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Control System Design of Water Filter Test Bench

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ABSTRACT

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Hydraulic filters are installed to hydraulic systems to decrease the amount of dirt particles. These filters are tested in test benches according to measuring standards. Test results will give better understanding of filters properties, such as filtration ratio and pressure drop. This information can be used for a product development and as an info for the costumers.

A new water filter test bench is to be built for Parker. A well-designed control system will be in key role for the use of the test bench and for the success of measuring events. The first model of test bench's control system was created in this thesis. The control system was modelled in Unified Modelling Language's state machine diagrams, which can be utilized later in the creation of the PLC program. This work can be seen as constructive research and it was commissioned by Parker Hannifin Manufacturing Finland Oy.

The work part started by designing the hydraulic circuit. After the hydraulic circuit was complete and all the needed components of the control system were defined, control system design began. Main states of the control system were modelled first. These states defined which of the components could be actuated during each state and which sensor/state data would be shown to the user by the Human-machine interface. Components' state machine diagrams were modelled after this. These diagrams defined every possible scenario where a certain component could be used. The actuations were possible only if the set conditions for the action were true. These guards were set for the state changes so that the system would be safe to use, and unwanted action wouldn't occur. Confidential parts of this thesis were omitted from this public version.

The result of this study was a model of a control system. It can be seen as the first prototype where all the critical functions of the control are defined. Several ideas for further development of the water filter test bench appeared during the work and they are explained in the discussion. Next step for this project would be the creation of a PLC program and its simulation. There the functionalities of the control system designed in this thesis could be tested and fixed if needed.

Key words: control system, state machine diagram, filtration

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GLOSSARY

E/E/PE	Electrical/electronic/programmable electronic
Gravimetric level	Contaminant content
HMI	Human-machine interface
PLC	Programmable logic controller

1 INTRODUCTION

Parker Hannifin Manufacturing Finland Oy is part of global Parker Hannifin Corporation, Filtration Group and Hydraulic and Industrial Process Filtration Division EMEA. It is mainly focused on production and design of hydraulic filters. Till today, these filters have mainly been for oil. Until now, a new need for water filters has risen.

To test filters and their properties such as filtration ratio and pressure drop, a test bench system is needed. Test benches and measuring events are defined in different standards. To research and develop water filtration, a new test bench must be made. This test bench will be controlled with a control system which preliminary designing is the topic of this thesis.

Test bench project is still on its early stages. Components or software to be used are not yet decided. Therefore, the model of the control system to be designed must be universal. Unified Modeling Language offers a great tool for this: a state machine diagram.

Theory part of this thesis aims to give all the needed instruments for safe and easily understandable modelling of the test bench control system. It will delve into the laws and safety regulations of control system's functions, explain the Unified Modelling Language and open up the measuring standards ISO 16889 and ISO 3968, which are to be followed in the test bench design process.

This work doesn't aim to offer a ready to be used control system, but a model, a first prototype where all the critical control functions are determined. This model strives to divide the system into different logical main states, where control of certain components are made possible. On a deeper level, a state machine diagram is to be created for every component of the control system. These diagrams define every possible scenario where a certain component can be actuated and what conditions needs to be fulfilled so that the actuation would be safe and allowed.

This work aims to give a model after which the PLC program can be made and to point out certain questions that needs to be considered during the creation of the final control system.

2 THEORY

2.1 Government Decree on the Safe Use and Inspection of Work Equipment 12.6.2008/403

There are many laws and regulations to be followed when designing a new machine or a system. In the following two chapters two decrees are looked into. These decrees contain a lot of general safety regulations for machinery, but only the parts that consider regulations for control systems, and especially control systems software, are examined.

The Government Decree on the Safe Use and Inspection of Work Equipment is applied for use and inspection of a machine, an equipment and other technical device or their combination at work. Safeness of control systems is also included into this.

It is stated in the decree that control system and safety devices must work flawlessly. Also, the controlling systems must be reliable, and must be secured where possible that a flaw in system or a change in its energy state won't cause any danger. Control system must be chosen and designed so that in planned usage, possible flaws, disturbances and restrictions are considered. (Valtioneuvoston asetus työvälineiden turvallisesta käytöstä ja tarkastamisesta 2008/403.)

2.2 Government Decree on the Safety of Machinery 12.6.2008/400

Minimum safety levels for commercial machines are defined in the Government Decree on Safety of Machinery (Valtioneuvoston asetus koneiden turvallisuudesta 2008/400). The parts of the decree where control systems safety and reliability are considered, are looked into in this chapter. Even though the water filter test bench will not be a commercial product, it must fulfil all the obligations set out in the Government Decree on the Safety of Machinery (European Commission, 2019).

Control systems must be designed and built so that it prevents any danger to occur. They must be designed and built so that:

-intended operating use and outer influences are handled

-errors in control systems hardware or software will not cause any danger

-errors in a control systems logic will not cause any danger

-reasonable and predictable human error on use will not cause any danger.

The following things in control system must be dealt with extra care:

-Machine cannot start unexpectedly.

-Machines parameters cannot change uncontrollably if this sort of change can cause any danger.

-Stop of machine cannot be cancelled if a stop command is given.

-None of machines moving parts or parts that it is holding cannot fall or dart.

-Automatically or manually operated stop of machine's moving part cannot be cancelled.

-Safety devices must be functional or they must give a stop command.

-Automatic stop of a machine has to happen if the connection is lost to its wireless controller.

(Valtioneuvoston asetus koneiden turvallisuudesta 2008/400.)

2.2.1 Control devices

If there are more than one control place, control system must be designed so that usage of one control place blocks the usage of others. Stops and emergency stops devices are exceptions.

User must be able to make sure from the control place that no one is in the danger zone. If that is not possible, the control system must be designed so that start will be blocked if someone is in the danger zone. If neither of the previous are possible, an alarm sound or light must be given before the machine can start. Adequate time must be given to persons to exit the danger zone or to block the start of a machine. (Valtioneuvoston asetus koneiden turvallisuudesta 2008/400.)

2.2.2 Start

The start of a machine can only be possible when a control device is purposely used. The same demand goes when a machine is being restarted by the user after a stop. Though, restart or change of operating conditions can happen by using purposely another device than a control device meant for this purpose, if it won’t cause any danger. If a machine is in an automatic state, it may start, restart or its operating condition can change by itself, if it won’t cause any danger. If a machine has several controllers for a start command and users might jeopardize each other, an extra device for safety must be installed. Also, if a start or a stop must be done in exact order, correct order must be ensured with extra devices. (Valtioneuvoston asetus koneiden turvallisuudesta 2008/400.)

2.2.3 Stop

In a normal stop, machines stop command must be primary to its start command. When a machine or its dangerous functions have been stopped, energy supply to competent actuators must be shut off. If a functional stop is needed where supply of energy is not shut off, it has to be supervised and maintained.

There must be at least one or more emergency stops in a machine so that real or threatening dangers can be prevented. This rule can be deviated in machines where risk of danger would not be lowered by emergency stop, because stop time would not be reduced, or because some actions for safety would be impossible to be executed.

Dangerous processes must be stopped by emergency stop device as soon as possible. Also, certain protective manoeuvres must be executed or their start have to be allowed if necessary.

The stop command executed by emergency stop device must stay on and locked until it is released with a special operation. Locking of an emergency stop device cannot be possible without a stop command. Locking of an emergency stop device can only be opened with intended action and the machine cannot be turned on by this same action, only the option of restart is made possible. Possibility of emergency stop function must always be available and functional regardless on the mode of operation. Emergency stop devices must be an additional way of protection with other safety operations and not their substituent.

In a combination of machines, every part that is connected to a part which is under the influence of stop command has to stop, if otherwise their action would cause a danger. (Valtioneuvoston asetus koneiden turvallisuudesta 2008/400.)

2.2.4 Selection of control and operating modes

The chosen control mode must be primary compared to other operations and ways of control, except for emergency stop. If a machine can be controlled with different control devices or modes of operations, it has to have a switch to select the wanted operation mode. This is a must in operation modes that requires safety measures. Switch has to be so that it can be locked to its current position. Also, every position has to be easily recognizable and they must answer to one operation mode only. Switch can be replaced with other selection methods if they fill the same requirements for safety.

If for some occasion, safeguard has to be moved or taken off, or a safety device has to be removed from a system, control or operation mode switch has to simultaneously:

-disable all other control and operation modes

-allow dangerous functions and their execution only for control devices that are constantly under an influence

-allow dangerous operations only under the circumstances of reduced risk, while preventing risks occurring from related operation periods

-prevent dangerous functions that intentional or unintentional effect on machines sensor can cause.

If these four abovesaid rules cannot be fulfilled simultaneously, choosing of control or operation mode must activate other safety measures. These safety measures must be designed and built so that they cover the void in the safety zone. Manual control of actions that user is working with, must be possible at the working area. (Valtioneuvoston asetus koneiden turvallisuudesta 2008/400.)

2.2.5 Special requirements for safety devices

Safety devices must be planned and connected to a control system so that moving parts cannot turn on when they are within the reach of a user. Persons cannot reach to moving parts when they are moving. Single fault or lack of a component in safety devices must block start or stop moving parts. Safety devices must be adjustable only with appropriate operation.

Action connected openable safeguards must have an action connected device, that blocks dangerous function from turning on until safeguard is closed. Also, stop command must be given when the safeguard is not attached anymore. (Valtioneuvoston asetus koneiden turvallisuudesta 2008/400.)

2.2.6 Warning devices

If a fault of a machine that is not under a supervision, jeopardizes a person’s health or security, that machine must be equipped so that it gives a proper sound or light sign as a warning. (Valtioneuvoston asetus koneiden turvallisuudesta 2008/400.)

2.3 Multi-pass ISO 16889

The main reason for faults in hydraulic fluid power systems is a wear caused by a contaminated hydraulic fluid. To decrease the amount of dirt particles within the fluid, hydraulic filters are installed to hydraulic systems.

Multi-pass ISO 16889 standard has been made for repeatable and standardized testing of hydraulic filters' properties. (ISO 16889:2008.) The water filter test bench will be designed to follow this multi-pass standard. In this chapter, standard's requirements for the system's components, hydraulic circuit and measuring event are viewed. The aforesaid information is crucial for the control system design process, and it is important to follow the standard precisely. When the water filter test bench will be built, it must be validated according to the ISO 16889 standard. Only the parts of the standard that affect to the control system design is looked into in this chapter.

2.3.1 Multi-pass test system example

Multi-pass standard provides guidelines for the required test system. An example of multi-pass system's hydraulic circuit is shown in the ISO 16889 standard (appendix 1). All the necessary components for the multi-pass test are shown in the diagram and the keys for the hydraulic circuit are following:

A. contaminant injection system
B. filter test system
1. reservoir
2. pump
3. test filter
4. particle counting system
5. flow control valve
6. clean-up filter
7. flow meter
8. temperature controller
9. temperature sensor

10. sampling valve
11. differential pressure indicator
12. pressure gauge
13. diffuser
14. shut-off valve
15. non-return (check) valve
16. optional return to reservoir
17. back pressure valve
18. optional bypass section.

As can be seen, the system consists of two different circuits, contaminant injection system and filter test system. In contaminant injection system, the contaminant is added in the reservoir and there it is mixed and injected to the filter test system. This dirty fluid is pumped through the test filter while two of the filter's properties are measured, the amount of dirt particles and their size before and after the filter and pressure drop over the filter. There are also one cleaning filter for both of the circuits, so that the fluid can be cleaned after and before each measuring event.

Temperature controllers are installed to the circuit to ensure the wanted kinematic viscosity within the fluid. ISO 16889 recommends an installation of optional bypass section, so that the pump can be driven at a higher speed while flow rate is lower. This eliminates overheating of the pump and high-flow ripples.

Multi-pass standard defines flow rates for injection flow and test flow. Therefore, there must be a flowmeter in both circuits. (ISO 16889:2008.)

2.3.2 Preliminary preparations

Before the final test, predicted test time, gravimetric level, quantity of contaminant, minimum injection system volume and flow rate must be calculated. (ISO 16889:2008.) For the control system design, this means that test time and the pump volume flow must be adjustable. Others aforesaid calculations and measurements can be ignored in the design process.

2.3.3 Filter performance test

Test flow rate and test temperature is to be established so that they maintain fluid's kinematic viscosity at 15 $\frac{mm^2}{s}$ ± 1,00 $\frac{mm^2}{s}$ during the test. Clean test assembly differential pressure is to be measured. The test filter element's differential pressure is calculated by subtracting the housing differential pressure from the clean assembly differential pressure.

Initial system contamination level is to be measured and recorded by using online particle counting upstream of the filter element. If the contamination level is higher than allowed, fluid must be circulated through the cleaning filter until it is less than specified in the standard. A sample is to be obtained from the contaminant injection system as an initial injection gravimetric sample. Injection system flowrate is to be measured and verified, and it shall be continuously monitored through the test so that it stays between the specified tolerances.

Test can be initiated by starting the timer and allowing the contaminant injection flow to enter the filter test system reservoir. (ISO 16889:2008.)

2.4 Evaluation of differential pressure versus flow ISO 3968

Fluid flowing through a filter meets resistance because of kinetic and viscous effects. The pressure required to overcome these effects is known as differential pressure. The differential pressure is the total pressure difference between filters inlet and outlets ports. It represents the pressure losses in the housing and in the filter element. ISO 3968 gives standardized tools to measure differential pressure in a hydraulic filter. (ISO 3968:2017.) It is wanted that the water filter test bench will be able to execute this measuring method. This will create requirements for the control system and therefore it must be opened up in this chapter. Though, the standard is introduced only shortly.

The ISO 3968 test is simple: clean fluid is run through a filter while its volume flow is raised step by step and the differential pressure versus flow is measured over the filter. These results are documented and a graph is drawn where the relation between volume flow and differential pressure can be seen. (ISO 3968:2017.)

2.4.1 Differential pressure versus flow example test system

Differential pressure versus flow standard provides guidelines for the required test system. An example of system's hydraulic circuit is shown in the ISO 3968 standard (figure 1).

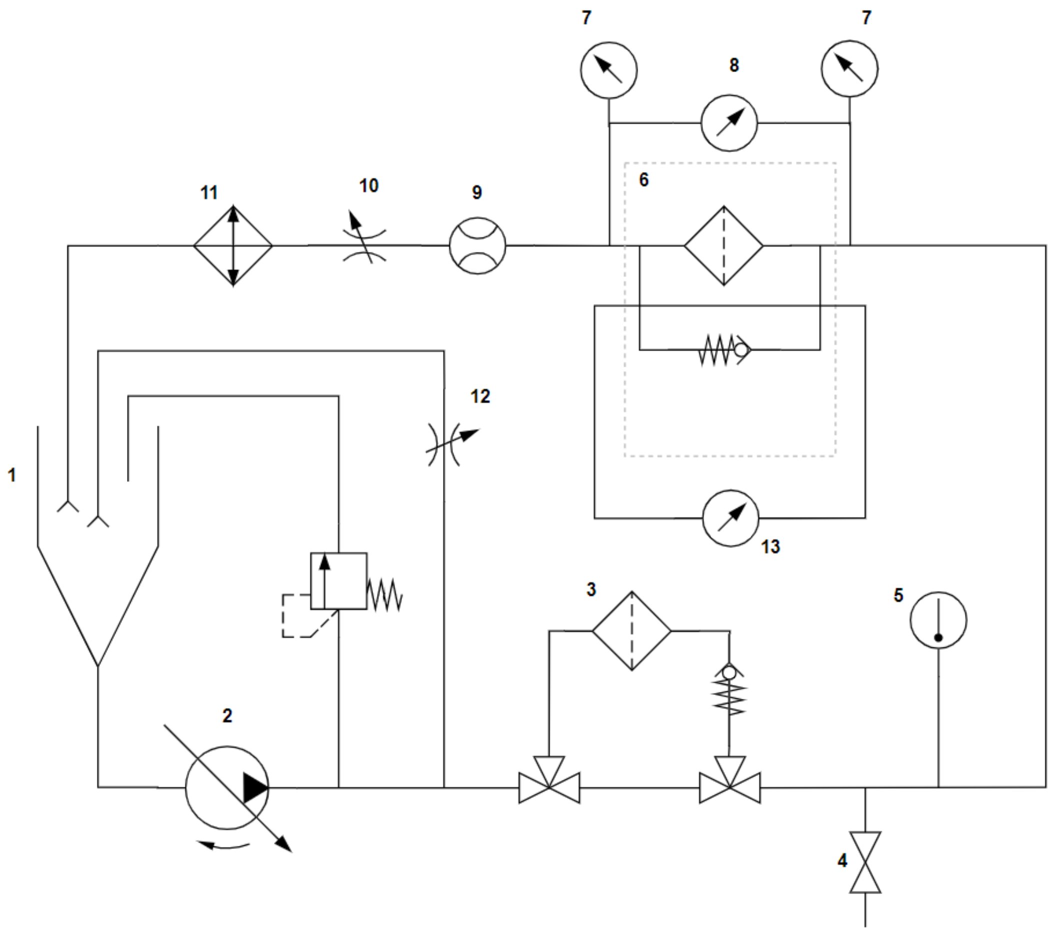

FIGURE 1. Example hydraulic circuit for ISO 3968 measurement (ISO 3968:2017).

All the necessary components for the test are shown in the diagram above and the keys for the hydraulic circuit are following:

1. reservoir
2. variable flow pump
3. clean-up filter

4. sampling valve
5. thermometer
6. filter under test
7. absolute pressure transducer
8. differential pressure transducer or two single pressure transducers to measure the differential pressure
9. flowmeter
10. counter pressure regulating valve
11. heat exchanger
12. bypass flow regulating valve
13. differential pressure transducer or two single pressure transducers to measure the differential pressure across the spin-on filter-element (ISO 3968:2017).

They key elements of this hydraulic circuit must be brought to the water filter test bench. From the control system's point of view, the requirements are simple: volume flow and throttle valves must be adjustable, valves must be controllable and certain sensor data must be shown to the user.

2.5 Unified Modelling Language

When something new is being designed, there is an idea of how the end product should be like. A model of its wanted features, such as productivity, reliability, functionality and look, is being made.

Nowadays there are countless amount of programmable languages and they each have their own features and specialities. (Erikkson & Penker 2002.) This same issue applies in the field of industrial automation, where different manufactures provide their own control systems and software. Many complex systems can be constructed from several different logics and programmable languages.

Many tools for the design process have been made, but most of them are incomplete or hard to understand. The problem is, how to create a uniform model to describe a system that can be understood and used by everyone. Standardized

Unified Modelling Language ISO/IEC 19505-2:2012, also known as UML, was designed to solve this issue. (Erikkson & Penker 2002.) UML offers excellent tools for many modeling purposes. Its diagrams made for dynamic modeling of a system will be used later on for the control system modelling of the water filter test bench.

2.5.1 Object-oriented programming

In a traditional top-down software design, design process is started from the highest level of system. Design is continued into smaller and more detailed parts, and in the end the actual code is created. This hierarchy is presented roughly in figure 2, where circles describe the different depths of the system and the matrix on the right side presents the final code. This type of design has many problems. For example, small changes in higher levels might have large scale effects to the whole system, software is hard to maintain and most of software cannot be reused. Top-down software design is well suited for small systems, but unlike object-oriented software design, it has severe problems with large and complex systems.

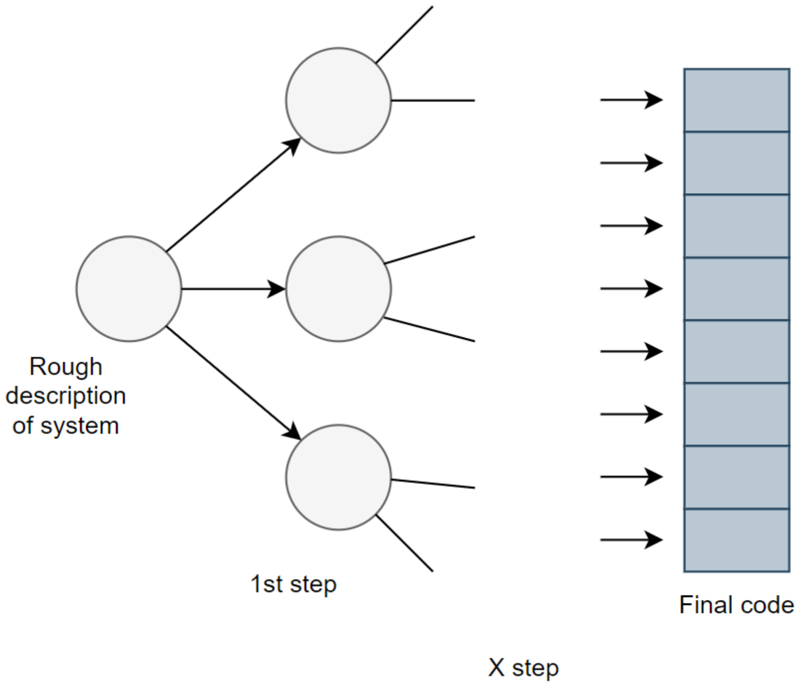

FIGURE 2. Top-down software structure (Koskimies 2000).

Unified Modeling Language is based on object-oriented design. This paradigm has to be understood, if one wants to understand the principles of UML (Erikkson & Penker 2002.) Object-oriented thinking is introduced only briefly in this thesis.

An object in object-oriented programming is the basic unit of structuring and it has the four following attributes:

1. It is able to execute a command that is typical for its characteristics. Each operation has its own name and possible parameters and a structure that defines its actions.
2. Object can record information into its data fields. These data fields are called attributes. Different combinations of attributes are called as objects states.
3. Each object has its own reference that identifies it. Two objects cannot have the same reference, even if they would be copies of each other.
4. Object is protected whole and its usage is limited to certain forms. Normally, only some of its characteristics are accessible from its outside.

Objects features are normally defined in objects class. Objects attributes and operations are told by its class, which is always is unambiguous. Every object that is made from the same class owns the same attributes and operations, though the values of the attributes can change.

Modelling a system based on object-oriented thinking gives many benefits. Changes are easier to be made in object-oriented programs. Changes in objects data are usually local and their effect is relative to the size of change. This is because object-oriented software simulates applications real world or abstract events. Software creation process becomes systematic, controllable process where applications actual code is derived from conceptual analysis. Also, reusable codes are easier to be made because code is divided into separate parts. It can be said that object-oriented planning has the largest common factor among all applications. That is why on a concept level, it is the most optimal method for describing a software.

Figure 3 of an object-oriented structure points out what were said in the paragraph above. In the figure, classes are demonstrated as grey squares. Same classes (same code) can be used by different applications, as can be seen. Proportional relation between parts of applications concept world and classes are presented as arrows. (Koskimies 2000.)

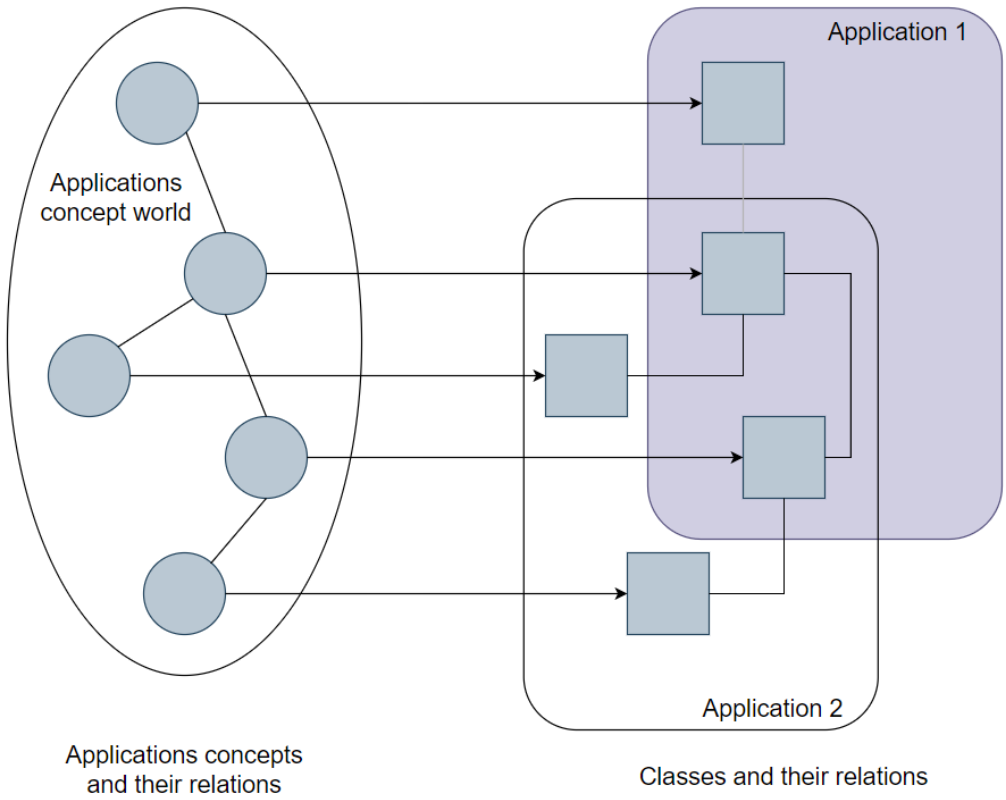

FIGURE 3. Object-oriented structure (Koskimies 2000).

