AUTOMATION OF RUN-OF-RIVER HYDROELECTRIC POWER PLANT

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AUTOMATION OF RUN-OF-RIVER HYDROELECTRIC POWER PLANT

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Abdurraouf Otman Ali ELMILADI

ABSTRACT

M. Sc. Thesis

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The importance of renewable energy resources has been increasing at a rapid rate throughout the world and a lot of investments are being made in this field. In the last 20 years in Turkey, there has been a considerable increase in the number of run-of-river type hydropower plants (RRHPP) and RRHPPs have had a significant contribution in electricity production. In this thesis, the automation of a real RRHPP has been performed in accordance with the presented working scenarios. Automation was implemented and simulated using the TIA Portal interface. By creating the SCADA screens, control and monitoring of the system were provided accordingly. In this way, it was ensured that the results of possible changes and improvements to be made on the real system are predicted without stopping the real system and putting it at risk. In addition, the simulations of the system were performed using MATLAB program and the results were evaluated.

Key Words **:** Run-of-river hydropower plant, Automation, PLC, SCADA

Science Code : 90526, 90513, 90544

ÖZET

Yüksek Lisans Tezi

NEHİR TİPİ BİR HİDROELEKTRİK SANTRALIN OTOMASYONU

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Bütün dünyada yenilenebilir enerji kaynaklarının önemi her geçen gün daha çok anlaşılmakta ve bu alanda yapılan yatırımlar artmaktadır. Türkiye'de son 20 yılda nehir tipi hidroelektrik santralların (RRHPP) sayısında ciddi oranda artış olmuş ve RRHPP'ler elektrik üretiminde önemli bir paya sahip sahip olmuşlardır. Bu tezde gerçek bir RRHPP'in otomasyonu çalışma senaryolarına uygun olarak gerçekleştirilmiştir. Otomasyon TIA Portal arayüzünde uygulanmış ve simülasyonu yapılmıştır. SCADA ekranları oluşturularak sistemin kontrolü ve izlenmesi sağlanmıştır. Böylece gerçek sistem üzerinde yapılacak muhtemel değişiklik ve iyileştirme işlemlerinin nasıl sonuç vereceğinin gerçek sistem durdurulmadan ve riske atılmadan öngörülmesi sağlanmıştır. Ayrıca MATLAB ortamında sistemin simülasyonları gerçekleştirilerek sonuçlar değerlendirilmiştir.

Anahtar Kelimeler : Nehir tipi hidroelektrik Santral, Otomasyon, PLC, SCADA.
Bilim Kodu : 90526, 90513, 90544

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SYMBOLS AND ABBREVITIONS INDEX

SYMBOLS

A : cross-sectional area of penstock

A_t : factor is account for base differences

B : moment of inertia

dw : speed deviation

d,q : the axis quantity

$D(t)$: the deviation observed from the desired operating point.

e : speed motor

f, k : Field quantity, damper winding quantity

$Fnet$: Net Force

G : gate position having a value between 0 and 1

G : gravitational acceleration

$gate$: gate opening

Hs : static head

H_l : loss head

H : head

I_{abc} : stator currents

J : friction coefficients

K_f : friction factor

K : valve constant

K_p : the proportional gain of the system.

K_i : the integral gain.

K_d : the derivative gain.

Ka : servo Motor gain

K_E : exciter gain

K_A : regulator gain constant

K_F : damping gain constant

l, m : leakage inductance, magnetizing inductance

L : penstock length.

Peo : electrical power

P_{ref} : reference mechanical power

P_m : mechanical power

ρ : mass density of the water.

Q : volumetric flow rate.

Rp : permanent droop

R, s : rotor quantity, stator quantity

Tw : starting time of the water

Td : derivative time constant

Tm : motor torque

T_A : regulator time constant

Tc : time constant of Transient gain reduction

T_B : time constant of Transient gain reduction

T_E : exciter time constant

T_r : low-pass filter time constant

Ta : servo Motor time constant

T_F : damping time constant

$U(t)$: the output signal of the system.

Vc : terminal voltage transducer

$Vref$: reference stator terminal voltage.

V_F : field voltage by Exciter

V_t : terminal voltage.

Vs : stabilizing voltage

V_{abc} : stator voltages

V_q : stator voltage in q axis

V_d : stator voltage in d axis

We : machine speed

$Wref$: reference speed

$\dot{\theta}$: error signal

ABBREVITIONS

KE	: Kinetic Energy
ME	: Mechanical Energy
MVA	: Mega Volt Ampere
PE	: Potential Energy
PID	: Proportional Integral Derivative
PLC	: Programmable Logic Controller
RE	: Rotational Energy
RRHPP	: Run-Of-River Hydropower Plants
SCADA	: Supervisory Control and Data Acquisition

CHAPTER 1

INTRODUCTION

The renewable energy share has been increasing in electricity generation day by day. As compared to renewable energy sources namely wind, solar, and geothermal energy, hydraulic energy is known to be the most widely used renewable energy type in electricity production in Turkey and in the World. As shown in Figure 1.1, while 16.3% of the electricity in the world was generated from hydraulic resources in 2017, the share of other renewable energy resources was 6.6%.

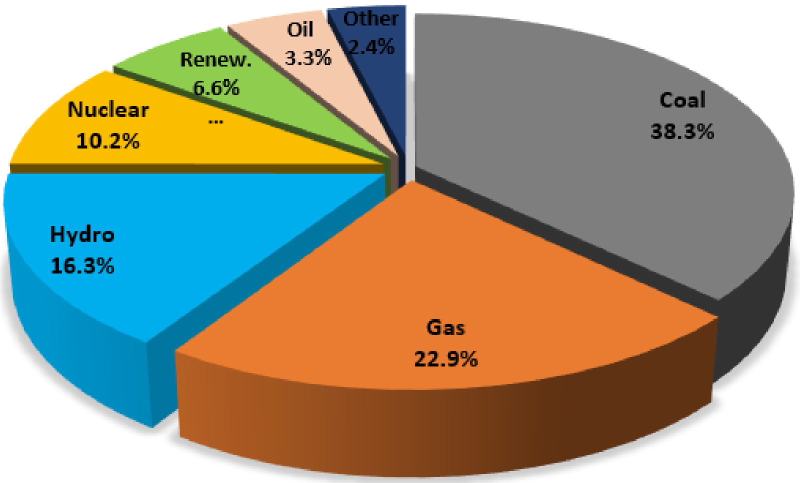


Figure 1.1. World electricity production by sources in 2017 [1].

As it can be seen in Figure 1.2, according to the primary energy sources as of end of 2019, 31.23% of the installed power consists of hydraulic resources, of which 8.61% comes from the river type HPP (RRHPP) and 22.62% comes from the hydroelectric dam (HPP with dam). In the last quarter of the year 2019, of the total 91267 MW of electricity produced, 7860.5 MW came from RRHPP and 20642.5 MW came from HPP with dam [2nd]. As shown in Figure 1.3, 7.67% of electricity in 2019 was produced using RRHPPs and 21.85% was produced by HPPs with dam. In 2019, of the total 300407 GWh electricity generation, 23032.6 GWh was obtained from RRHPPs and 65635.8 GWh was obtained from HPPs with dam [2].

