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Modeling and implementation of central functions in a nuclear power plant

Master's Thesis in Systems, Control and Mechatronics

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Abstract

Knowledge and quality of process variable measurements are essential for a safe nuclear reactor operation. A thorough understanding of how measurements are obtained yields valuable information regarding the safety analysis of the plant, enabling more accurate studies of hypothetical critical scenarios. Regarding the benefits of an increased quality of measurements, there are both safety and financial aspects. An increased quality implicitly means a greater reliability. In turn this results in a reactor operation which is undisturbed by faulty measurements and is properly aborted when required due to undesirable reactor conditions.

This thesis contributes with results which increases both the knowledge and quality of process variable measurements in a nuclear reactor. The results presented are divided into two categories. The first category comprises models of dynamics associated with the acquisition, processing and distribution of measurement signals. The second category comprises some of the possible adjustments of the water level measurement equipment to increase measurement credibility. Models of the first category are represented as block diagrams consisting of component models based on plant documentation. The presented adjustments comprising the second category are based on regression analysis where process variable data is used to fit parameters of statistical models. Each adjustment is validated using an independent set of collected process variable data.

The models show that there are reasons to believe that an update of the current models implemented in the safety analysis software is required. The adjustments presented show that it is possible to solve the measurement quality issue with relatively simple means. An adjustment based on a linear estimate of the water level measurements can favorably be applied and is presented as a thesis suggestion. A utilization of these results would likely improve the credibility of both the plant's safety analysis and the measurements of the reactor water level.

Acknowledgements

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1

Introduction

This chapter provides an introduction to the thesis consisting of three sections. The first section, *1.1 Background*, presents descriptions of thesis notations and describes the need for the contribution of the thesis. The second section, *1.2 Contribution*, presents the thesis contribution and the third, *1.3 Outline*, summarizes the structure of the thesis.

1.1 Background

The power production of the nuclear power plants in Sweden comprises a substantial part of the total Swedish power production. Companies that operate these plants continuously work with improvements of the reliability and safety of plant operation. The nuclear reactor is central for improving reliability and safety of plant operation due to its key role in the nuclear power plant [1].

The safety of operation of a nuclear reactor is to a large extent based on measurements of physical quantities such as steam pressure, water level and neutron flux. This is due to that these measurements are used as inputs to protection, control and surveillance systems of the reactor. The physical quantities which are measured and used for safety and control purposes are denoted *process variables* [2][3][4].

Studies of how the process variables change during simulations of critical scenarios associated with nuclear reactor operation do to some extent comprise the safety analysis of the plant. The safety analysis of a nuclear power plant is essential for improving the safety of operation and is partly carried out using a simulation software [5].

A complete study of the change of a process variable for a simulated scenario requires a consideration of the dynamics associated with the acquisition, processing and distribution of the process variable measurement. Knowledge of these dynamics yields knowledge of what can be expected of the measurement equipment in a critical situation. This regards e.g. the time delay between the occurrence of a critical process variable value in the reactor and the initialization of a safety procedure of the reactor protection system.

The dynamics are studied in the safety analysis by the use of models included in the simulation software [5][6][7].

The company that operates the nuclear power plant in Oskarshamn, *OKG AB*, is currently making efforts to improve the quality of the safety analysis of their largest nuclear reactor, *O3*. Recent observations made by *OKG AB* staff suggest that there may be some faulty parameters included in the models of the dynamics currently included in the simulation software. Such faulty model parameters may decrease the credibility of the safety analysis. *The first contribution* of this thesis is to provide new developed models of the dynamics which show that the existing models likely include faulty model parameters.

Measurements of process variables in the *O3* reactor are obtained by measurement equipment configured for both a wide- and a narrow range of process variable values. Within the measurement range of the narrow range equipment both the wide- and narrow range equipment is supposed to yield the same measurements. There is however a problem with a specific measurement (visualized in Figure 1.1); the wide range water level measurements deviate from the narrow range measurements when the reactor power output is high. The reason to the problem is that the wide range measurement sensors in the reactor are affected by flow dynamics associated with the main circulation pumps. *The second contribution* of this thesis is to provide a solution to the problem. The solution consists of counteracting the deviation using a linear estimate of the difference between the narrow- and wide range measurements. The estimated difference is added to the wide range measurement aligning it with the more credible narrow range measurements [3].

The equipment used to obtain, process and distribute measurements of a process variable is denoted a *measurement function*. Measurement functions are important for both the first and second thesis contributions. The first thesis contribution consists of new developed models of dynamics associated with the measurement functions. The second thesis contribution consists of a suggested change of a wide range water level measurement function.

Measurement functions

A measurement function is composed by a set of components, the *measurement function components*. The structure of a measurement function can be visualized by a block diagram called the *measurement function structure*. In a measurement function structure each block represents a measurement function component. A measurement function structure example is visualized in Figure 1.2. As visualized, the measurement function input is generated by measurement sensors. Outputs are distributed to a number of systems including systems of control and protection. Each output is associated with a specific *branch* of the measurement function structure [2][3][5][7].

Process variables are measured by both wide- and narrow range measurement functions. To increase reliability and safety of plant operation each wide- and narrow range measurement is carried out by a number of identical measurement functions. All iden-

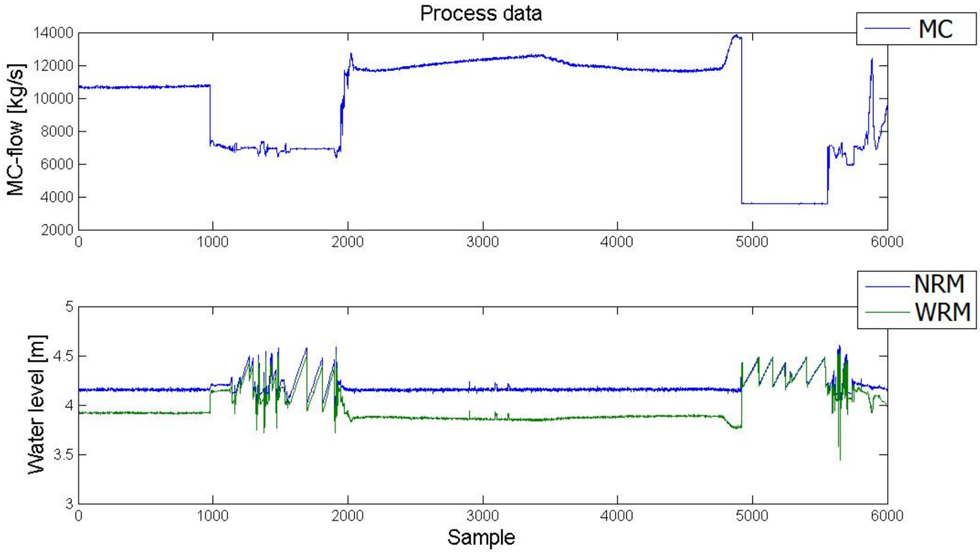

Figure 1.1: A visualization of the problem; the wide range water level measurements deviate from the narrow range measurements when the power output of the reactor is high. Above: The main circulation flow (MC), typically a high level of main circulation flow is associated with a high level of reactor power output. Below: The narrow range measurements (NRM) and the wide range measurements (WRM).

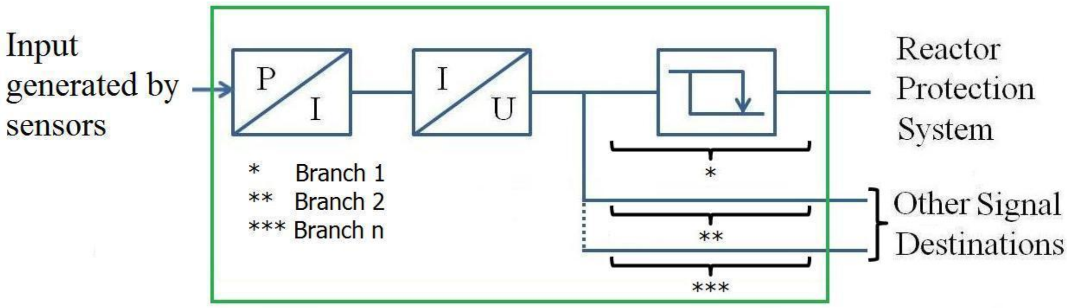

Figure 1.2: Within the green boundary: a measurement function structure, each block represents a measurement function component.

tical measurement functions providing values of a process variable in a specific range compose a *measurement function set*. A study of a single measurement function hence implicitly yields a study of a set of measurement functions. A picture is provided in Figure 1.3 which clarifies the difference between a measurement function and a measurement function set [2][3][7].

Each measurement function has its own plant documentation identity. An example is: *set 1P (3.211.KA101)*. The first part, *set 1P*, reveals that it belongs to measurement function set number one associated with the process variable P. The letter P corresponds to reactor steam pressure. Other possible letters are: L corresponding to the

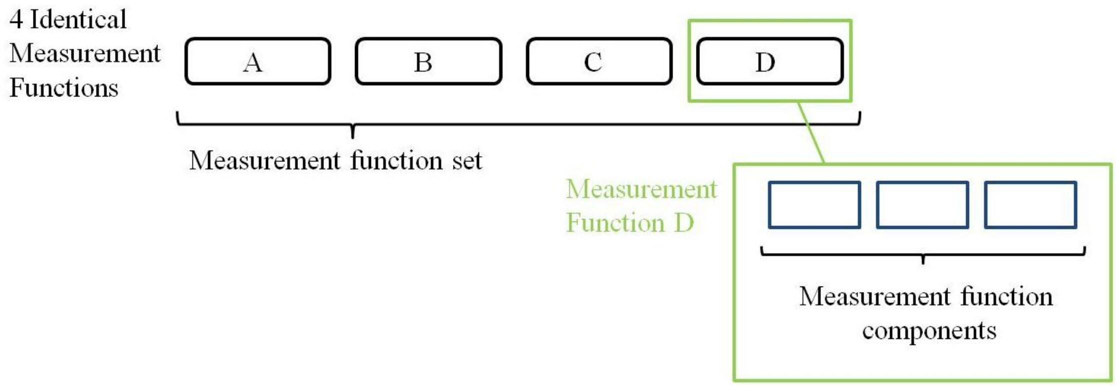

Figure 1.3: A measurement function and a measurement function set.

water level in the reactor, N corresponding to the neutron flux in the reactor and T corresponding to temperature measurements. The part within parenthesis, *3.211.KA101* is a measurement function identity number. Often a measurement function set consists of four identical measurement functions. The letter A in the identity number *3.211.KA101* then denotes the first measurement function of the four, A-D, in the set. All measurement functions sharing the same letter constitute a set of measurement functions called a *sub* [3][4][7].

The *physical implementation* of a measurement function is the realization of its measurement function structure i.e. the way the measurement function components are connected and located in the plant.

Measurement function components

The measurement functions frequently incorporate a number of specific measurement function components. These are

1. Transmitters
2. Converters
3. Trip amplifiers
4. Isolation amplifiers
5. Amplifiers
6. Filters

Their symbols are shown in Figure 1.4.

A transmitter is a component used to convert a measurement of a process variable to a processable signal and to distribute it. The symbol used for a transmitter is equal to the symbol of a converter due to a plant documentation standard [7].

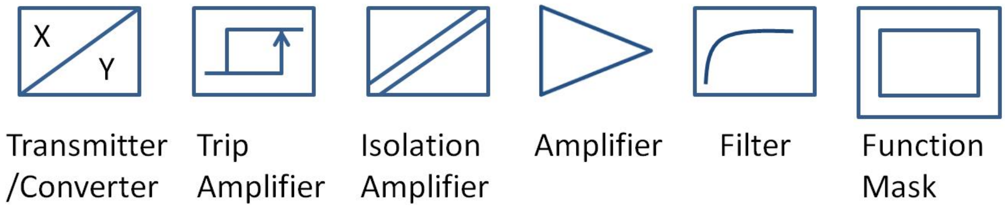

Figure 1.4: Frequently occurring measurement function structure symbols.

The trip amplifiers incorporated in the measurement function structures are essential for the reactor protection system as their outputs act as alarm triggers. The trip amplifiers send out binary signals and are configured with hysteresis. When the input activation value has been exceeded, corresponding to a maximum/minimum allowed process variable value, the trip amplifier is activated. When activated, the output is changed to the complement triggering an alarm in the reactor protection system. For the trip amplifier to deactivate, the input needs to reach a deactivation value which is well below/above the activation value depending on the configuration of the trip amplifier. A measurement function trip amplifier can also activate in the event of a measurement function failure. The four possible trip amplifier configurations are summarized in Figure 1.5 [8].

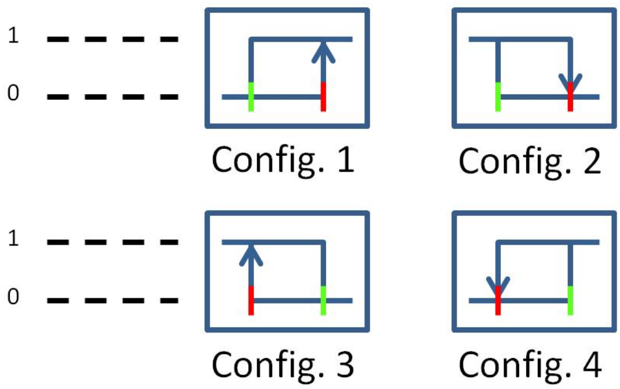

Figure 1.5: The trip amplifier configurations. The red marking represents the activating input and the green marking represents the deactivating input.

An isolation amplifier is a measurement function component which provides an electrical safety barrier between electrical systems while passing a signal through. Ideally the signal is not subject to change while being passed through [9].

Amplifiers incorporated in the measurement functions are used to amplify signals which have been subject to undesired amplitude attenuation in preceding measurement function components [7][8].

A filter incorporated in a measurement function performs a predefined filtering of its input signal. Examples of filters are low-pass filters which attenuate high-frequency signal content.

The symbol denoted ”function mask” represents a set of components. It is used to give a single symbol representation of an involved series of components.

Developed measurement function models

In the safety analysis each measurement function is represented with a block diagram where each block is associated with a measurement function component. A block can either represent the operation or the dynamics associated with the operation of a measurement function component. This block diagram representation of a measurement function is denoted a *measurement function model*. An example of a developed measurement function model is presented in Figure 1.6 [5][6].

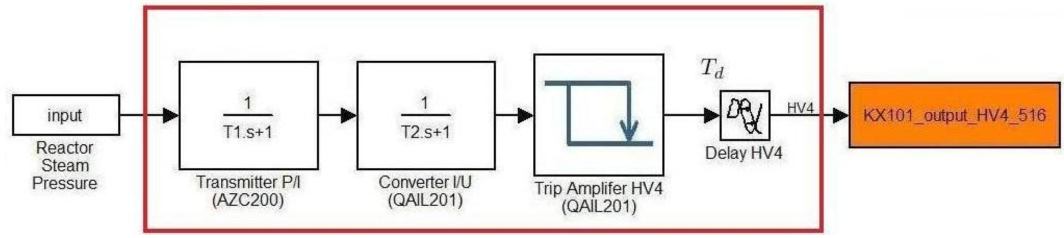

Figure 1.6: Within the red boundary: the corresponding measurement function model to the measurement function structure in Figure 1.2. Each block either represent the operation or the dynamics associated with the operation of a measurement function component.

