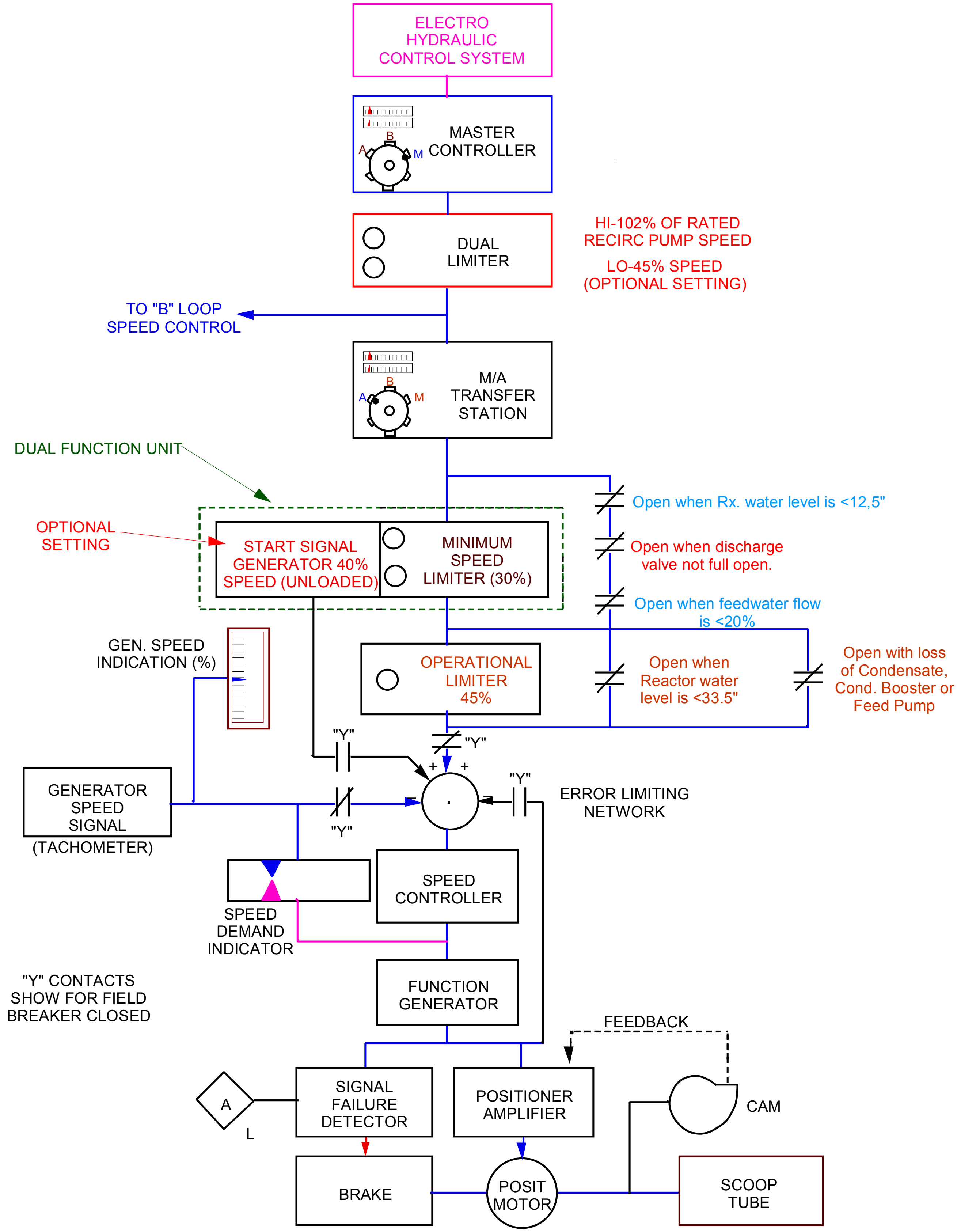

Figure 6.2-4 Recirculation System Flow Control Network (BWR/3/4)