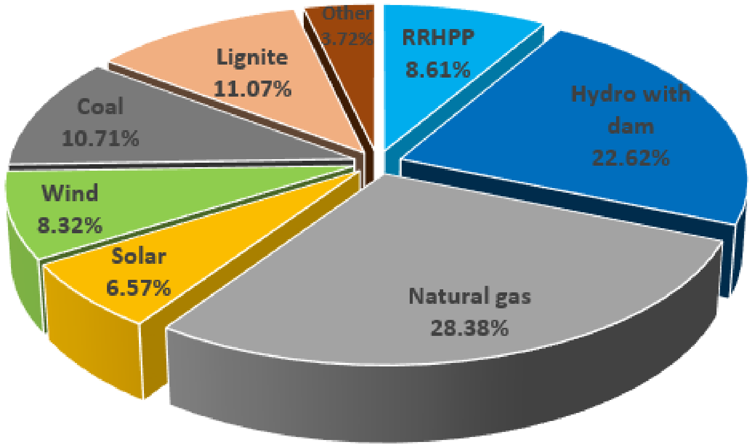


Figure 1.2. The installed power rates in the last quarter of 2019 according to primary sources in Turkey [2].

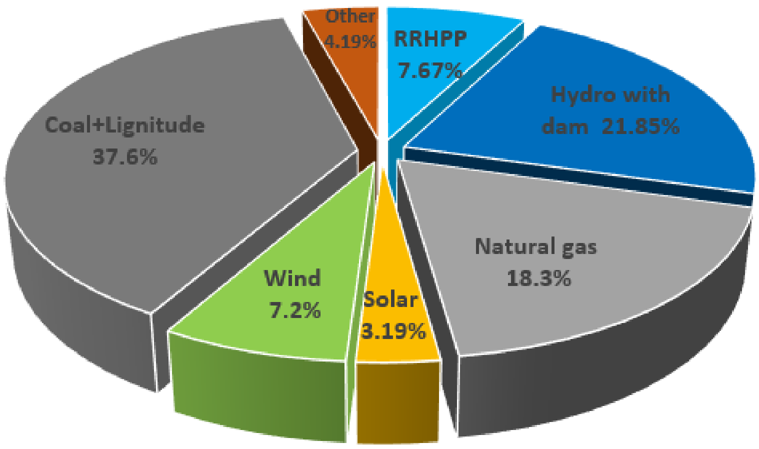


Figure 1.3. The electricity production rates in the last quarter of 2019 according to primary sources in Turkey [2].

As seen in Figure 1.4, there have been significant increases in the number and installed power capacities of RRHPPs and HPPs with dam in the last decade. While the installed power of RRHPPs in Turkey in 2010 was 2764 MW, this number rose to 7888.6 MW in July 2020. While the installed power of the HPP dams was 13067 MW in 2010, it was found to be 21877.1 MW in July 2020. As shown in Figure 1.5, the power generated by RRHPP was found to be 7392 GWh in 2010, while this figure rose to

23032.6 GWh in 2020 in Turkey. While 44563.2 GWh of electricity was produced from the HPP dams in 2010, 65635.8 GWh of electricity was found to be produced in 2020.

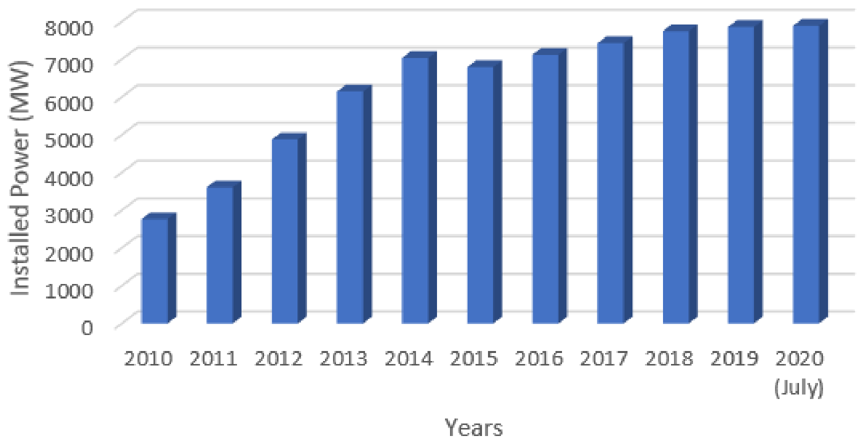


Figure 1.4. RRHPP installed power in Turkey in 2010-2020 (July) [2].

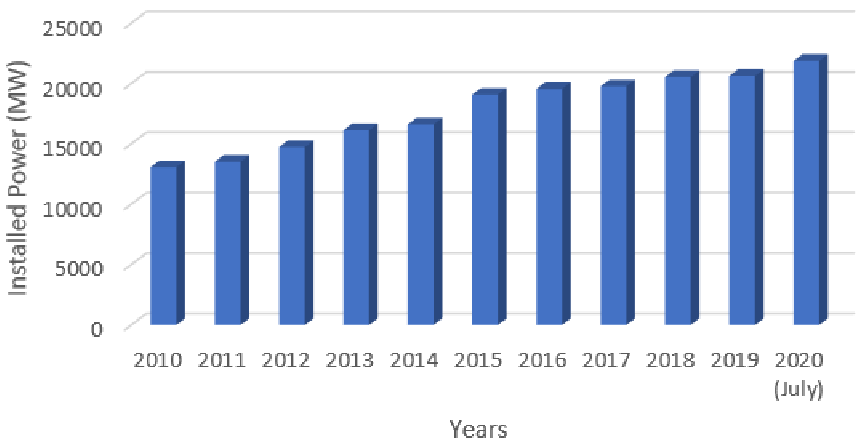


Figure 1.5. Installed power of HPP with dam in Turkey in 2010-2020 (July) [2].

In the last decade, it is seen that there has been an approximately three times increase in the installed power and share of RRHPPs in electricity generation.

Automation has become an indispensable element in almost all industrial areas today. Automation minimizes errors caused by human factors. With SCADA, the system can be monitored and controlled 24/7 from the remote or control room. Different brands or models of PLCs and SCADA software of different founding companies are used in order to control and monitor HPPs with dam and RRHPPs. Many of these software also offer simulation opportunities to programmers.

Making some changes on real operating systems always involves some risks. Therefore, using simulation programs before making changes on the real system minimizes these risks.

In this thesis, it was aimed to use the PLC and SCADA software in accordance with real working scenarios of a real RHPP and to predict the behavior of the system for different case studies.

A literature review is presented in Chapter 2. General information regarding HPPs (theoretical background) has been given in Chapter 3. Parts and working principle of RRHPPs are explained in Chapter 4. The automation and simulation of Filyos-Yalnizca RRHPP is explained in Chapter 5. In the final section, the results of the study are given.