2.5.2 Sequence diagram

Sequence diagram is an UML tool to describe how group of objects cooperates with each other in example cases. Although sequence diagram is not used in this thesis, it is important to understand the relation between it and state machine diagram. Test bench's measuring events can be modeled with sequence diagrams.

A simple example of alarm clocks sequence diagram can be seen in figure 4. Objects of the system are located on the top edge. Time is on the vertical axis and interaction between objects are shown as black arrows. The time an object is affected is shown as an activation bar.

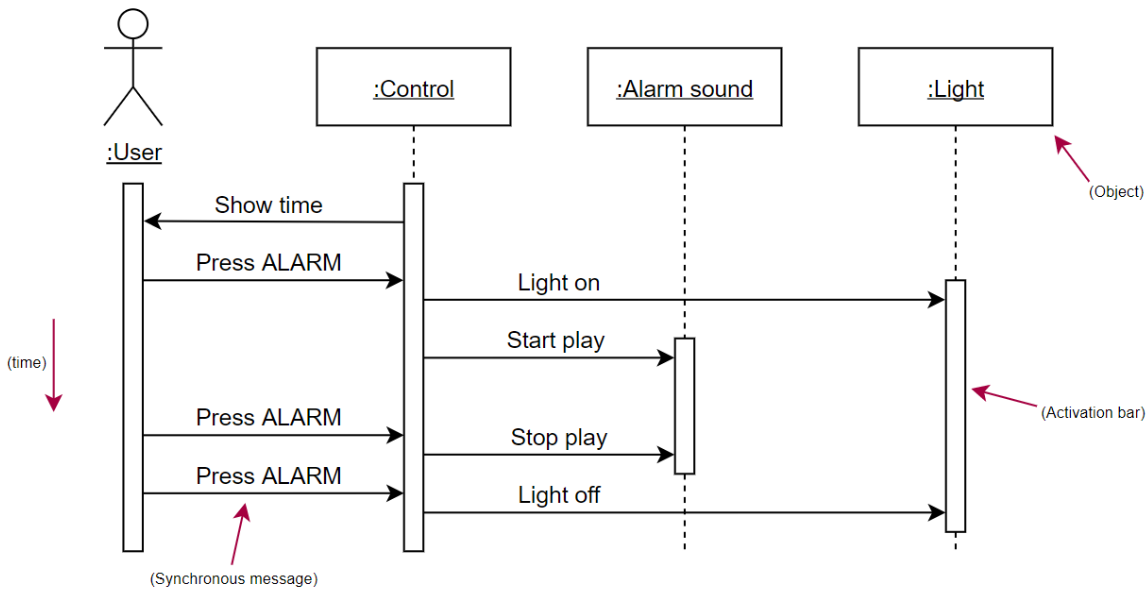

FIGURE 4. Example of an alarm clocks sequence diagram (Koskimies 2000).

The system above has an object for control, alarm sound and light, which also is the wake-up mode. Control object is being affected from its HMI by a user (figure 5). Time is always shown to a user by the control object, as can be seen from the figure 4. When the alarm button is pressed, a light is appeared to the HMI and the wake-up mode is activated. Alarm sound turns on when the set ring time is reached and it stays activated until the alarm button is being pressed again. One more press to the alarm button will turn off the light and the wake-up mode.

FIGURE 5. Alarm clocks HMI (Koskimies 2000).

2.5.3 State machine diagram

Objects change of behavior, when it's affected by its environment, is described by state machine diagram. State machine diagram can be used for classes of which objects are on clearly identified states during their lifetime. Such classes are called state-oriented.

State machine diagram can have an end or a start point. An object is created from a start point and it dies at the end point. There are no inputs to a start point and no outputs from the end point.

Each state can, but not must have a name, actions, activities, internal transitions, deferred events and sub-modes.

Actions occur either when state is entered (entry action) or left (exit action). Time is not spent during actions, because they are thought as instants.

Unlike actions, activities (do/ command) spend time during state. An activity is ended when its task is executed or when it is interrupted by a state transition. Entry and exit actions will be executed by activities.

Objects reaction to a certain event without leaving its state is possible with time dependent internal transition (event). Entry or exit actions will not be executed by it. An action can be added to an internal transition and it occurs during its transition. Events can have conditions that must be true, if the internal transaction is to be executed.

Events that are not executed during their current state, but are saved for later on event buffer, are called as deferred events. Such events are being handled in the first state that does not include this saved event in it.

Transition between different states is occurred when the current state is on its end state and conditions set by the trigger are true or there is none. Timers can be set as triggers conditions and triggers can be branched.

States are able to have consecutive and parallel sub states. In consecutive sub state, an object is in one sub state at a time, while in parallel sub state, an object is on each of its sub states at the same time. Consecutive sub states are particularly good, when system has states with the same trigger and target state.

State machine diagram and sequence diagram are strongly dependent on each other. For that reason, they must always be equivalent. This means the following: if a class X object is appeared in a sequence diagram, and a state machine diagram has been given to class X, horizontal line of an object X in sequence diagram must equate one path in state machine diagram. If object X's horizontal line is followed from top to bottom in sequence diagram, each incoming message must correspond an outgoing message in state machine diagram and each outgoing message from objects horizontal line must correspond either entry, exit or transfer action, start or end of an activity in state machine diagram.

This similarity between the two diagrams that was stated in the paragraph above is demonstrated by alarm clocks control objects state machine diagram (appendix 2). If it is compared to the sequence diagram (figure 4) given in chapter 2.5.2, it can be seen that they are equal. By using sequence and state machine diagrams, systems dynamic behavior can be modeled in illustrative and logical way.

The state machine diagrams are used in this thesis due their modular and universal nature. They can easily be modified and they can be utilized in almost every software's design. (Koskimies 2000).

3 TEST BENCH CASE

3.1 Introduction

A new water filter test bench is to be designed. A preliminary sketch of its 3D layout can be seen in the figure 6 below. The figure gives a slight idea of the system's look and size. It is important to notice, that the figure is based on the first sketch of the system, and it is not up to date.

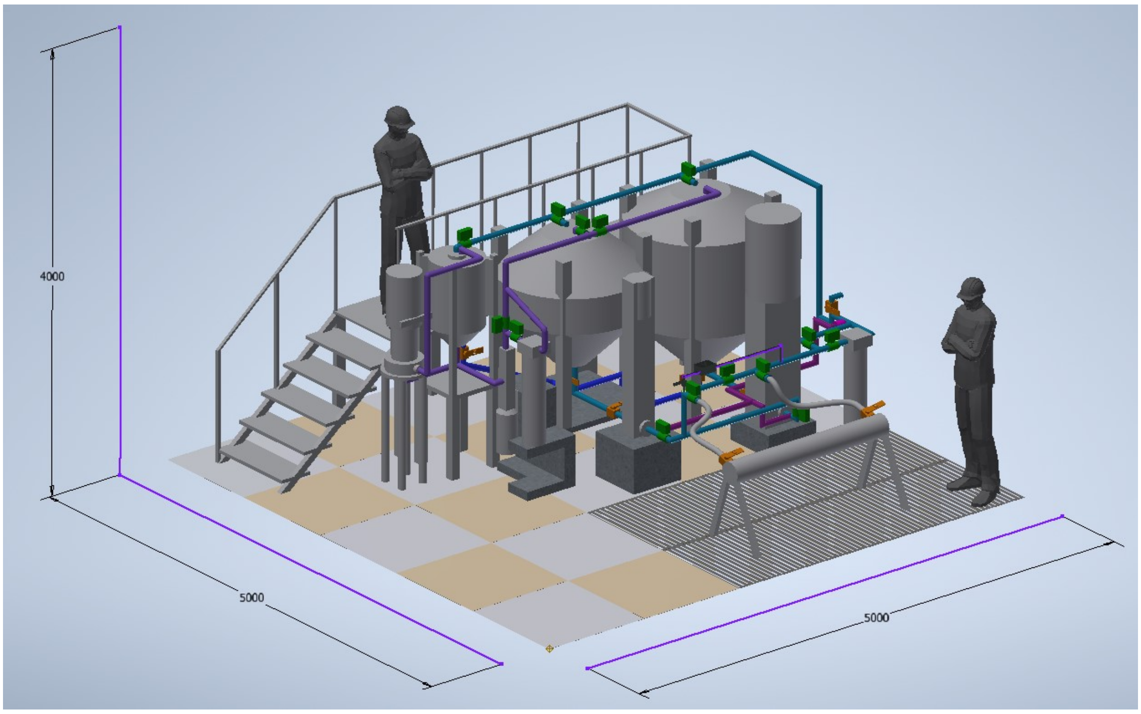

FIGURE 6. Test bench's 3D layout sketch.

In this chapter, system's specification of requirements is done and its main components are defined. Note that some parts of this chapter are hidden due the secrecy reasons.

3.2 Specification of requirements

It is a must to define and understand the process before the control system design can be started, therefore the first thing to do is to specify the requirements for the system.

For a copyright reasons, only the most important parts of the standards are introduced in this thesis theory section. It is important to note that the requirements for the system are set by the complete standards.

The system needs to have a user-friendly human-machine interface with clear controls, so that working with the test bench will be safe and easy. A user must be able to control all of the components from the HMI, expect city water inlet valve, city water outlet valve and the two sampling valves shown in appendix 3.

System must be safe. The safeness of the control system is to be ensured with precise risk evaluation, safe design and by following the Government Decree on the Safe Use and Inspection of Work Equipment and Government Decree on the Safety of Machinery in the control system design process.

3.3 Hydraulic diagram design and system's components

This chapter is hidden due the secrecy reasons.

4 TEST BENCH CONTROL SYSTEMS DESIGN

4.1 Introduction

In this chapter, the preliminary control system model of the water filter test bench is being designed. Some of the functions are designed together with Parker's R&D laboratory team.

Control system's hardware or test bench's components are not yet chosen and therefore it is not possible to design a finished control system. For example, the safeness of the system is a combination of built hardware and programmed control system. It is also impossible to secure that the control system will work as wanted, without testing it in the physical world. Therefore, the system model designed in this thesis will be a prototype and it will most likely need a lot of adjustments and changes before it is ready to be used in the final system. It is important to understand that the ongoing project and its demands might change after this control system design process, which might also affect on its relevance.

4.2 Risk spotting

Before the design of the control system can be started, a risk spotting must be made. This is to recognise the possible dangers in the upcoming system. It is critically important to spot the possible dangers, so they can be considered during the control system design process. Note that this chapter is not a proper risk assessment and one must be made for the test bench as soon as the system is known in more detail.

The system includes several pumps that generates volume flow and pressure to the system. Volume flow and pressure can cause several hazards. If a hydraulic circuit of an operating pump is blocked, a pressure in the system can rise dangerously fast and system's components might fail. In the worst case, this can cause spraying of high pressurised water, an explosion of a component or a whip alike effect of a broken piping. Therefore, pressure is the number one hazard in the system.

Faulty hardware and buggy software can cause major dangers and their effects are unpredictable. Broken valves and control valves can create blocks in the hydraulic circuit. Faulty sensors can cause severe problems for the control system's safety functionalities and therefor for the whole system itself. For example, if a pressure gauge is broken, the pressure might be able to rise over the allowed limits.

If a possibility of human-error is left to the control system, it is likely that at one point it will event. Therefore, the control system must be designed so that it's safe to use in every scenario.

Bad or sloppy design or program in the control system or wrong connections in the hardware are also likely reasons for danger. If the system is not tested thoroughly accidents may occur.

4.3 Control system's safety

Control systems safety is a complex whole, and it is only viewed superficially in this thesis. This chapter is a practical approach to the safeness of control functionalities in the test bench system.

After spotting the possible risks that can be affected by the control system, general rules must be made to ensure that such risks are minimized by a safe control system design.

Pumps must be stopped by the control system when emergency stop is pressed, the pressure in the system rises too high, a valve is closed and it blocks the streaming of water in a circuit where a pump is turned on or when a reservoir before the active pump runs out of water. Pumps cannot be turned on if the emergency stop is not reset, their hydraulic circuit is blocked by a closed valve, the pressure in the system is over the allowed limit or if the water in the reservoir is below the allowed limit. Pumps cannot be turned on and they must shut off if the water temperature in its reservoir rises too high.

Valves cannot be closed in a circuit where a pump is on if this would block the flow of water, or if the closing is allowed, doing so must first shut off the pump. The control system must ensure that the reservoirs cannot drain over or run out of water.

Only one of the systems four main states can be active at a time. Only those controls can be visible and can be actuated from the HMI that are meant to be used in the current state. Going to a normal state from another main state can only be possible if no pumps and no measuring events are on.

Control system state change triggered by a safety state activation must always be prior and possible. Pumps cannot be turned on if the system is not in a safe state.

Government Decree on the Safe Use and Inspection of Work Equipment and Government Decree on the Safety of Machinery must be followed in the control system design process.

4.3.1 Required performance level

For each component of the control system that is responsible for safety, must be defined their required performance level, also known as PLr. Performance level indicates of how common and how critical is the risk of danger that safety component must prevent. Defined PLr value sets certain requirements for the safety feature and its execution. Before performance level evaluation can be done, a proper risk assessment must be made. (ISO 13849-1:2015.) Note that PLr values are not defined in this thesis.

In water filter test bench, PLr evaluation must be made for emergency stop. Then if needed for each pressure sensor that is responsible for shutting down the pumps if the pressure is risen too high, if this is described as safety function. In the current system this would mean defining PLr value for pressure sensors B.P.1 and B.P.2.

ISO 13850:2015 is a standard for emergency stop functions. It is an addition for the ISO 13849-1, and must be noted that it states that minimum required performance level for emergency stop is PLr c. (ISO 13850:2015.)

4.3.2 Safety integrity level

Safety integrity level, also known as SIL, is for defining the safety integrity requirements of the safety functions allocated to the E/E/PE systems. SIL and PLr values are related to each other.

If a safety related control function is to be designed by using one or more safety related parts of the control system, each of them must be designed according to standard 13849 (PLr) or according to IEC 62061/IEC 61508 (SIL). (ISO 13849-1:2015.)

4.4 Test bench's sensors and control devices

The components that can be controlled or read by the control system are named in appendix 4. As can be seen, each component is given a unique symbol to separate it from the others. These components create two tables, one for the sensors (table 1) and one for the control devices (table 2).

The first letter of the symbol refers to which part of the system the component belongs to. Letter A refers to contaminant injection system and letter B refers to filter test system. The second letter or letters refers to the type of component and the last number specifies the component of a certain type.

TABLE 1. Hardware's sensors.

Sensors	
Symbol	**Specification**
A.W.1	Water level sensor
A.T.1	Temperature sensor
A.DP.1	Differential pressure sensor
A.F.1	Flow meter
B.W.1	Water level sensor (small tank)
B.W.2	Water level sensor (large tank)
B.W.3	Water level sensor (reservoir system)
B.T.1	Temperature sensor (small tank)
B.T.2	Temperature sensor (large tank)
B.P.1	Pressure indicator
B.P.2	Pressure indicator
B.P.2	Pressure indicator (upstream)
B.P.3	Pressure indicator (downstream)
B.DP.1	Differential pressure indicator (test filter)
B.DP.2	Differential pressure indicator (clean-up filter)
B.PCS.1	Particle counter
B.F.1	Flowmeter
B.F.2	Flowmeter

TABLE 2. Hardware's control devices.

Control devices	
Symbol	**Specification**
A.V.1	Valve (3-way)
A.V.2	Valve (3-way)
A.V.3	Valve
A.PM.1	Variable pump
A.PM.2	Mixing pump
B.V.1	Valve
B.V.2	Valve
B.V.3	Valve
B.V.4	Valve
B.V.5	Valve
B.V.6	Valve
B.V.7	Valve
B.V.8	Valve
B.V.9	Valve
B.V.10	Valve (3-way)
B.V.11	Valve
B.V.12	Valve (3-way)
B.V.13	Valve
B.V.14	Valve
B.TV.1	Throttle Valve (electrical)
B.TV.2	Throttle Valve (electrical)
B.PM.1	Variable pump (small)
B.PM.2	Variable pump (large)
B.PM.3	Variable pump (reservoir system)
B.PM.4	Pump (reservoir system emptying)
B.SP.1	Upstream sensor pump
B.SP.2	Downstream sensor pump
Emergency stop	(1 or more, not visible in annex 4)

4.5 State machine diagrams

4.5.1 General notes

Transitions between states are indicated with arrows (figure 7). Transitions may have conditions that needs to be fulfilled if the transition is to be triggered. These conditions are called as guards. If there are several guards, they might be numbered for clearance. If the conditions are fulfilled, transitions may trigger by themselves, or they need an event to occur. If a transition is successfully triggered it may have some actions to be executed. An example of a transition can be seen below. Note that the movement from a state to another is always one act and it is not always mentioned if its destination can be seen from the state machine diagram. Also note that the current state from which the arrow is leaving, must also always be true in order to execute the transition, even though it is not shown in guards.

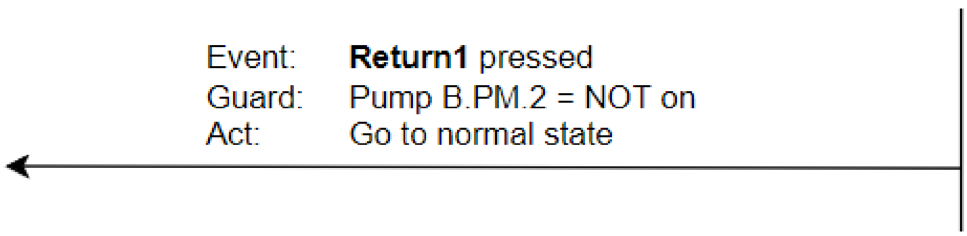

FIGURE 7. An example of transition.

Push buttons are shown as a bolded text in the state machine diagrams to come. Most of the internal transitions push buttons don't have any conditions shown in the main states. The conditions are mainly defined in components state machine diagrams to make the main states less complex. In figure 8, the red rectangle borders the push button. The blue rectangle borders the action to come if all the conditions set for the action are fulfilled, when the push button is being pressed. In other words, red rectangle equals event and blue rectangle equals act. Guards are defined in components state machine diagram.

FIGURE 8. Example of pushbutton and its action.

The state machine diagrams used in this thesis are simplified due states for movement are missing. Therefore, one might not be able to copy them straight to the actual PLC program. For example, 3-way and 2-way valve's state machine diagrams have two states open and closed or right and left. In reality these valves don't turn instantly open or closed between the two states, there is always a delay. An example of a complete state machine diagram of a 2-way valve can be seen below (figure 9). The blue rectangles represent the parts that are currently missing: a guard that ensures that the valve is open or closed before the 1 or 0 state can become true. If the valves don't have positions sensors, which they most likely don't, this could be made with a delay. If the actuation time of the component is short enough or it doesn't affect to the operation of the system negatively, these states for movement are unnecessary.

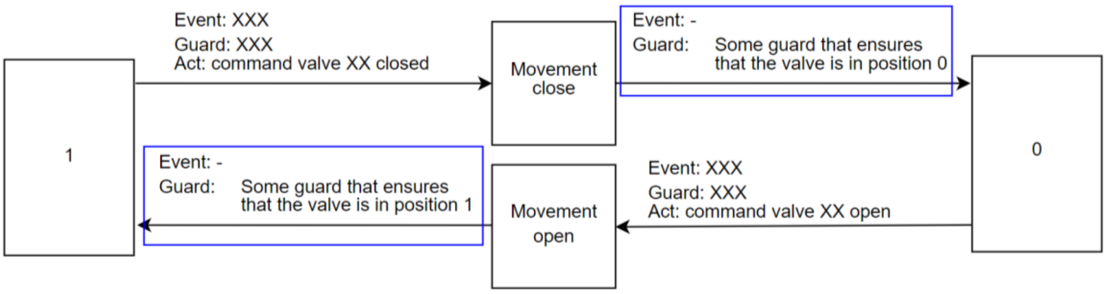

FIGURE 9. Movement states example.

The word command in act's describes the action to be executed, but it doesn't define how the action is to be executed. This is something that has to be decided later when the system is better known.

None of the limit values set as guards, acts and events in the state machine diagrams to come are defined due the system's details are unknown, therefore they're presented as X. These values has to be set later.

4.5.2 Main states

The system is divided into 4 main states (figure 10). Normal state is the basic state of the system. From the normal state, a user can choose which other main state to enter. Options are two different measuring states ISO 16689 and ISO 3968 and a manual control state. A user can return to the normal state from the other main states when certain conditions are fulfilled and a return button is pressed. Purpose of main states are to define when and which components can be actuated from the HMI and what information is shown to the user.

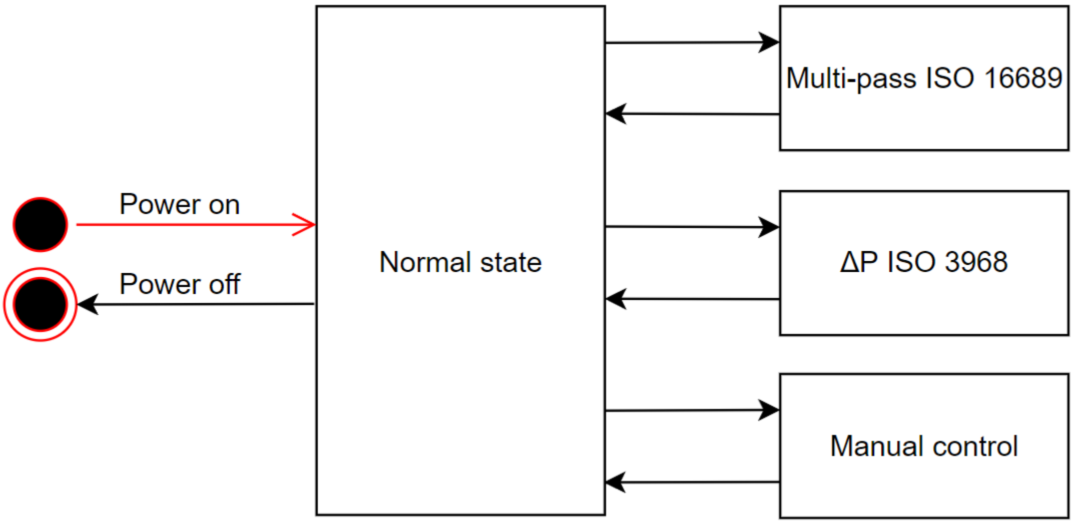

FIGURE 10. Systems main states.

When the power is turned on to the system the components are set into their initial states (figure 11). Inputs to and outputs from the normal state are numbered so that they can be linked to the other main states. Route E.1 is a stop feature, that triggers when system parameters are over or under their allowed limits or when the emergency stop is pressed. E.1 can be entered from every state of the system.