For the *OKG AB* reactor *O3* there is plant documentation covering details on all measurement function components. A data sheet for a measurement function component, e.g. a current-to-voltage converter, typically provides a first order filter approximation of the dynamics associated with the component. Dynamics of measurement function components are modeled according to these first order filter approximations in the developed measurement function models. Measurement function components with negligible dynamics are left out of the measurement function models. The dynamics of a measurement function component is considered to be negligible if the time constant of its component model is significantly smaller than the time constants of the other component models in the same measurement function [5][8].

Solving the problem with the deviating water level measurements

Logged process variable data presented in Figure 1.1 show that wide range measurements of the water level in the *O3* reactor deviate from the narrow range measurements.

The problem with the deviating wide range measurements can be solved by tuning the wide range measurements with the narrow range measurements. This can be achieved by an adjustment of each of the wide range measurement functions. The adjustment consists of adding a measurement function component which adds the estimated measurement deviation from the narrow range measurements to the wide range measurements. An estimate of the deviation is calculated using logged process variable measurement data.

Recent updates of the *O3* reactor has limited the amount of logged process variable measurement data available for estimation of water level measurement deviation. Available process variable measurement data is limited to data for the year 2012 and the first quarter of 2013.

1.2 Contribution

The contribution consists of:

- Developed measurement function models for measurement functions providing measurements of steam pressure, water level and neutron flux. The developed measurement function models based on plant documentation include parameters which differ from the parameters of the existing measurement function models. This suggests that the existing models potentially incorporate faulty parameters. [Chapter 3]
- A suggested solution to the problem of the undesirable water level measurement deviation. The solution consists of incorporating an additional measurement function component within the wide range measurement function. This component adds the estimated measurement deviation between the outputs of the wide- and narrow range measurement functions to the output of the wide range measurement function. This deviation estimate is linear and is based on measurements of the main circulation flow. [Chapter 5]

1.3 Outline

The second chapter, *Chapter 2. Nuclear power basics*, covers basics on nuclear power forming a context for the modeling and implementation of measurement functions associated with the *OKG AB* reactor *O*3. Even though the chapter does not provide any critical thesis related information it serves as a succinct introduction to the area of nuclear power. The first main thesis contribution is presented in the following chapter, *Chapter 3. Existing and developed measurement function models.* An analysis of the existing and developed measurement function models is carried out in *Chapter 4. Analysis of existing and developed measurement function models.* The second main thesis contribution is presented within *Chapter 5. Counteracting undesirable water level measurement function behavior.* The last chapter, *Chapter 6. Conclusions*, provides conclusions regarding the thesis contribution.

2

Nuclear power basics

This chapter provides succinct basics on nuclear power and the nuclear power plant as a system. The first section, *2.1 Neutron physics*, mainly summarizes relevant neutron-matter interactions. Sections: *2.2 The nuclear power plant* and *2.3 The nuclear reactor* touches upon plant design and plant operation.

2.1 Neutron physics

Nuclei are composed of neutrons and protons, both of which are nucleons. Neutrons are similar to protons but lack an electric charge. The lack of electric charge gives neutrons a penetrating property, due to the small extent of interaction with electron shells of atoms. Free neutrons can interact with matter in several different ways e.g. scattering, capture and fission. The probability distribution of interaction is dependent on the circumstances; fission for example requires the neutron to interact with a fissionable nuclide. For an increased probability of fission, the neutron energy should be relatively low [1][10].

A general fission process in a Uranium based nuclear reactor consists of a neutron splitting a heavy nucleus into two medium-heavy nuclei while releasing two to three new neutrons along with energy [1].

2.2 The nuclear power plant

There is a number of nuclear power plants in operation around the world. Although designs differ, a common denominator is the utilization of nuclear fission for extraction of nuclear energy in all nuclear reactors. The nuclear power plants operated in Sweden are either based on *Boiling Water Reactor* (BWR) or *Pressurized Water Reactor* (PWR) designs. The three nuclear reactors in operation in Oskarshamn, *O1*, *O2* and *O3* are all BWR:s [11].

The concept of utilizing nuclear fission in a BWR is based on using the kinetic energy of steam produced by the boiling of water in the reactor. Steam turbines are used to transform the kinetic energy into mechanical energy in order to power a generator. The generator transforms the mechanical energy into electrical energy, which is distributed over the power grid. The steam produced in the reactor and utilized in the steam turbines is condensed and returned to the reactor. Notable is that this water-steam cycle is a closed system and that the water is in direct contact with the nuclear fuel [11].

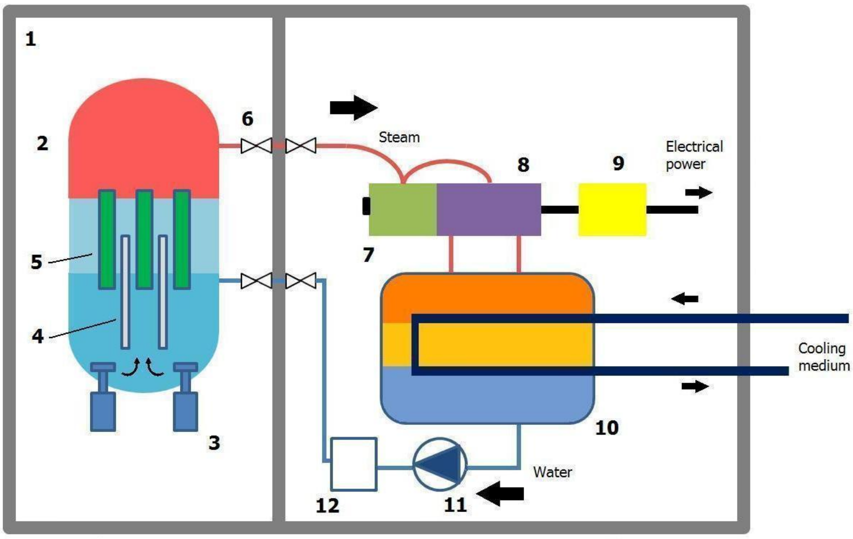

Figure 2.1: Simplified diagram showing the main process in a BWR based plant. The name of each enumerated object is presented in Table 2.1.

Table 2.1: The name of each enumerated object in Figure 2.1.

Object no.	Object name
1	Reactor containment
2	Reactor pressure vessel
3	Circulation pumps
4	Control rods
5	Fuel
6	Isolation valves
7	High-pressure turbine
8	Low-pressure turbines
9	Generator
10	Condenser
11 & 12	Feedwater pumps and preheaters

2.3 The nuclear reactor

The boiling of water in the BWR is powered by the energy release in the fission processes. It was previously stated that the probability for fission is increased when the neutron energies are decreased. The decrease of neutron energies is made in the reactor using a moderator. A moderator slows down neutrons (decreasing their energies) via scattering interactions. The light water surrounding the fuel elements in the BWR works both as supply for steam production and as a moderator [1].

From an operational perspective the number of fission processes per unit time should be optimized around a beneficial operating point. There are two ways of controlling this number in a BWR. The first is the speed of the main circulation pumps. A speed decrease of the main circulation pumps results in a greater reactor void (steam/liquid-ratio). This decreases the density of water surrounding the fuel elements which decrease the probability of fission interaction. The second control option is the use of control rods. The control rods are situated in between the fuel elements in the reactor and can be extended to desired extents. The function of the control rods is to absorb neutrons preventing fission processes. A high speed of the main circulation pumps and a low level of control rod extension increases the probability of fission interactions and is hence associated with a high level of reactor power output [1].

3

Existing and developed measurement function models

This chapter provides the first main contribution of the thesis, the developed measurement function models. The chapter consists of three main sections where each presents information for measurement function sets associated with the same process variable. The information provided consists of the measurement function structure, the existing measurement function model and the developed measurement function model of each measurement function set.

3.1 Measurement functions: steam pressure

The measurement functions providing steam pressure measurements measures the gauge pressure in the upper regions of the reactor. There are two steam pressure measurement function sets. The first set, *set 1P* (3.211KX101) provides narrow range measurements and the second set, *set 2P* (3.211.KX111), provides wide range measurements [3].

3.1.1 Measurement function set 1P (3.211.KX101)

The narrow range steam pressure measurement function set is configured for an input range associated with normal reactor operation [12].

Measurement function structure

The measurement function structure is presented in Figure 3.1. Measurement function components include a transmitter, a current-to-voltage converter and a trip amplifier [7].

Measurement function model: existing

The existing measurement function model of the *set 1P* measurement functions is presented in Figure 3.2. The measurement function model includes a single first order filter

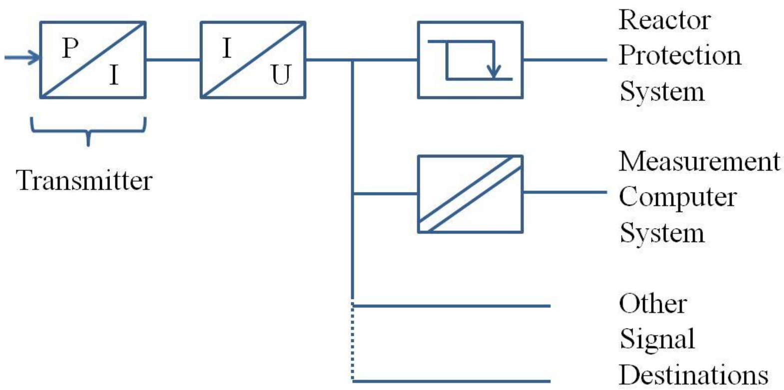

Figure 3.1: Visualization of the measurement function structure of the *set 1P* functions.

with a time constant of T=0.1s and a trip amplifier block with an associated processing delay of $0.036s \leq T_d \leq 0.054s$. A typical value for this delay is $T_d = 0.045s$. This typical value corresponds to the expected value

$$E[T_d] = \int_{-\infty}^{\infty} \tau f(\tau) d\tau = \int_{0.036}^{0.054} \tau f(\tau) d\tau = 0.045s, \tag{3.1}$$

where $f(\tau)$ is the density function of the continous random variable T_d [6][13].

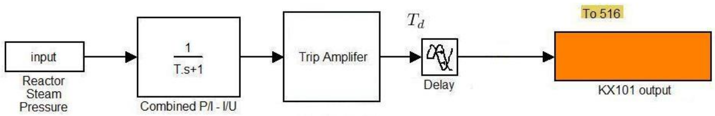

Figure 3.2: Block diagram of the existing *set 1P* (3.211.KX101) measurement function model.

Measurement function model: developed

The measurement function structure is shown to include both a transmitter and a current-to-voltage converter in Figure 3.1. Each component has its own dynamics and is according to plant documentation possible to model as a first order filter. The transmitter can be modeled as a first order filter with a time constant of $T_1 = 0.3$s and the converter can be modeled as a first order filter with a time constant of $T_2 = 0.02$s. The trip amplifier is associated with a time delay of T_d=0.045s.

The mathematical representation of the developed *set 1P* measurement function model is formed by a block diagram presented in Figure 3.3 [8][14].

3.1.2 Measurement function set 2P (3.211.KX111)

The outputs of the wide range *set 2P* measurement functions are utilized as inputs to the water level measurement functions enabling a required density compensation [3][12].

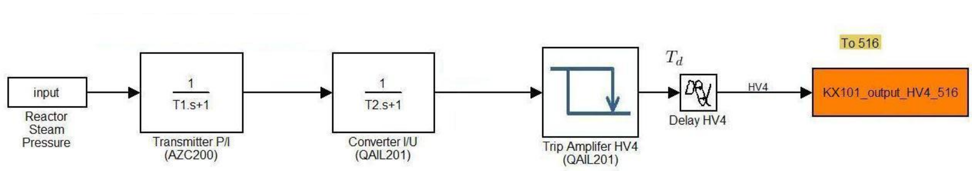

Figure 3.3: Block diagram of the developed *set 1P* (3.211.KX101) measurement function model.

Measurement function structure

The measurement function structure of the *set 2P* measurement functions is visualized in Figure 3.4. It is similar to the measurement function structure of the *set 1P* measurement functions, though with more branches associated with the reactor protection system [7].

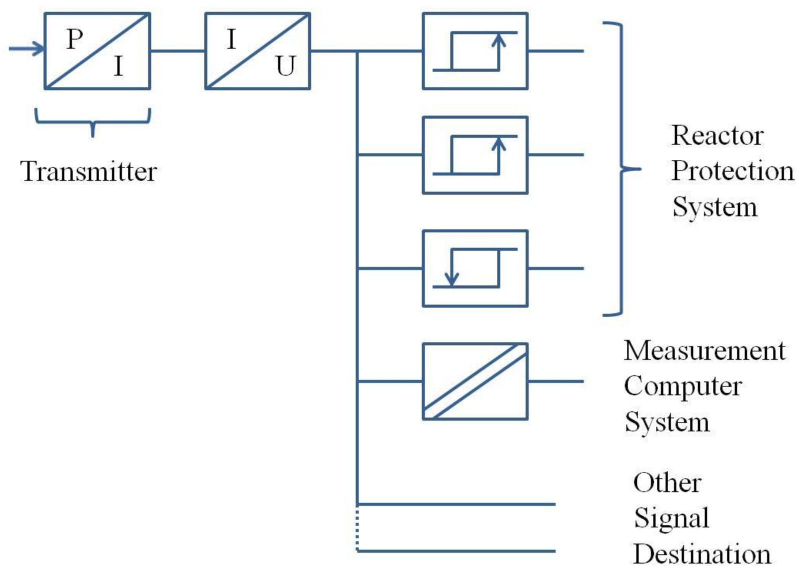

Figure 3.4: Visualization of the measurement function structure of the *set 2P* (3.211.KX111) functions.

Measurement function model: existing

The existing model of the *set 2P* measurement functions is identical to the existing model of the *set 1P* measurement functions. The block diagram of the existing measurement function model of the *set 2P* measurement functions is presented in Figure 3.5 [6].

Measurement function model: developed

The main differences between the *set 1P* and *set 2P* measurement functions are the amount of branches associated with the reactor protection system and the input range

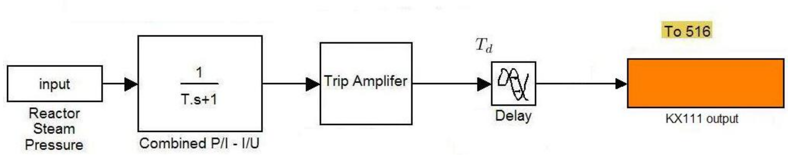

Figure 3.5: Block diagram of the existing *set 2P* (3.211.KX111) measurement function model.

configurations of the transmitters. A transmitter input range configuration change does not affect the dynamics of the transmitter. Also, the increased number of branches in the *set 2P* measurement functions include trip amplifiers with the same dynamics as the one included in each *set 1P* measurement function. This means that the measurement function component models used for the *set 1P* measurement function components can be applied for the *set 2P* measurement function components as well.