CHAPTER 2

LITERATURE REVIEW

In the recent years, the problems identified with the energy factors, for example, climatic change and oil crisis, which refer to the ecological aspect, electricity demand and the financial or in some cases regulatory restrictions concerning the wholesale markets have emerged worldwide. The afore-mentioned difficulties are increasing at a rapid rate and seem to be far from finding effective solutions that suggest the ultimate need of the technological alternatives. The idea of using the renewable energy sources such as photovoltaic, hydraulic, wind etc., which do not cause any environmental concerns or pollution need to be considered in order to overcome energy related problems [3].

Throughout the history, several models regarding hydropower electricity generation were investigated by scientists to put an end to the energy crisis. Current models are solely dependent upon some requirements that have been included in the study. According to the scientists, of these models, some were analytical whereas some others were made using the robust system models that show some dynamic characteristics. Working group of Institute of Electrical and Electronics Engineering (IEEE) [4, 5] have shown several models of hydropower plant as well as techniques used to have control over power production. In a study conducted by Vournas and N. Kishor et al., [6] an approximation was described for the studies that were related to the hydro turbine transfer function and multi-machine stability. In a similar study by Qijuan et al., [7] a novel hydro turbine model was introduced which was using an estimation of recursive least square algorithm and the model was dynamic.

When the topic of concern is performance of hydro-turbine, the determiner of that performance is mainly the parameters assigned to water that is supplied to turbine which generates electricity. In a study conducted by Singh et al. in the year 2011, [8] the parameters that determined the performance of turbine included the effects created by water inertia, the compressibility of water and last but not the least the elasticity of pipe wall in penstock pipe.

Furthermore, existing models that explain the linear and the non-linear hydro turbine set along with the effects of elastic and non-elastic water column. In the literature, there have been some studies that were carried out regarding water columns and the studies largely handling the non-elastic ones were performed by Ramey et al., Malik et al., Luqing et al., and Bhaskar, respectively [9-12].

In a similar study performed by Gagan Singh in 2011, [13] considering the time response that was calculated during various states of the gate, the modeling and simulation of hydropower plant was investigated. The hydraulic turbine gate state affects the Hydropower plant operating asynchronously which is dependent on speed changes of the turbine-generator set. Singh, G., and Chauhan [14] represented a hydropower plant using the integration of invariant model of a gate linear time, turbine, generator and penstock to investigate the dynamic response of the gate input. Their study revealed the simulation results proving that the turbine speed at steady state depends upon the gate position and head. This result is feasible because the gate position and as well as the head determine the volume and flow of water which rotate the turbine and determine the shaft speed coupled to the generator. In the above-mentioned model, a fully equipped power plant with all the necessary aspects was presented, whereas, in contrast with this model, previous models just focused on a single aspect.

In a study, Munoz Hernandez, in order to develop a so-called model named as Predictive Control for the hydropower plant, used Simulink in the year 2004 [16]. The study made few comparisons between PID controller response and the plant response. The control was quite successful as the results had shown improvement.

A simulation model of hydropower plant named SHKOPETI was designed by Fred Prillwitz in 2007 [15]. On the other hand, Zagona in the year 2013, [16] worked on the modeling of hydropower using river basin modeling tool namely RiverWare which provides the flexibility in order to model a wide range of events in real time along with multiple tools including optimization and simulation. RiverWare can facilitate the user with four basic ways to design the model of the hydropower and can be named as generator unit power method, peak base power method, simple power method and plant power method. There are many studies in the literature presenting the controllers that are based on the 'MHPP' transfer function models. In a study by Salhi I. et al. [17], the authors presented a completely modern approach that was based on the mathematical model construction and numerical simulation of a power plant.

A research was carried out by a team of researchers at MathWorks inc. [18] to evaluate efficiency of the models that were proposed and also the MHPP control algorithms. Moreover, using the SimPowerSystem, digital simulations were performed using MATLAB/Simulink program. A total of two simulation sets were performed in order to validate both control strategies of the hydro power plant station which are APCM and VCM.

According to some studies, due to various hydropower system constructions and differing operational hydraulic turbines principles, it has become hard to make models and design automatic control systems [19,21,22]. There are also major differences when it comes to the structure of the mentioned models. In addition, huge differences in the reservoirs' storage capacities as well as water supply systems emerging right out of the reservoir and heading towards the turbine with or in other cases without surge tank. Dynamic models with surge tank and penstock are complicated as compared to run-of-river plants, because the systems feeding water in these models are quite sophisticated systems. It is important to have mathematical models made for plants that contain a water tunnels between reservoir and surge tank, penstock and hydraulic turbine, to make the control system. [20-22].

The SCADA system architecture is implemented to optimize the river resources usage and monitor as well as control the HPPs in case of cascade systems placed along-side a river [23]. The SCADA system is run at central dispatcher. There is a local and control monitoring system that is interconnected with the central dispatcher through radio communication buses and the modem.

CHAPTER 3

CLASSIFICATION AND TYPES OF HPP

Working principles and units of RRHPPs and HPPs with dam are almost the same. In this section, HPPs are classified. In Chapter 4, the operation process and units of channel type HPPs are explained. type. The Hydro power plants are generally site-specific. The installation of HPPs requires a vast search of locations and also some other factors. But they can be classified based on the following parameters;

- Size of the HPPs
- Head size of the HPPs
- Operation of the HPPs
- Purpose of the HPPs
- Turbine types of the HPPs

3.1. CLASSIFICATION of HPPs by SIZE

Hydro power plants are generally classified according to the installed capacity in P (MW). There are some opinions that might change, regarding the threshold separating the individual HPP classes. The widely accepted classification according to size is as follows; but the classification criteria may change according to the region.

- Micro: P < 0.1 MW
- Small: 0.1 MW < P < 10 MW
- Medium: 10 MW < P < 100 MW
- Large: P > 100 MW

The Micro HPPs have the capacity to supply electricity to a small-scaled industry, or even a small community. Micro HPPs can be rendered as standalone plants, as these type of HPPs are not grid connected. And this type of HPP is always run-of-river HPP. In Micro Hydro power plants, there are some small water storage tanks constructed which give a guaranteed hydro generation for minimum period during the day. These water tanks help when there is a low-water flow condition. They are commonly found in the rural areas where they facilitate the area with economical energy source.

Many smaller hydro power plants are considered to be run-of-river type as these power plants are connected to a power grid. The power capacity of such hydro power plants is greater than 0.1 MW but smaller than 10 MW. As small HPP generally exploits low discharges, the dimension of small HPP is considerably small compared to that of medium and large hydro power plants.

Medium HPPs are known to be storage type or run-of-river type. These type of HPPs directly feed into power grid. The medium HPPs' layout can include dam in order to have a head pond. Electro-mechanical equipments used in these HPPs are similar to the ones used in large hydropower plants.

Large hydro power plants are known to be connected to larger grids. They may either be storage or run-of-river type. The layouts used in such HPPs are specific to site and the electro-mechanical equipment for large HPP are designed to meet local needs and to fulfil certain conditions.