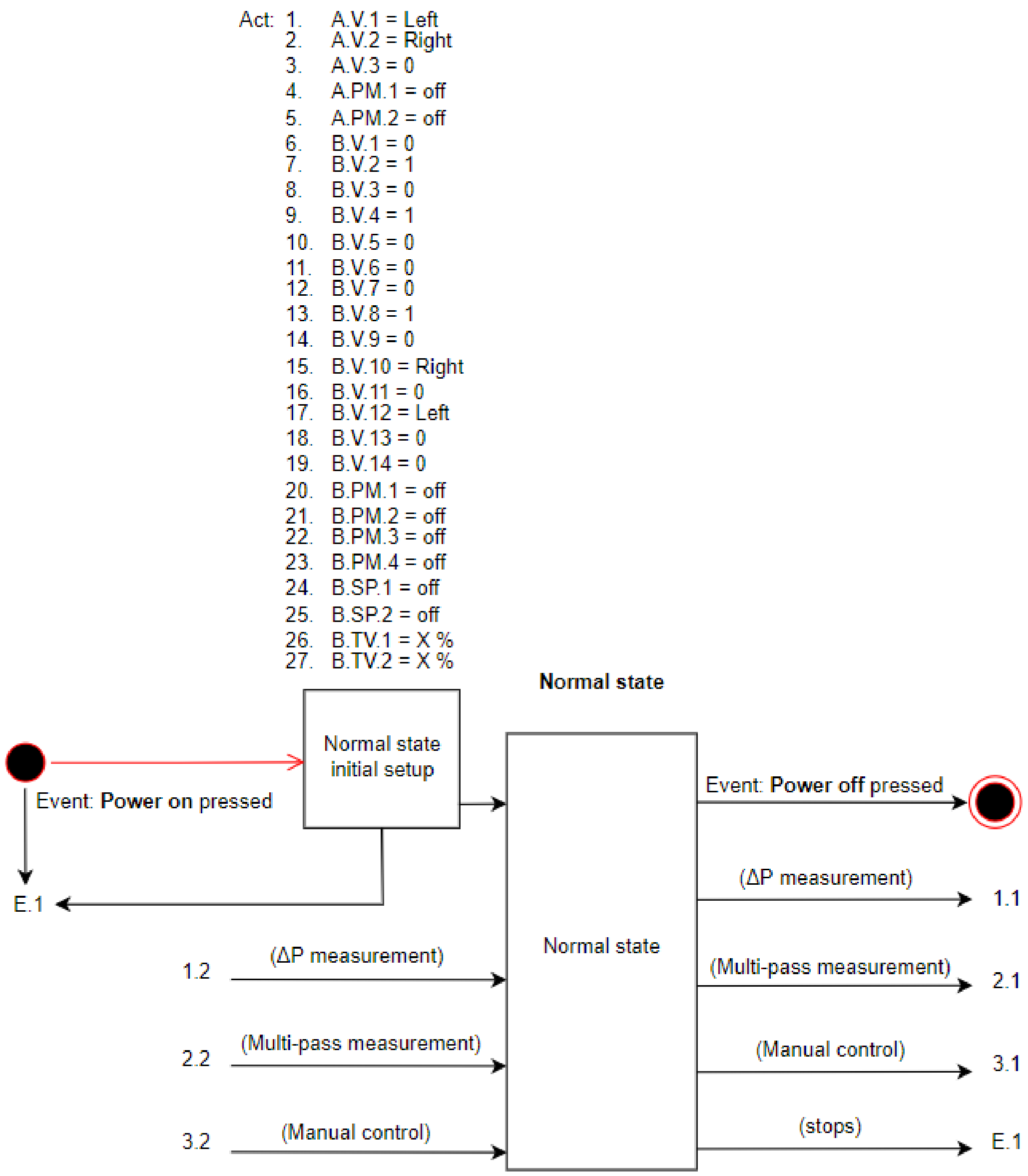

FIGURE 11. Normal states State Machine Diagram.

ΔP Measurement has only one state and it is called Lobby1 (appendix 5). When the state is entered, valves are set into initial states suited for the ΔP measurement. In lobby1 a user can control pump B.PM.2, Throttle valves B.TV.1 and B.TV2, valve B.V.12 for cleaning the system and test filter bypass. All the necessary component states and sensor data for ΔP measurement are shown in HMI when lobby1 is active. There is no automatic testing state because it is wanted that the measuring and documenting is done manually. When the pump B.PM.2 is not on, a user can return to the normal state by pressing the Return1 button in Lobby1. The bypass button has to be so, that when it’s pressed, the valves have enough time to turn to their new positions before the bypass button can be pressed again.

Multi-pass measurement's state machine diagram can be seen in appendix 6. It is divided into three parts due its size. When the state is entered, a lobby2 state becomes active and systems valves are set into their initial multi-pass states. There the user can control all the necessary components of the multi-pass test. Test and sample values, particle sizes, counter and report and TEST2 states are not determined in this thesis.

When one wants to start the multi-pass test, pumps A.PM.1, B.PM.1, B.PM.3 and A.PM.2 has to be on, sensor pumps must be off, valve A.V.2 must be right, valve B.V.12 must be left and bypass must be active. Starting the test will trigger the following events: dirt feed is turned into the filter test system, extra water is being collected by the reservoir system so that the volume in the filter test system stays the same (a user is responsible that the volume of injected dirt water is the same as the volume of water collected to the reservoir system), sensor pumps are turned on and all the needed counters for the multi-pass test are turned on and their data are being gathered. The user is able to control frequencies of the active pumps during the test.

The test ends when the test is finished, when stop2 is pressed or when automatic stop1 state or safety stop2 becomes active. Last three of the four options mentioned will stop every pump of the system and also ends the measuring event. When the test is finished, the system turns on the bypass, turns the valve A.V.1 back to the contaminant injection system, activates the contaminant injection system's and filter test system's cleaning by turning the valves A.V.2 to left and B.V.12 to right and also shuts off the pump B.PM.3. A user can move back to the normal state from the lobby2 when Return2 is pressed while every pump is in off state.

Working principle of the manual control system is simple. There, a user can control every control device of the system and see all the available sensor and state data (appendix 7). Like the measuring states, it can be entered from the normal state. However, lobby3 is also entered when automatic stop1 or safety stop2 state becomes active. When one of the aforesaid stop states becomes active, one or several parameters of the system are out their allowed limits or emergency stop is pressed. The idea is that by entering the manual control state, the user can identify the problem because all the possible information of the systems current status is available. Also, the user can affect to the system's state by controlling the valves or pumps even when automatic stop1 is active. For example, if the automatic stop1 would trigger a stop event because system's cleaning filter's differential pressure sensor reading would be too high due a plugged filter, a user could change the 3-way valves state in the manual control state and change the filter to a new one. Note that when safety stop2 is active, pumps cannot be used because system's pressure is dangerously high or emergency stop is pressed.

4.5.3 Valves

There are three types of valves to be controlled with the control system, 3-way, 2-way, and throttle valves. 3-Way valves state machine diagrams have two states right and left. State right means that control valve is in a state where the flow of water is guided right and state left means that the control valve is in a state where the water is guided left, seen from the direction of flow (figure 12).

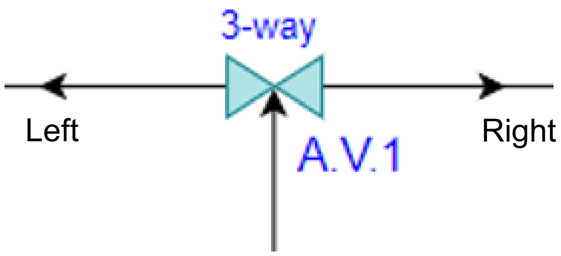

FIGURE 12. Example of a 3-way valve.

On 2-way valves the logic is similar, state 1 means that the control valve is in a state where the hydraulic valve is open and state 0 means that the control valve is in a state where the hydraulic valve is closed. Both 3-way and 2-way valves control valves could be type 4/2. It is recommended that the control valves are actuated by solenoid coils. The reason for this is that the valves stay in the same positions for longer periods. This way, the control valve needs to be actuated only for a short time and relatively rarely. Also, if the system would become powerless, the valves would stay in their current positions. This would increase safety because the system's state would be known. Example of a possible control valve can be seen below (figure 13). The commands in 3-way and 2-way valves state machine diagrams represents an activation of solenoid Y1 or Y2.

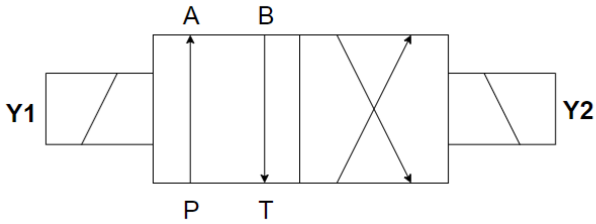

FIGURE 13. Example of a 4/2 control valve.

3-way and 2-way valve's control valves solenoids are actuated only for a short period. During this period, control valve will change its position to its other end and after the actuation is ended, the control valve will stay in that position.

A.V.1 valve is a 3-way valve (figure 14). Its initial state is left. It can be turned to right in manual control lobby3 if reservoir B.W.1 is not full and a button A.V.1 is pressed. It will be turned right when the multi-pass test is started, note that the guards here must be the same as to start the multi-pass test.

Valve A.V.1 can be turned to left in manual control lobby3 by pressing the A.V.1 button. Control valve is turned back to left when multi-pass measurement or ΔP measurement is pressed in the normal state, multi-pass test (TEST2) is finished or if reservoir of B.W.1 sensor is full.

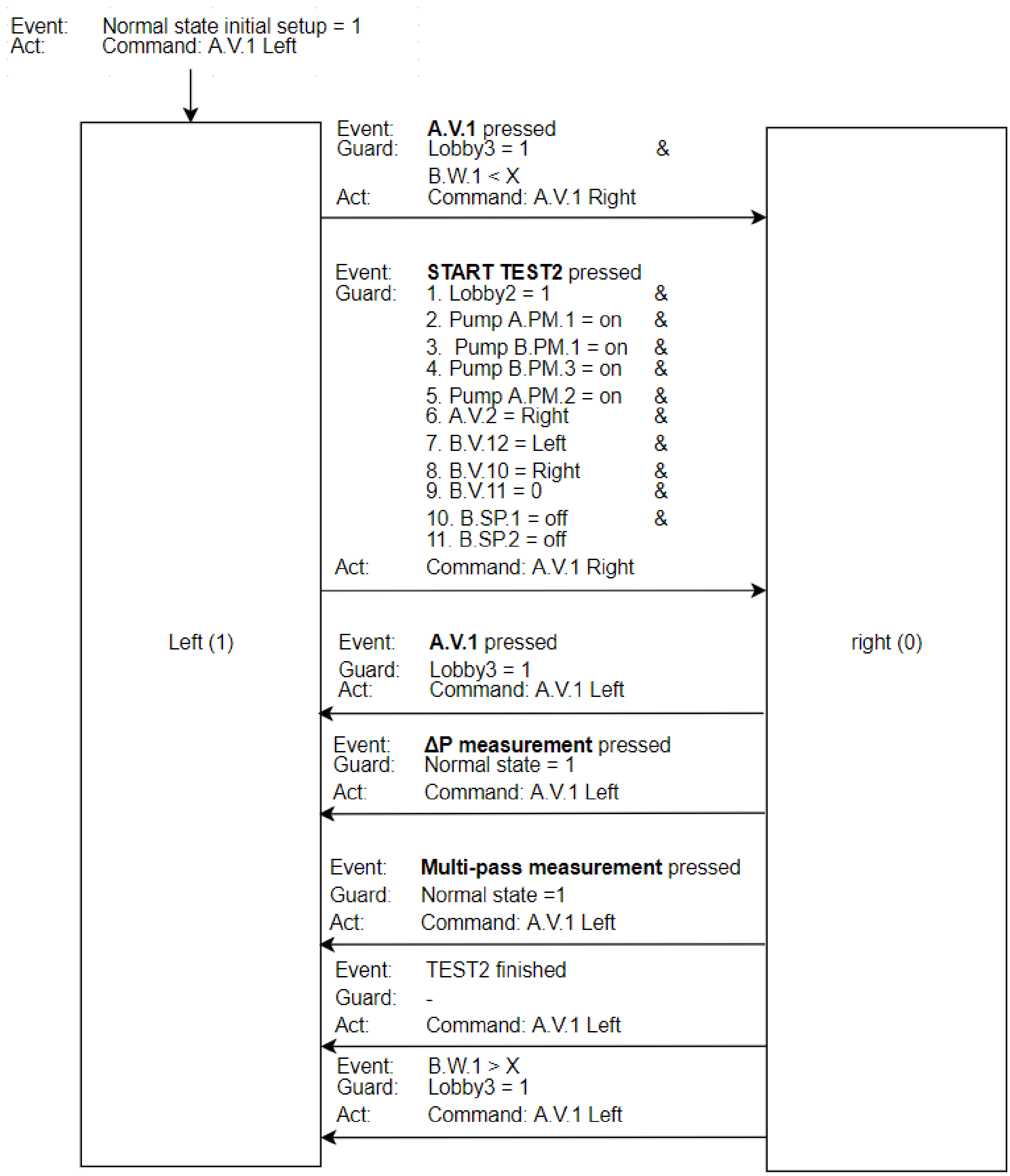

FIGURE 14. Valve A.V.1 state machine diagram.

A.V.2 valve is also a 3-way valve (figure 15). Its initial state is right. It can be turned to left when A.V.2 button is pressed in multi-pass measurement lobby2 or in manual control lobby3. When multi-pass test is finished (TEST2), it will automatically turn to left to start the cleaning of the contaminant injection system.

It can be turned back to right by pressing A.V.2 button in multi-pass measurement lobby2 or in manual control lobby3 or when multi-pass measurement or ΔP measurement button is pressed in the normal state.

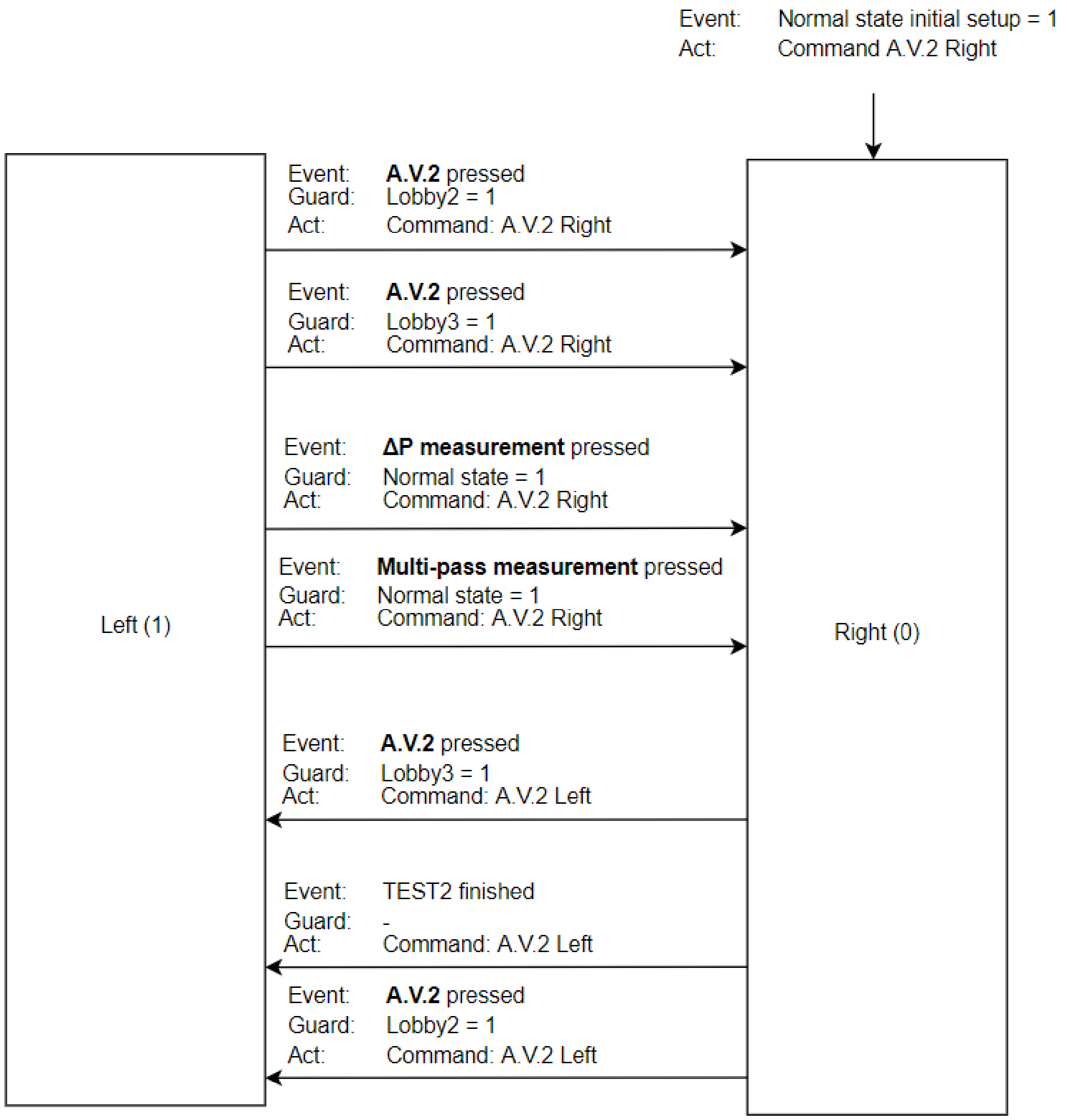

FIGURE 15. Valve A.V.2 state machine diagram.

A.V.3 valve is a 2-way valve (figure 16). Its initial state is 0. Its state can be changed between 0 and 1 in manual control lobby3 by pressing A.V.3 button. The valve cannot be opened if either of the pumps A.PM.1 or A.PM.2 is on. When multi-pass measurement or ΔP measurement button is pressed in a normal state the valve will go to the state 0.

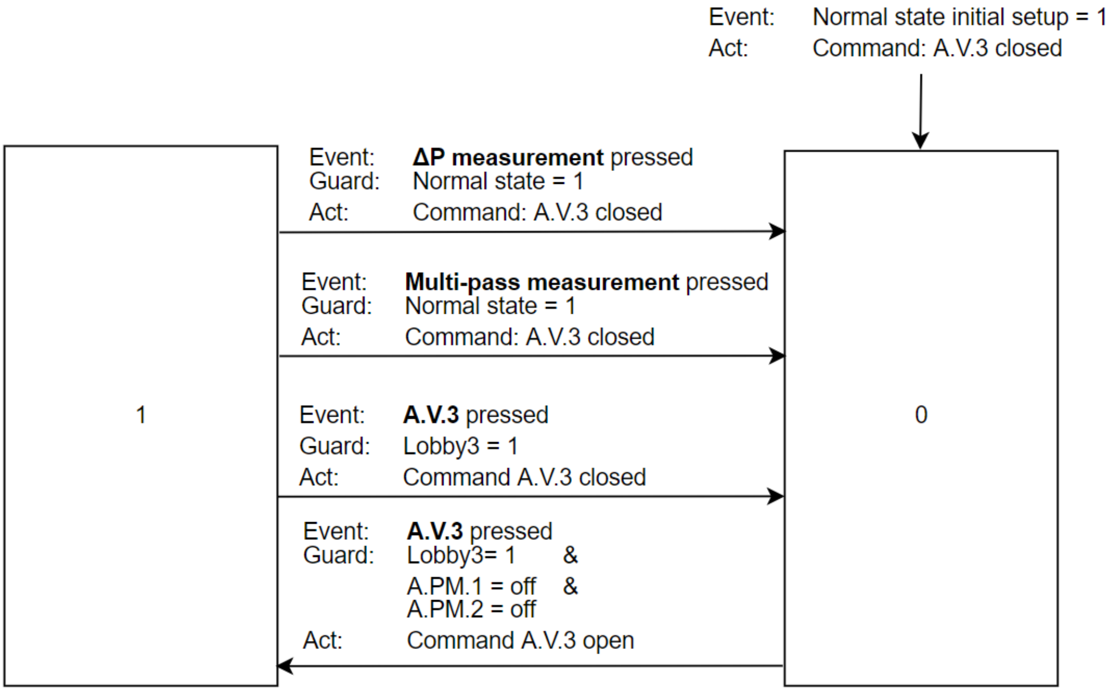

FIGURE 16. Valve A.V.3 state machine diagram.

B.V.1 valve is a 2-way valve (figure 17). Its initial state is 0. Its state can be changed between 0 and 1 in manual control lobby3 by pressing B.V.1 button. When multi-pass measurement or ΔP measurement button is pressed in a normal state the valve will go to the state 0.

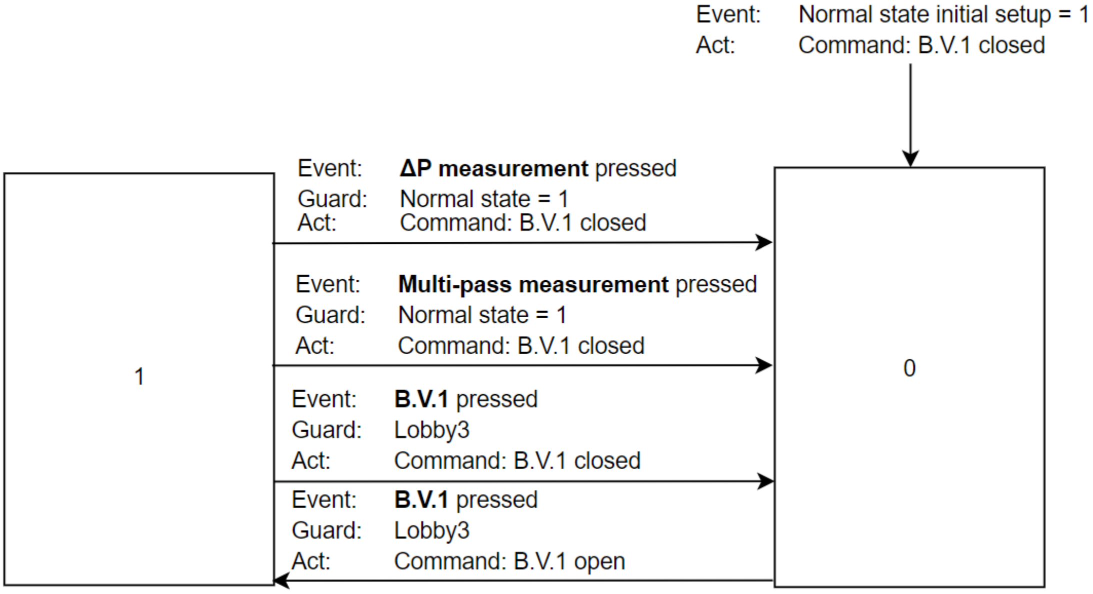

FIGURE 17. Valve B.V.1 state machine diagram.

B.V.2 valve is a 2-way valve (figure 18). Its initial state is 1. The valve is closed when ΔP measurement is being entered or when B.V.2 button is pressed in manual control lobby3, note that the pump B.PM.1 cannot be on in order to do so.

The valve is opened when multi-pass measurement is being entered from the normal state or when B.V.2 is pressed in manual control lobby3.

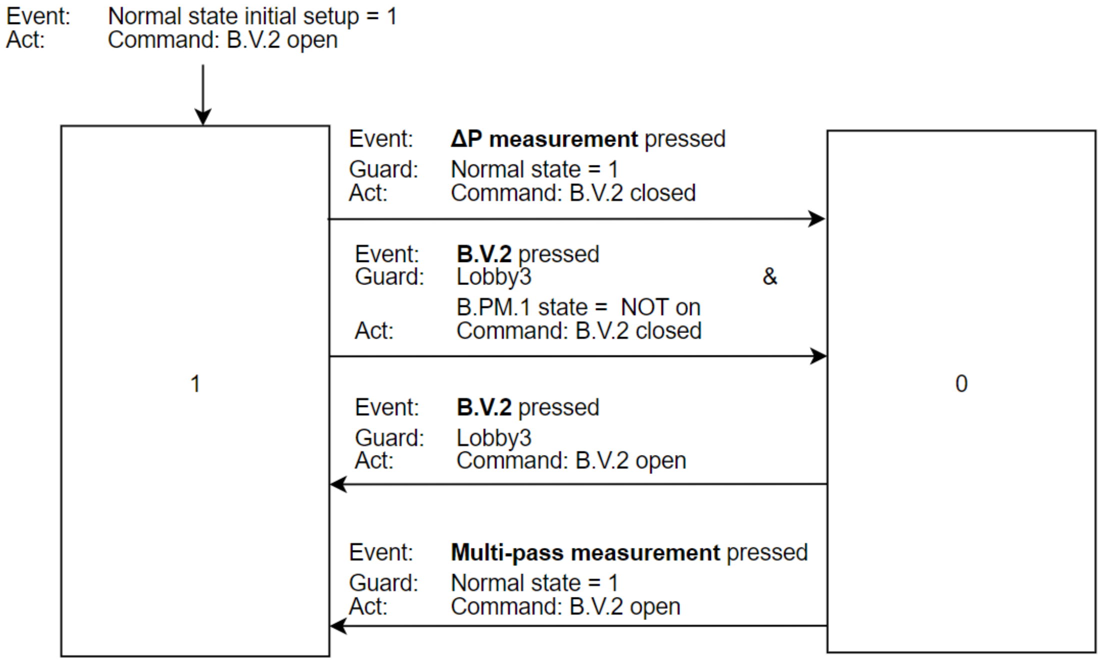

FIGURE 18. Valve B.V.2 state machine diagram.

B.V.3 valve is a 2-way valve (figure 19). Its initial state is 0. The valve is opened when ΔP measurement is being entered from the normal state or when B.V.3 is pressed in manual control lobby3.

The valve is closed when multi-pass measurement is being entered or when B.V.2 button is pressed in manual control lobby3, note that the pump B.PM.2 cannot be on in order to do so.