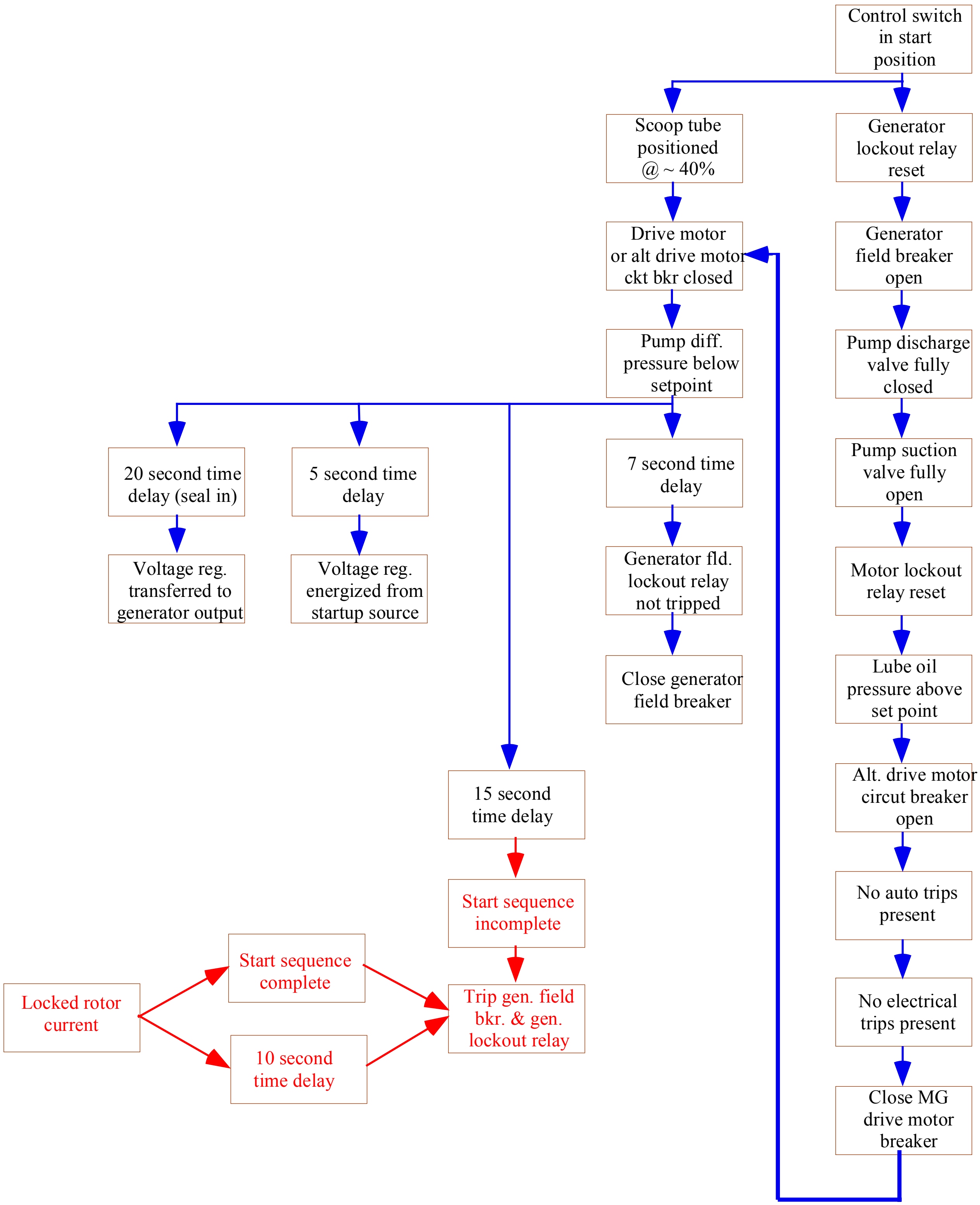

Figure 6.2-5 Recirculation Pump Motor Generator Start Sequence