3.2. CLASSIFICATION OF HPPs ACCORDING TO HEAD SIZE

Hydropower plants are classified in terms of head size in order to produce electricity and they are classified into three categories as follows;

- Low Head: $H < 30$ m
- Medium Head: $30 \text{ m} < H < 100$ m
- High Head: $H > 100$ m

The classification of Head size may vary from country to country and organization to organization. Classification of Hydro power plants by head size might be somehow inconsistent when compared to the classification by power capacity. Mountainous areas may provide favorable conditions for the implementation of high or medium head HPPs, often the storage type. However, low-land areas which have wide river valleys may provide favorable locations that are feasible for the installation of low head HPPs, often the run-of-river type.

3.3. CLASSIFICATION of HPPs by OPERATION

The Hydro power plants can also be classified based on the type of operation. Classification of HPPs by operation can be shown as follows;

- Storage HPPs
- Run-of-river HPPs
- Pump storage HPPs

Storage HPPs can be characterized by the water storage capacity of dams used to create water reservoir during the higher flow and then to generate energy when there is a low flow. This type of hydro power plants aid in electricity generation when there is a fluctuation in the availability of water thus caused by the seasonal variation and weather conditions.

Run-of-river HPPs generate electricity using the immediate inflow of water. Therefore, run-of-river HPPs get affected due to the seasonal as well as climatic variations and this may result in a variable power output. Most of the run-of-river HPPs have limited storage capacity or in some cases they have no storage capacity.

Pumped storage HPPs can store water using a pump system which pumps the water from a river or a lower reservoir to a higher reservoir. The pumping process of water is carried out by reversing the turbine operation in order to provide water for generating electricity.

3.4. CLASSIFICATION of HPPs by PURPOSE

The HPPs have many uses such as provision of water for the human development and subsistence. Approximately one-third of the current hydropower plants serve some other functions beside energy production (LeCornu 1998). The above-mentioned functions of HPPs include;

- Protection from flood: water storage of HPPs mitigate the effects of floods.
- Drought alleviation: supplement of water during dry periods.
- Irrigation: water supply for agriculture.

3.5. CLASSIFICATION of HPPs by TURBINES

There are three types of turbines that are used commonly in the hydro power plants which are as follows:

- Kaplan Turbine
- Pelton Turbine
- Francis Turbine

3.5.1. Kaplan Turbine

It is a propeller type water turbine that consists of blades which can be adjusted. It is a combination of adjusted automatically propelled blades and adjusted wicket gates which also function automatically, to acquire the planned effectiveness over quite a huge amount of water flow. The shape of the Kaplan Turbine along with its parts is shown in the figure below;

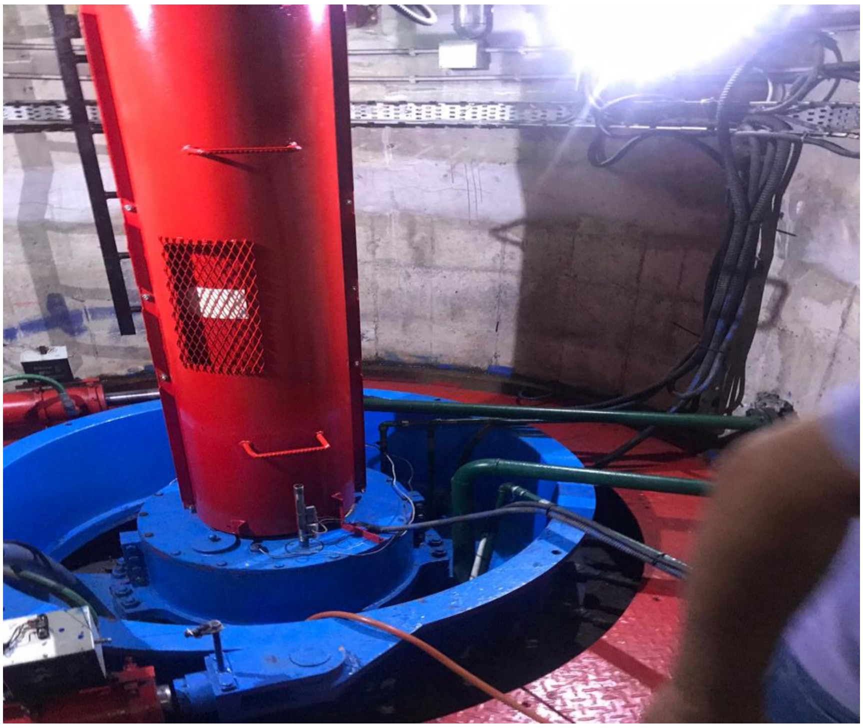


Figure 3.1. Kaplan turbine.

Kaplan Turbine has 4 main parts given as follows:

Scroll Case: A spiral case with a decreased cross section in Kaplan Turbine. Water that is present in the penstock pipe flows towards the scroll case. This moves towards the valves where the water is turned to 90 degrees and starts flowing into the runner axially. This case keeps some parts such as guide valves, runner blades, and some internal parts of turbine against the external damage, protected throughout.

Guide Valve Mechanism: The part that controls the whole turbine is the guide valve. This valve opens and closes according to the power demand. In case, more power is required in the output, it wide opens in order to let the water hit the rotor blades. When low power is required in output, it closes so that the water flow is ceased. If the guide valves are absent, then the efficiency of the turbine decreases and cannot work properly.

Draft Tube: At the opening of runner of the turbine, the pressure is observed to be less as compared to atmospheric pressure. It is impossible to directly discharge the water at the exit to tail race. Pipe or a tube with a gradual increase in the area is used to discharge water from exit to the tail race. Such a tube comprising of an area increasing gradually is called as the Draft Tube. There are two ends of the draft tube; one connected to runner outlet, whereas, the other sub-merged into the water in tail-race.

Runner Blades: These blades may be called as the heart of all the components present in Kaplan turbine, because it is the rotating part that aids in the electricity production. The shaft of runner blades is connected to the generator shaft. These blades are connected and attached in a way that these can be adjusted to such an angle for maximum output of power. Runner blades have a so-called twist throughout their lengths.

Function of Kaplan Turbine: The water flowing right from the pen-stock pipe is made to flow towards the scroll casing. This part is manufactured in such a shape that the pressure of water flow might not be lost. Then the water is directed towards the runner blades with the help of the guide valves. The guide valves are self-adjustable which means that they can easily adjust themselves depending on the required rate of water flow. As the direction of flowing water is completely axial to rotating runner blades, a 90 degrees water turn is observed.

The water hits the runner blades and the blades start rotating because of the reaction force. The Kaplan Turbine rotates at the rate of 300-1000 rev/min. As mentioned above, the runner blades comprise of twist throughout their lengths, in order to achieve the optimum angle for a higher efficiency of all the runner blades.

After rotating the runner blades, the water flows into draft tube. In this part, the kinetic energy and pressure energy of the water is observed to be decreased. The kinetic energy converts into the pressure energy and this causes an increase in the water pressure. The rotation of the runner blades and hence the turbine is used in order to rotate the generator shaft for the production of electricity.