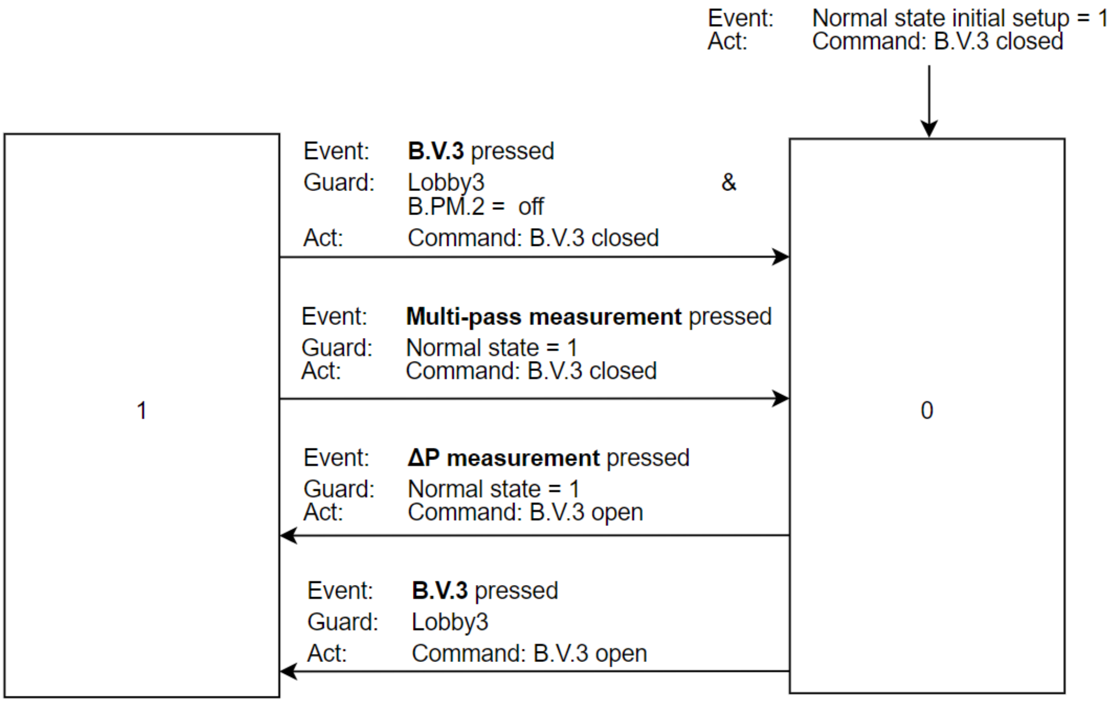

FIGURE 19. Valve B.V.3 state machine diagram.

B.V.4 valve is a 2-way valve (figure 20). Its initial state is 1. It works with the same logic as valve B.V.2.

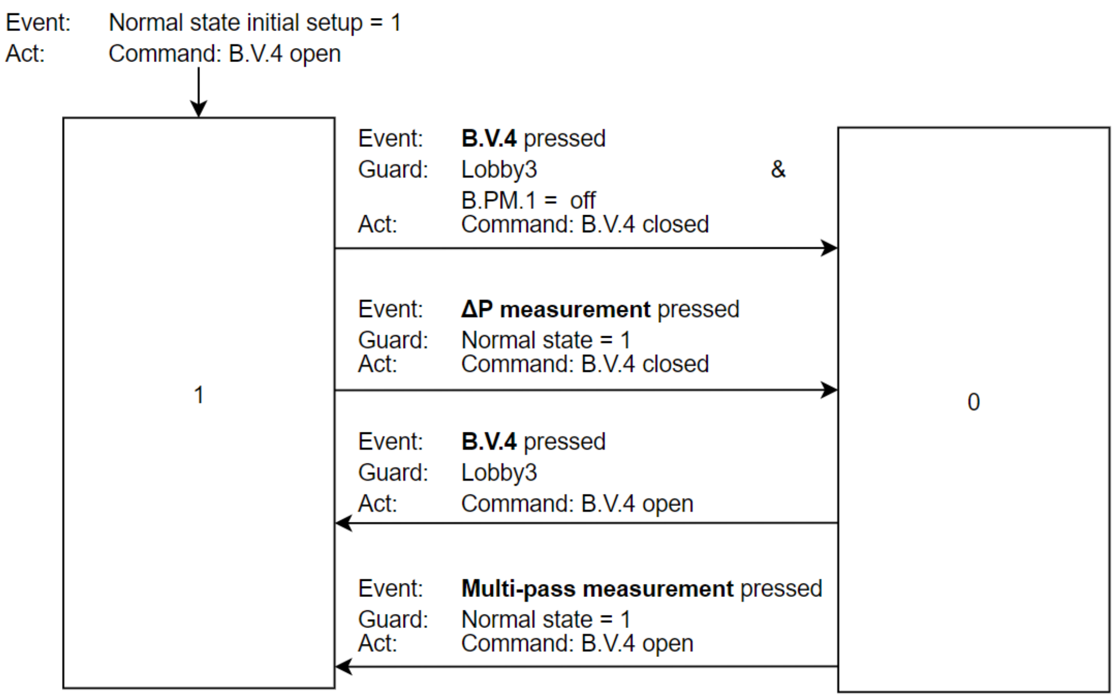

FIGURE 20. Valve B.V.4 state machine diagram.

B.V.5 valve is a 2-way valve (figure 21). Its initial state is 0. It works with the same logic as valve B.V.3.

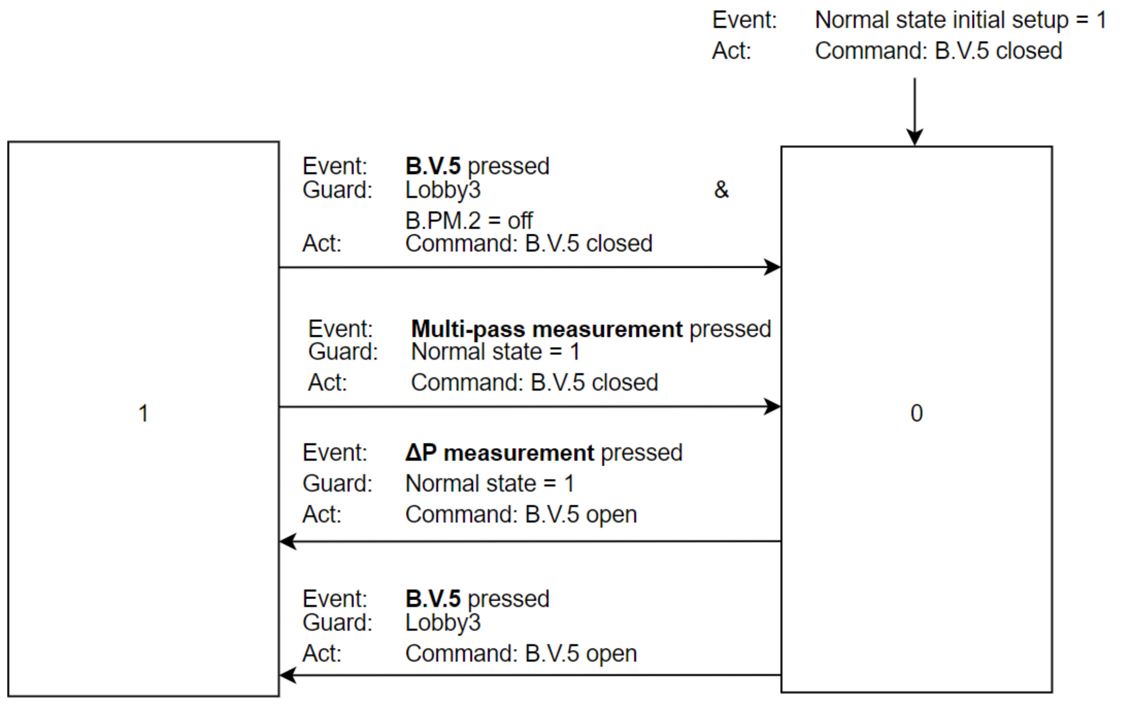

FIGURE 21. Valve B.V.5 state machine diagram.

B.V.6 valve is a 2-way valve (figure 22). Its initial state is 0. The valve can only be opened in manual control lobby3 when pump B.PM.1 is not on. It is closed during other main states.

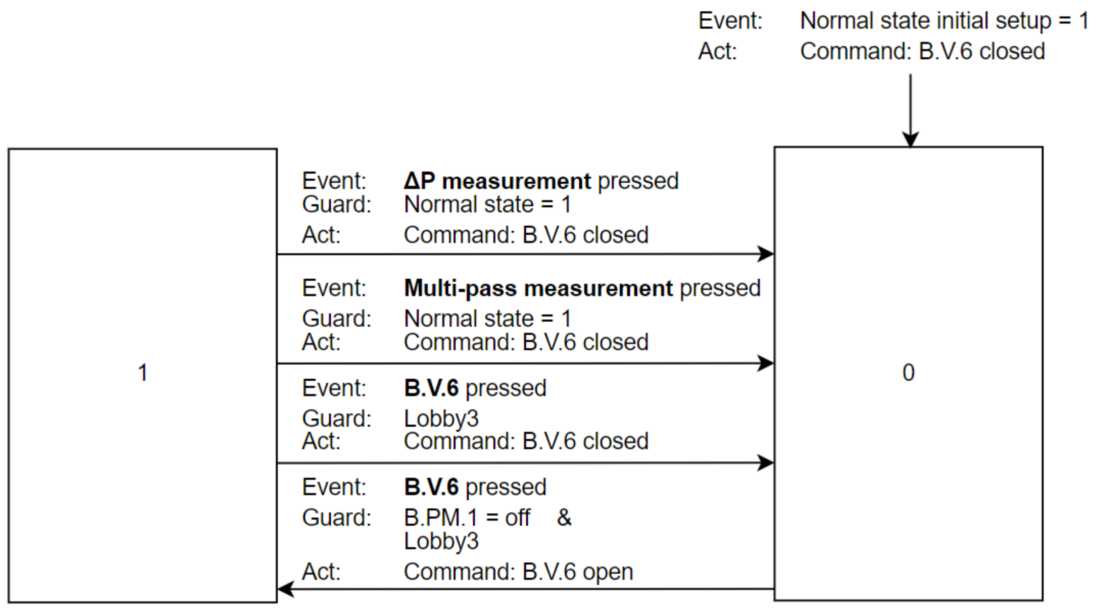

FIGURE 22. Valve B.V.6 state machine diagram.

B.V.7 valve is a 2-way valve (figure 23). Its initial state is 0. It works with the same logic as valve B.V.6, except the guard pump is different for opening the valve.

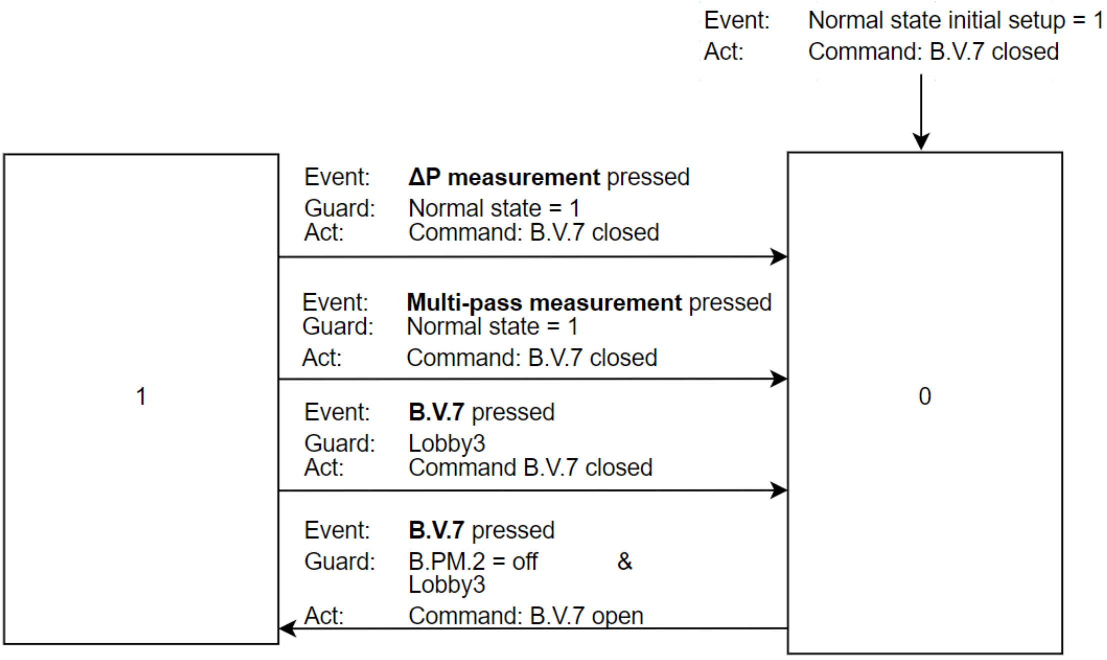

FIGURE 23. Valve B.V.7 state machine diagram.

B.V.8 valve is a 2-way valve (figure 24). Its initial state is 1. It works with the same logic as valve B.V.2.

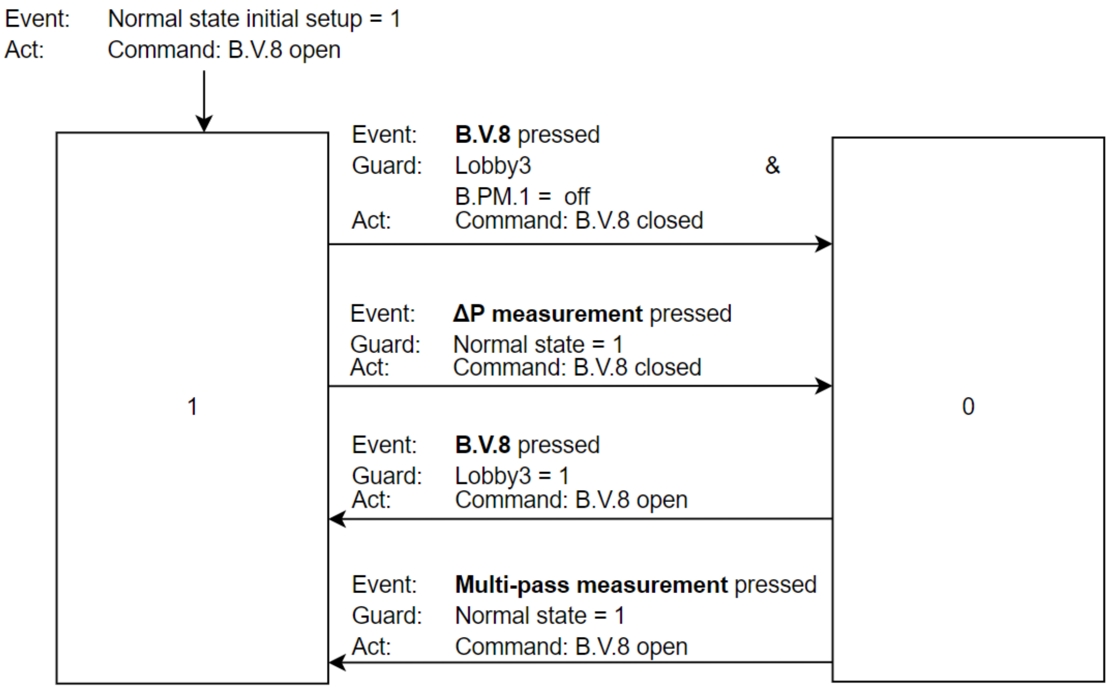

FIGURE 24. Valve B.V.8 state machine diagram.

B.V.9 valve is a 2-way valve (figure 25). Its initial state is 0. It works with the same logic as valve B.V.3.

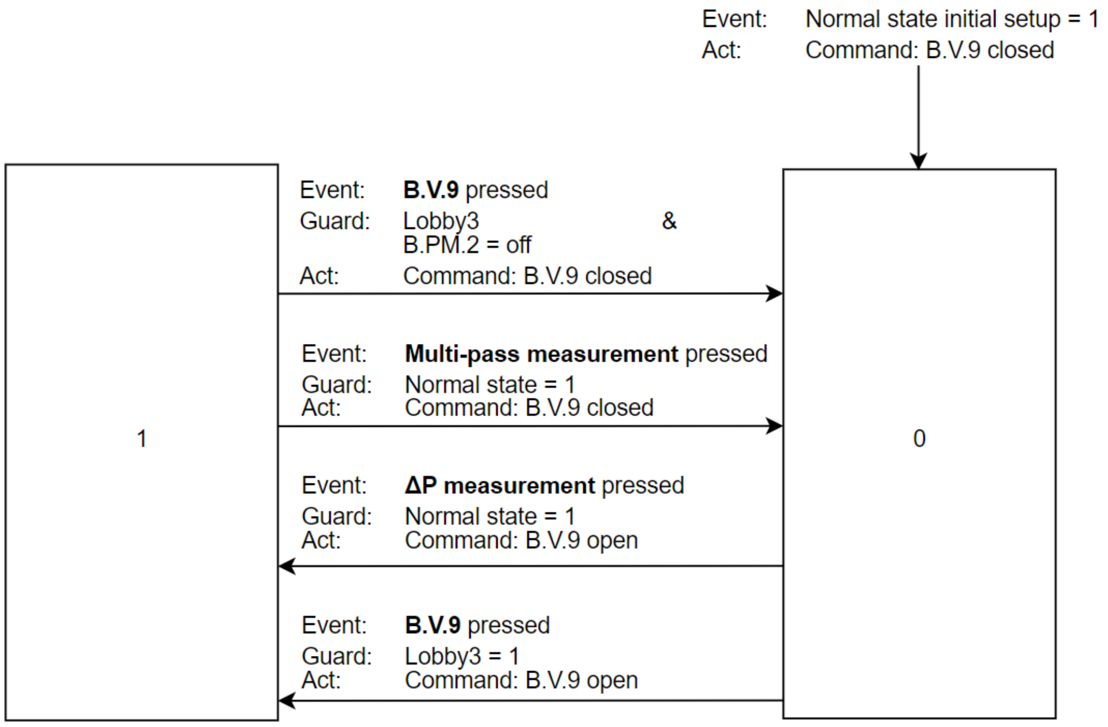

FIGURE 25. Valve B.V.9 state machine diagram.

B.V.10 valve is a 3-way valve (figure 26). Its initial state is right. Control of B.V.10 and B.V.11 valves are the most complex of the valves in the system. These valves belong to test filter bypass system and it is critical to ensure that valves change their positions synchronously.

B.V.10 valve can be turned left manually in lobby1, lobby2 and lobby3 by pressing bypass button, or by pressing B.V.10 button in lobby3 when valve B.V.11 is open or when it is closed and pumps B.PM.1 and B.PM.2 are not on. Note that there is a delay added before the turn left command. This is to ensure that the valve B.V.11 will have enough time to open before the flow is guided to the test filter line. Start of the multi-pass test will also change the valves position to left.

B.V.10 can be turned right manually in manual control lobby3 by pressing B.V.10 or by pressing bypass in lobby1, lobby2 or lobby3. The valve will automatically turn to right when ΔP measurement state or multi-pass measurement state is being entered or when multi-pass test (TEST2) is finished.

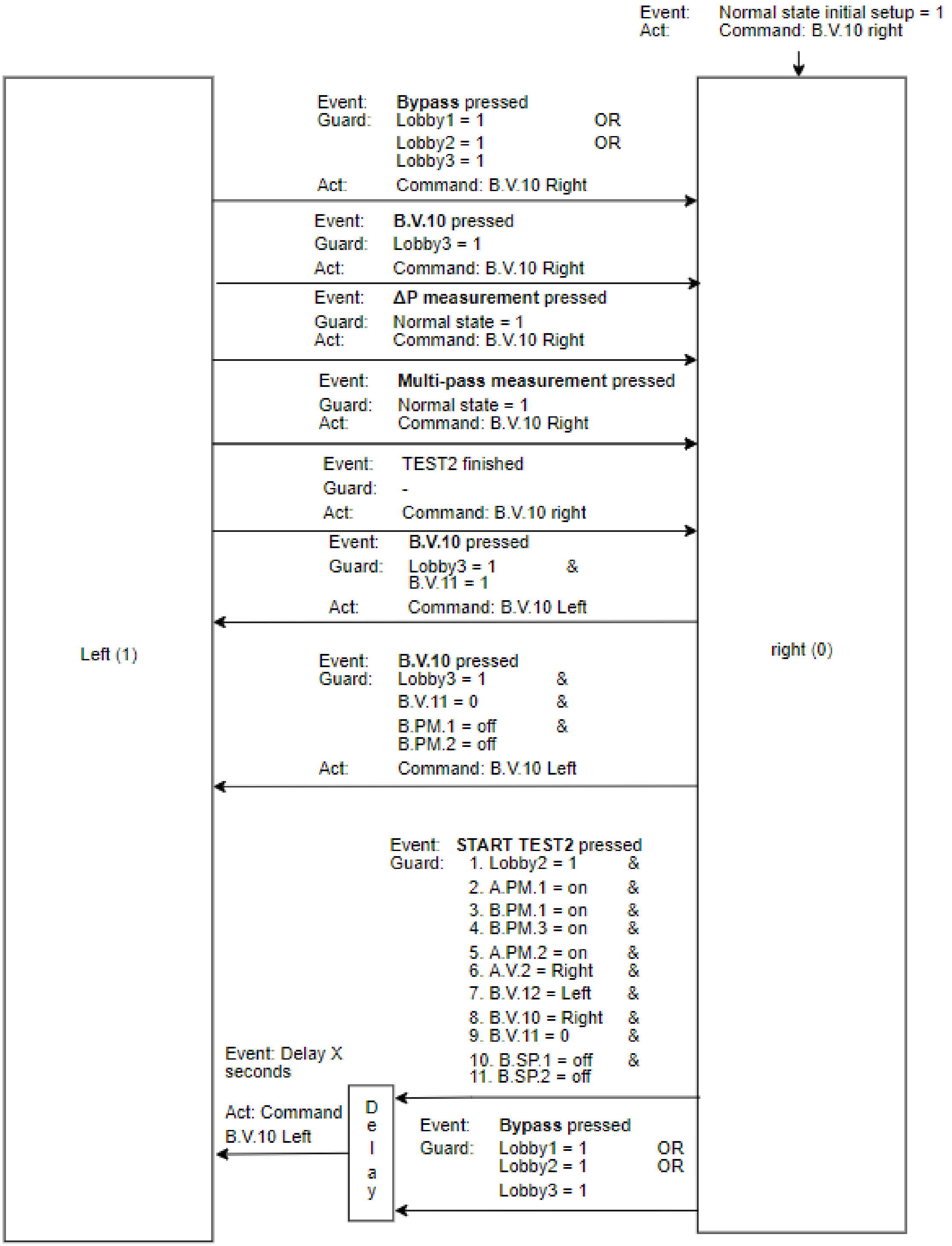

FIGURE 26. Valve B.V.10 state machine diagram.

B.V.11 valve is a 2-way valve (figure 28). Valves initial state is 0. The valve can be turned to state 1 by starting the multi-pass test (TEST2), pressing bypass button in lobby1, lobby2 or lobby3 when B.V.10 state is right or by pressing B.V.1 button in lobby3.

If bypass is pressed in lobby3 when B.V.10 state is left and B.V.11 state is 0, valve B.V.11 state stays 0 and valve B.V.10 state is changed to right (figure 27). The reason for this is simple. Pressing a bypass button should always open the bypass line while closing the test filter line or open the test filter line while closing the bypass line. If the valves are in asynchronous state, pressing a bypass button will synchronize the valves. The aforesaid scenario should only be possible in manual control state.

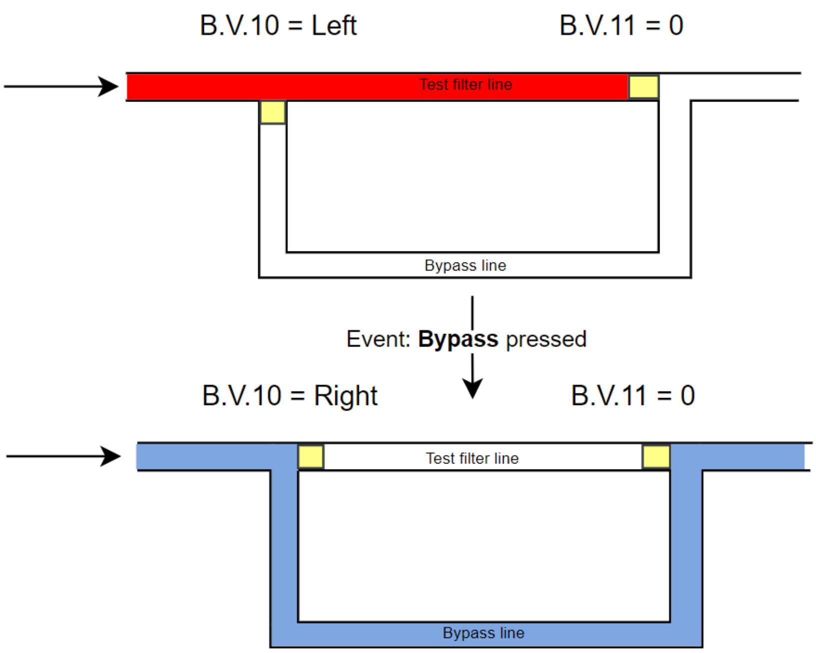

FIGURE 27. Example of bypass synchronization.