The mathematical representation of the developed *set 2P* measurement function model is formed by a block diagram presented in Figure 3.6.

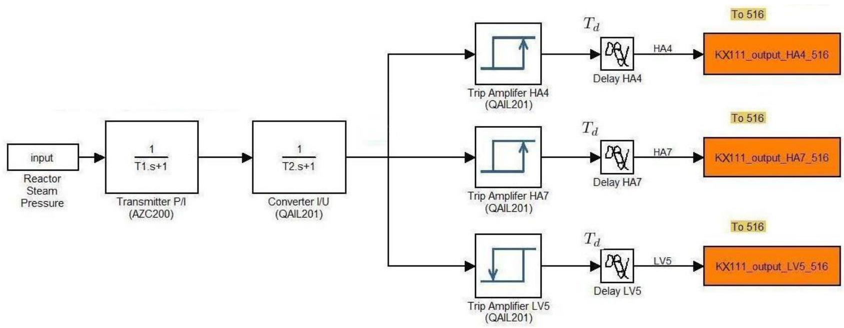

Figure 3.6: Block diagram of the developed *set 2P* (3.211.KX111) measurement function model.

3.2 Measurement functions: water level

The water level in the reactor is measured by six measurement function sets. Three of these supply the reactor protection system with alarm triggering signals and are the ones studied within this thesis. The water level measurement function sets, *set 1L* (3.211.KX401), *set 2L* (3.211.KX411) and *set 3L* (3.211.KX441) provide measurements of range width in ascending order. The measurements are carried out using a differential pressure method, utilizing a reference vessel. Unlike the steam pressure measurement functions, the water level measurement functions are dependent on more than one input. The extra inputs are used to compensate for medium density differences [3][12][14].

3.2.1 Measurement function set 1L (3.211.KX401)

The four *set 1L* water level measurement functions provide narrow range measurements. In addition to using the differential pressure measurement as an input the *set 1L* measurement functions also use measurements of temperature and steam pressure as inputs. The temperature measurements are provided by the *set 1T* (3.211.KX501) reference temperature measurement functions and the steam pressure measurements are provided by the *set 2P* measurement functions [3][15].

Measurement function structure

The *set 1L* measurement function structure is presented in Figure 3.7. It includes a transmitter, a current-to-voltage converter, a density compensation block and a set of trip amplifiers. A process where the extra inputs are used to adjust the output of the converter is incorporated in a density compensation block to carry out the necessary density compensation. This process consists of a number of mathematical operations carried out by several measurement function components masked as a single block in the measurement function structure in Figure 3.7. The adjusted voltage signal is distributed to the branches where it is processed by trip amplifiers before being sent to the reactor protection system [3][7].

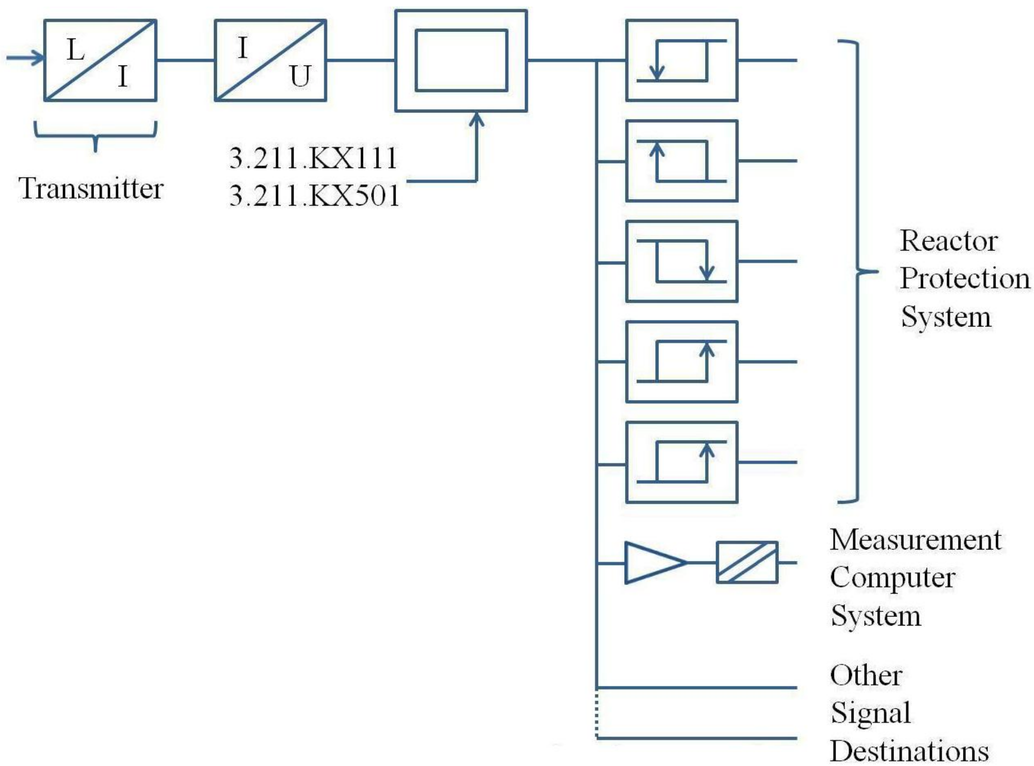

Figure 3.7: Visualization of the measurement function structure of the *set 1L* functions.

Measurement function model: existing

The existing measurement function model of the *set 1L* measurement functions is presented in Figure 3.8. Several first order filters are incorporated to represent the dynamics associated with measurement and processing of each input. *Filter 1* represents the dynamics associated with the measurement of the reference temperature and has a time constant of T_1=2s. *Filter 2* represents the dynamics of the transmitter measuring the differential pressure corresponding to the water level and has a time constant of T_2=0.12s. Before being sent to the *set 1L* measurement functions, the pressure measurements of the *set 2P* measurement functions are subject to filtering. This filtering is part of the existing *set 2P* measurement function model but is still represented in Figure 3.8 as *Filter 3* with a time constant of T_3=0.1s. *Filter 4* represents the dynamics of the density compensation process and has a time constant of T_4=0.5s. The delay associated with the processing of the trip amplifiers is $0.036s \leq T_d \leq 0.054s$, where $E[T_d] = 0.045s$ [5][6].

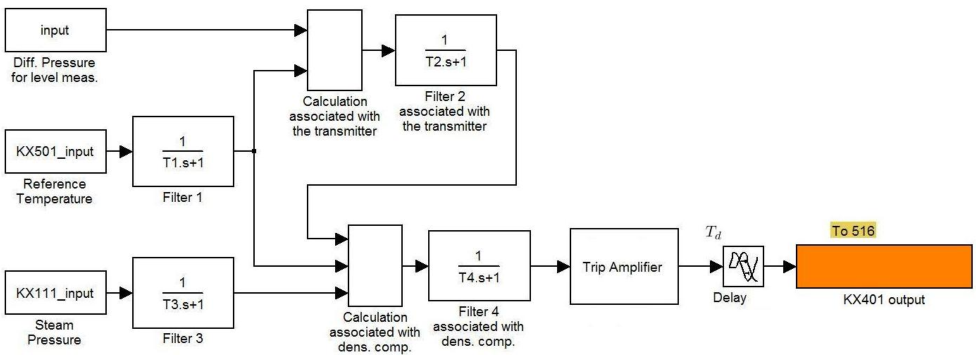

Figure 3.8: Block diagram of the existing *set 1L* (3.211.KX401) measurement function model.

Measurement function model: developed

For a basic configuration of the transmitter it can be modeled as a first order filter with a time constant of T_{1a}=0.3s. As opposed to the transmitters incorporated in the steam pressure measurement functions, the transmitters utilized in the *set 1L* measurement functions are configured such that the time constant is increased with T_{1b}=0.35s. This yields a first order filter model of the transmitter with a time constant of T_1=T_{1a}+T_{1b}=0.65s [12][14].

The dynamics associated with the measurement of the temperature used as input is modeled as a first order filter with a time constant of T_5=0.04s. The current-to-voltage converter is modeled as a first order filter with a time constant of T_2 = 0.02s [8][15].

The density compensation block of the measurement function structure comprises components such as summarizers, function generators and a multiplier. These are used to realize the mathematical operations carried out in the density compensation process.

The time constants associated with the first order filter models of the summarizers and function generators are of magnitudes $T \approx 1 \cdot 10^{-5}$s. The filter model time constant of the multiplier in the same block is about a hundred times larger. Alone it is used as the time constant for a first order filter representation of the dynamics of the density compensation block with T_3=0.005s. The trip amplifiers yield signal time delays in the same way as with the steam pressure measurement functions, a delay of T_d=0.045s [7][8][16][17][18][19].

The mathematical representation of the developed *set 1L* measurement function model is formed by a block diagram presented in Figure 3.9.

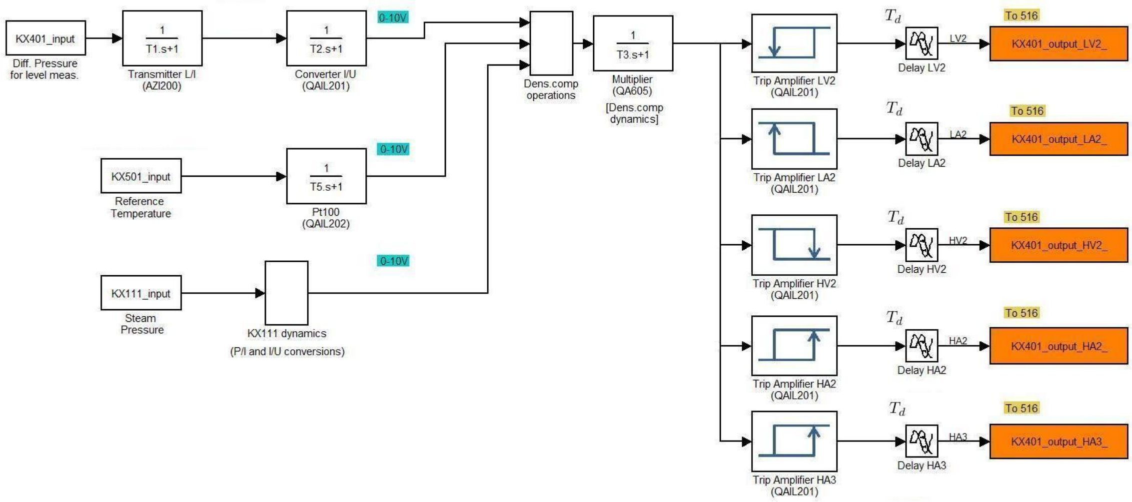

Figure 3.9: Block diagram of the developed *set 1L* (3.211.KX401) measurement function model.

3.2.2 Measurement function set 2L (3.211.KX411)

The four *set 2L* functions are configured to operate a wider region of water level inputs (differential pressures) than the *set 1L* functions. The additional inputs of pressure and reference temperature equal the inputs of the *set 1L* functions [3][7].

Measurement function structure

The *set 2L* measurement functions are structured in the same way as the *set 1L* measurement functions with a smaller set of branches associated with the reactor protection system. The measurement function structure is visualized in Figure 3.10 [7][20].

Measurement function model: existing

The existing measurement function model is based on the existing *set 1L* measurement function model. Filters 1-4 equal the ones of the existing *set 1L* measurement function model and the time delays associated with the trip amplifiers, T_d, are also equal [6].

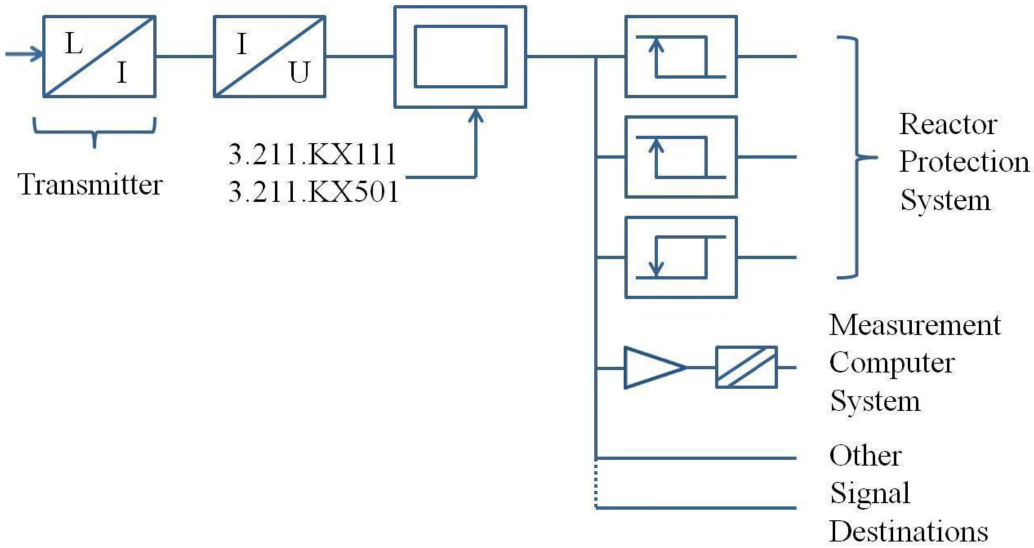

Figure 3.10: Visualization of the measurement function structure of the *set 2L* functions.

The block diagram of the existing measurement function model of the *set 2L* measurement functions is visualized in Figure 3.11.

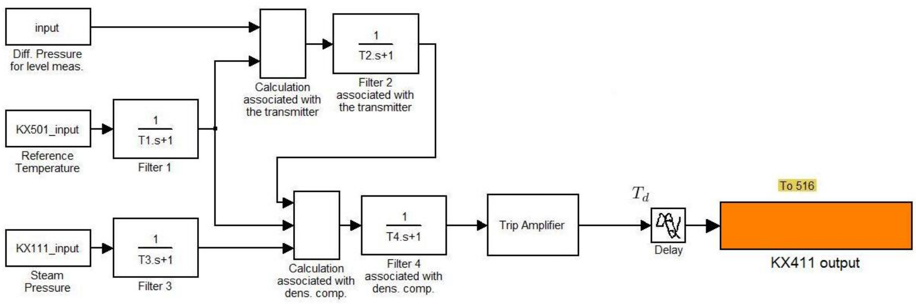

Figure 3.11: Block diagram of the existing *set 2L* (3.211.KX411) measurement function model.

Measurement function model: developed

The main differences between the *set 1L* and *set 2L* measurement function structures are differing branches associated with the reactor protection system and the configuration of the transmitter. As with the case of the steam pressure measurement functions the measurement function component models of the *set 1L* measurement functions can be used for the *set 2L* measurement functions as well. There is one exception however. The transmitter configuration does not only differ on the set region of inputs. It also affects the time constant of the component model. The developed *set 2L* measurement function model incorporates a first order filter model of the transmitter with a time constant of

T_1=T_{1a}+T_{1b}=0.3+1.5=1.8s [12][14].

The mathematical representation of the developed *set 2L* measurement function model is formed by a block diagram presented in Figure 3.12.