3.5.2. Pelton Turbine

A Pelton turbine consists of a Pelton wheel and said to be Pelton wheel hydro turbine (a kind of impulse turbine) mostly used in hydroelectric plants. These turbines are preferable where heads of water reservoir are greater than 300 meters. This turbine was built-up by Lester Pelton 1880 [23]. The water moves fast in a Pelton turbine and the turbine gets that energy from the water by slowing down the speed of water. Therefore, it is said to be an impulse Stream of water exists from nozzle with a high velocity (with high velocity head) and hits the Pelton turbine and rotates it. The water then moves towards the bottom with relatively a very small amount of energy left.

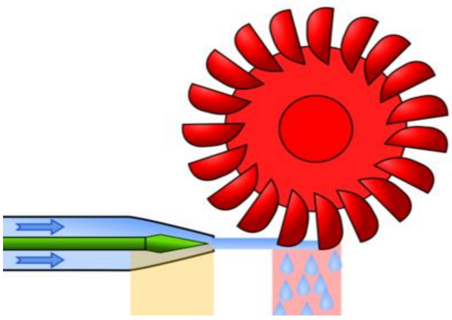


Figure 3.2. Working Principle of Pelton Turbine.

3.5.3. Francis Turbine

Francis Turbine consists of both impulse and reaction turbine. Blades of this turbine rotate using both reaction and impulse forces of water flowing through them thus producing electricity more efficiently. Francis turbine is used to convert hydro power to generate electricity and has two types of flow turbines operating as; radial and axial flow types. American engineer James B. Francis in Lowell, Massachusetts [24] gives us a concept of combining both impulse and reaction turbines where water enters the turbine radially and exits axially. The reason behind the higher efficiency is due to the design and arrangement of blades of Francis turbine, using both reaction and impulse forces of water passing through them. The drawback of this turbine is that water head availability is eliminated because turbine uses both the kinetic and potential energy to generate power.

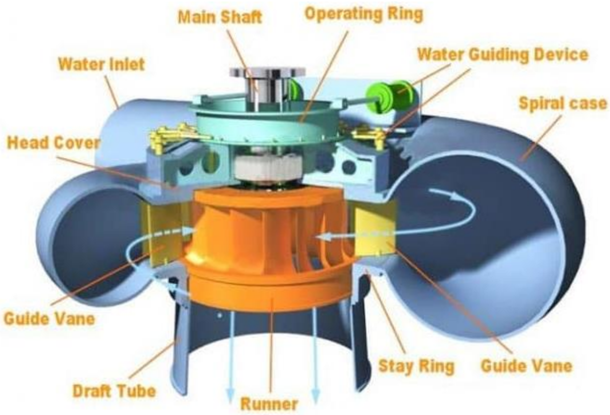


Figure 3.3. Components of Francis turbine.

CHAPTER 4

RUN-OF-RIVER HPPs

4.1. WORKING PRINCIPLE OF RRHPP

Both dam and run-of-river HPPs operate based on several stages involving the conversion of the potential energy of water into kinetic energy; the conversion of kinetic energy into mechanical energy; and the conversion of mechanical energy into electric energy. This energy conversion process is illustrated with the block diagram show in Figure 4.1.

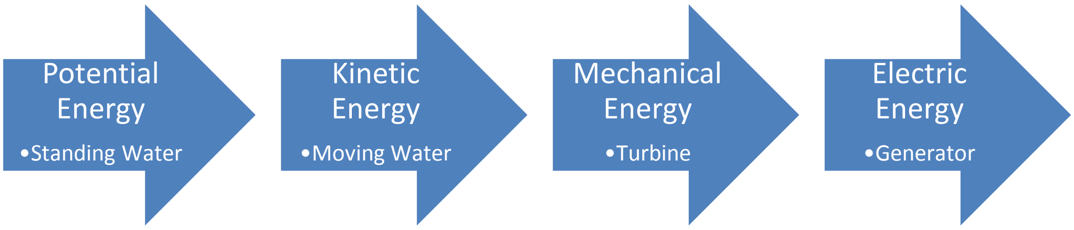


Figure 4.1. Energy conversion processes in HPPs.

The electric energy production process of most run-of-river plants takes place as follows: river water is first transferred to a waterway through the action of a weir (a regulator), and is then carried through the waterway into the forebay. Standing water in the forebay is then transferred through the penstocks into the turbines, causing the turbine blades to turn, along with the rotor of an generator connected to the turbine by a shaft. As a result, the potential energy in the water is converted into kinetic energy by the penstock; the kinetic energy is converted into mechanical energy by the turbines; and mechanical energy is converted into electric energy by the generator. The electric energy produced by the generator is then amplified by transformers, and transferred into power transmission lines. Figure 5.1 provides a diagram illustrating the working principle of run-of- river plants.

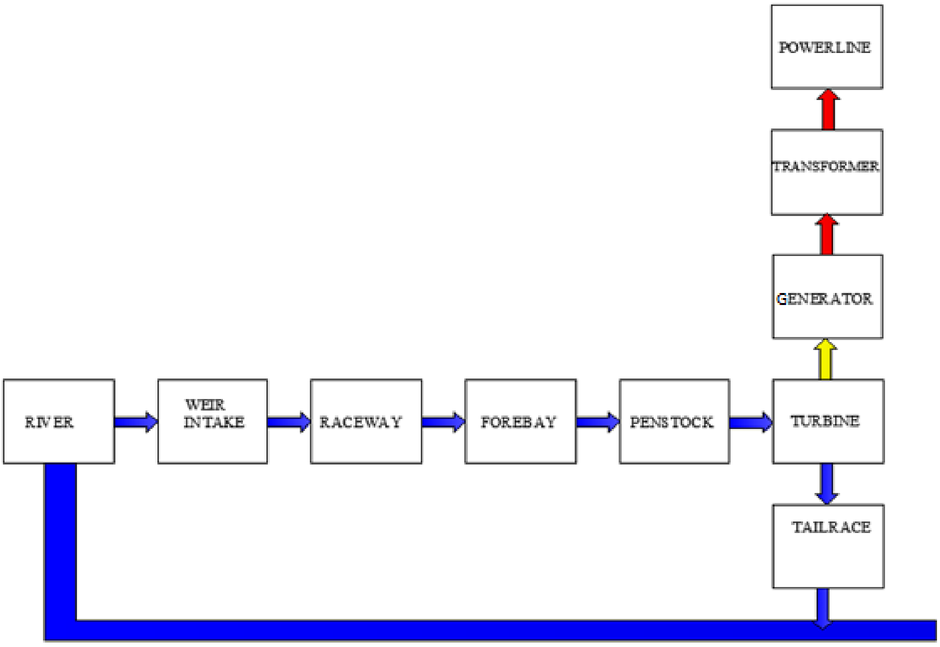


Figure 4.2. Energy production process in run-of- river plants.

The electricity production processes of HPPs involves numerous different equipment and intermediate stages. Without delving too much into the details of the process, we will provide information regarding the turbines, alternators, and power control systems, which are considered as the most important elements.