Valve B.V.11 initial state is 0. It can be turned right by pressing the bypass button in lobby1, lobby2 or lobby3 or by pressing the B.V.11 button in lobby3. Starting the multi-pass test will also trigger the valve to move to state 1.

Valve B.V.11 can be turned back to state 0 by pressing B.V.11 in manual control lobby3 when valve B.V.10 is right or when it’s left and pumps B.PM.1 and B.PM.2 are not on. Also, by pressing the bypass in states lobby1, lobby2 or lobby3 when B.V.10 is left will change the valve B.V.11 state to 0. Note that there is a delay set as a guard. This is needed to ensure, that the valve B.V.10 is turned right before valve B.V.11 will be closed. If the valve B.V.10 is not left when bypass is pressed in lobby3, bypass will get synchronized and valve B.V.11 will stay in state

1. Entering ΔP measurement state or multi-pass measurement state or when multi-pass test is finished will trigger the valve to change its state to closed.

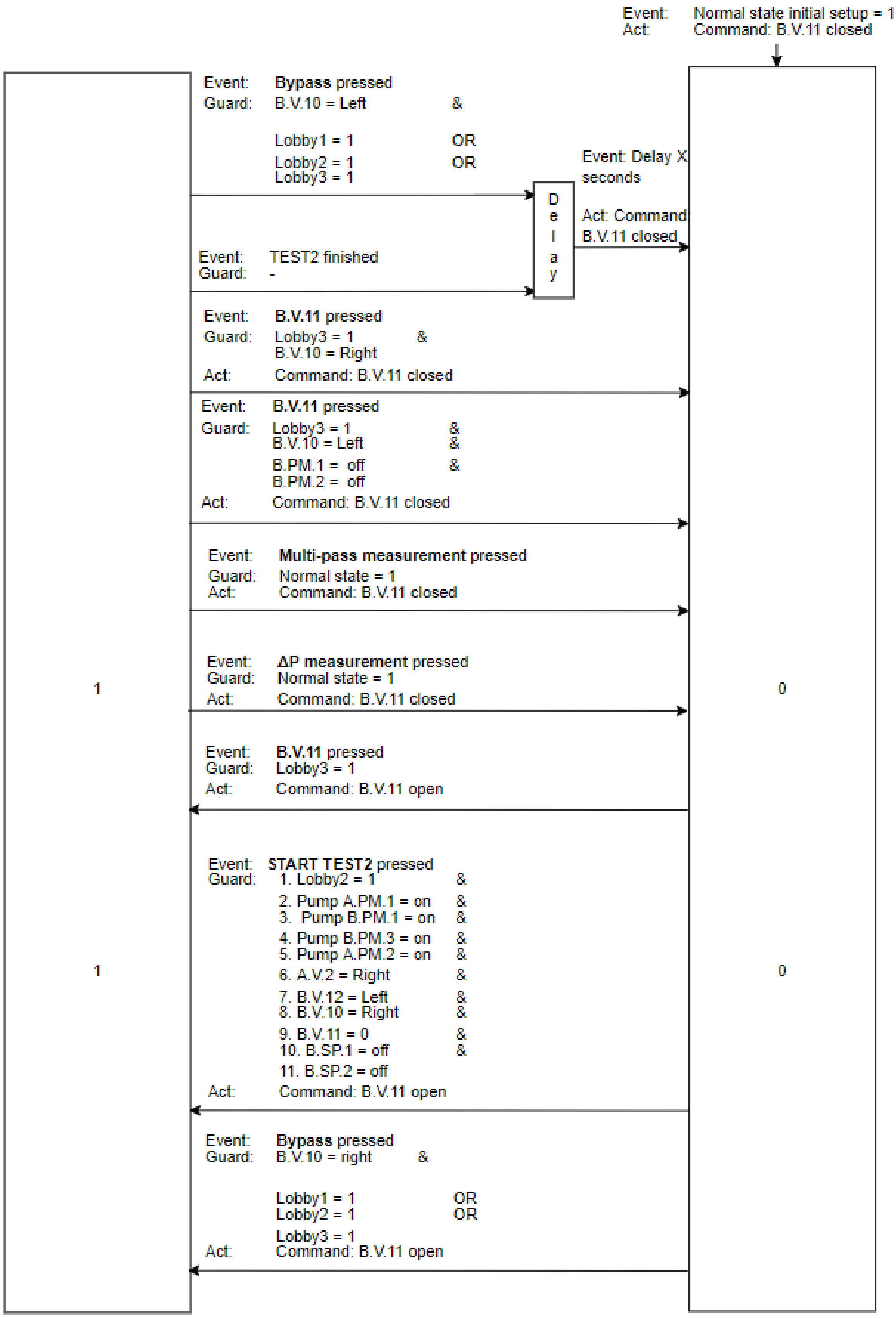

FIGURE 28. Valve B.V.11 state machine diagram.

B.V.12 valve is a 3-way valve (figure 29). Its initial state is left. It can be turned right when B.V.12 button is pressed lobby1, lobby2 or lobby3. When multi-pass test is finished (TEST2), it will automatically turn to right to start the cleaning of the filter test system.

B.V.12 can be turned to state left by pressing B.V.12 button in ΔP measurement lobby1, multi-pass measurement lobby2 or in manual control lobby3 or when multi-pass measurement or ΔP measurement states are being entered from the normal state.

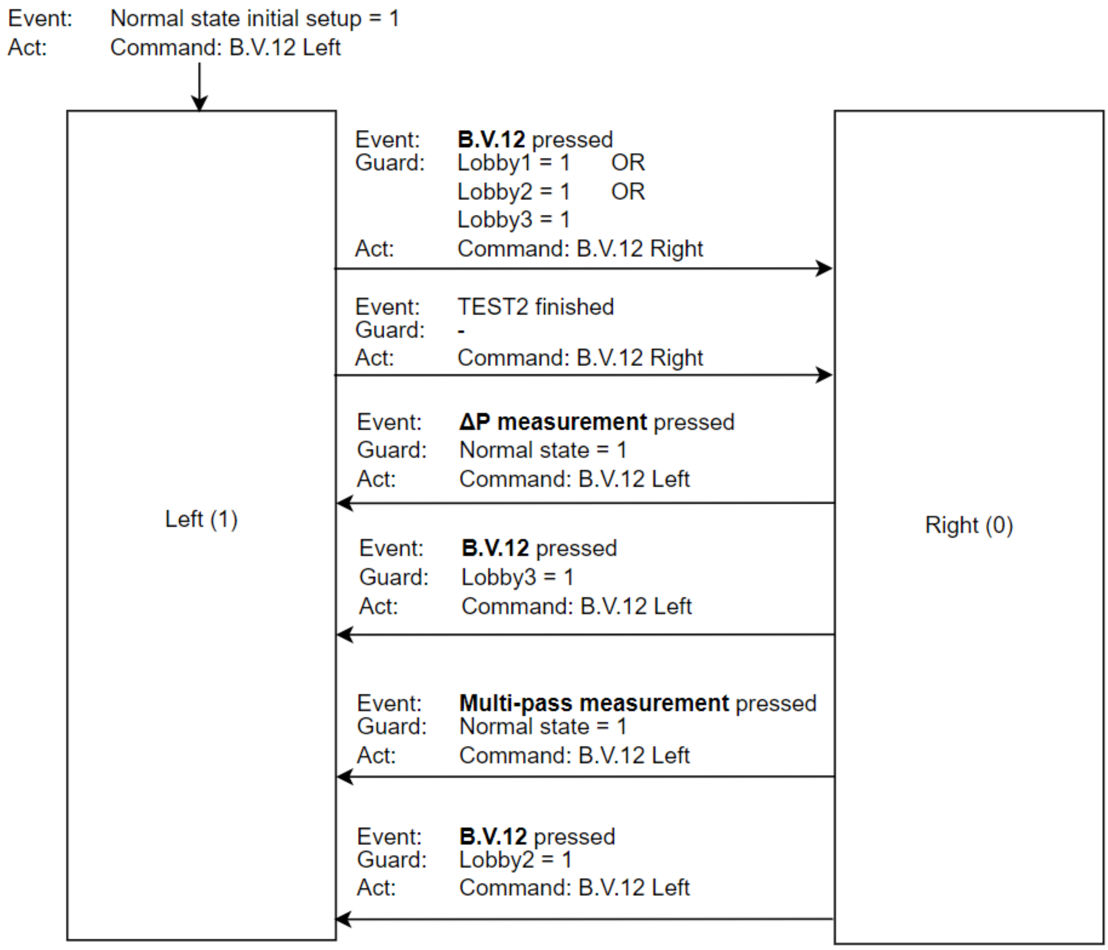

FIGURE 29. Valve B.V.12 state machine diagram.

Valve B.V.13 is a 2-way valve and its initial state is 0 (figure 30). B.V.13 and B.V.14 valves are mainly controlled by controlling the pumps next to them. B.V.13 can be turned to state 1 by pressing B.V.13 button in manual control lobby3, when pump B.PM.3 is off. It can also be turned to state 1 by pressing B.PM.3 in lobby2 or lobby3, when the pump B.PM.3 is in the state off and the safety stop2 is not active. In order to do this, either pump B.PM.1 or pump B.PM.2 has to be on, because the guards here are the same as to turn on the pump B.PM.3. Valve will be opened automatically when the pump B.PM.3 is being started and the user don't have to open the valve separately.

The valve will also be closed when the pump B.PM.3 is off and is stopped during lobby2. B.V.13 will also close automatically when multi-pass measurement or ΔP measurement states are being entered. A user can close the valve manually by pressing B.V.13 button during lobby3, when the pump B.PM.3 is off.

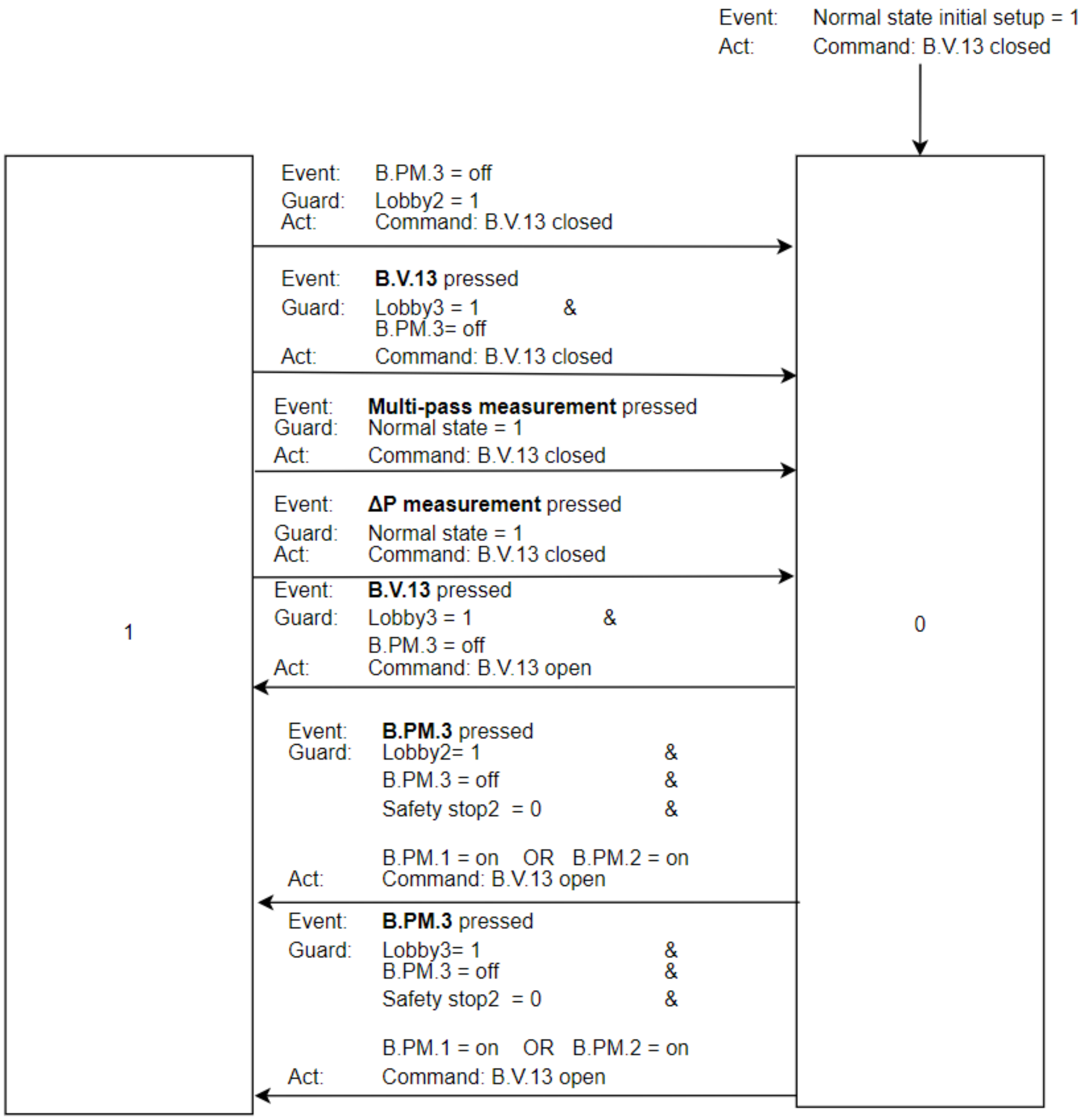

FIGURE 30. Valve B.V.13 state machine diagram.

Valve B.V.14 is a 2-way valve and its initial state is 0 (figure 31). B.V.14 works exactly the same way as the previous B.V.13 valve, but the pumps in transitions are changed to B.PM.4 from B.PM.3, and the push buttons are changed to B.V.14 from B.V.13. Also, an extra guard has to be added. Due the valve will change its state when the pump B.PM.4 is being turned on, the guards have to be the same. Therefore, the water level in the reservoir B.W.3 cannot be below a certain limit when B.PM.4 button is pressed.

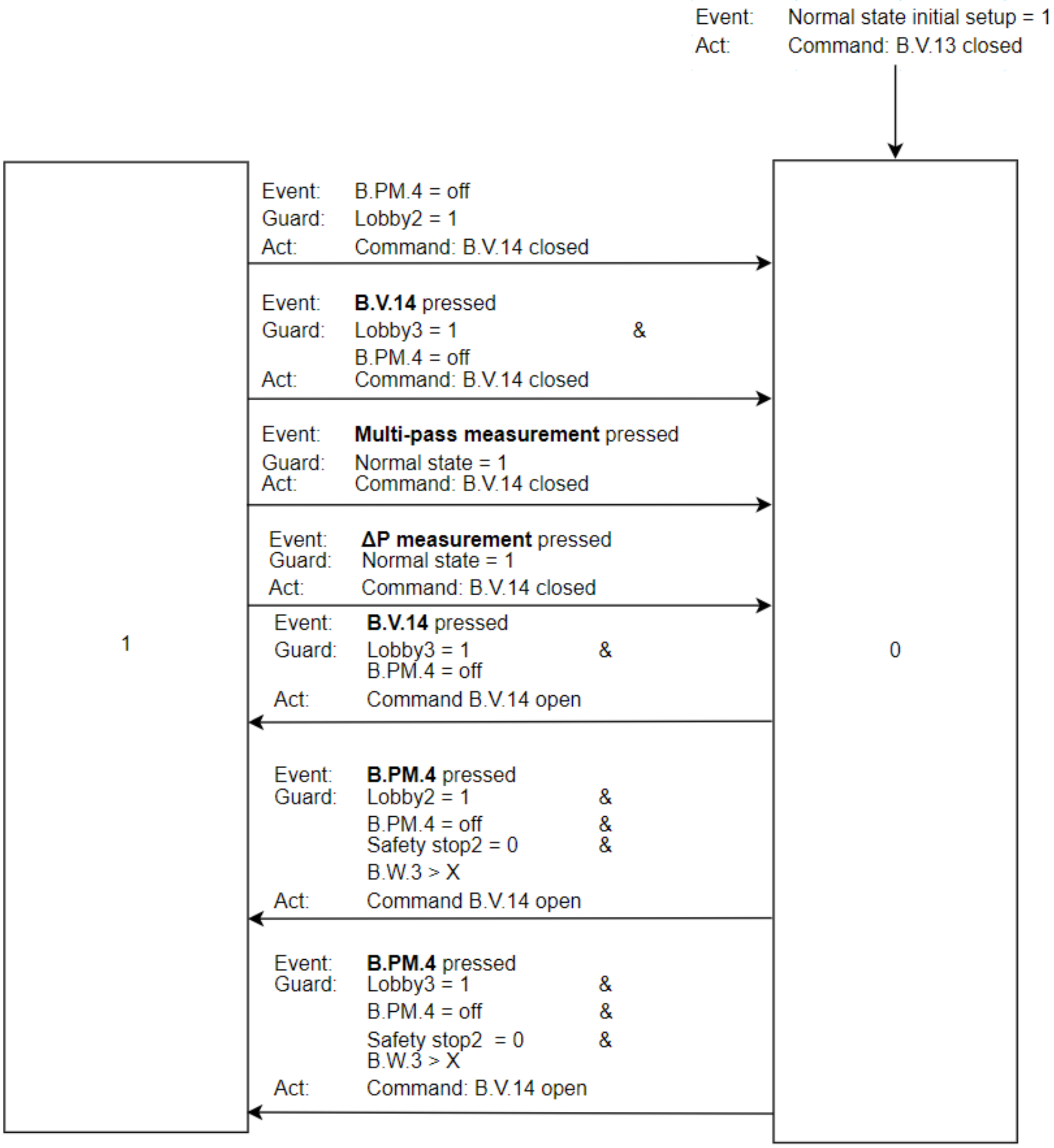

FIGURE 31. Valve B.V.14 state machine diagram.

Throttle valves are always open. A throttle valve can be opened completely but for closing, a certain limit must be set. This limit must be so, that it is impossible to shrink the size of the throttle, if that would cause the system pressure to rise over the allowed. Throttle valve B.TV.1 can be affected during ΔP measurement and manual control lobbies (appendix 8). When the system is turned on or when

ΔP measurement lobby1 is being entered, a certain initial state is given for the throttle valve B.TV.1. The precision needed for the throttle valves adjust depends on the pump B.PM.2's volume flow's adjustability. Certain requirements are set for the volume flow in ISO 3968 to achieve the wanted test opening pressure.

Throttle valve B.TV.2 can be actuated manually in lobby1, lobby2 and lobby3 (appendix 9). When the system is turned on, when ΔP measurement lobby1 is being entered or when multi-pass measurement lobby2 is being entered, a certain initial state is given for the throttle valve B.TV.2.

4.5.4 Pumps

Every pump's initial state is off. Pumps can never be turned on when safety stop2 state is active and they must always be turned off when automatic stop1 state or safety stop2 state becomes active. When a pump with frequency converter is turned on, a certain initial frequency/rpm is given and the pump is turned on. When the pump is on, its frequency can be increased from the HMI when its maximum frequency condition is not exceeded. Also, pumps frequency can be lowered from the HMI when its minimum frequency condition is not passed underneath. When pumps powers are turned off they will enter slow down state first, and then after a delay, they enter the state off from which the pump can be turned on again. This delay between states slow down and off is needed to ensure that the pump has stopped completely before it can be turned on again. This delay could be replaced with frequency converters information of when the pumps motor is stopped. Also, energy supply to pumps motors must be shut off after the command off is given. Government Decree on the Safety of Machinery demands these two previously mentioned features and therefor they must be obeyed.

Pump A.PM.1 can be turned on from its off state when button A.PM.1 is pressed in lobby3 or lobby2 (appendix 10). If A.PM.1 is to be turned on in lobby3 state, valve A.V.3 cannot be open. A.PM.1 will shut off when A.PM.1 is pressed in lobby3 or lobby2. Also, by pressing stop2 in multi-pass test will shut off the pump. It is wanted, that the pump will stay on after the multi-pass test, so that the contaminant injection system will start cleaning itself automatically.

Pump A.PM.2 can be turned on and off with the same conditions as pump A.PM.2 except the push buttons name is different (figure 32). A.PM.2's frequency cannot be controlled. It is wanted, that the pump will stay on after the multi-pass test, so that the contaminant injection system will start cleaning itself automatically.

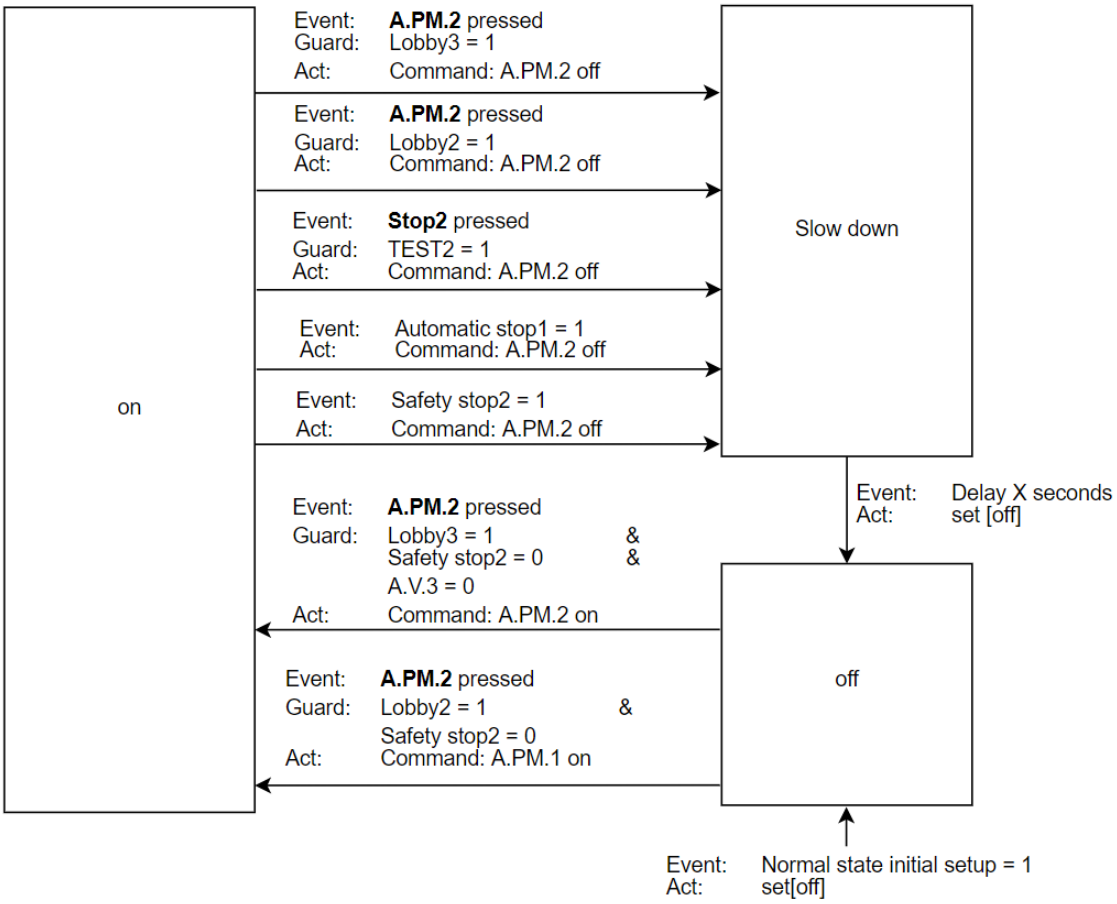

FIGURE 32. Pump A.PM.2 state machine diagram.

Pump B.PM.1 can be turned on in lobby3 by pressing button B.PM.1, when valves B.V.2, B.V.4 and B.V.8 are open, B.V.6 is closed, and bypass is either open or closed (appendix 11). It can be turned on in lobby2 by pressing the button B.PM.1. The pump will shut off when the previously mentioned button is re-pressed during lobby2 and lobby3. Pressing stop2 during the multi-pass measurement test will also shut off the pump.