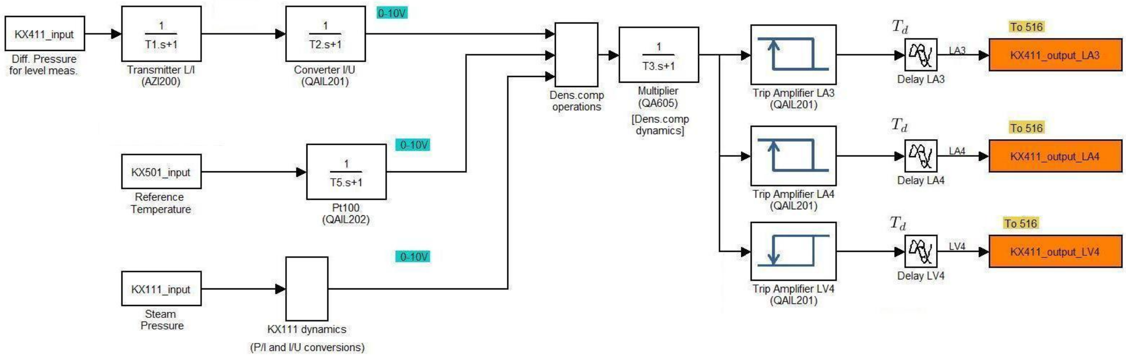

Figure 3.12: Block diagram of the developed *set 2L* (3.211.KX411) measurement function model.

3.2.3 Measurement function set 3L (3.211.KX441)

The *set 3L* water level measurement functions are configured to operate within an even larger region than the *set 2L* measurement functions. Like the *set 1L* and *set 2L* measurement functions the *set 3L* measurement functions have an incorporated density compensation of the level measurements. The difference is that the density compensation is dependent on three extra input signals, as opposed to two for the other functions. The function set utilizes reference temperature measurements from the *set 2T* measurement functions (3.211.KX511) along with inputs from the *set 1T* and *set 2P* measurement functions. The *set 2T* measurement functions are physically implemented in the plant in the same way as the *set 1T* measurement functions [7][12].

Measurement function structure

The *set 3L* measurement function structure is visualized in Figure 3.13. Apart from a differing set of trip amplifiers and an extra added input to the density compensation process, the structure of the *set 3L* measurement functions equal the structures of the *set 1L* and *set 2L* measurement functions [7].

Measurement function model: existing

Recent updates of *O3* have implied utilization of the *set 3L* measurement functions in the safety analysis of the plant to be necessary. Currently there is no existing measurement function model for the *set 3L* measurement functions [6].

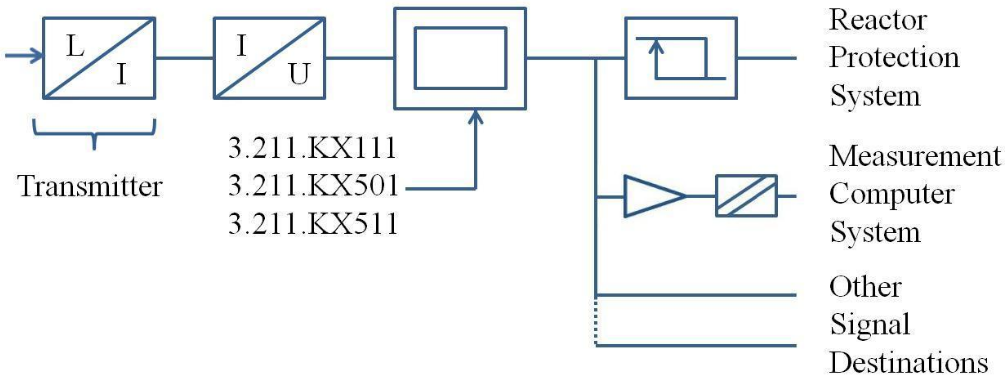

Figure 3.13: Visualization of the measurement function structure of the *set 3L* functions.

Measurement function model: developed

When comparing with the *set 1L* and *set 2L* measurement functions the extra input to the density compensation process does not result in an incorporation of additional division operations using multiplier components. This means that the dynamics of the density compensation process still can be modeled as a single first order filter with a time constant of T_3=0.005s. As the physical implementation of the *set 2T* measurement functions equal the implementation of the *set 1T* measurement functions, their measurement dynamics can be modeled in the same way. The measurement dynamics of the *set 2T* measurement functions are hence modeled as a first order filter with a time constant of T_5=0.04s [7][12][21].

Regarding the rest of the function components, each component can be modeled as the corresponding component in the *set 2L* measurement functions [7][12][21].

The mathematical representation of the developed *set 3L* measurement function model is formed by a block diagram presented in Figure 3.14.

3.3 Measurement functions: neutron flux

Measurement of the neutron flux density in a nuclear reactor requires a more sophisticated function structure relative measurement of pressure and water level. A large number of measurement channels with sensors placed within the reactor monitor the neutron flux density. Narrow range measurements of neutron flux density is desired within a wide range. In order to accomplish this the neutron flux measurement system is divided into three subsystems composed of narrow range measurement functions

- Source Range Monitoring (SRM)

- Intermediate Range Monitoring (IRM)

- Power Range Monitoring (PRM)

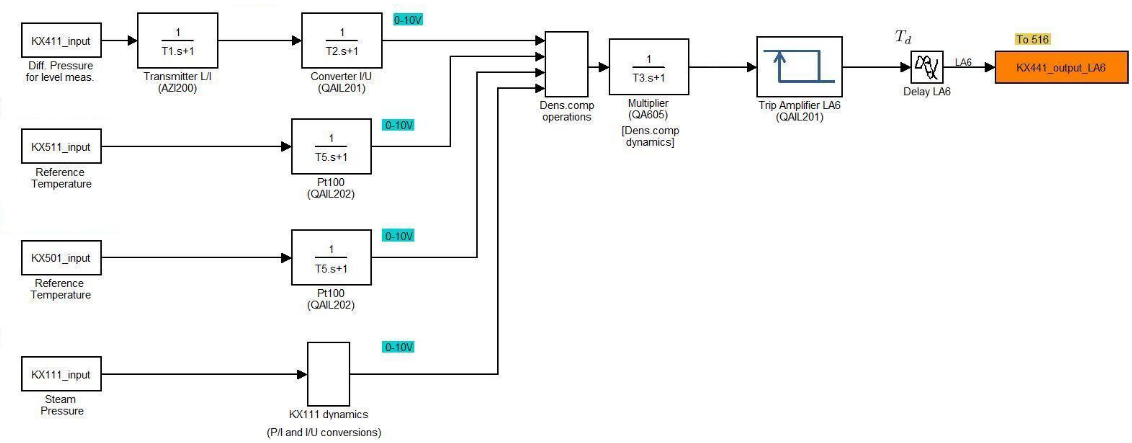

Figure 3.14: Block diagram of the developed *set 2L* (3.211.KX441) measurement function model.

Each subsystem has its own neutron flux density operation range. The system relevant for normal operating conditions, the PRM system, is divided into two subsystems where one is used for local power range monitoring (LPRM) and the other is used for average power range monitoring (APRM). The LPRM system provides information on momentary power distribution in the reactor core and the APRM system uses this information to provide information on the momentary total rector power [4].

3.3.1 Measurement function set 1N (3.531.KX077) APRM

The four *set 1N* measurement functions constitute the APRM system. Each *set 1N* measurement function yields a value of the total reactor power by averaging a set of the local values of neutron flux density provided by the measurement functions in the LPRM system. APRM system outputs headed for the reactor protection system are divided into two categories. The first category of outputs comprise signals which have been subject to trip amplifier processing dependent on fixed activation/deactivation values. The second category of outputs comprise signals which have been subject to trip amplifier processing with variable activation/deactivation values dependent on the main circulation flow [4].

Measurement function structure

Depending on which of the *set 1N* measurement functions regarded, between 36 and 40 LPRM measurement signals are used as inputs. Each LPRM measurement signal is associated with a fixed LPRM channel. There are 148 LPRM channels in total and each consists of a fission detector, an amplifier and signal processing equipment [4][7].

The averaging operation is carried out within a computer. The measurement function structure is visualized in Figure 3.15 [7].

The neutron flux is locally measured by fission detectors. The detectors are fission chambers and produce current signals proportional to the local neutron flux density in the reactor. This current signal is converted and amplified in a Fission-Chamber-Input component (FCI) . The output signal is a voltage signal of 0-10V sent to the input port of the computer, which consists of an input module. The module carries out successive approximation of the input taking 30 μs. The processor of the module runs a cyclic measurement acquisition with instantaneous value encoding for the 16 input ports taking 5ms/cycle [7][22][23].

The computer has a set execution interval of $T_e = 0.03$s. This means that all internal processing is carried out within this interval and that the computer inputs and outputs are updated every 0.03s [4].

Inside the computer each LPRM input signal is filtered creating the filtered LPRM signals. The mean of these are created yielding the APRM signal. The APRM signal is sent to eight circuit branches associated with the reactor protection system. For six of these eight branches the APRM signal is subject to further computerized filtering before being passed through the static trip amplifier of the branch. Each trip amplifier output exits the computer via a digital output module. Before reaching the reactor protection system each output passes a relay module and a Digital input unit[7].

There is one feature which differs two of the *set 1N* trip amplifiers from the rest. These two are configured online with activation/deactivation values set according to the current main circulation flow in the reactor (MC-flow (3.211.KX032)). Like the LPRM signals the MC-flow measurement is filtered within the computer after being read as a computer input. The filtered MC-flow is then passed to each measurement function branch which includes a configurable trip amplifier. Before reaching the trip amplifier of each branch the filtered MC-flow signal is passed through a branch specific measurement function block. This block determines the value of the configuration signal based on the magnitude of the MC-flow input [7].

Measurement function model: existing

The existing measurement function model of the *set 1N* functions is presented in Figure 3.16. It has two inputs, the averaged neutron flux density (APRM signal) and the MC-flow. Due to that all neutron flux measurement inputs, LPRM signals, are subject to the same dynamics before reaching the mean creation process they are represented as a single signal, the APRM signal. The main circulation flow input is included in the model for a representation of the online configuration of activation/deactivation values of the trip amplifiers [6].

In the existing measurement function model both inputs are separately subject to filtering before being processed by trip amplifiers associated with the reactor protection system. The main circulation flow input is passed through a single first order filter, *Filter 3*, with a time constant of $T_5 = 1s$ which represents the dynamics of the filtering carried out by the computer [6].

The APRM input is first filtered by a first order filter, *filter 1*, with a time constant of T_1=0.1s yielding the unfiltered APRM signal. The dynamics of the filter represents

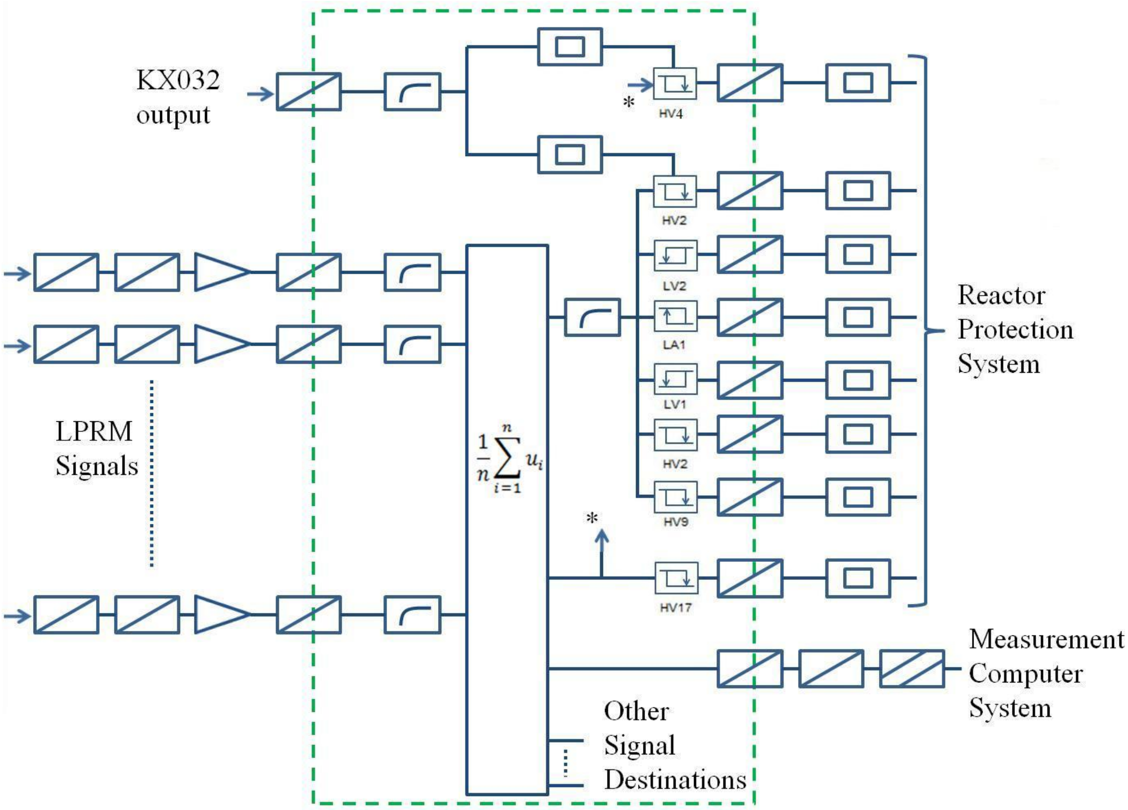

Figure 3.15: Visualization of the measurement function structure of the *set 1N* functions. The dotted green area represents the computer boundary.

the dynamics associated with the processing of each LPRM signal carried out before the APRM signal is retrieved. The unfiltered APRM signal is then sent to branches directly associated with the reactor protection system. For some of these branches the unfiltered APRM signal is filtered further before being sent to the corresponding trip amplifier. This further filtering comprises two filters in series

$$\frac{1+sT_2}{1+sT_3} \cdot \frac{1}{1+sT_4}, \tag{3.2}$$

where T_2=1.7s, T_3=3.6s and T_4=1.1s [6].

The total delay that an alarm triggering neutron flux level measurement is subject to passing the measurement function to the reactor protection system is denoted D. The delay is set to $0.06s \leq D \leq 0.1s$ with a typical (expected) value of $E[D]$=0.075s. This delay is associated with the computer execution interval and the delay of the relay module [6].