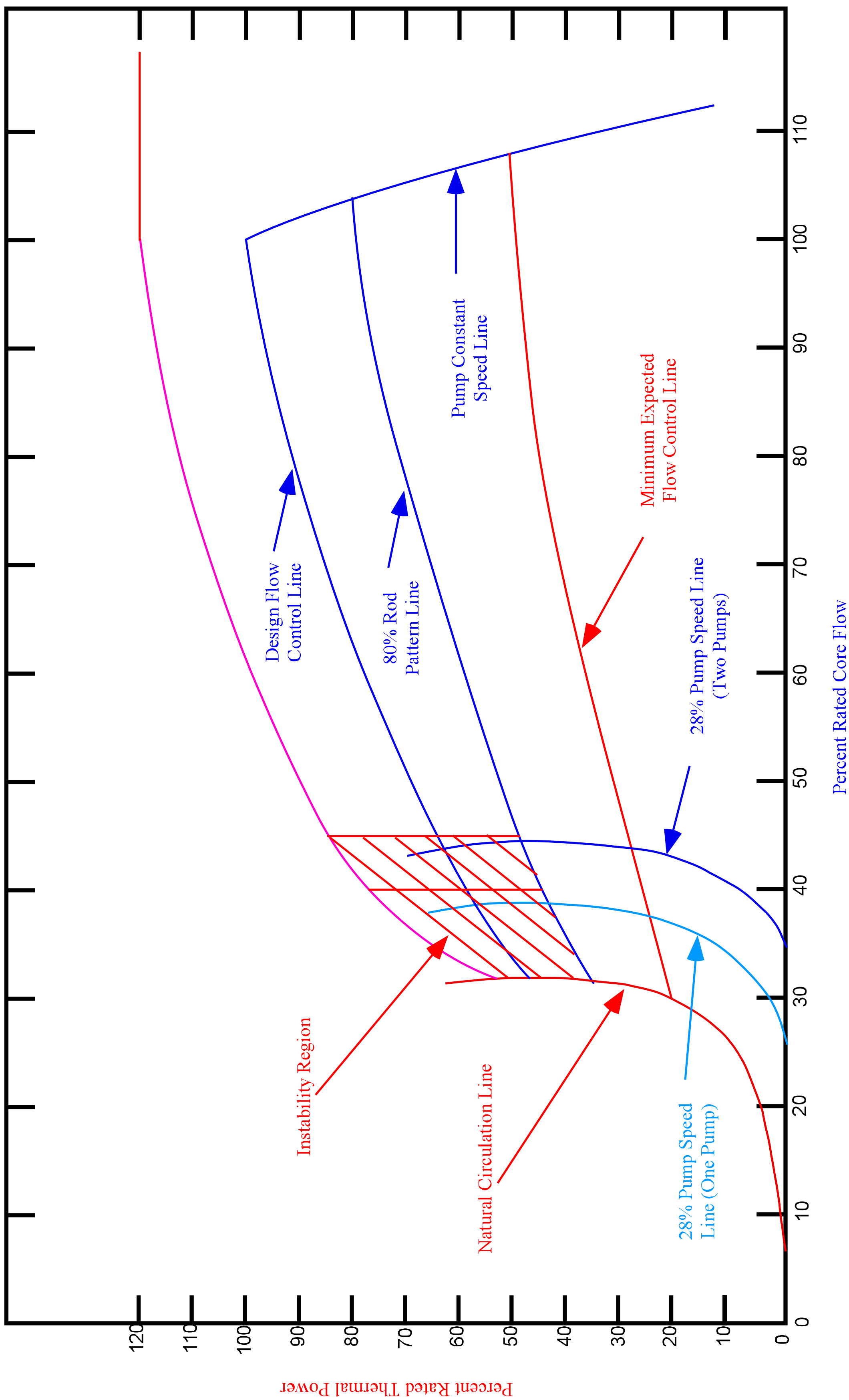

Figure 6.2-6 Power to Flow Map (BWR/3 & BWR/4)