Pump B.PM.2 can be turned on in lobby3 by pressing button B.PM.1, when valves B.V.3, B.V.5 and B.V.9 are open, B.V.7 is closed, and bypass is either open or closed (appendix 12). It can be turned on in lobby1 by pressing the button B.PM.2. The pump will shut off when B.PM.2 is pressed in lobby3 or Lobby1.

Pump B.PM.3 can be turned on in lobby3 or lobby2 by pressing B.PM.3 button, but either pump B.PM.1 or pump B.PM.2 must be on (appendix 13). Pump B.PM.3 will always turn on with a delay, due it controls the valve B.V.13. This delay ensures that when B.PM.3 is about to turn on, the valve B.V.13 will be open first. Pump B.PM.3 will turn off when the B.PM.3 button is repressed in lobby2 or lobby3. Also, when dirt feeding is ended during multi-pass test and valve A.V.1 is turned left, the pump B.PM.3 will shut off. This is to ensure that the volume of water stays the same in the multi-pass system. In the current state machine diagram this is shown as TEST2 finished guard, this might be a faulty trigger due the dirt feed might end earlier. Pressing stop2 during the multi-pass measurement test will also shut off the pump. It is particularly important that the delay set between the states slow down and off and delay and on, is long enough for the pumps B.PM.3 and B.PM.4, because the pumps control the valves.

Pump B.PM.4 can be turned on in lobby2 or in lobby3, when the water level in the reservoir B.W.3 is above certain limit (figure 33). Like B.PM.3, B.PM.4 turns on with a delay. The reason for this is the same as for B.PM.3. The pump must be shut if the reservoir before it runs out of water. It can be manually closed by pressing B.PM.4 in Lobby3 or Lobby2. Starting the multi-pass test will close the pump, due the reservoir has to start collecting the water.

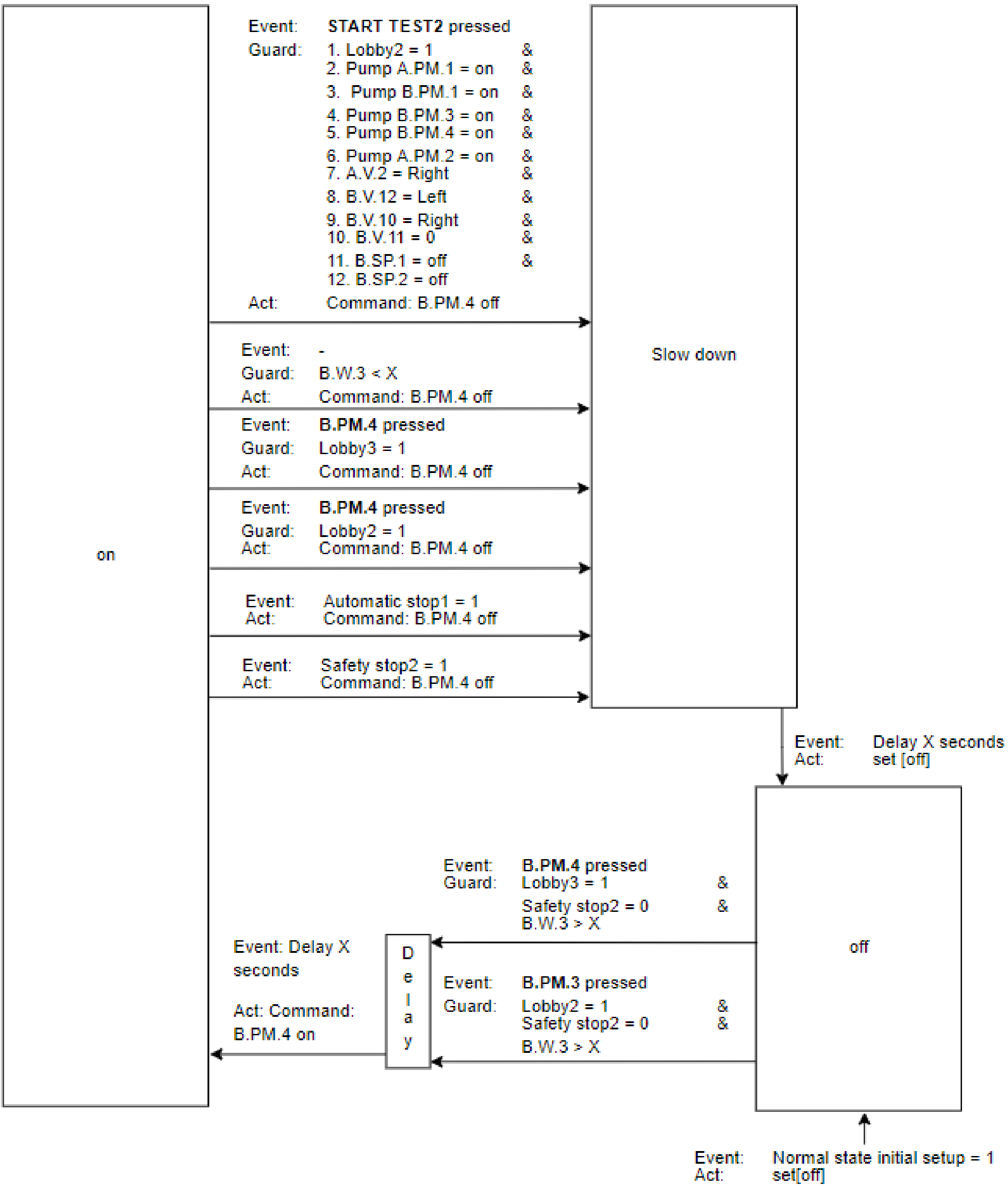

FIGURE 33. Pump B.PM.4 state machine diagram.

The two sensor pumps B.SP.1 and B.SP.2 are controlled at the same time (figure 34). Pumps can be turned on by starting the multi-pass test or by pressing sensor pumps button in lobby2 or lobby3. If the pumps are to be turned on, either pump B.PM.1 or B.PM.2 must be on.

Sensor pumps will turn of when multi-pass test is finished, stop2 is pressed during multi-pass test or when sensor pumps button is pressed during lobby2 or lobby3.

Also, if neither of the pumps B.PM.1 or B.PM.2 are on, the sensor pumps will be shut off automatically.

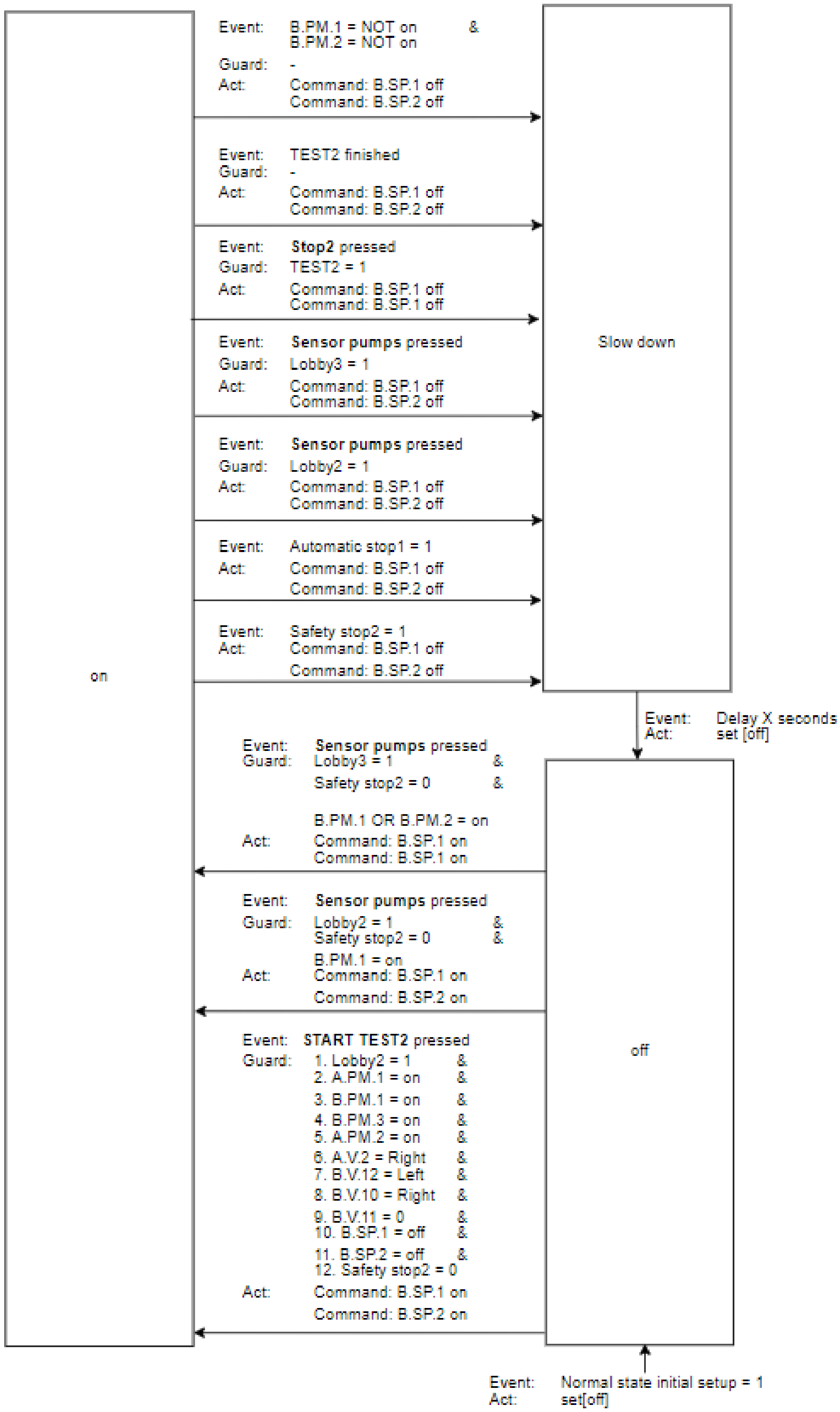

FIGURE 34. Pump B.SP.1 and B.SP.2 state machine diagram.

4.5.5 Inner states

There are two different states that will trigger the stop of the pumps in the system automatically. Both will also interrupt all the measuring events and calculators. The first one is an automatic stop1 state, that acts as a warning if something is not correct (figure 35). Even the pumps are turned off by this state, they can still be turned on afterwards. This state will be activated if one or several of the system's parameters are over their allowed limits. It will move the system to the manual control state, where the problem can be looked more closely and it can be affected. This automatic stop state can be left when system parameters are back to normal and reset is pressed. It must be kept in mind that this state is not a safety feature.

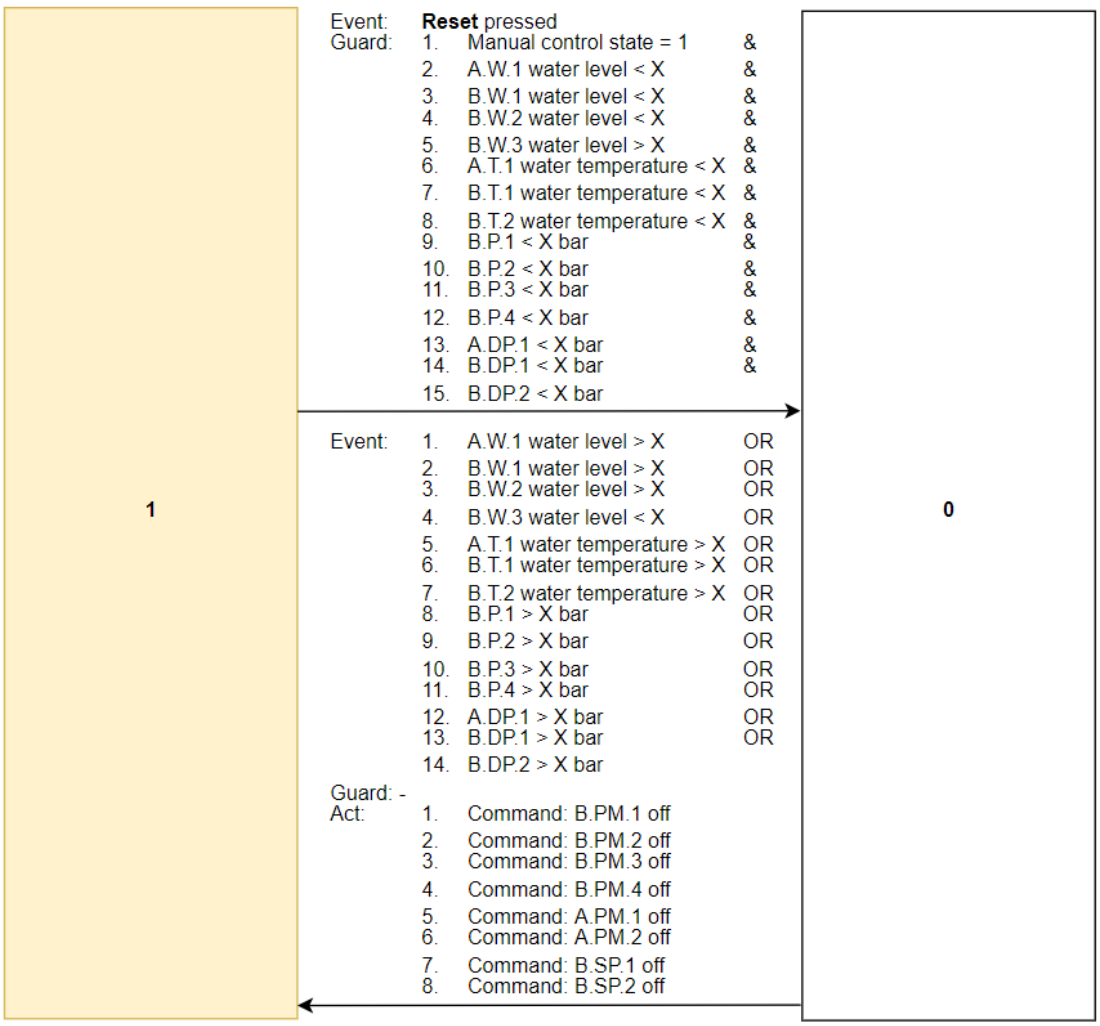

FIGURE 35. Automatic stop's state machine diagram

Safety stop2 state is a safety feature. It will have the value 1 when emergency stop is being pressed or when one of the pressure sensors that are classified as safety features, has a pressure reading that is over the critical allowed limit. When safety stop state is active, pumps in the system cannot be turned on. If the state is to be left, reset must be pressed while the system's pressure is normalized and emergency stop is not pressed.

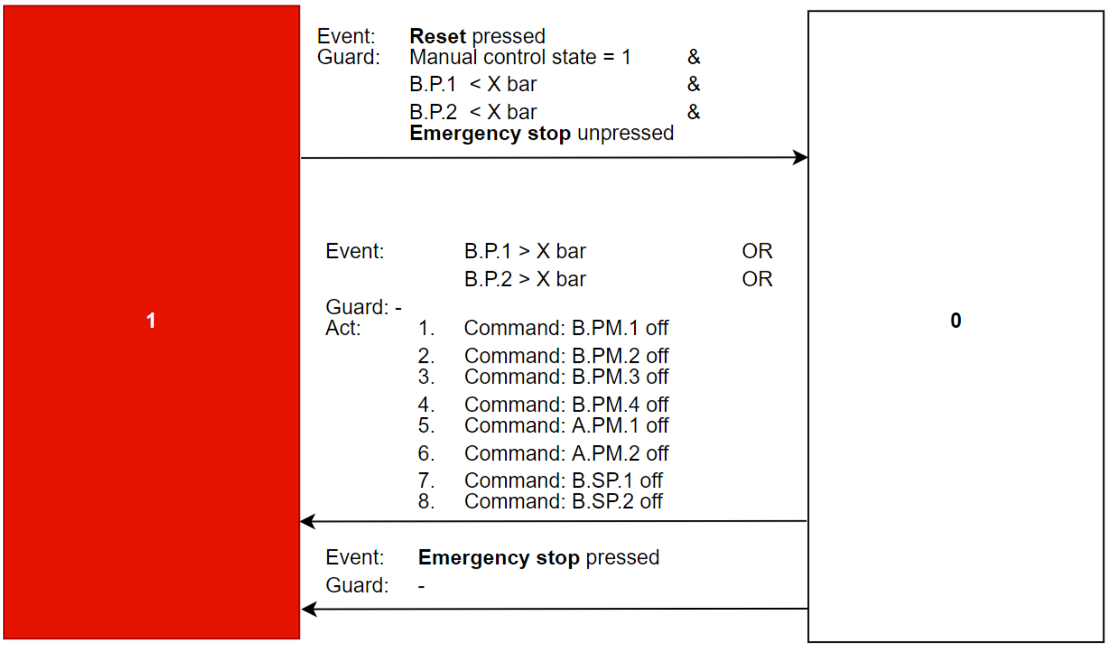

FIGURE 36. Safety stop2 state machine diagram

4.6 HMI outline

The control system modelled in this thesis is designed to be controlled from a single HMI. The buttons to be used are defined in main states' state machine diagrams.

Each main state's HMI view and functionalities should be done so, that they fit to the states purpose. Only the needed sensor data should be shown and only the needed buttons should be available. This is to reduce the amount of unnecessary information. To increase the HMI's user friendliness, there should be a visual indicator in addition to the numerical value for each sensor reading, excluding the sensors that are used for saving the measurement event data. The view in each main state should be so, that the used part of the hydraulic circuit and control components are shown in the screen on their correct places. Sensor readings should be places near the sensors in the HMI view. The visuality would help the user to understand the current status of the system faster and with less effort.

There should also be warning pop-up windows, if the user would try an actuation of a component when it would not be possible, or when the system parameters would be out or close of being out from their allowed limits.

5 DISCUSSION

This thesis was able to produce a prototype of a control system for the water filter test bench. State machine diagrams were created for each component and HMI's state. From that view, it can be seen as a success. Though the level of this work's usefulness will be seen when the actual software is programmed based on the state machine diagrams done in this thesis. How well the program will answer to the demands and needs of the commissioning company, will tell how successful this control system model actually was.

Even though hydraulic circuit design was not originally meant to be in this thesis, it was something that had to be done before the control system design could be started.

Few development proposals rose during the control system design process. Currently, there are no safety features in the reservoir circuit. If the pressure would rise above or under the allowed limits, the system or user would not be informed. Pressure sensors could be added between the pump B.PM.3 and valve B.V.13 to monitor vacuum pressure and between pump B.PM.4 and valve B.V.14 to monitor excess pressure. Also, one pressure sensor could be added after the pump A.PM.3 for the same reason. If these three pressure sensors would be classified as a safety features, they would have to be added to the safety stop state as triggering factors and their required performance level would have to be evaluated.

Also, if the reservoir of B.W.3 sensor would be lifted on top of the reservoir of B.W.1 sensor, the pump B.PM.4 could be removed. The water could be run straight to the B.W.1 reservoir by only opening the valve B.V.14. This would simplify the working of the reservoir system significantly. When the volume flow of B.PM.3 would be adjusted before the start of multi-pass test, valve B.V.14 could be open and the water could be returned straight back to the filter test system. When multi-pass test would start, it would close the valve B.V.14 and the reservoir system would start collecting the water so that volume in the test system would stay the same. Another option would be setting sensors for the high and low limits of the water level in the reservoir, and control the pump by exploiting these. The control of the B.PM.4 pump is currently manual and a bit tricky.

Because water level sensors’ types had not yet been chosen, it was uncertain how they could be utilized in the control system. For example, will they only inform when a reservoir is full or empty or are they able the recognize the volume in the tank. Currently it is thought that A.W.1, B.W.1 and B.W.2 recognize the high limit and B.W.3 recognizes the low limit of water level in tank.

As told, this thesis is the first prototype of the water filter test bench control system. Next step would be to create the actual PLC program and drive it in a simulation. There, all the needed functions and safety features could be tested. If needed the program could be adjusted and fixed based on results of the simulation. After the simulation of the control system would work as wanted, it could be driven into to the hardware.

Writer of this thesis was familiar with two different PLC software during this work, LOGO! and SIMATIC STEP7. LOGO! cannot be considered as a software for the test bench due the complexity of the system, while STEP7 is a flexible and systematic software that is well suited for large and complex control systems. It would serve well for the test bench’s purposes. It is good to remember that there are many other options in the market and STEP7 is only one option among many others.

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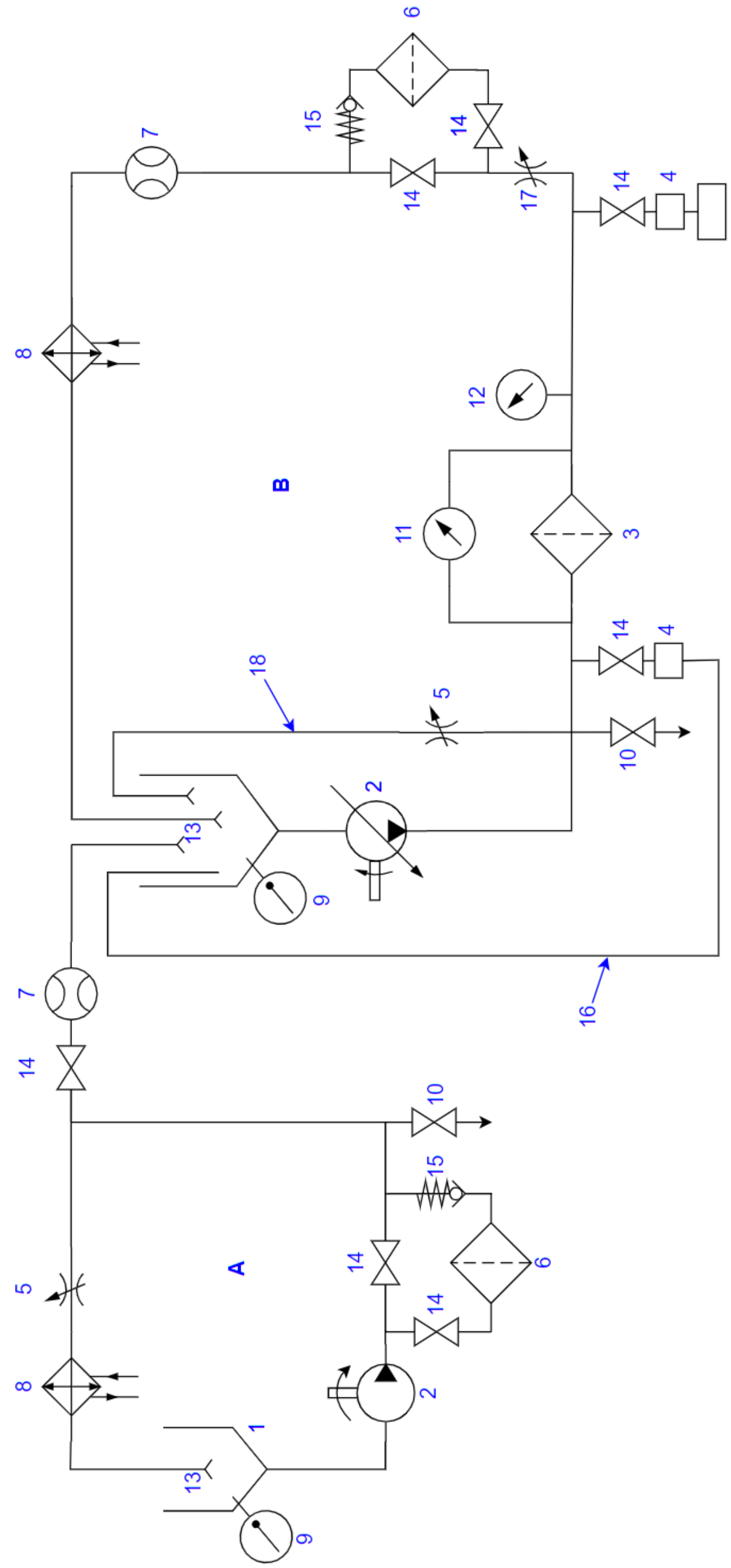
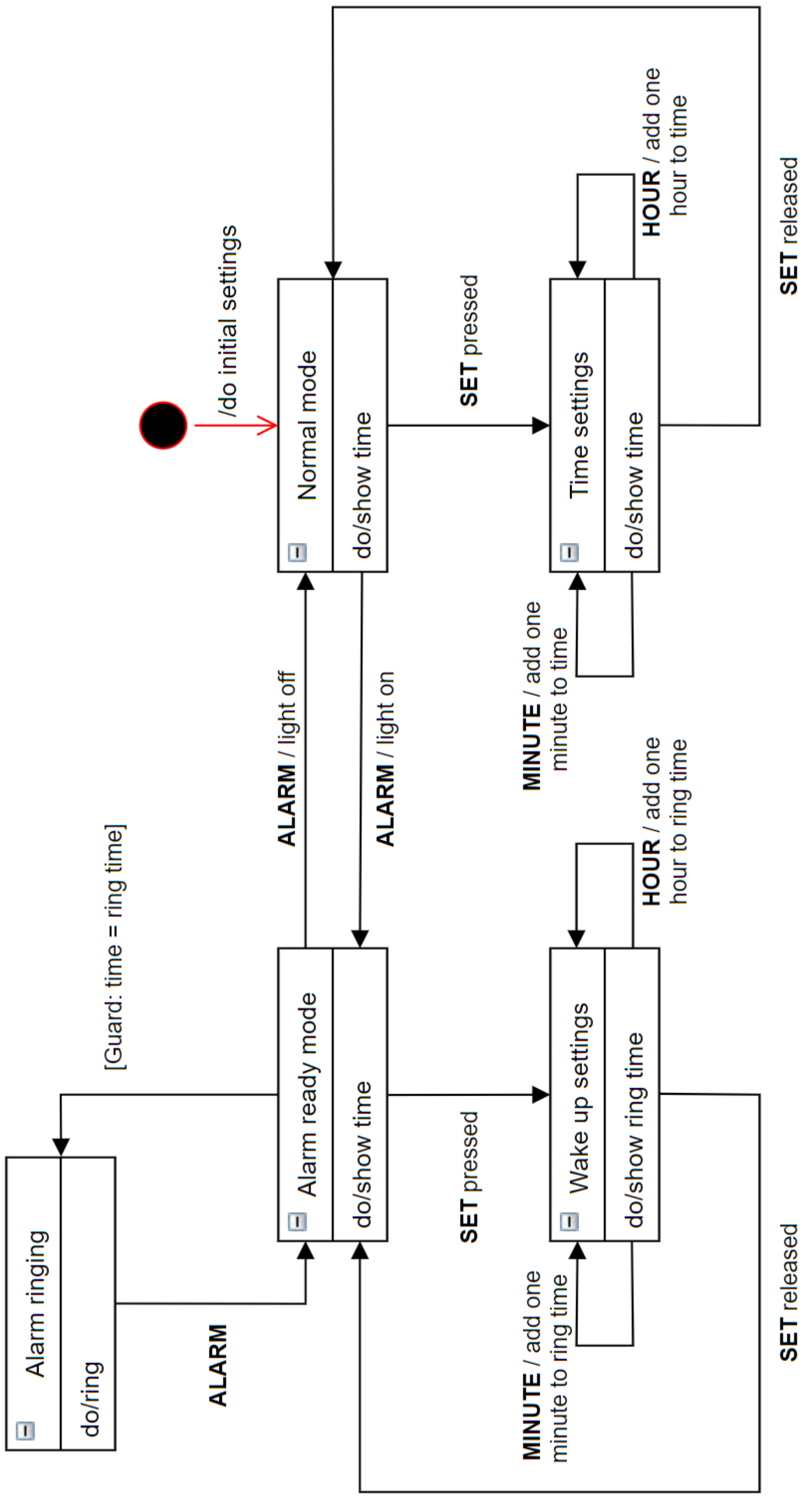
Valtioneuvoston asetus työvälineiden turvallisesta käytöstä ja tarkastamisesta 2008/403. Read 28.10.2021. https://www.finlex.fi/fi/laki/ajantasa/2008/20080403?search%5Btype%5D=pika&search%5Bpika%5D=turvallisuus