With their turbine blades, turbines capture the kinetic energy generated by water moving from a higher to a lower level through the penstocks and convert it into mechanical energy. The type of turbine to be used in a plant is selected based on the pressure and flow rate of the water that will rotate the turbine. In all turbines, the non-moving part is called the spiral casing, while the rotating part is called the rotor. Three types of turbines are currently in use: the Kaplan, Francis, and Pelton turbines. These turbines are not mentioned in this section as they are explained in Chapter 3.

Generators are synchronous machines that convert mechanical energy from the turbine shaft into electric energy. They operate based on the principle of electromagnetic induction by a moving armature (rotor) in a fixed magnetic field. The rotors of generators used in HPPs are generally manufactured with vertical shafts and salient poles. The revolution rate of these generators' rotors ranges from 32 rpm to 1000 rpm. Smaller generators utilize open air cooling, while larger generators utilize closed air cooling. Synchronous generators are generally the self-excited type, and the excitation current is generally supplied by an AC/DC rectifier circuit.

The powerhouse is an enclosed area within the HPP that houses the plant's electromechanical equipment. It generally contains the following equipment:

- Valve
- Turbine
- Generator
- Control System
- Condenser
- Protection System
- DC Emergency Supply

Previously determined voltage and frequency values are continually controlled and adjusted according to the reference values. During operation, the turbine speed decreases when the generator is being charged. To bring the turbine speed and the generator frequency to the desired values, it is necessary to increase the water flow rate by adjusting the turbine wicket gates and valves. On the other hand, in case the generator charge decreases, it becomes necessary to adjust the turbine wicket gates and valves such that the water flow rate is decreased. Modern speed/rate controls are performed using the PID control system. The system is constantly monitored using the PLC-SCADA, and the relevant data are recorded in a database.

Civil Structure: The civil structures of the run-of-river HPPs consist of headworks, waterway and powerhouse. A brief explanation of the components has been given below:

- Headworks: The function of the headworks is to create the head and extract water flowing from the river towards the equipments, thus allowing the safe passage of flood water.
- Waterway: It transfers the water to the powerhouse
- Powerhouse: It consists of structures that have electro-mechanical equipments

which convert the energy of the flowing water into mechanical energy and then this energy is converted into electrical energy.

Headworks: The headworks consist of some structures which raise the water level to the required height and safely divert the water flowing from the river to the waterway. Furthermore, the headworks are designed in a way to allow the flood water to flow without posing a risk to the structural instability.

In a run-of-river HPP, the function of headworks as mentioned above is to discharge the flood water flowing through its intake, as well as the safe passage of the flood water, sediment load, floating debris and suspended sediments which are managed and controlled by the settling basins [22].

Waterway: The waterway involves some parts that pass on the water flowing from the intake to powerhouse. The waterway conveys the water through a design that can incorporate either pressure exhibitions or pressurized pipes. It has some extra structures that help an appropriately working of the HPP, and depending upon nearby geographical and topographical conditions, the structures include a few or all of the following:

Surge Tank (Surge Chamber): It controls the pressure fluctuations in the penstock, thus eliminating the water hammer when fluctuations occur because of the abrupt shutdown of the water flow to the powerhouse. Besides, the surge chamber regulates the water flow to installed turbine by the provision of necessary head. The surge tanks can be classified as:

- Simple surge chamber
- Orifice type surge chamber
- Differential surge chamber

Water Reservoir: Water reservoir is somehow an artificial water structure that is built in order to store the flowing water in run-of-river hydroelectric power plants. This controls inflow of water to the units. As there are three units being operated, the water is distributed among the three units according to the amount of water stored and the electricity production being planned. This value might show a slight difference in other hydro power plants depending on the size and capacity of the plant. The water after being kept in the regulator is drained into the water reservoir.

Figure 4.3. Forebay of RRHPP.

Penstock Pipe: These pipes are big pipes, gates or tunnels which transfer the water to the turbines. This pipe has a uniform shape throughout the length because a change of shape along the length can create fluctuations in the pressure of water being transferred. A larger area inside the pipe has a lower pressure and the smaller area has a higher pressure. Therefore, the uniformity in shape along the length ought to be considered.

Powerhouse: The powerhouse of the Hydro power plant hosts the generator, turbine and the auxiliary equipments. It is constructed in a way that allows the easy installation of the afore-mentioned equipments and gives an easy access to maintenance works and inspection. The size of the powerhouse generally depends on the type, number of units installed and the dimensions. Powerhouses include three primary areas in general.

- The main structure which houses the generating units
- Service areas which include some offices and rooms for storage, control and testing, auxiliary equipment, maintenance, and some other special uses.
- The Erection Bay

Powerhouses can be built above or below the ground which generally depends on the type of architecture to be applied. One of the components of the powerhouse called crane is an essential powerhouse component which is used to put turbines, generators and other components all together. The maximum capacity of a crane has to be equal to carrying the heaviest equipments which are generator parts, turbine runner etc. The type of crane should be selected according to the powerhouse dimensions and layout during the design process.

Butterfly Valves: Basically, butterfly valves are used to cut the water supply when needed, however these valves can also regulate the water level under low pressures.

Figure 4.4. Penstock and Butterfly Valves.

4.2. THE YALNIZCA RUN-OF-RIVER HPP

The Filyos Energy Yalnızca run-of-river plant is located in the Karabük province within Turkey’s Western Black Sea region. The plant began its operations on September 2009. The plant has an installed power capacity of 15 MW, and consists of three units of 5 MW each.

The Yalnızca HPP is located on the Yenice (Filyos) River, with waters from the river being directed to the plant by a 2 km waterway and tunnel. The diameter of the plant’s penstocks is 2.75 m, while their length is 43 m. The flow rate through the penstocks is 25 m^3/s. The water elevation (altitude) of the forebay is 221.6 m, while the water elevation of the tailwater channel is 199.2 m. The net head (falling height) of the plant is, on average, 22 m. Table 4.1 shows The nominal power of the alternators (generators) is 5100 KW, while their voltage is 6.3 KV, their nominal current is 550 A, their revolution speed is 333.3 rpm, and their frequency is 50 Hz. The plant uses Kaplan type horizontal-axis turbines. The fully automated plant is controlled and monitored with the SCADA system. Geographically, the plant is located on the 32.5176 meridian east and 41.1633 parallel north. Table 4.1 gives default values of alternators.

Table 4.1. Design values of generators.