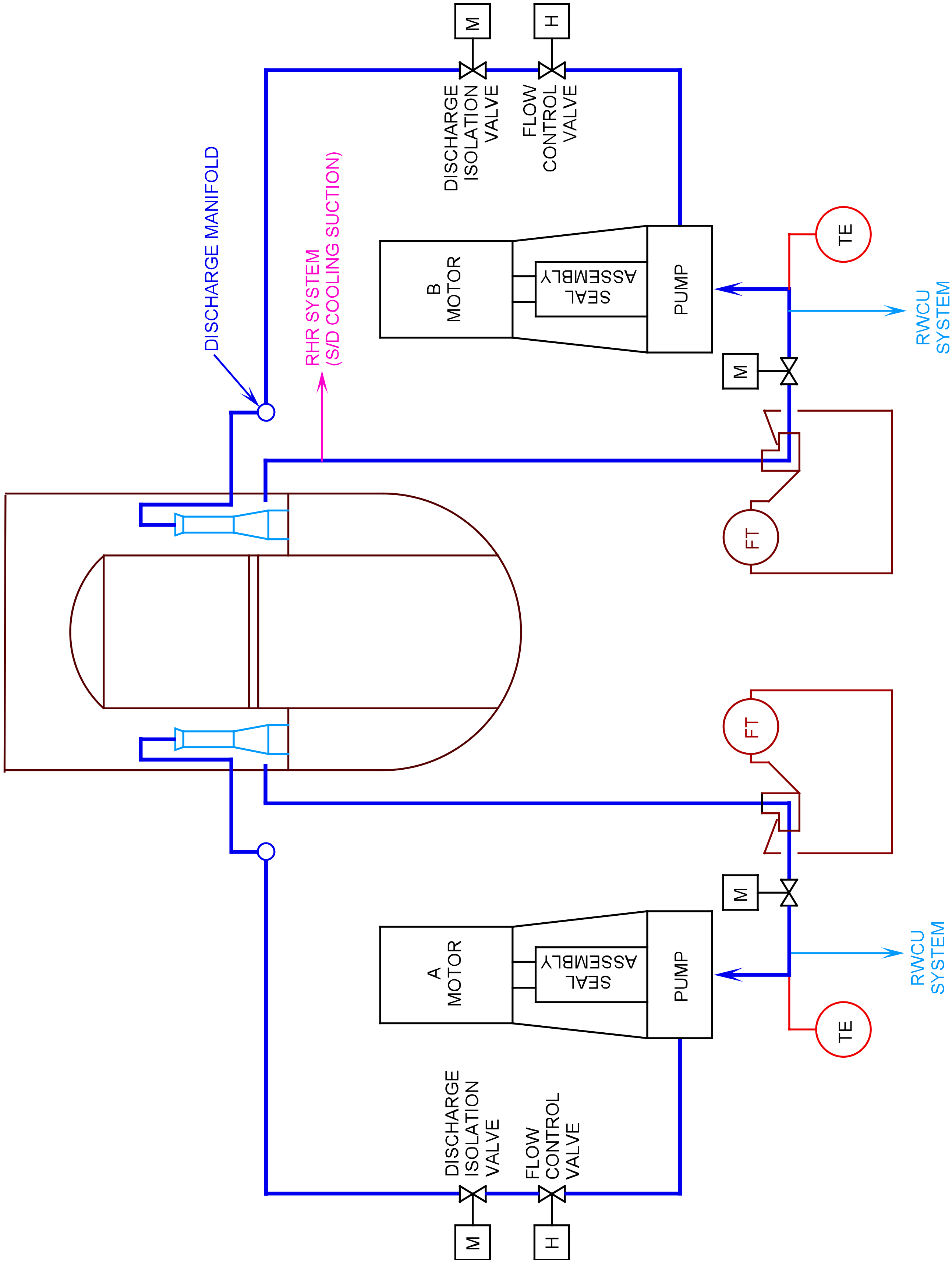

Figure 6.2-7 Recirculation System (BWR/5 & 6)