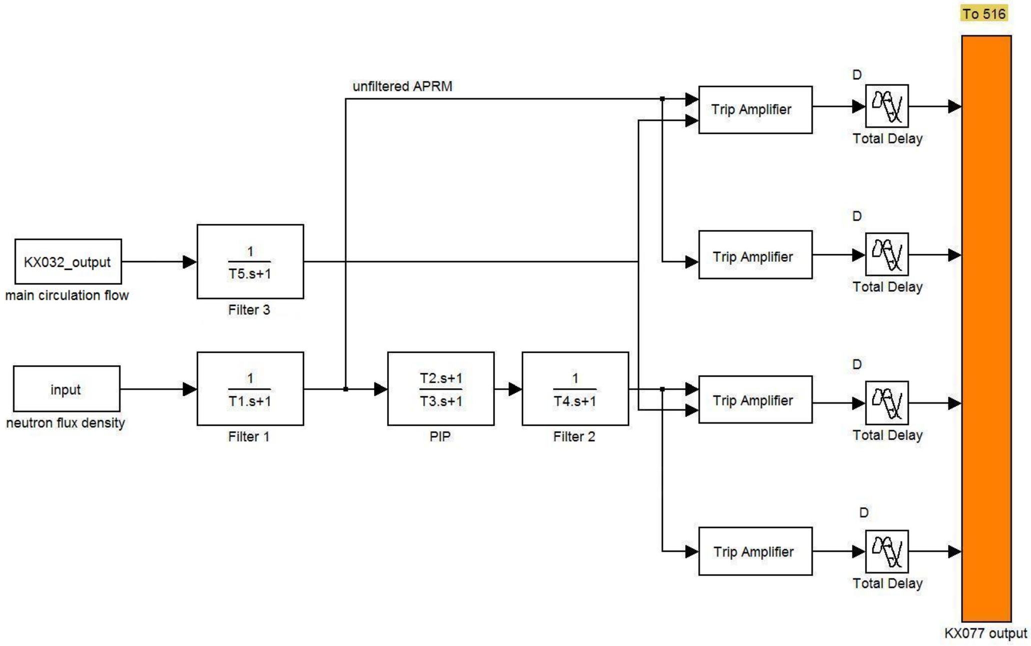

Figure 3.16: Block diagram of the existing *set 1N* (3.531.KX077) measurement function model.

Measurement function model: developed

The developed measurement function model utilizes the same inputs as the existing measurement function model. Regarding the neutron flux input, plant documentation suggests that the dynamics of a fission detector and a FCI combined are negligible. The output of this component combination is processed by an input module, the computer input port. When a new computer execution interval is initiated the last set of values obtained by the cyclic measurement acquisition of the computer input port are read for further processing in the computer [22][23].

The neutron flux computer input is passed through a first order filter with a time constant T_1=0.05s. Looking at the measurement function structure in Figure 3.15, this filter represents the dynamics of each of the filters which process the LPRM signals before they enter the mean creation process. The process of creating the mean of the LPRM signals can be considered as static, the dynamics of the process can hence be neglected. Modeling the dynamics of the *set 1N* measurement functions it is consequently possible to just use the APRM signal as the input instead of all the LPRM inputs and retroactively subject the signal to the filtering dynamics of the LPRM signal filtering. After the APRM signal has been subject to the retroactive dynamics in the developed model it is denoted the *unfiltered APRM* signal [7].

According to the measurement function structure of Figure 3.15 the unfiltered APRM signal is filtered further before being sent to six of the eight trip amplifiers associated with the reactor protection system. The filtering consists of two filters in series who equal the corresponding filters of the existing function model (3.2) [7].

The dynamics associated with the filtering of the main circulation flow input is also included in the developed measurement function model. Before being used for trip amplifier configuration the signal is subject to computerized filtering in a first order filter, *Filter 3*, with a time constant of $T_5 = 1s$. The function blocks which determine the configuration values to be sent to the trip amplifiers, denoted $pTA\ 1$ and $pTA\ 2$, are static [7].

The outputs of the trip amplifiers exit the computer via digital output modules. These modules are not associated with any processing delay. The output of each digital output module is passed through a relay module. The relay module dynamics can be modeled as a pure time delay. According to plant documentation the time delay associated with the relay module is $T_r \leq$ 0.04s with $E[T_r]$=0.03s. Keeping in mind that the computer execution interval is set to T_e=0.03s the expected minimum total function processing delay of each *set 1N* function is $D_{min} = T_e + E[T_r] = 0.06s$. Depending on when an alarm triggering neutron flux level arise in the reactor it may be delayed with as much as $D_{max} = 0.1s$, given a maximum relay delay $T_{r,\max} = 0.4$s. This is due to that a computer execution interval may just have been initiated when the alarm triggering level arises. It then takes an entire additional computer execution interval of time before an alarm triggering level can be passed through the system, $D_{max} = 2T_e + T_{r,\max} = 0.1s$. A reasonable assumption is that a typical value of the total processing delay of the *set 1N* functions is $D = 1.5T_e + E[T_r]$=0.075s, where an alarm triggering neutron flux level typically arises in the middle of a running computer execution [24][25].

The final component which the unfiltered/filtered APRM signals pass before reaching the reactor protection system is a digital input unit. It adjusts the digital relay output according to specification in a process with negligible dynamics. The unfiltered APRM signal sent to two of the eight branches associated with the reactor protection system skips the pre-trip amplifier processing (the two filters in series) but is otherwise subject to the same processing steps as the filtered APRM signals [7][26].

The mathematical representation of the developed *set 1N* measurement function model is formed by a block diagram presented in Figure 3.17. Measurement function model outputs are divided into categories of associated trip amplifier configurations.

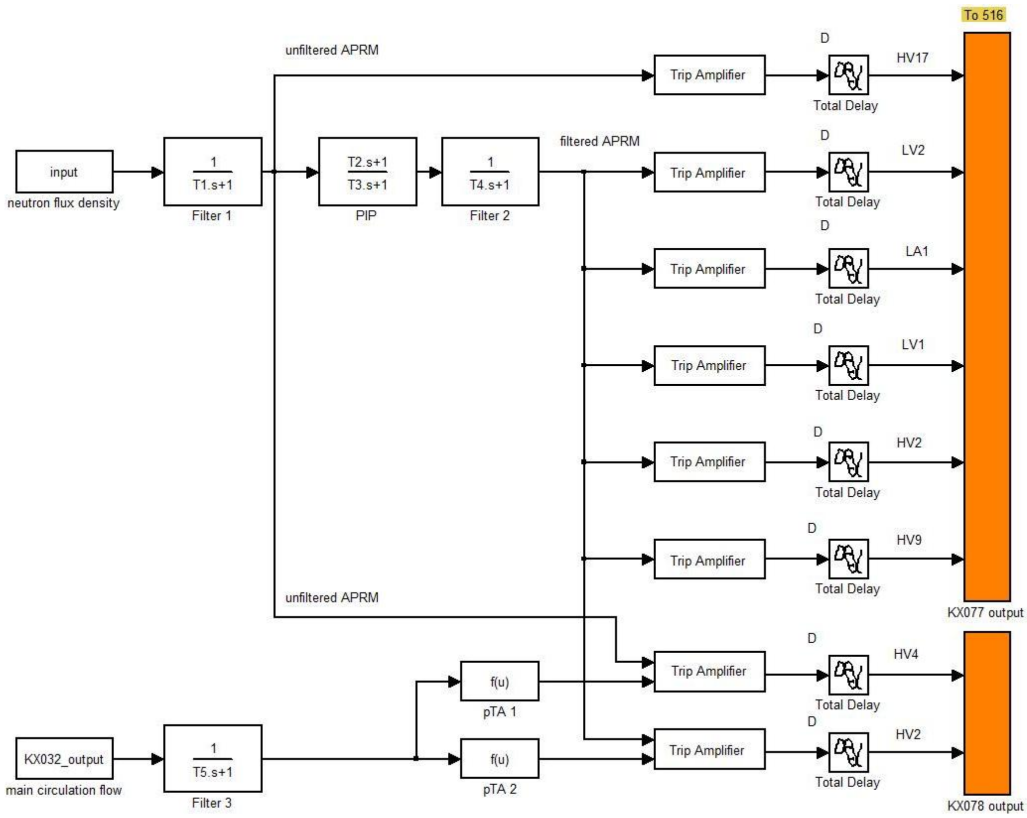

Figure 3.17: Block diagram of the developed *set 1N* (3.531.KX077) measurement function model.

4

Analysis of existing and developed measurement function models

A difference between an existing and a developed measurement function model yields a reason to question the credibility of the existing measurement function model. This chapter identifies differences by comparing the measurement function component models of the existing and developed measurement function models in *Chapter 3. Existing and developed measurement function models*.

4.1 Measurement functions: Steam pressure

There are two differences between the developed and the existing measurement function models of the *set 1P* and *set 2P* measurement functions. The first is that the developed measurement function models include separate first order filter models for both the transmitter and the current-to-voltage converter. The existing measurement function models instead combine the dynamics of the two measurement function components in a single first order filter model. The second difference is that the time constants of the measurement function component models included in the existing and developed measurement function models differ.

4.2 Measurement functions: Water level

The existing *set 1L* and *set 2L* measurement function models utilize a single first order filter model for the transmitter and converter combined, whereas the developed models use separate component models. A comparison of the existing and developed measurement function models shows that there are significant differences between parameters incorporated in the measurement function component models.

4.3 Measurement functions: Neutron flux

The existing and developed measurement function models show that there is a single difference between the two regarding the modeling of measurement function dynamics. The existing measurement function model includes a time constant of *Filter 1* which differs from the time constant of the corresponding filter in the developed measurement function model.

5

Counteracting undesirable water level measurement function behavior

This chapter presents a solution to the problem of the deviating wide range water level measurements. The first section, *5.1 Method of least squares and correlation* provides a theoretical background. The second section, *5.2 Estimates of water level measurement deviation*, presents estimates of how the water level measurement deviation is dependent on the values of three process variables. The estimates are based on regression analysis. Section *5.3 Adjustments to counteract the measurement deviation* presents some of the possible adjustments of the *set 2L* measurement functions based on the deviation estimates. The last section, *5.4 The suggested solution to counteract the deviating water level measurements* provides a suggested measurement function adjustment.

5.1 Method of least squares and correlation

This section provides a brief explanation of the method of least squares. To a lesser extent the section also describes linear correlations and the forming of confidence intervals.

For simplicity the method is explained by the problem of fitting the line $y = \beta_0 + \beta_1 x$ to a set of data $\{(x_i,y_i) : i = 1,...,n\}$ where $\{\beta_j : j = 0,1\}$ are unknown parameters. x is denoted the independent variable and y is denoted the dependent variable.

When applying the method of least squares the intercept and slope is chosen to minimize

$$S(\beta_0,\beta_1) = \sum_{i=1}^{n}(y_i - \beta_0 - \beta_1 x_i)^2. \tag{5.1}$$

Setting the partial derivatives, $\frac{\delta S}{\delta \beta_0}$ and $\frac{\delta S}{\delta \beta_1}$, to zero yields two linear equations with the minimizers $\hat{\beta}_0$ and $\hat{\beta}_1$

$$\begin{aligned}\sum_{i=1}^{n} y_i &= n\hat{\beta}_0 + \hat{\beta}_1 \sum_{i=1}^{n} x_i \\ \sum_{i=1}^{n} x_i y_i &= \hat{\beta}_0 \sum_{i=1}^{n} x_i + \hat{\beta}_1 \sum_{i=1}^{n} x_i^2\end{aligned} \tag{5.2}$$

Since the line to be fitted is linear in the unknown parameters the equations in (5.2) are linear. This is a special case of the method of least squares called *linear least squares.* Solving for $\hat{\beta}_0$ and $\hat{\beta}_1$ yields

$$\begin{aligned}\hat{\beta}_0 &= \bar{y} - \hat{\beta}_1 \bar{x} \\ \hat{\beta}_1 &= \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2}\end{aligned} \tag{5.3}$$

where $\bar{x}$ is the mean of $\{x_i : i = 1,...,n\}$ and $\bar{y}$ is the mean of $\{y_i : i = 1,...,n\}$. The calculations yield estimates of the line intercept, $\hat{\beta}_0$, and the line slope, $\hat{\beta}_1$ [13].

Whether $\hat{\beta}_0$ and $\hat{\beta}_1$ are applicable in e.g. a linear adjustment of a measurement function is a question regarding their reliability when noise is present. To address the noise associated with measurements a statistical model for the noise is required. The following model can be used for this purpose

$$y_i = \beta_0 + \beta_1 x_i + e_i, \qquad i = 1,...,n \tag{5.4}$$

where e_i are random independent variables with $E(e_i)$=0 and $Var(e_i) = \sigma^2$. The x_i are assumed to be fixed [13].

Given the model 5.4 with corresponding assumptions the following holds

$$\begin{aligned}E(\hat{\beta}_j) &= \beta_j, \qquad j = 1,2 \\ Var(\hat{\beta}_0) &= \frac{\sigma^2 \sum_{i=1}^{n} x_i^2}{n\sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2} \\ Var(\hat{\beta}_1) &= \frac{n\sigma^2}{n\sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2}\end{aligned} \tag{5.5}$$

The intercept and slope of the line to be fitted have variances dependent on only the x_i and the error variance, σ^2. Since the x_i are known, finding an estimate of the intercept and slope is a matter of estimating σ^2. An estimate, $s^2 \approx \sigma^2$, can be found by

$$s^2 = \frac{\sum_{i=1}^{n}(y_i - \hat{\beta}_0 \hat{\beta}_1 x_i)^2}{n-2}. \tag{5.6}$$

Estimates of the variances of $\hat{\beta}_0$ and $\hat{\beta}_1$ are found by replacing σ^2 in 5.5 with s^2 which yields

$$\begin{aligned} s^2_{\hat{\beta}_0} &= \frac{s^2 \sum_{i=1}^n x_i^2}{n\sum_{i=1}^n x_i^2 - (\sum_{i=1}^n x_i)^2} \\ s^2_{\hat{\beta}_1} &= \frac{ns^2}{n\sum_{i=1}^n x_i^2 - (\sum_{i=1}^n x_i)^2} \end{aligned} \tag{5.7}$$

Due to the fact that the model assumptions dictates e_i to be independent normal random variables then $\hat{\beta}_0$ and $\hat{\beta}_0$ are normally distributed as well. This enables the construction of a confidence interval for the slope and intercept estimates, a confidence interval which provides information on the reliability of estimates. It is possible to show that

$$\frac{\hat{\beta}_i - \beta_i}{s_{\hat{\beta}_i}} \sim t_{n-2}, \tag{5.8}$$

allowing the t distribution to be used for confidence intervals

$$\hat{\beta}_i = \pm t_{n-2}(z) s_{\hat{\beta}_i}, \tag{5.9}$$

where z is dependent on the chosen confidence interval [13].

Analyzing correlations and carrying out straight line fittings via the method of least squares are closely related. The correlation coefficient, r, between the independent variable x and the dependent variable y is defined as

$$r = \frac{S_{xy}}{\sqrt{S_{xx}S_{yy}}}, \tag{5.10}$$

where

$$\begin{aligned} S_{xx} &= \frac{1}{n}\sum_{i=1}^n (x_i - \bar{x})^2, \\ S_{yy} &= \frac{1}{n}\sum_{i=1}^n (y_i - \bar{y})^2, \\ S_{xy} &= \frac{1}{n}\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y}). \end{aligned} \tag{5.11}$$

Notable is that

$$r = \hat{\beta}_1 \sqrt{\frac{S_{xx}}{S_{yy}}}. \tag{5.12}$$

The correlation between x and y is zero if and only if the slope is zero, a situation which arises when measurements of y are cluttered horizontally when plotted against x. A strong linear correlation is achieved when r=1 [13].