APPENDICES

Appendix 1. Example hydraulic circuit of multi-pass system (ISO 16889:2008)



Appendix 2. Example state machine diagram of alarm clocks control object (Koskimies 2000)



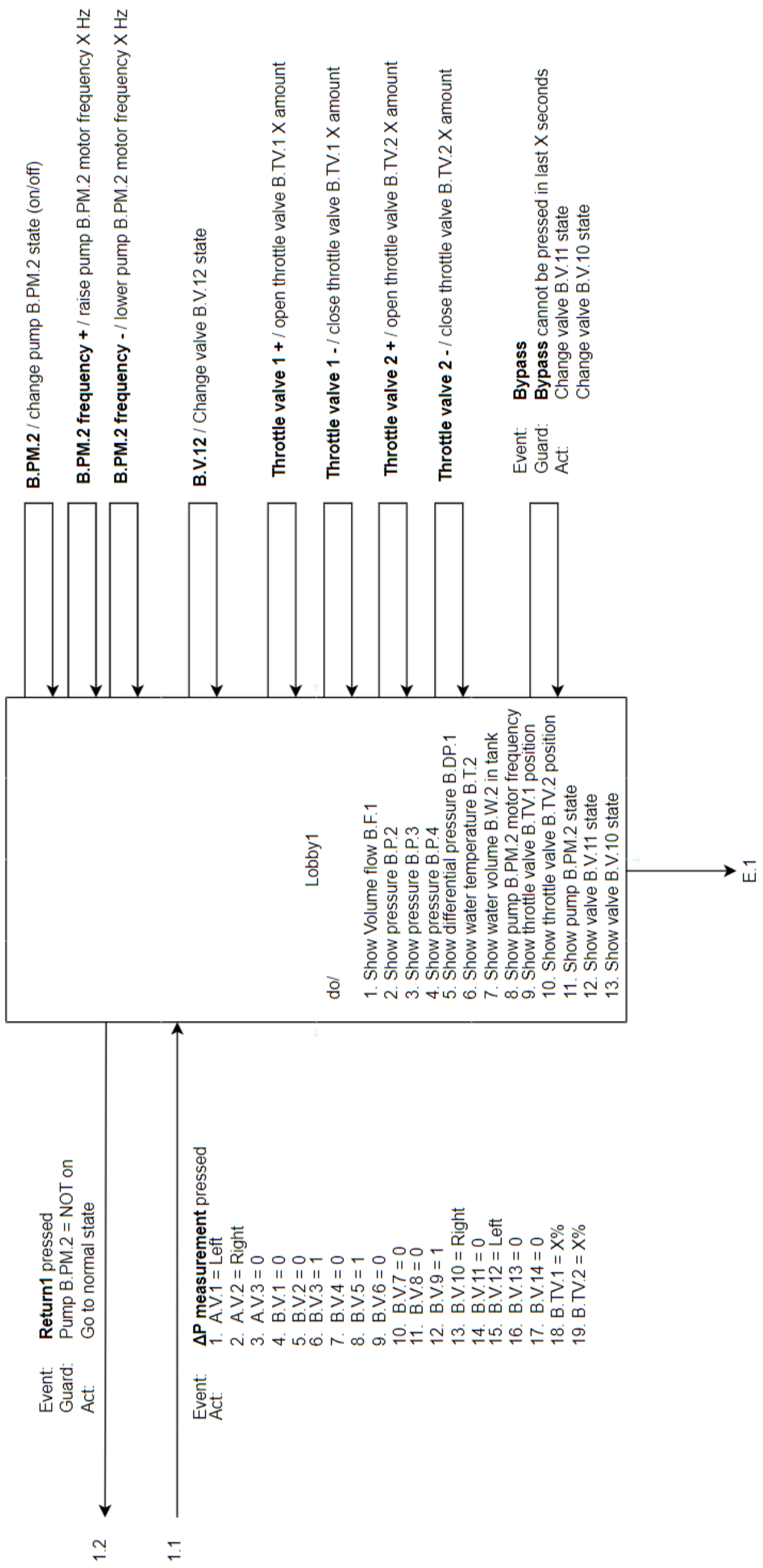
Appendix 3. Hydraulic circuit diagram of water filter test bench

HIDDEN
DUE THE
SECRECY RESONS

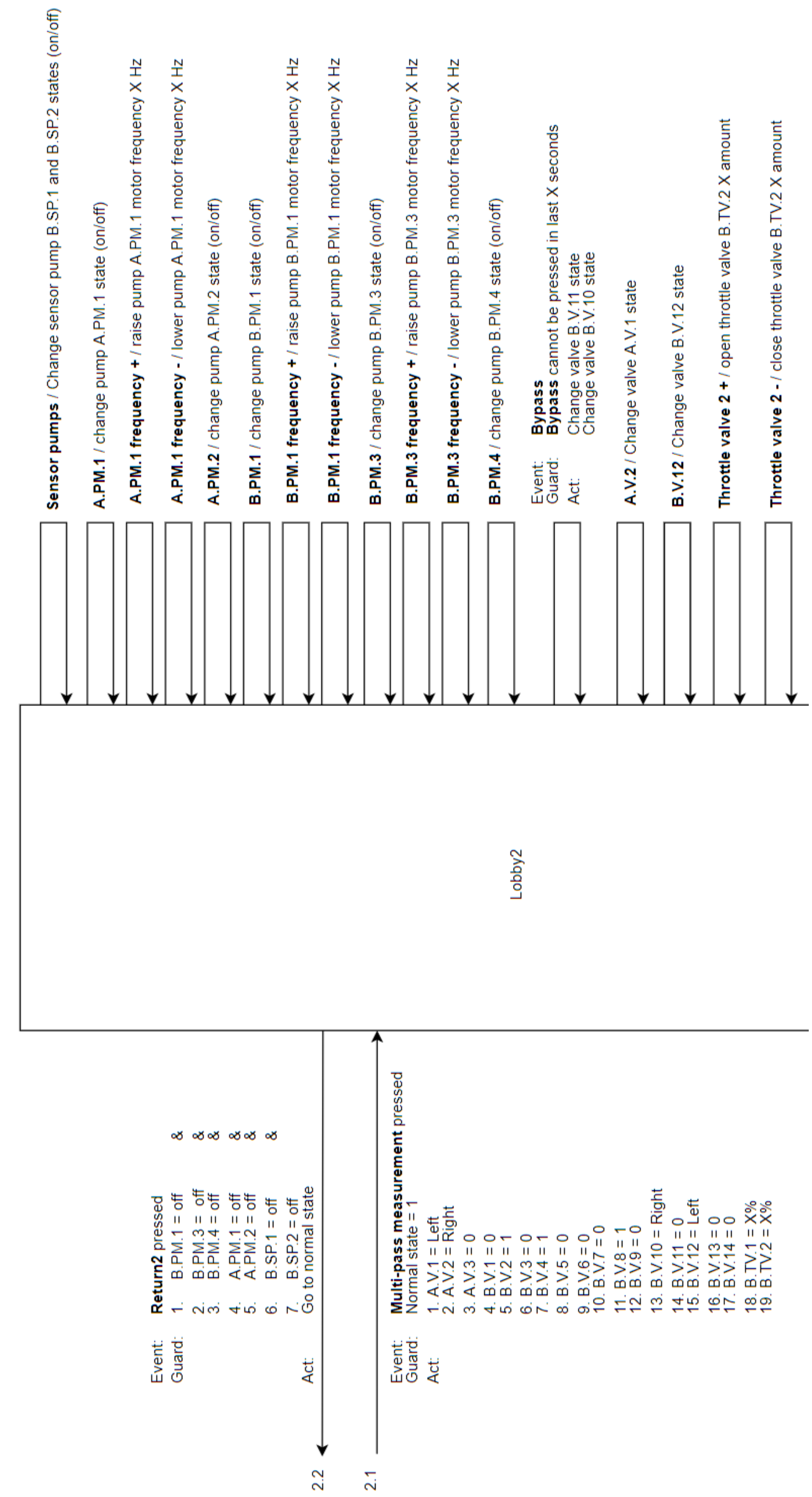
Appendix 4. Control system components

HIDDEN
DUE THE
SECRECY RESONS

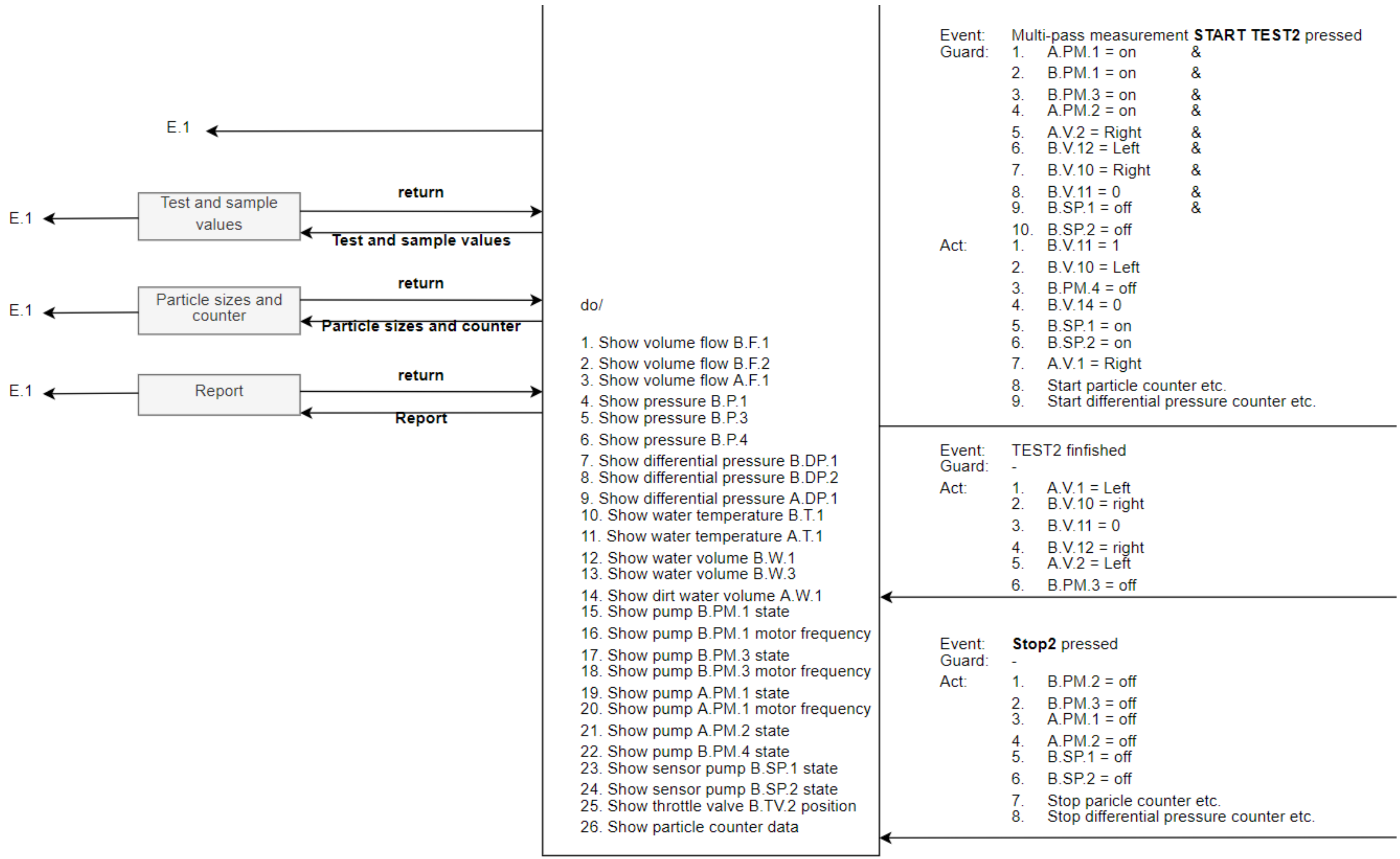
Appendix 5. ΔP Measurement state machine diagram

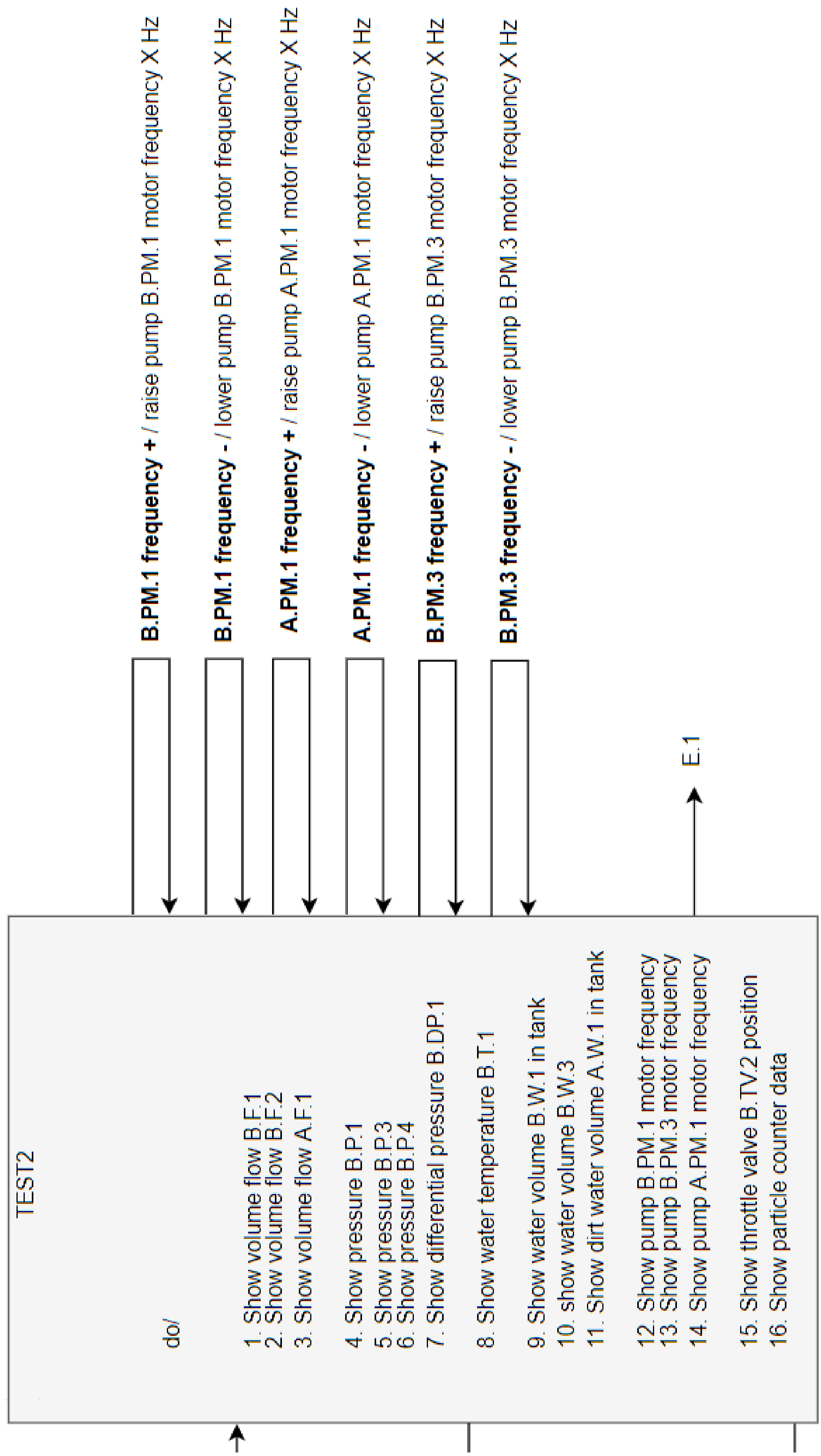


Appendix 6. Multi-pass measurement state machine diagram 1 (3)

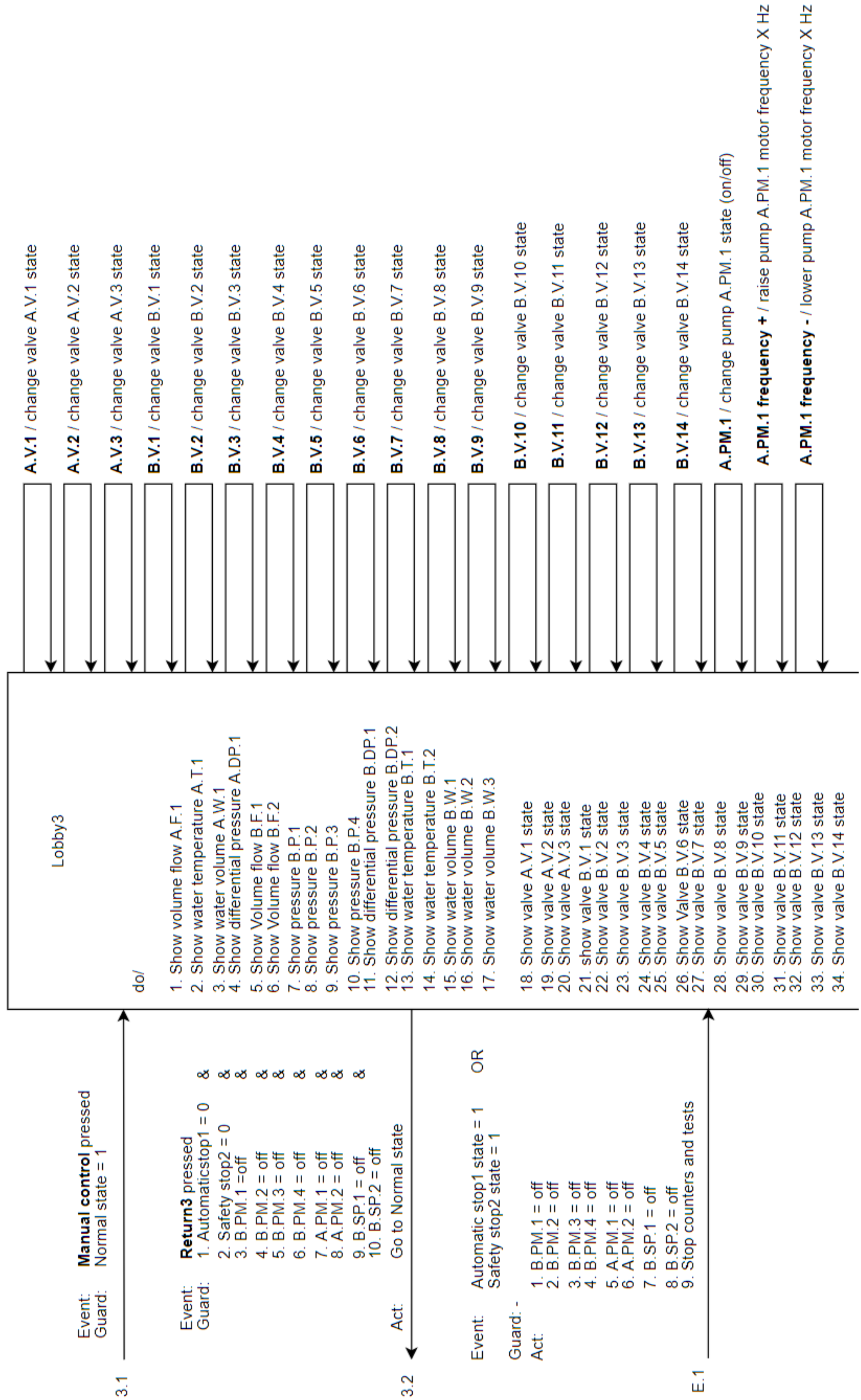


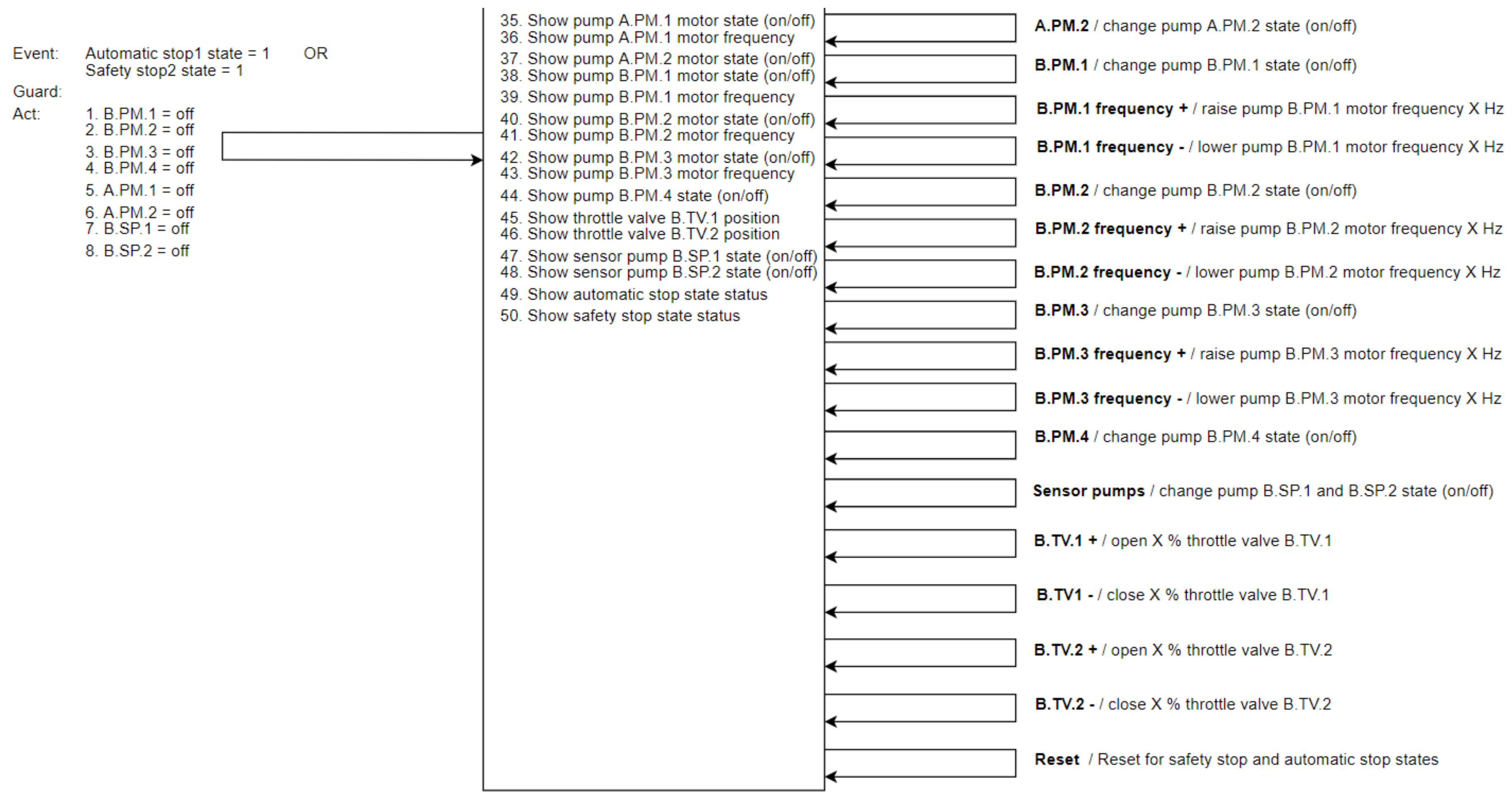
2/3)