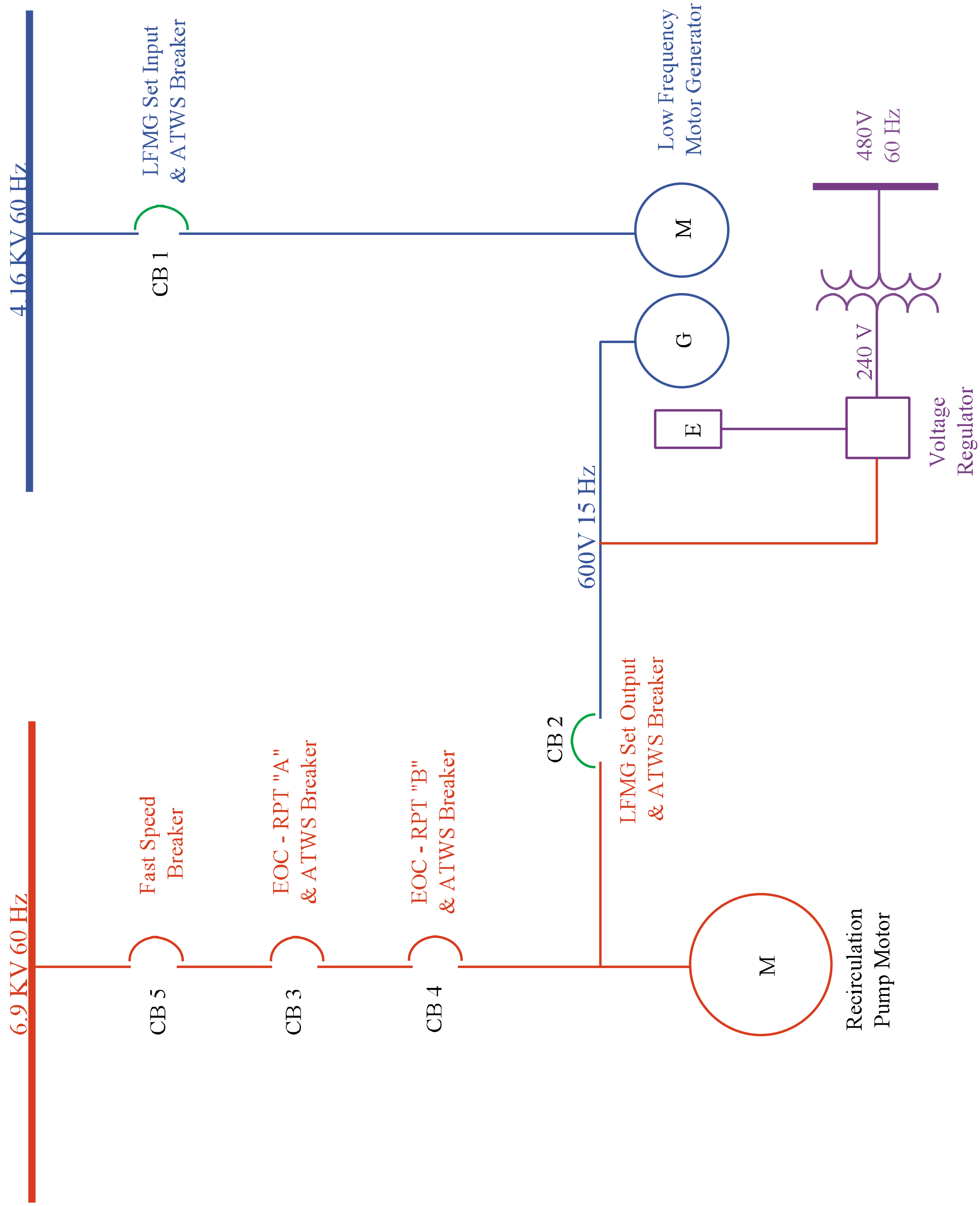

Figure 6.2-8 Recirculation Pump Power Supplies

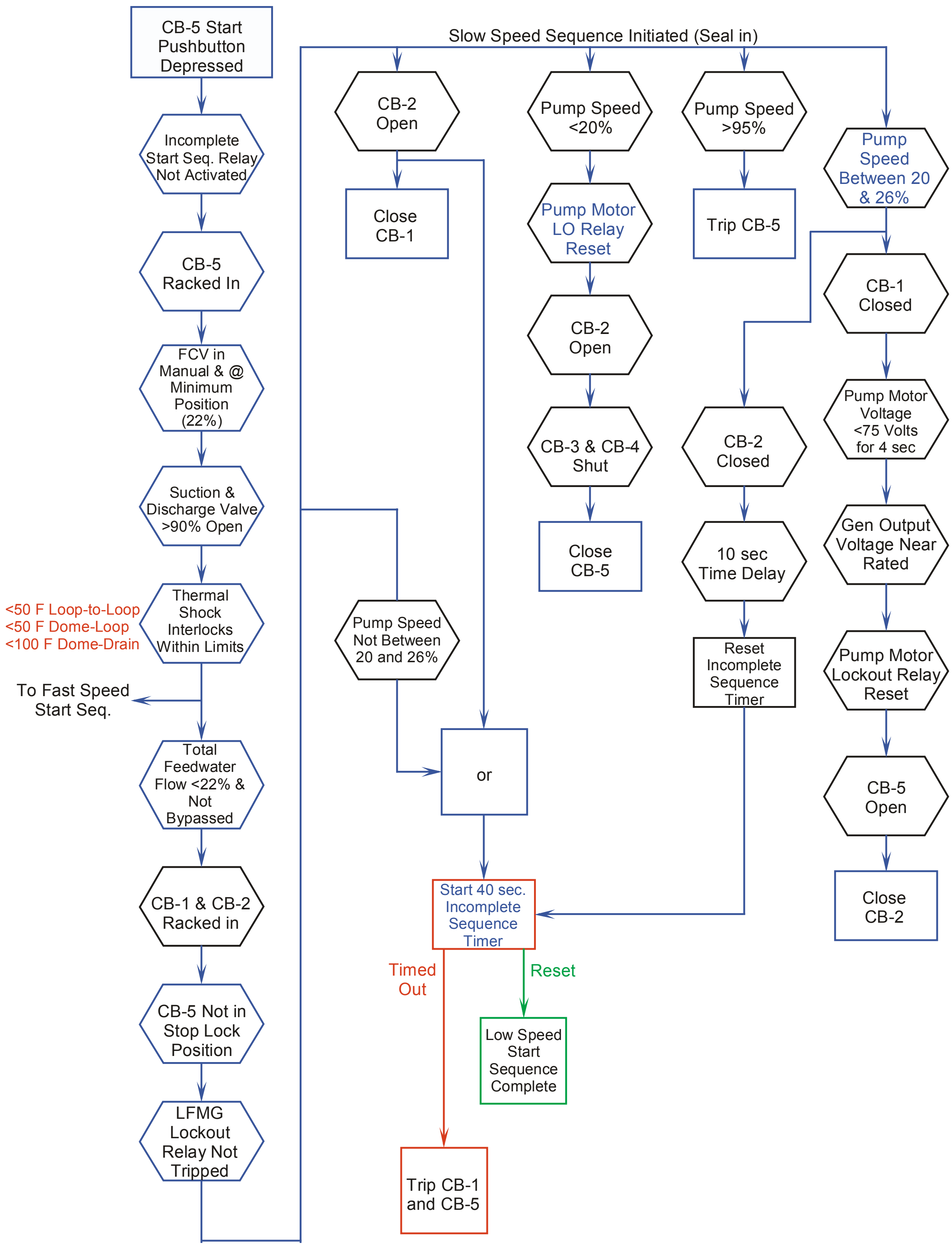