There are more complex line fittings which in a least square sense provide more accurate results, and if desired it is still possible to keep the relatively simple structure of linear least squares (5.2). Considering the statistical model used to acquire the results of the thesis

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \cdots + \beta_{p-1} x_{i,p-1} + e_i, \qquad i = 1,...,n \tag{5.13}$$

where x_{ij} is observation i of independent variable j. This difference from (5.4) provides the possibility of either utilizing observations of different process variables or utilizing powers of a single process variable ($x_{i2} = x_{i1}^2$ and $x_{i3} = x_{i1}^3$ etc.) when carrying out line fittings. Utilizing powers of a single process variable yields a polynomial fitting of order $p-1$. Before looking closer at statistical aspects of multiple linear regression or polynomial regression it is convenient to introduce matrix notations [13][27].

As similar to before, suppose that the line $y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_{p-1} x_{p-1}$ is to be fitted to data y_i, x_{ij} where $i = 1,...,n$ and $j = 1,...,p-1$. The minimizers, $\hat{\beta}_0, \hat{\beta}_1,...,\hat{\beta}_{p-1}$, are then found by solving the p equations yielded from the partial derivatives of

$$S(\beta_0,\beta_1,...,\beta_{p-1}) = \sum_{i=1}^{n} (y_i - \beta_0 - \beta_1 x_{i1} - \beta_2 x_{i2} - \cdots - \beta_{p-1} x_{i,p-1})^2, \tag{5.14}$$

which are set to zero. Given that the following matrices are defined

$$\mathbf{Y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} \qquad \boldsymbol{\beta} = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_{p-1} \end{bmatrix} \tag{5.15}$$

$$\mathbf{X} = \begin{bmatrix} 1 & x_{11} & x_{12} & \cdots & x_{1,p-1} \\ 1 & x_{21} & x_{22} & \cdots & x_{2,p-1} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & x_{n1} & x_{n2} & \cdots & x_{n,p-1} \end{bmatrix}$$

then 5.14 can be written as

$$S(\boldsymbol{\beta}) = (\mathbf{Y} - \mathbf{X}\boldsymbol{\beta})^T (\mathbf{Y} - \mathbf{X}\boldsymbol{\beta}) = ||\mathbf{Y} - \mathbf{X}\boldsymbol{\beta}||^2. \tag{5.16}$$

The p linear equations can hence be written in matrix form

$$\mathbf{X}^T \mathbf{X} \hat{\boldsymbol{\beta}} = \mathbf{X}^T \mathbf{Y} \tag{5.17}$$

which means that the minimizers, $\hat{\boldsymbol{\beta}}$, can be found by $\hat{\boldsymbol{\beta}} = (\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T\mathbf{Y}$ given that $(\mathbf{X}^T\mathbf{X})^{-1}$ is nonsingular. Matrix inversions are however generally not to prefer from a computational point of view. One can instead utilize the QR method in which the matrix $\mathbf{X}$ is factored in the form

$$\underset{n\,X\,p}{\mathbf{X}} = \underset{n\,X\,p}{\mathbf{Q}} \; \underset{p\,X\,p}{\mathbf{R}} \tag{5.18}$$

where the columns of $\mathbf{Q}$ are orthogonal ($\mathbf{Q}^T\mathbf{Q} = \mathbf{I}$) and $\mathbf{R}$ is upper-triangular ($r_{ij} = 0$ for $i > j$). This means that 5.17 can be written as

$$\mathbf{R}\hat{\boldsymbol{\beta}} = \mathbf{Q}^T\mathbf{Y} \tag{5.19}$$

hence $\hat{\boldsymbol{\beta}}$ can be found through backsubstitution and matrix inversion is avoided.

Again looking at the statistical aspects via 5.13 with assumptions given in 5.4. Since $E[\hat{\boldsymbol{\beta}}] = \boldsymbol{\beta}$ and Var$[\hat{\boldsymbol{\beta}}]$=$\sigma^2(\mathbf{X}^T\mathbf{X})^{-1}$ the standard error of $\hat{\beta}_j$ can be estimated as

$$s_{\hat{\beta}_j} = s\sqrt{(\mathbf{X}^T\mathbf{X})^{-1}_{jj}} \tag{5.20}$$

where

$$s^2 = \frac{||\mathbf{Y} - \mathbf{X}\boldsymbol{\beta}||^2}{n-p}. \tag{5.21}$$

Like in the case of fitting straight lines, confidence intervals can be constructed

$$\hat{\beta}_j \pm t_{n-p}(z)s_{\hat{\beta}_j} \tag{5.22}$$

where z depends on the chosen confidence interval [13][27].

5.2 Estimates of water level measurement deviation

This section presents estimates of water level measurement deviation dependent on process variables as a basis for measurement function adjustments. Presented estimates are based on regression analyses using measurement data associated with sub C of each measurement function set. These estimates are used for the adjustments of the C-sub *set 2L* measurement function in section *5.3 Adjustments to counteract the measurement deviation*. To recall, all measurement functions with the same letter (A, B, C or D) in the identity number constitute a *sub*.

In the regression analyses the measurement deviation, the difference between the outputs of the *set 1L* and the *set 2L* water level measurement functions, is regarded as the dependent variable. Three process variable measurements are utilized as independent variables

- Main circulation flow,
- Reactor pressure,
- Neutron flux.

Unlike the reactor pressure and neutron flux, the main circulation flow is used to control the operating conditions of the reactor. The reactor power output is controlled by changing the main circulation flow and/or control rod positions. The change of neutron flux is a consequence of changing these. This fact should be taken in regard when considering an adjustment of the *set 2L* measurement functions.

Independent variables of the regression analyses comprise process variable measurement data. This means that there is a disturbance among as well independent variables as dependent variables. For the model (5.4) an ideal situation would be if the independent variables could be held fixed and that there was no disturbance among them, this is however not the case.

5.2.1 Fitting to main circulation flow

The first process variable studied for the purpose of being utilized as an independent variable in a regression analysis is the main circulation flow (MC-flow *(3.211.KX032)*). In Figure 5.1 MC-flow data is plotted along with the corresponding water level measurements. The difference between the narrow range *set 1L* and the wide range *set 2L* water level measurements decreases as the MC-flow is decreased.

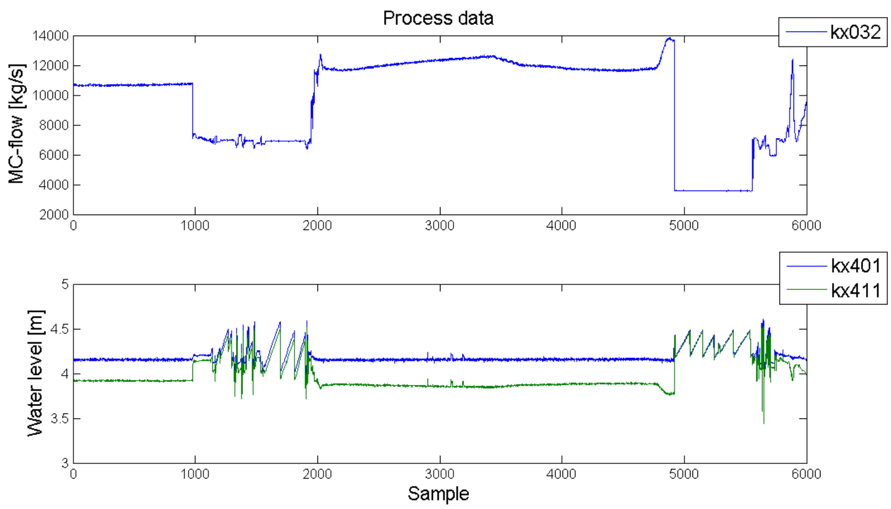

Figure 5.1: Process data used as a basis for estimation. Above: the main circulation flow (kx032). Below: the narrow (kx401) and wide (kx411) range water level measurement function outputs.

In Figure 5.2 the difference between the narrow- and wide range water level measurements from Figure 5.1 are plotted versus the corresponding MC-flow. The MC-flow values are sorted in an ascending order to simplify an interpretation of the relationship. For MC-flow values above 6000kg/s there is a prominent linear characteristic of the relationship. Even with the lesser values of the MC-flow included a linear fitting seems to be viable. The linear correlation coefficient is $r = 0.98086$ which suggests a strong linear correlation. Within the same figure polynomials with parameters fitted to the data set have been included. The polynomials have been fitted using the method of *linear least squares* presented in the previous section. The polynomials are structured as

$$y_k = \beta_1 + \beta_2 x + \cdots + \beta_n x^{n-1}, \quad i = 1,...,4, \quad n = k+1, \tag{5.23}$$

where y_k corresponds to the estimated dependent variable calculated with a polynomial of order k, x is the independent variable and $\{\beta_1,...,\beta_n\}$ are the fitted model parameters.

The fitted parameter values are presented in Table 5.1.

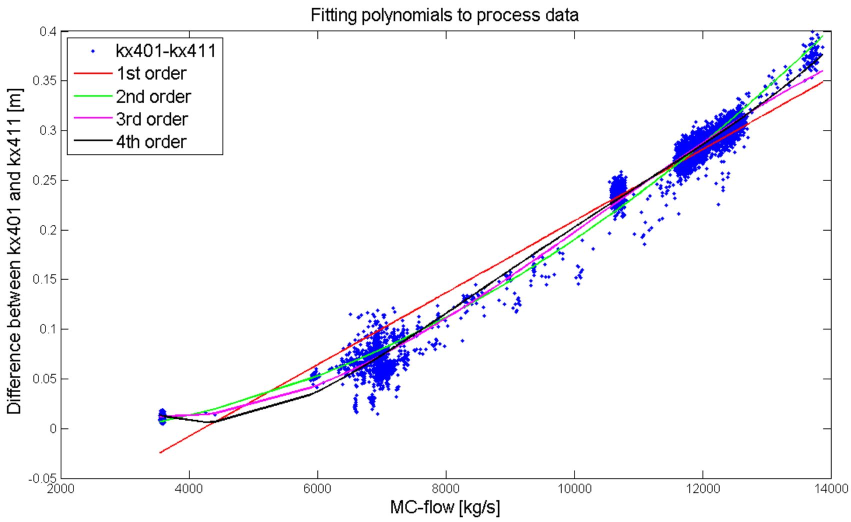

Figure 5.2: Linear least square polynomials of orders one to four fitted to process data. The independent variable is the MC-flow and the dependent variable is the difference between the narrow (kx401) and the wide (kx411) range water level measurements.

Table 5.1: Fitted parameters for each polynomial estimate of the relationship between the independent and dependent variables of Figure 5.2.

Polynomial order	β_1	β_2	β_3	β_4	β_5
Order 1	-0.1526	$3.613 \cdot 10^{-5}$			
Order 2	$-9.163 \cdot 10^{-3}$	$-3.940 \cdot 10^{-6}$	$2.383 \cdot 10^{-9}$		
Order 3	0.1234	$-6.462 \cdot 10^{-5}$	$1.059 \cdot 10^{-8}$	$-3.393 \cdot 10^{-13}$	
Order 4	0.3928	$-2.227 \cdot 10^{-4}$	$4.201 \cdot 10^{-8}$	$-2.906 \cdot 10^{-12}$	$7.415 \cdot 10^{-17}$

The confidence intervals of the polynomial estimates presented in Figure 5.3 suggests that higher order polynomial estimates are to be considered as less trustworthy regarding their estimating ability.

5.2.2 Fitting to reactor pressure

Reactor steam pressure data is presented along with the corresponding measurements of water level in Figure 5.4. Some of the pressure measurements are zero-valued. This represents errors in the logging system which means that zero-valued pressure measurement data is to be considered as unreliable.

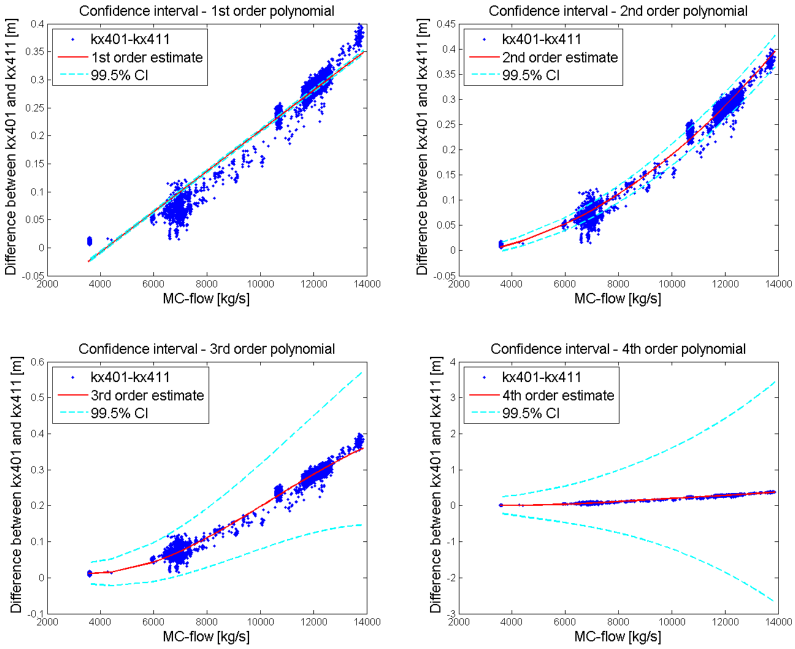

Figure 5.3: Polynomial estimates of the relationship between differences in water level measurements and main circulation flow along with their 99.5% confidence intervals.

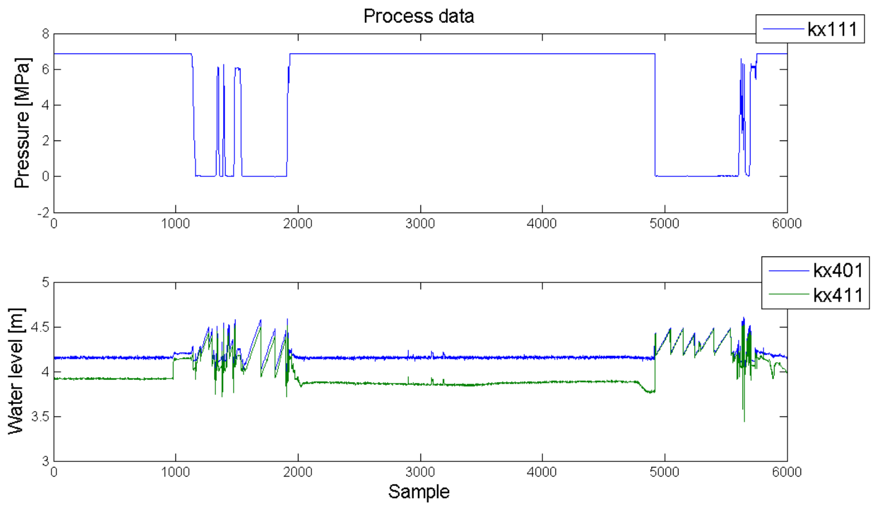

Figure 5.4: Process data. Above: the steam pressure (kx111). Below: the narrow (kx401) and the wide (kx411) range water level measurement function outputs.