PARAMETER NAME	**VALUE**
Nominal Power	5100 kW
Volts	6300 V
Amps	549.9 A
Power factor	0.85
Frequency	50 Hz
Connect	Y
Phase	3
Speed	333.3 rpm
Runaway speed	790 rpm
Field volts	155 V
Field Amps	345 A

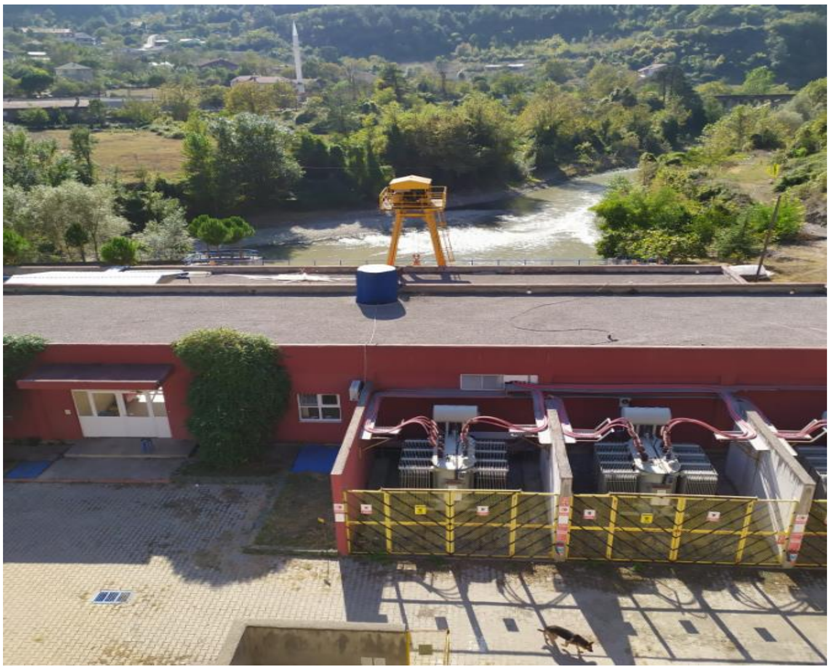


Figure 4.5. Yalnızca RRHPP.

CHAPTER 5

MATLAB SIMULINK MODELLING AND SIMULATION OF MICRO SCALED HYDRO POWER PLANT

Within the past few decades, hydroelectricity has become a significant part of the world's sustainable power source. Power age on the earth has been on expansion within this course, and particularly within the developing countries where hydropower remains the wellspring of power age. In addition, hydro-electric is a sort of sustainable power source, originating out of streaming water. For power generation, water should be moving. Hence, if water falls due to gravitation applied by the gravity, potential energy changes to dynamic energy. Active energy of the streaming water rotates the turbine blades during the process being implemented in a pressure driven turbine, and thus the energy is converted into mechanical energy. Generator rotor is turned by turbine which at that time changes over mechanical energy received into electrical energy to be used. Electrical energy that needs to be provided to top clients is converted through simultaneous generators. Overseeing framework alters speed of the generator hooked in to data signs for the reference settings. This is often used in order to ensure that the generator works at or on the brink of required speed consistently and to adjust the generator parameters.

HPP fundamentally consists of a turbine, a generator, wicket entryways and a penstock. In hydropower plant (HPP) turbines used are Kaplan turbines which are utilized for low head and high stream plants. Kaplan, Pelton and Francis are three turbine types, which are widely used in commercial. The turbine selection depends on the head of the plant and available water flow. The type of turbine used in the RHPP is the Kaplan type which is favorable for use in conditions with low head and high flow, and is compatible with the available height and flow.

The turbine and generator are connected generally with each other through vertically held shaft. High head forms rapid streaming water which moves through penstock heading towards turbine. Wicket doors constrain progression of flowing water in turbine. They can be balanced with outer sides of turbine in order to control water amount streaming into turbine. Actuators used in such plants help to modify these entryways. The water streamed into the turbine start-ups turbine-generator and driven generator generates power. During this stage, water has the possible energy. Moves from penstock, water loses its kinetic energy and an additionally gained potential energy prior to reaching at turbine. The concept of energy conversion cycle by HPP shows that these models tend to be dependent on framework (penstock-turbine), electric generator and control frameworks.

A precise mathematical model of components of power grid has been critical for the dynamic and the transient stability studies. Therefore, various dynamic models had been introduced in the past for simulation programs as well as for other purposes in the literature. Parameters regarding afore-mentioned models are supposed to be evaluated by engineers and operators accurately in order to understand behavior of the elements used in power grid simulations.

In addition, another essential application of above mentioned modeling is the fine parameters tuning of unit controller, for example, the governor. Hence, in order to ensure good performance during processes involved in power production considering various conditions, parameters of controllers need to be tuned properly. In this study, the research of modeling system of necessary components of hydro-electric station was aimed, and this model was aimed to be used to create a model of RRHPP within the scope of the software program that we will choose.

5.1. MATHEMATICAL MODEL OF THE TURBINE GOVERNOR SYSTEM

While evaluating the turbine models performance, non-linear models may be more accurate for simulations of signal-time of giant domains. Therefore, in this study, the mathematic approximation of non-linear system was implemented for improving our models. As per our research, an appropriate non-linear model is needed for the time-domain simulations of large-signals, for example, rejection of load, islanding, restoration of system, etc. The electric-mechanic dynamics and the hydrodynamics were included in the models. These models are represented generally by diagrams. And, non-linear models are therefore required at instants where the changes in power and speed are quite immense. Mathematical models including ordinary differential equations that represent dynamic behaviour for the governor are used. The regulator in this condition comprises two parts; PID Controller which is electrical part and the electrohydraulic part**.** Actually, the generator model is created from circuit equations, which use Park Transformation. Park Transformation can be used to evaluate and define the equations for synchronous machines. And ordinary differential equations are used for the exciters.

In order to analyze the response of power system in case of disturbances thus created in the system, ideal modeling of components of HPPs comprising turbine, the governing system and synchronous machine is essential. The performance of power system is thus affected due to the characteristics (dynamic) of the hydraulic turbine as well as the governor system during disturbances, for example; the harmonics on the network, presence of faults, line losses and immediate load changes. In the figure 5.1 below, the block diagram depicts governor, synchronous machine, servomotor and generator excitation of the Hydraulic Turbine.

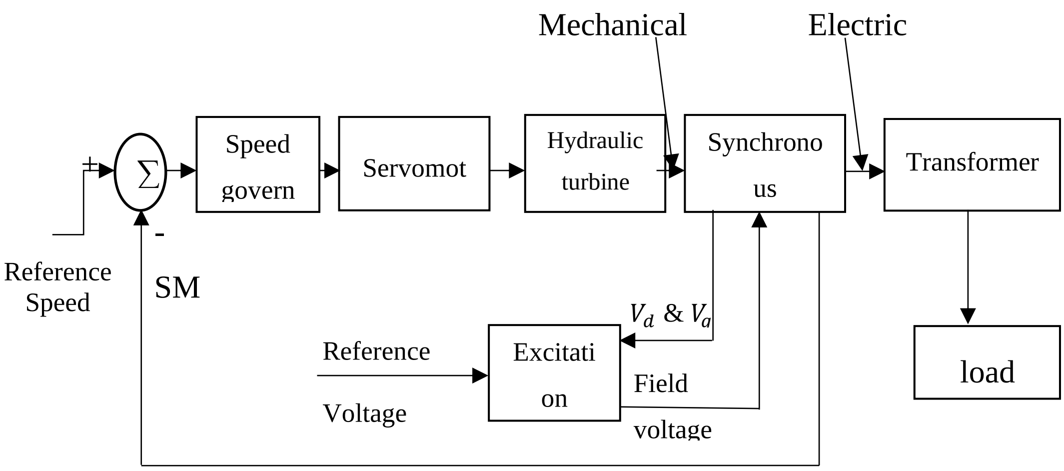


Figure 5.1. Block diagram of HPP [24].