Figure 6.2-9 BWR/5 & BWR/6 Slow Speed Start Sequence

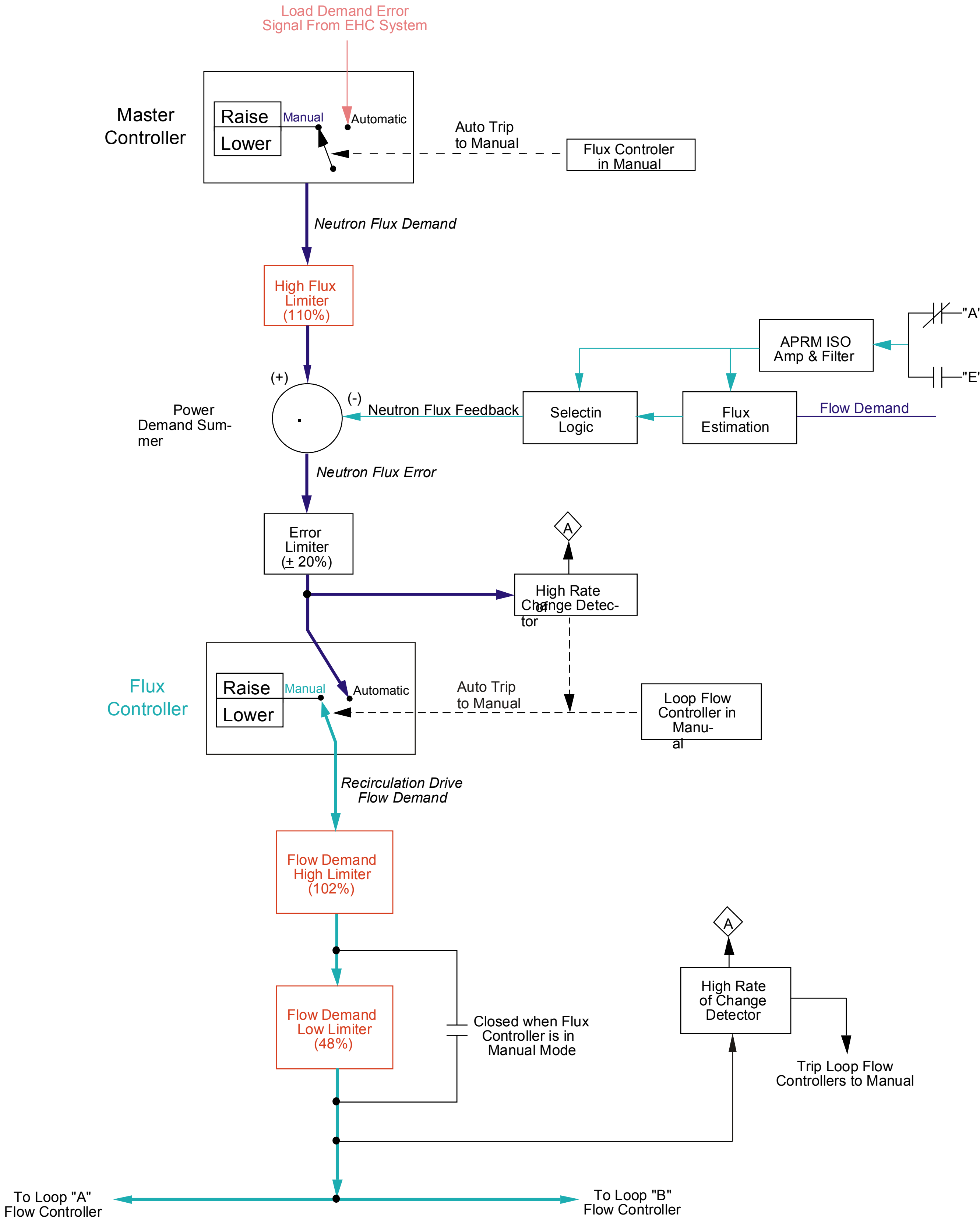

Figure 6.2-10 Recirculation Flow Control Network (BWR/5 & BWR/6)