Looking at the reliable pressure data in Figure 5.5, it is shown that pressure variations are small. It is also shown that differences between the narrow- and wide range water level measurements are uncorrelated with the operational pressure. This means that the reactor pressure is not to be regarded as a viable candidate for contributing to the adjustment of the *set 2L* water level measurement functions.

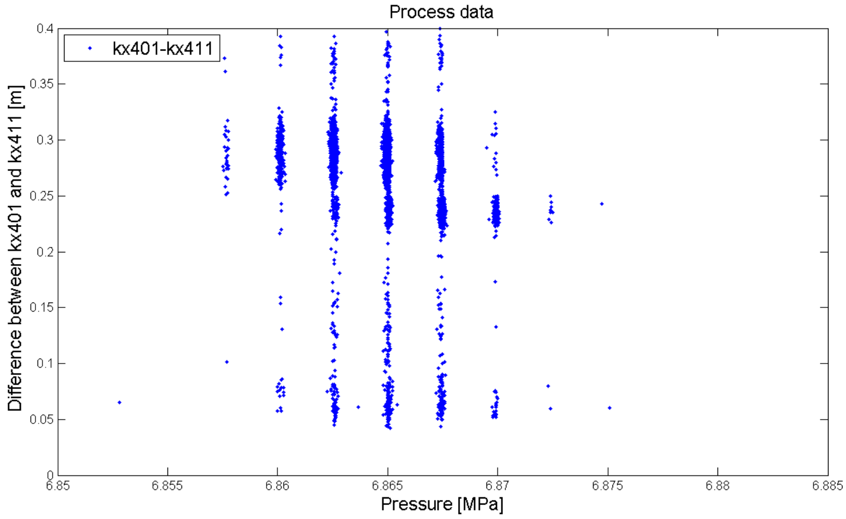

Figure 5.5: The difference between the outputs of the narrow (kx401) and wide (kx411) range water level measurements plotted versus the corresponding pressure measurement. Unreliable pressure measurements have been removed.

5.2.3 Fitting to neutron flux

Measurements of neutron flux given as percentages of a predefined value are presented along with narrow- and wide range water level measurements in Figure 5.6. Like in the case of the MC-flow, the difference between the narrow- and wide range measurements increases as the neutron flux increases.

Figure 5.7 presents the water level measurement differences plotted versus the corresponding neutron flux together with polynomial estimates of the water level measurement differences. The plotted water level measurement difference data is scattered around certain neutron flux levels to a greater extent than the scattering in the corresponding data plot for MC-flow, Figure 5.2. This suggests a smaller linear correlation coefficient for the data in the neutron flux case. Computation yields a linear correlation coefficient of $r = 0.88170$. This implies a lesser linear correlation compared to the case of the MC-flow.

The process variable data in Figure 5.7 which the polynomial estimates are based on in accordance with the structure in (5.23) is limited to neutron flux values above $50APRM\%$. The reason is that neutron flux values below this value are considered as unreliable. The fitted parameter values of the polynomial estimates in Figure 5.7 are presented in Table 5.2.

The confidence intervals of the polynomial estimates are presented in Figure 5.8.

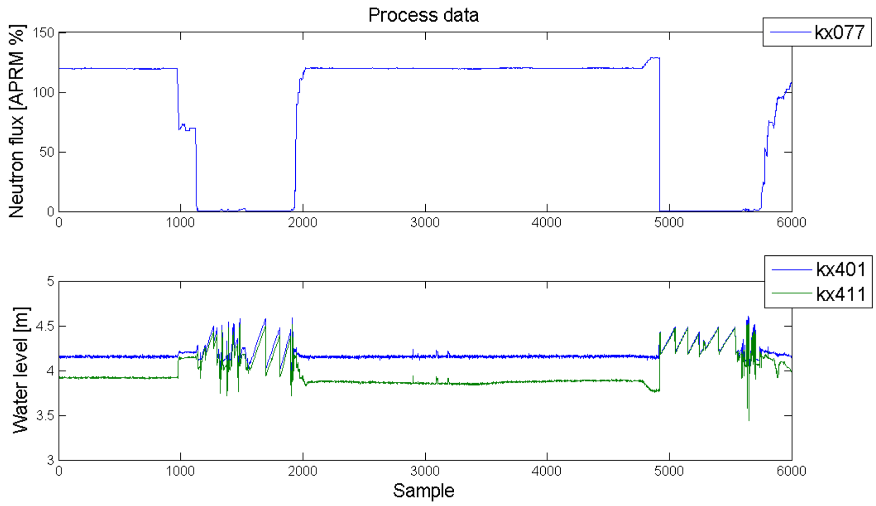

Figure 5.6: Process data used as a basis for estimation. Above: the neutron flux (kx077). Below: the narrow (kx401) and wide (kx411) range water level measurement function outputs.

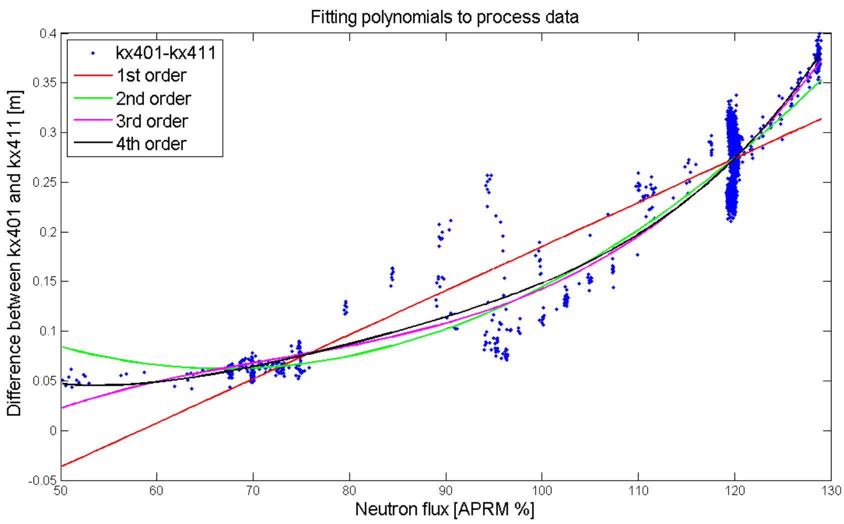

Figure 5.7: Linear least square polynomials of orders one to four fitted to process data. The independent variable is the neutron flux and the dependent variable is the difference between the narrow (kx401) and wide (kx411) range water level measurements.

5.2.4 Fitting to both main circulation flow and neutron flux

In this section both the MC-flow and the neutron flux comprise the independent variables of the regression analysis. As presented in previous sections the water level measurement difference increases as the MC-flow and neutron flux increases. It is also presented here in Figure 5.9.

Table 5.2: Fitted parameters for each polynomial estimate of the relationship between the independent and dependent variables of Figure 5.7.

Polynomial order	β_1	β_2	β_3	β_4	β_5
Order 1	-0.2586	$4.437 \cdot 10^{-3}$			
Order 2	0.4026	$-1.015 \cdot 10^{-2}$	$7.571 \cdot 10^{-5}$		
Order 3	-0.4693	$1.913 \cdot 10^{-2}$	$-2.418 \cdot 10^{-4}$	$1.117 \cdot 10^{-6}$	
Order 4	0.8525	$-4.263 \cdot 10^{-2}$	$8.082 \cdot 10^{-4}$	$-6.590 \cdot 10^{-6}$	$2.067 \cdot 10^{-8}$

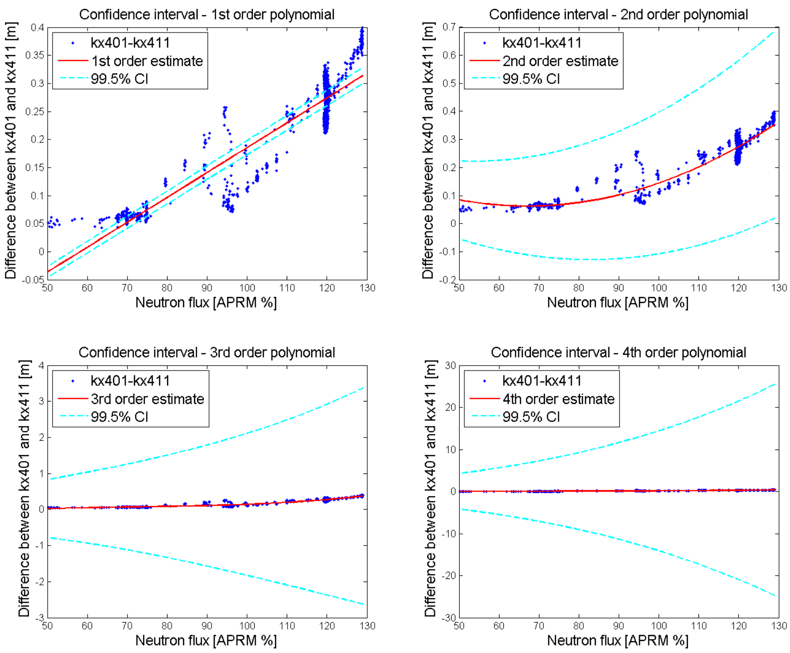

Figure 5.8: Polynomial estimates of the relationship between differences in water level measurements and neutron flux along with their 99.5% confidence intervals.

The two process variables used as independent variables results in a two dimensional estimate of the dependent variable. Only one two dimensional estimate has been created and it is presented in Figure 5.10. The estimate is based on

$$y = \beta_1 + \beta_2 x_1 + \beta_3 x_2, \tag{5.24}$$

where x_1 is the MC-flow, x_2 is the neutron flux and y is the estimated water level measurement difference. The fitted parameter values $\{\beta_j : j = 1,...,3\}$ are presented in Table 5.3.

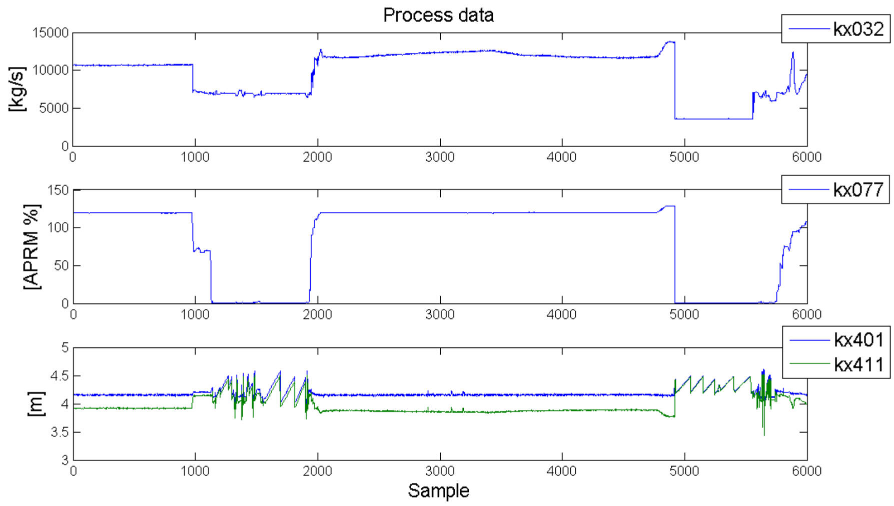

Figure 5.9: Process data used as a basis for estimation. Top: the main circulation flow (kx032). Middle: the neutron flux (kx077). Bottom: the narrow (kx401) and wide (kx411) range water level measurement function outputs.

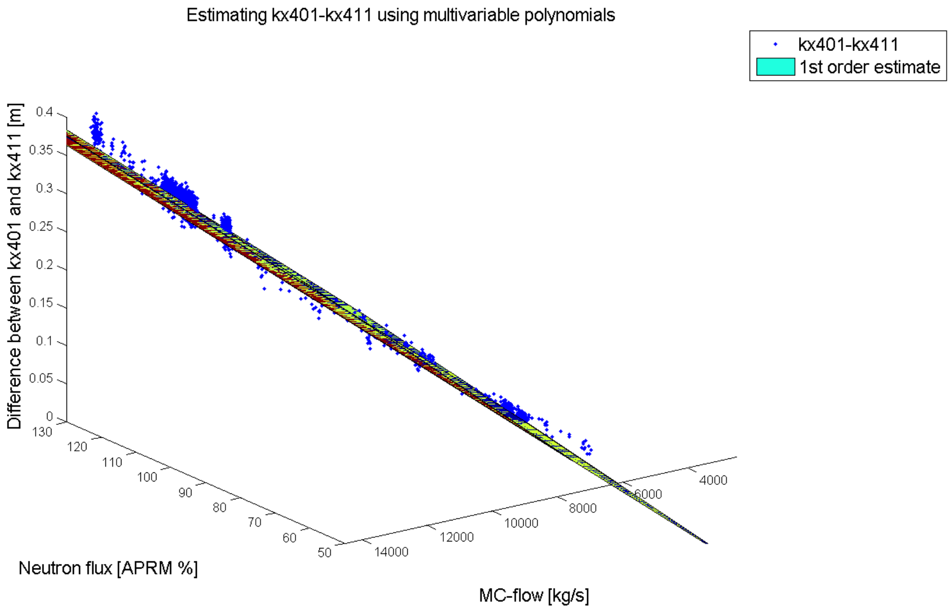

Figure 5.10: Linear least square multivariable polynomial fitted to process data. Independent variables are the main circulation flow and the neutron flux. The dependent variable is the difference between the narrow (kx401) and wide (kx411) range water level measurements.

Table 5.3: Fitted parameters for the polynomial estimate of the relationship between the independent and dependent variables of Figure 5.10. β_2 is associated with the main circulation flow and β_3 is associated with the neutron flux.

Polynomial order	β_1	β_2	β_3
Order 1	-0.2727	$3.785 \cdot 10^{-5}$	$8.676 \cdot 10^{-4}$

5.3 Adjustments to counteract the measurement deviation

A number of polynomial estimates of the water level measurement deviation have been formed. This section presents some of the possible adjustments of the *set 2L* water level measurement functions based on the estimated polynomials of the previous section.

5.3.1 Adjustments based on the main circulation flow

The adjustments of the *set 2L* measurement functions presented in this section consists of adding the value of the polynomial deviation estimate for a given value of the MC-flow onto the value of the measurements of the *set 2L* measurement functions.

$$\text{KX411}_{\text{adjusted}} = \text{KX411} + y_k, \quad k = 1,...,4, \tag{5.25}$$

where y_k is equal to y_k of (5.23), KX411 is the output of a *set 2L* measurement function and $\text{KX411}_{\text{adjusted}}$ is the adjusted output. The adjustments of the *set 2L* measurement functions have been tested on an individual set of data of sub C (KC401 & KC411 & KC032) and the results are presented in Figure 5.11. The results shown in the above plot pair in Figure 5.11 show that all polynomial based adjustments manage to decrease the difference between the narrow- and wide range measurements significantly for varying operating conditions. A closer look at a selected subset of the results in Figure 5.11 show that the linear adjustment, though it is the adjustment decreasing the difference the least, manages to decrease the difference from about 0.33m to about 0.03m.