E.1
Test and sample values
return
Test and sample values
E.1
Particle sizes and counter
return
Particle sizes and counter
E.1
Report
return
Report
E.1
do/
1. Show volume flow B.F.1
2. Show volume flow B.F.2
3. Show volume flow A.F.1
4. Show pressure B.P.1
5. Show pressure B.P.3
6. Show pressure B.P.4
7. Show differential pressure B.DP.1
8. Show differential pressure B.DP.2
9. Show differential pressure A.DP.1
10. Show water temperature B.T.1
11. Show water temperature A.T.1
12. Show water volume B.W.1
13. Show water volume B.W.3
14. Show dirt water volume A.W.1
15. Show pump B.PM.1 state
16. Show pump B.PM.1 motor frequency
17. Show pump B.PM.3 state
18. Show pump B.PM.3 motor frequency
19. Show pump A.PM.1 state
20. Show pump A.PM.1 motor frequency
21. Show pump A.PM.2 state
22. Show pump B.PM.4 state
23. Show sensor pump B.SP.1 state
24. Show sensor pump B.SP.2 state
25. Show throttle valve B.TV.2 position
26. Show particle counter data
Event: Multi-pass measurement START TEST2 pressed
Guard: 1. A.PM.1 = on &
2. B.PM.1 = on &
3. B.PM.3 = on &
4. A.PM.2 = on &
5. A.V.2 = Right &
6. B.V.12 = Left &
7. B.V.10 = Right &
8. B.V.11 = 0 &
9. B.SP.1 = off &
10. B.SP.2 = off
Act: 1. B.V.11 = 1
2. B.V.10 = Left
3. B.PM.4 = off
4. B.V.14 = 0
5. B.SP.1 = on
6. B.SP.2 = on
7. A.V.1 = Right
8. Start particle counter etc.
9. Start differential pressure counter etc.
Event: TEST2 finfished
Guard: -
Act: 1. A.V.1 = Left
2. B.V.10 = right
3. B.V.11 = 0
4. B.V.12 = right
5. A.V.2 = Left
6. B.PM.3 = off
Event: Stop2 pressed
Guard: -
Act: 1. B.PM.2 = off
2. B.PM.3 = off
3. A.PM.1 = off
4. A.PM.2 = off
5. B.SP.1 = off
6. B.SP.2 = off
7. Stop paricle counter etc.
8. Stop differential pressure counter etc.

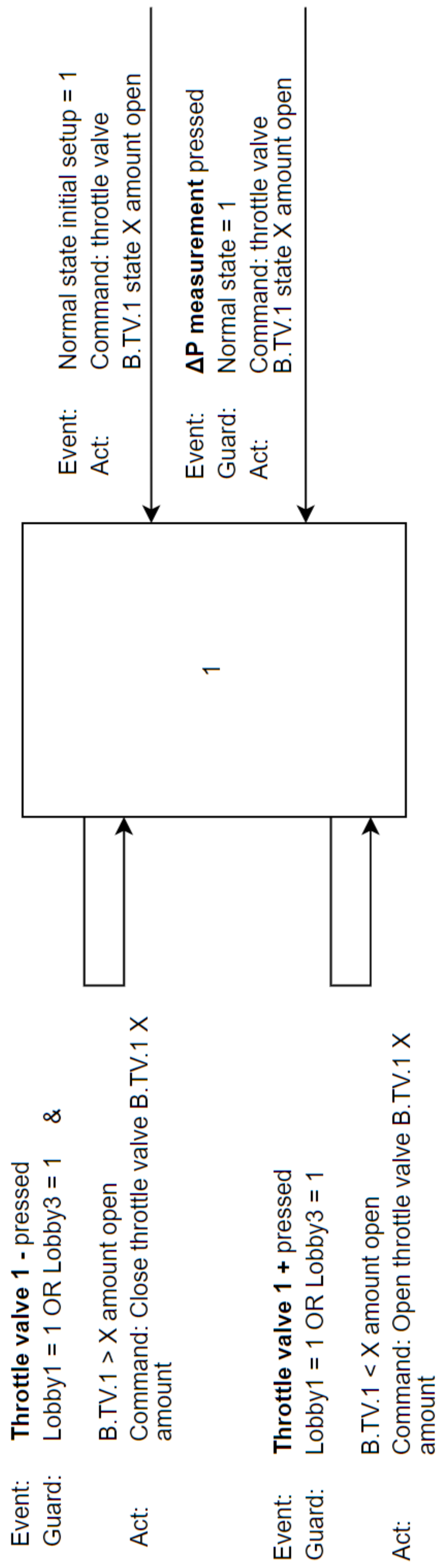

B.PM.1 frequency + / raise pump B.PM.1 motor frequency X Hz
B.PM.1 frequency - / lower pump B.PM.1 motor frequency X Hz
A.PM.1 frequency + / raise pump A.PM.1 motor frequency X Hz
A.PM.1 frequency - / lower pump A.PM.1 motor frequency X Hz
B.PM.3 frequency + / raise pump B.PM.3 motor frequency X Hz
B.PM.3 frequency - / lower pump B.PM.3 motor frequency X Hz
E.1
TEST2
do/
1. Show volume flow B.F.1
2. Show volume flow B.F.2
3. Show volume flow A.F.1
4. Show pressure B.P.1
5. Show pressure B.P.3
6. Show pressure B.P.4
7. Show differential pressure B.DP.1
8. Show water temperature B.T.1
9. Show water volume B.W.1 in tank
10. show water volume B.W.3
11. Show dirt water volume A.W.1 in tank
12. Show pump B.PM.1 motor frequency
13. Show pump B.PM.3 motor frequency
14. Show pump A.PM.1 motor frequency
15. Show throttle valve B.TV.2 position
16. Show particle counter data

Appendix 7. Manual control state machine diagram 1 (2)

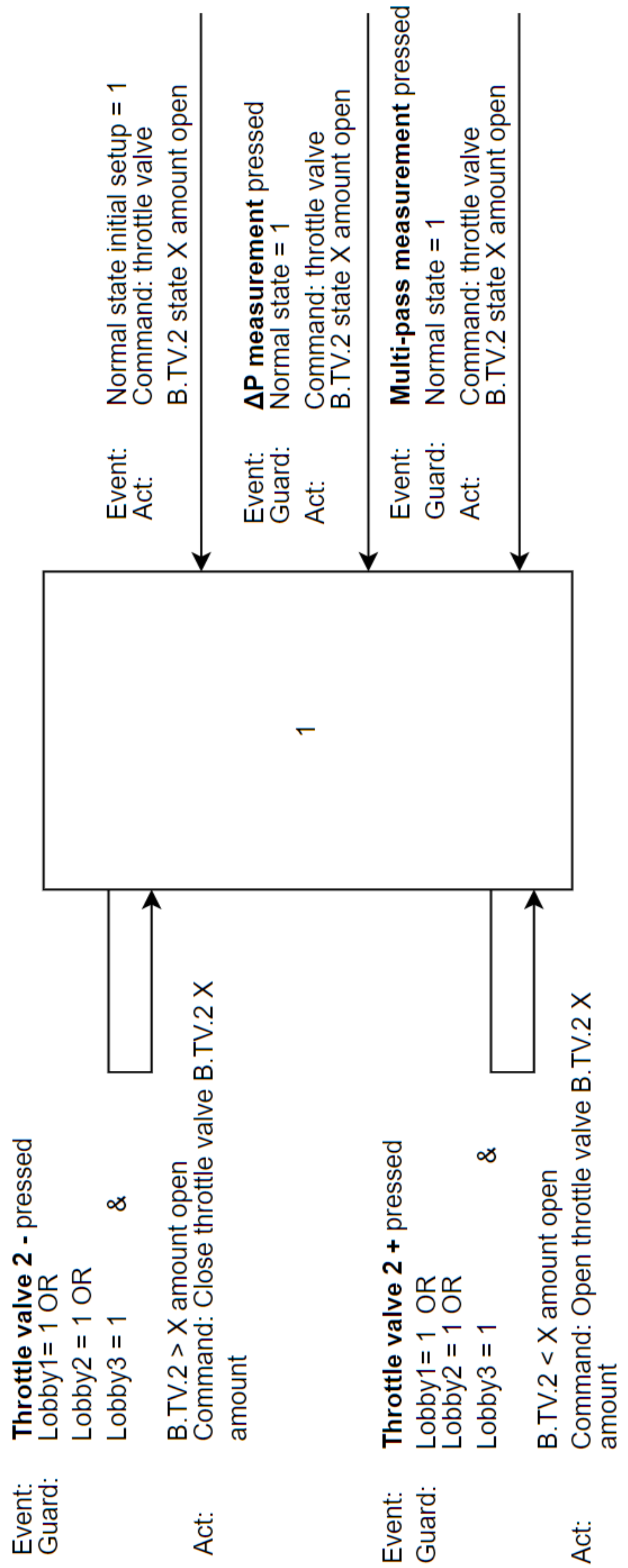



Event: Automatic stop1 state = 1 OR
Safety stop2 state = 1
Guard:
Act: 1. B.PM.1 = off
2. B.PM.2 = off
3. B.PM.3 = off
4. B.PM.4 = off
5. A.PM.1 = off
6. A.PM.2 = off
7. B.SP.1 = off
8. B.SP.2 = off
35. Show pump A.PM.1 motor state (on/off)
36. Show pump A.PM.1 motor frequency
37. Show pump A.PM.2 motor state (on/off)
38. Show pump B.PM.1 motor state (on/off)
39. Show pump B.PM.1 motor frequency
40. Show pump B.PM.2 motor state (on/off)
41. Show pump B.PM.2 motor frequency
42. Show pump B.PM.3 motor state (on/off)
43. Show pump B.PM.3 motor frequency
44. Show pump B.PM.4 state (on/off)
45. Show throttle valve B.TV.1 position
46. Show throttle valve B.TV.2 position
47. Show sensor pump B.SP.1 state (on/off)
48. Show sensor pump B.SP.2 state (on/off)
49. Show automatic stop state status
50. Show safety stop state status
A.PM.2 / change pump A.PM.2 state (on/off)
B.PM.1 / change pump B.PM.1 state (on/off)
B.PM.1 frequency + / raise pump B.PM.1 motor frequency X Hz
B.PM.1 frequency - / lower pump B.PM.1 motor frequency X Hz
B.PM.2 / change pump B.PM.2 state (on/off)
B.PM.2 frequency + / raise pump B.PM.2 motor frequency X Hz
B.PM.2 frequency - / lower pump B.PM.2 motor frequency X Hz
B.PM.3 / change pump B.PM.3 state (on/off)
B.PM.3 frequency + / raise pump B.PM.3 motor frequency X Hz
B.PM.3 frequency - / lower pump B.PM.3 motor frequency X Hz
B.PM.4 / change pump B.PM.4 state (on/off)
Sensor pumps / change pump B.SP.1 and B.SP.2 state (on/off)
B.TV.1 + / open X % throttle valve B.TV.1
B.TV1 - / close X % throttle valve B.TV.1
B.TV.2 + / open X % throttle valve B.TV.2
B.TV.2 - / close X % throttle valve B.TV.2
Reset / Reset for safety stop and automatic stop states

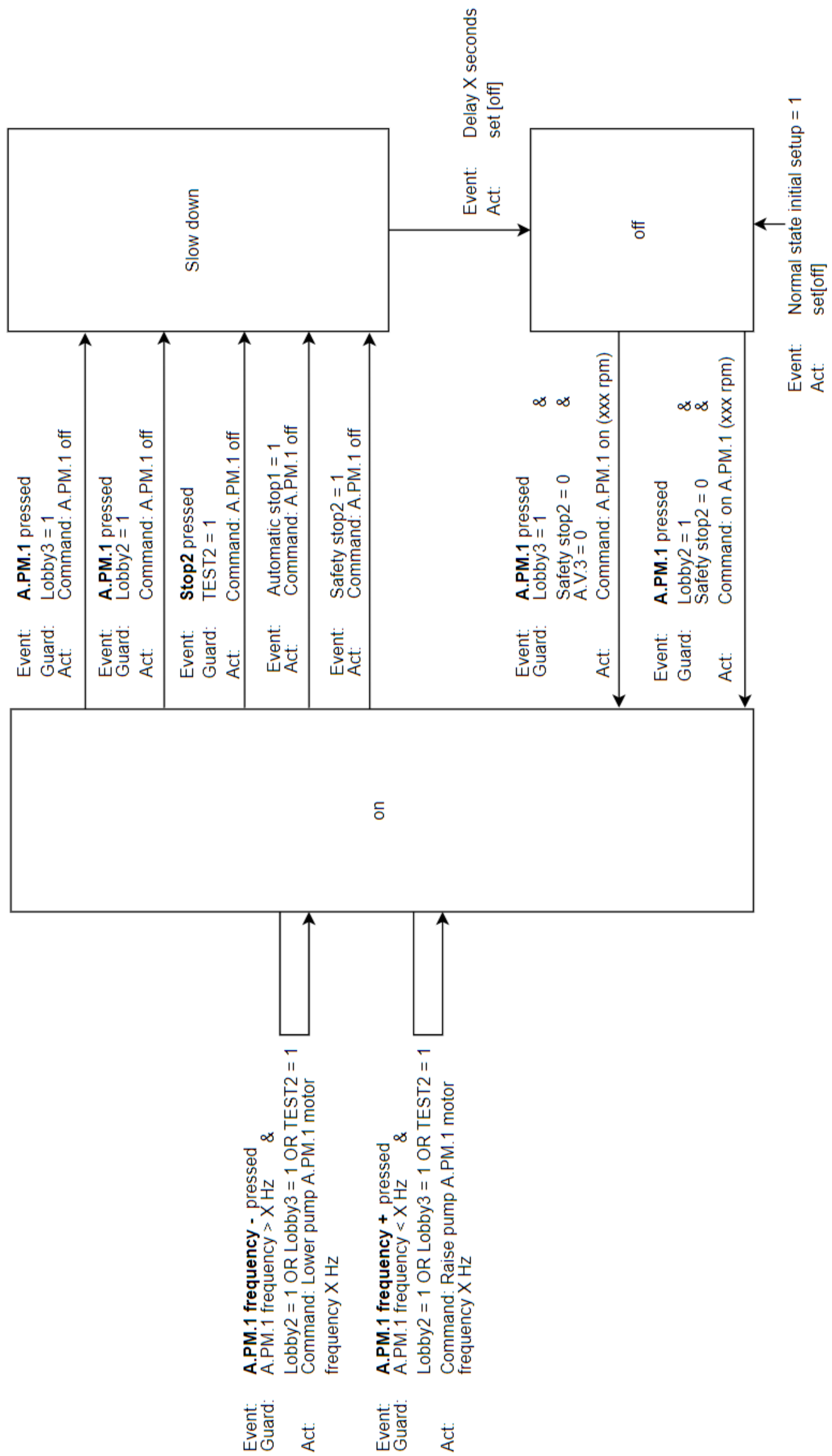
Appendix 8. Throttle valve B.TV.1 state machine diagram.



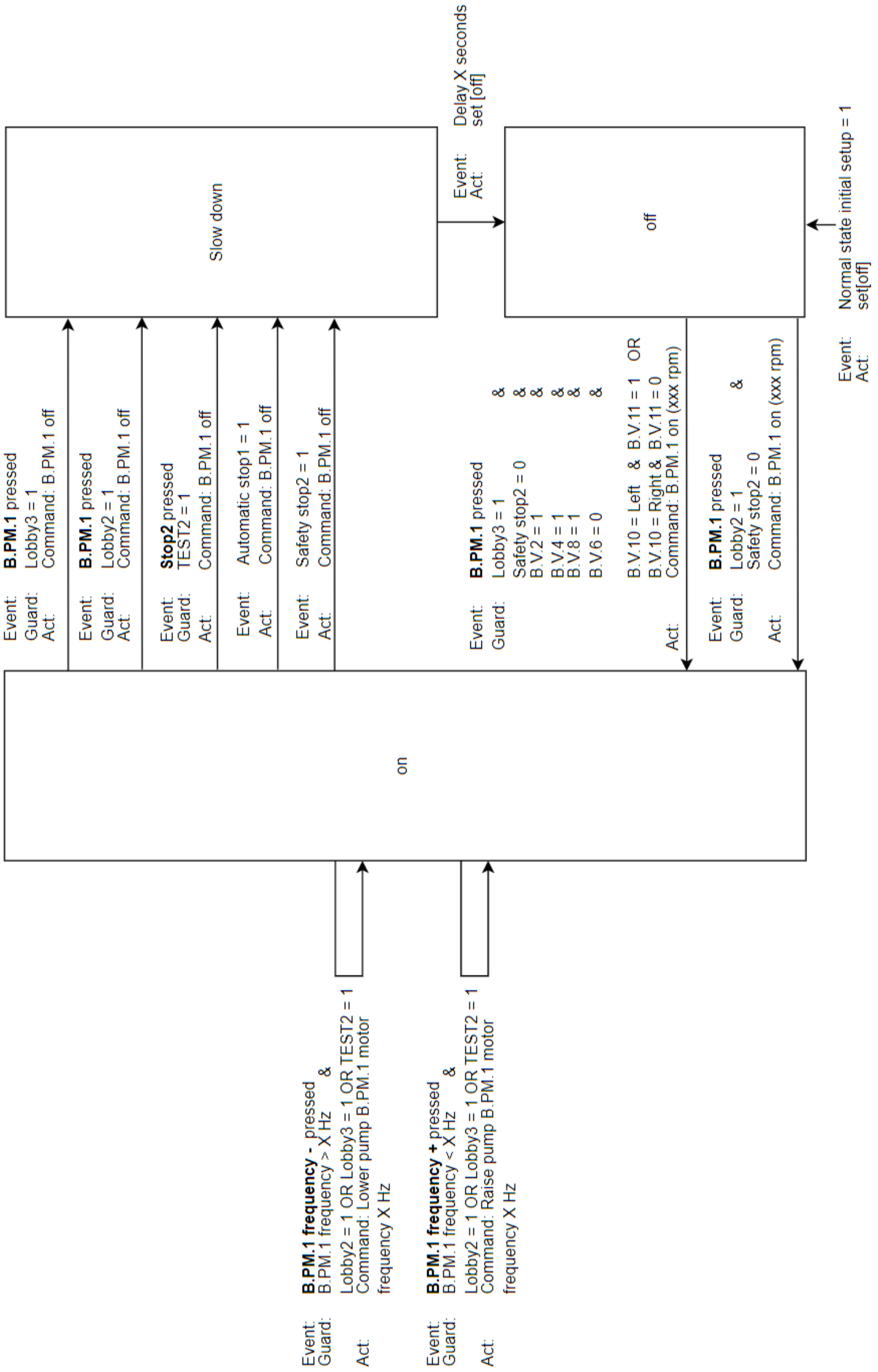
Appendix 9. Throttle valve B.TV.2 state machine diagram.



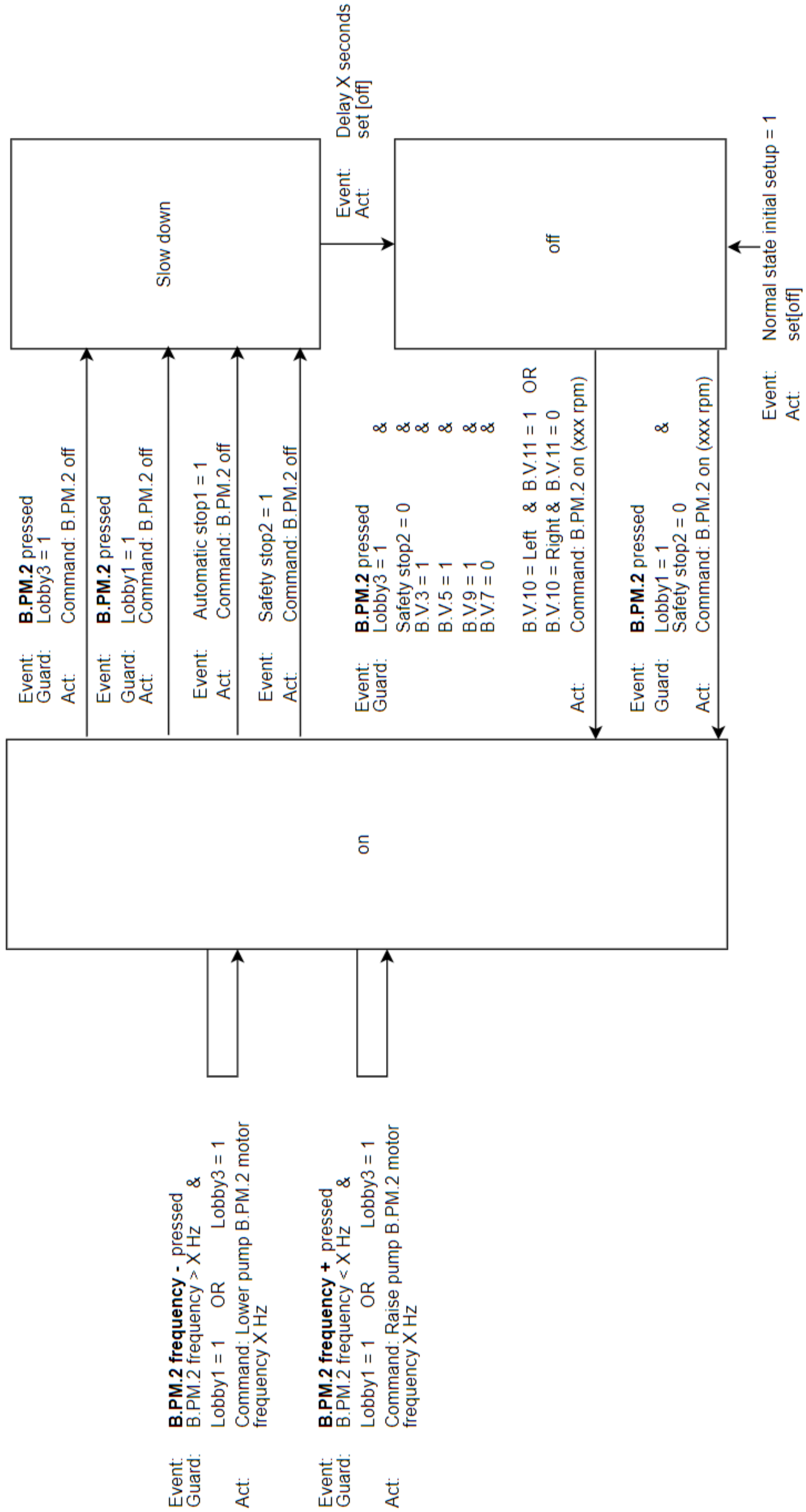
Appendix 10. Pump A.PM.1 state machine diagram.



Appendix 11. Pump B.PM.1 state machine diagram.



Appendix 12. Pump B.PM.2 state machine diagram.



Appendix 13. Pump B.PM.3 state machine diagram.