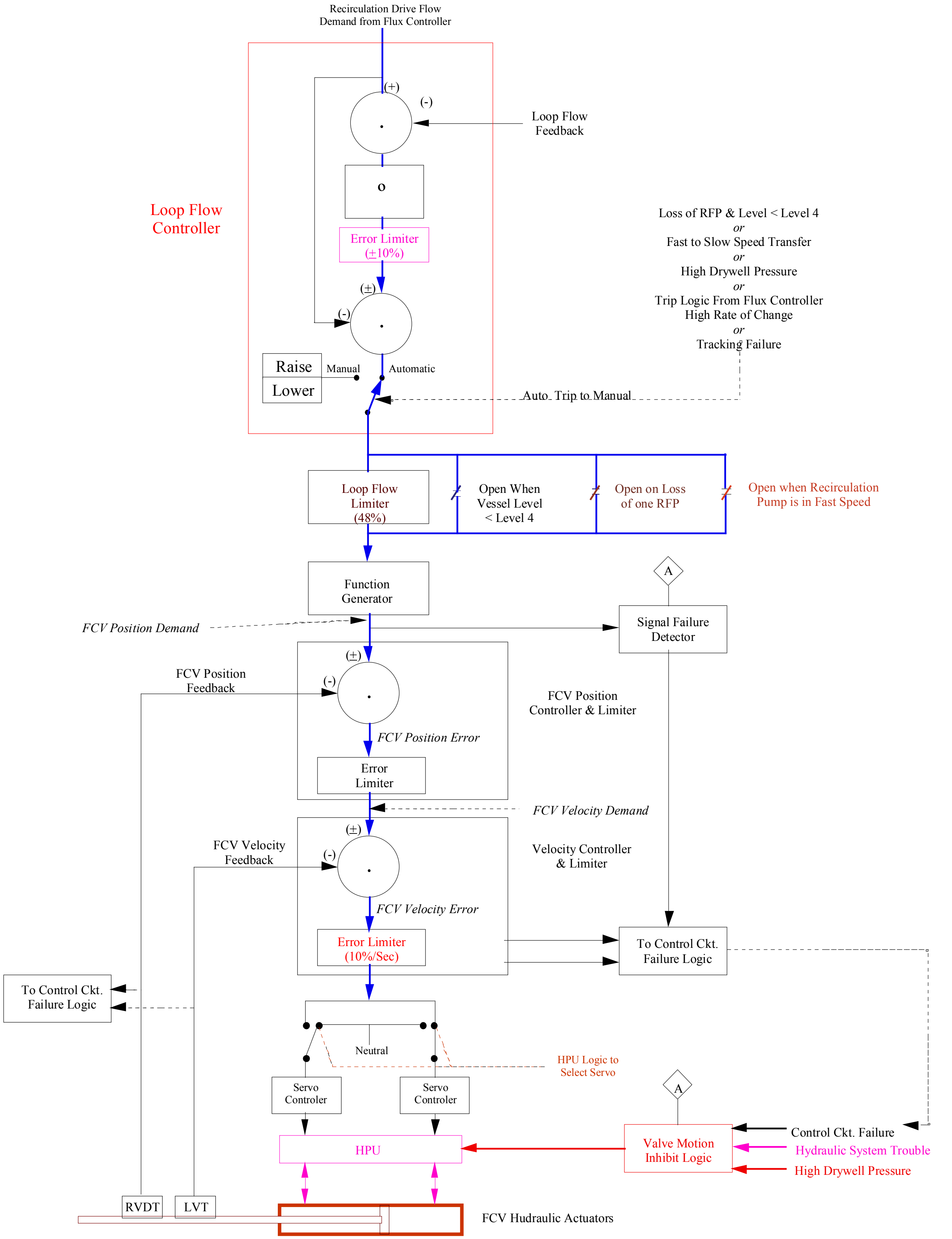

Figure 6.2-11 Recirculation Flow Control Network (BWR/5 & BWR/6) (continued)