5.3.2 Adjustments based on the neutron flux

Adjustments of the *set 2L* measurement functions presented in this section are based on the structure of (5.25) with neutron flux instead of MC-flow. The adjustments have been tested on the same set of independent water level measurement data as in the previous section and the results are presented in Figure 5.12. Apart from unreliable subsets of the data where the neutron flux drops to around zero the adjustments manage to decrease the difference between the *set 1L* and *set 2L* measurements. The adjustments are however less robust than the adjustments based on the MC-flow.

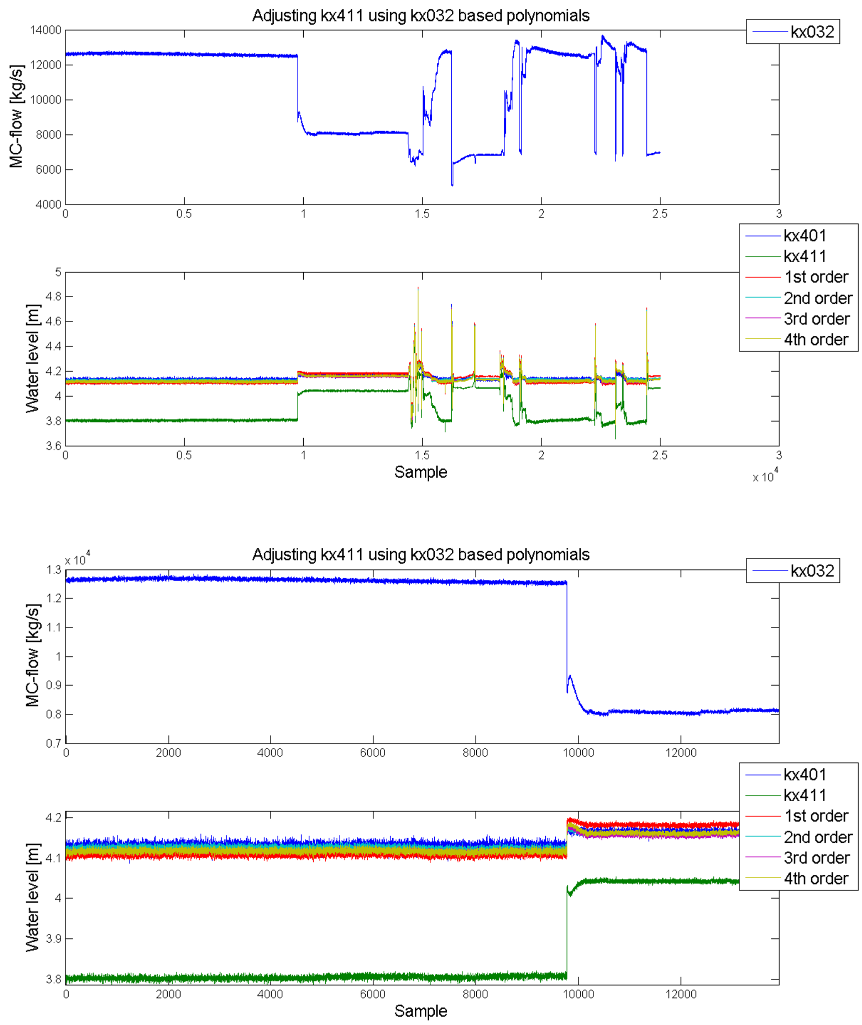

Figure 5.11: Testing the main circulation flow based polynomial adjustment on an independent data set. Above plot pair: the entire data set. Below plot pair: a subset of the data set.

5.3.3 Adjustments based on the main circulation flow and the neutron flux combined

This section presents a single adjustment. The adjustment is based on the same idea of (5.25)

$$\mathrm{KX411}_{\mathrm{adjusted}} = \mathrm{KX411} + y, \tag{5.26}$$

where y is equal to the y of (5.24).

The adjustment has been tested on the same independent set of water level measurement data as previously presented adjustments and the result is presented in Figure 5.13. The result shows that the single linear adjustment based on the two dimensional estimate performs rather well as the difference is diminished for a variety of MC-flows and neutron

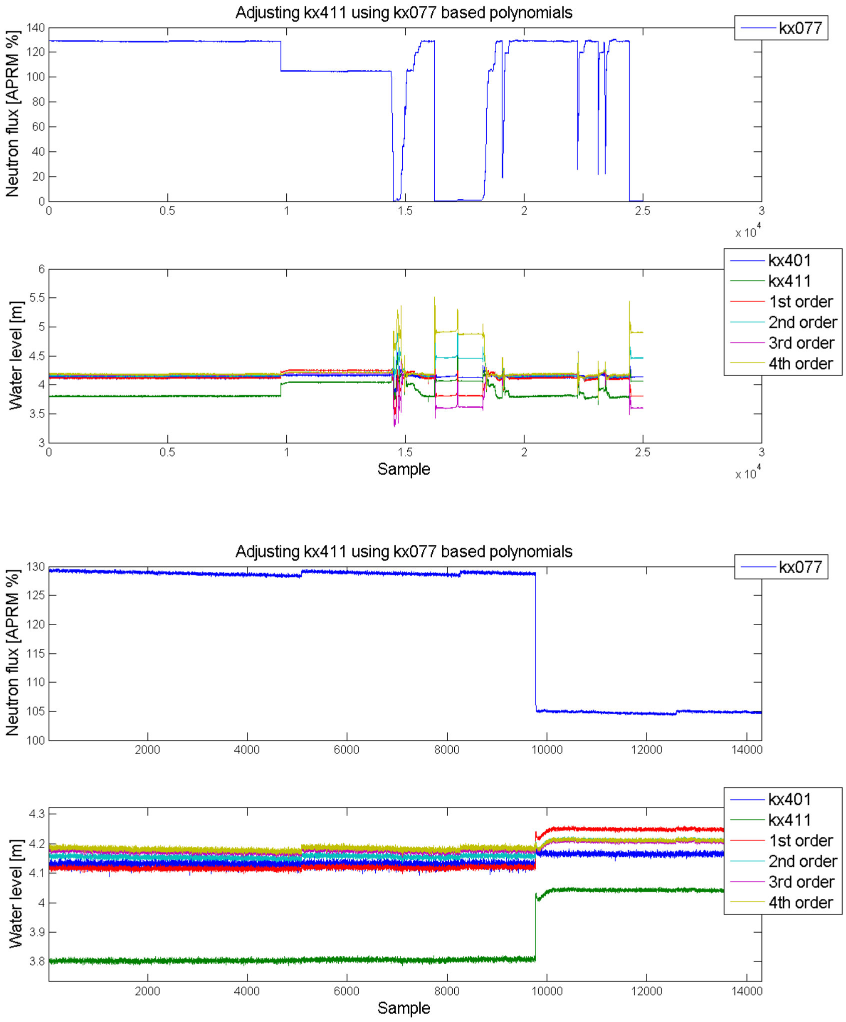

Figure 5.12: Testing the neutron flux based polynomial adjustment on an independent data set. Above plot pair: the entire data set. Below plot pair: a subset of the data set solely containing reliable data.

flux levels.

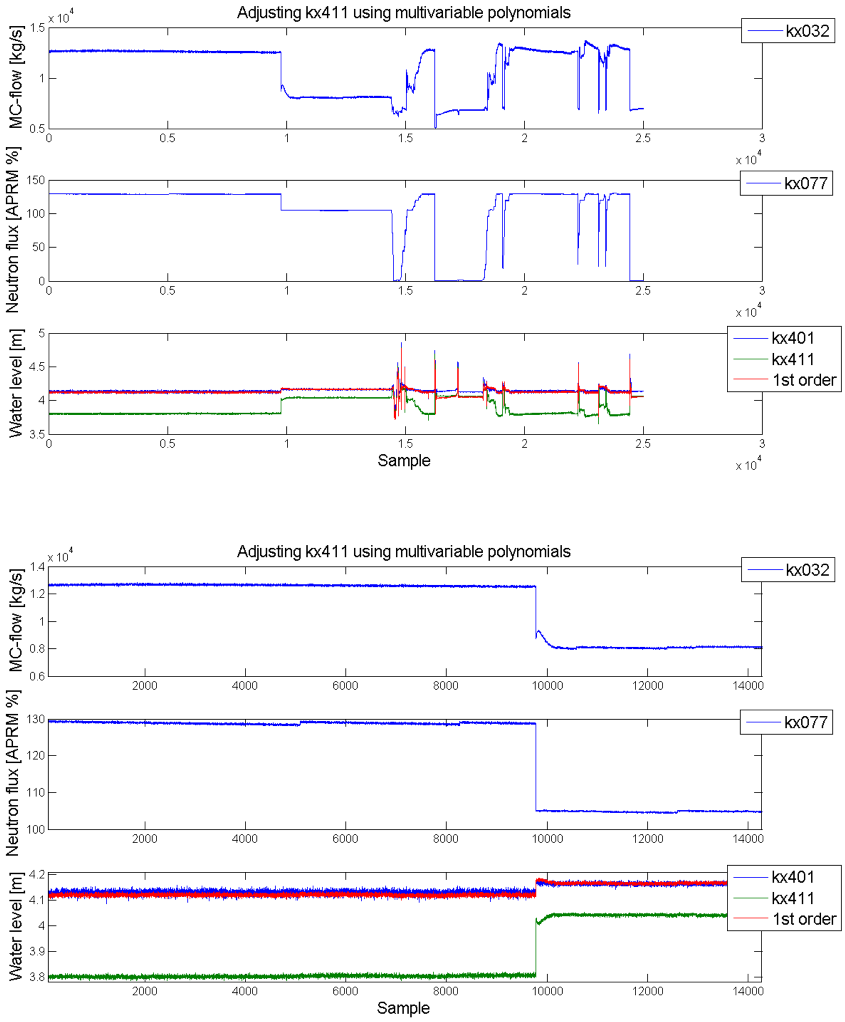

Figure 5.13: Testing the multivariable polynomial adjustment on an independent data set. Above plot pair: the entire data set. Below plot pair: a subset of the data set solely containing reliable data.

5.4 The suggested solution to counteract the deviating water level measurements

The suggested solution is the linear first order polynomial adjustment based on the main circulation flow according to (5.25). Values for the β_1 and β_2 parameters of (5.23) associated with the MC-flow based deviation estimates of each sub are presented in table 5.4.

Table 5.4: Fitted parameters, β_1 and β_2, and the linear correlation coefficient, r, for the first order polynomial deviation estimate associated with each *set 2L* measurement function. In accordance with (5.23) and (5.25).

Sub	β_1	β_2	r
A	-0.1686	$2.955 \cdot 10^{-5}$	0.9795
B	-0.1236	$2.560 \cdot 10^{-5}$	0.9744
C	-0.1526	$3.613 \cdot 10^{-5}$	0.98086
D	-0.1398	$2.643 \cdot 10^{-5}$	0.98306

Each sub-specific adjustment yields a result corresponding to the result presented in Figure 5.11, which is considered to be a viable solution to the problem. The suggested adjustment can be realized in the plant by a modification according to the block diagram presented in Figure 5.14.

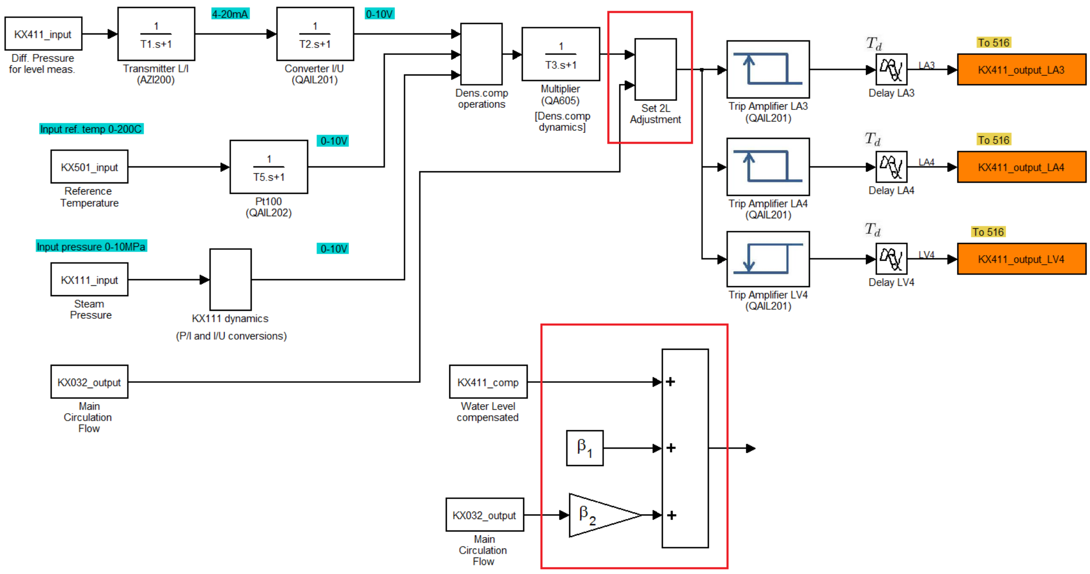

Figure 5.14: Block diagram of the developed *set 2L* function model with the suggested linear adjustment structure included (marked with the red boundary).

The choice of the suggested adjustment as a solution to the problem of the deviating water level measurements is based on the following:

- It is desirable to find a relatively simple solution. A linear first order polynomial based adjustment is easier to implement in the plant than a higher order polynomial based adjustment.

- First order polynomial based adjustments of the *set 2L* measurement functions have been shown to perform well when applied to independent sets of data. Adjustments based on higher order polynomial estimates only tend to decrease the difference between the *set 1L* and *set 2L* measurements to a slightly larger extent.

- The adjustments based on first order polynomials are more reliable from an estimation point of view. The confidence intervals of the first order deviation estimates are significantly narrower than they of the higher order polynomials estimates.

- Figures 5.11-5.12 show that the first order polynomial adjustment based on the MC-flow is more robust than the first order polynomial adjustment based on the neutron flux.

- Figure 5.13 show that an adjustment based on the linear two dimensional estimate manages to decrease the difference between the *set 1L* and *set 2L* measurements to a large extent. However since the neutron flux is dependent on the MC-flow it might not be the best variable to use as an independent variable in a regression analysis. The adjustment based on the two dimensional estimate is hence not preferable.

6

Conclusions

In this thesis it has been shown that

1. The developed measurement function models differ from the existing measurement function models. The differences comprise differing measurement function component models. As the developed models are based on plant documentation this suggests that the existing models inaccurately model the dynamics associated with acquisition, processing and distribution of measurement signals. A utilization of the developed measurement function models in the safety analysis is likely to result in an improvement of the safety analysis credibility.

2. The problem with the deviating water level measurements can be solved. A solution is to adjust each wide range *set 2L* measurement function such that the measurement deviation from the narrow range measurement is counteracted. This is done by adding the estimated difference between the narrow- and wide range measurements to the wide range measurement.

   The amount of measurement data applicable for testing of the measurement function adjustments is limited. It is hence a good idea to postpone any adjustments of the *set 2L* measurement functions until further testing can be carried out.

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