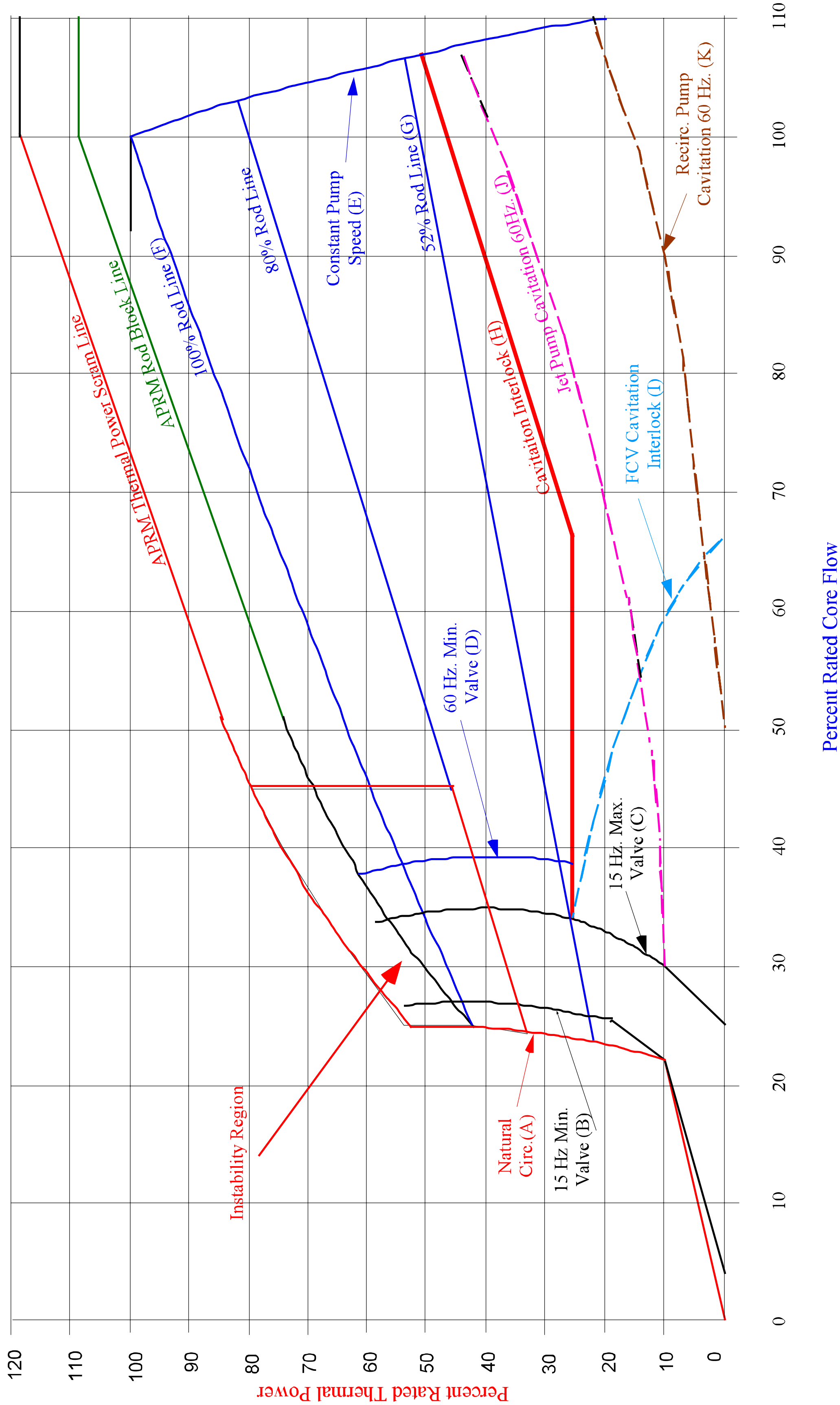

Figure 6.2-12 Power to Flow Map