As the water stored in the head posseses Potential Energy (P.E), the energy can be transformed into the K.E (Kinetic Energy). The stored water passes through the penstock, the kinetic energy is converted from P.E (potential energy) to M.E (Mechanical Energy) or R.E (Rotational Energy) which allows water to fall from the stationary position to o turbine runner blades. Shaft of the generator is coupled with turbine and this allows the generator to convert the mechanical energy into electrical energy, thus producing the required energy form. There is a system that governs speed of the turbine thus adjusting the generator speed with feedback signals that are received due to deviations in both the system frequency as well as power with respect to the reference settings. Hence, the power production is ensured at synchronous frequency.

The reference speed signal was obtained through penstock from the K.E of the falling water in this simulation model. Synchronous machine speed was measured and the feedback was given as to compare it with obtained reference speed signal. Deviation in speed was found by comparing the reference speed and the synchronous generator speed and was used as the input for speed governor which was PID regulated. Generally, PID regulates the turbine governor, as such control includes strong robustness, stability, simple structure, and state error. Governor produces control signal, and causes a change in the gate opening. Then the turbine produces torque that drives synchronous machine and eventually generates output which is electrical power. Deviations in speed are continuously checked by the speed governor so that it may take actions.

5.2. SYNCHRONOUS MACHINE MODEL

The model known as the Synchronous Machine model is known to operate in the generators or the motor modes. Operating mode in this case is dictated through the mechanical power sign and is determined to be negative for the motor mode and positive for the generator mode. The state space model of order six represents electrical part of machine, and mechanical part is known to be exactly same as it has been indicated in Synchronous Machine block. The model takes into consideration the damper windings, dynamics of stator, and also the field. This model’s equivalent circuit is hence shown in reference frame of rotor which is denoted as qd frame. The electrical quantities as well as rotor parameters are observed from stator. And, these quantities are shown by the variables assigned for them. In this model, the subscripts have been denoted as shown below;

- R, s: Rotor quantity, stator quantity
- d, q: denote the axis quantity.
- *f*, *k*: Field quantity, damper winding quantity.
- *l*, *m*: Leakage inductance, magnetizing inductance.

Using the above-mentioned model, the obtained electrical model is shown as follows:

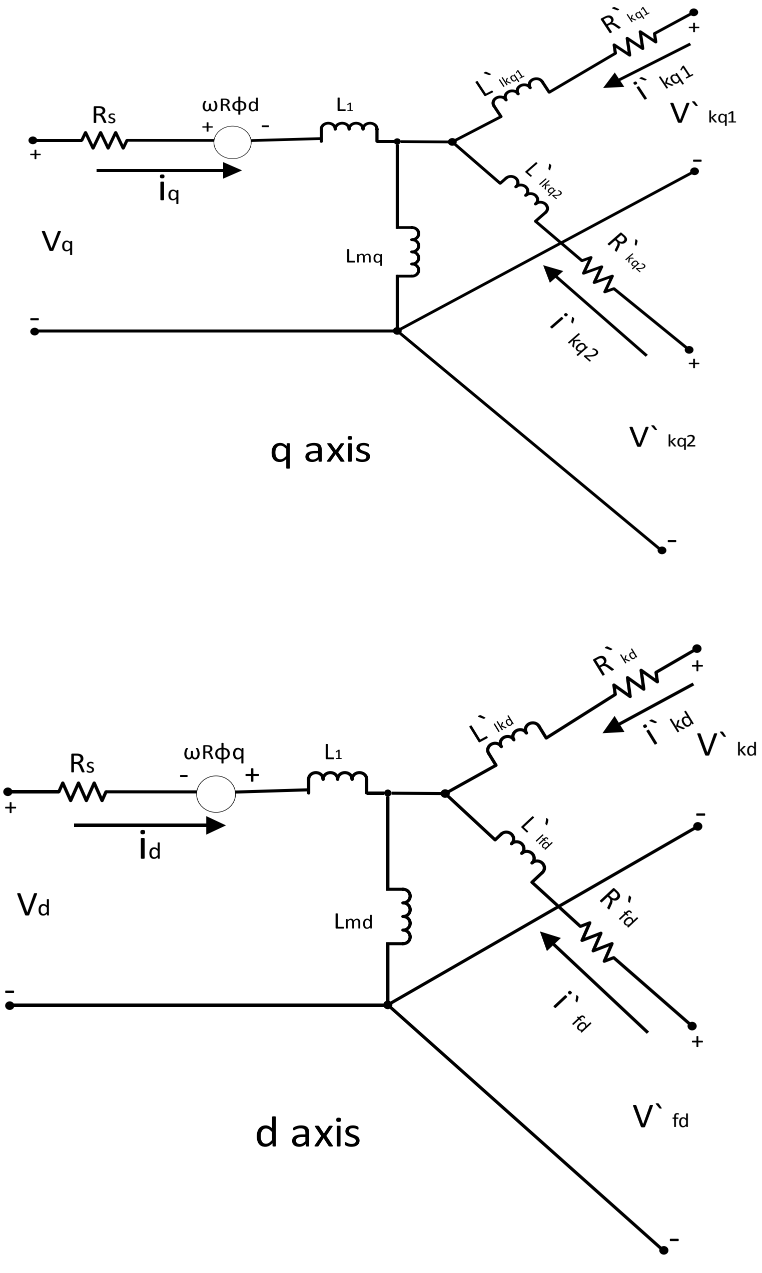


Figure 5.2. Equations for the synchronous machine electrical model [25].

$$V_d = R_S \; i_d + \frac{d}{dt}\varphi_d - \omega_R \varphi_q \qquad \varphi_d = L_D i_d + L_{md}\left(i_{fd} + i_{kd}\right) \tag{5.1}$$

$$V_q = R_S \ i_q + \frac{d}{dt}\varphi_q - \omega_R\varphi_d \qquad \varphi_q = L_q i_q + L_{mq} \ \dot{i}_{kq} \tag{5.2}$$

$$\dot{V}_{fd} = \dot{R}_{fd} \ \dot{i}_{fd} + \frac{d}{dt}\dot{\varphi}_{fd} \qquad \dot{\varphi}_{fd} = \dot{L}_{fd}\dot{i}_{fd} + L_{md}\left(i_d + \dot{i}_{kd}\right) \tag{5 .3}$$

$$\dot{V}k_{kd} = \dot{R}_{kd} \ \dot{i}_{kd} + \frac{d}{dt}\dot{\varphi}_{kd} \qquad \dot{\varphi}_{kd} = \dot{L}_{kd}\dot{i}_{kd} + L_{md}\left(i_d + \dot{i}_{fd}\right) \tag{5.4}$$

$$\dot{V}_{kq1} = \dot{R}_{kq1} \ \dot{i}_{kd1} + \frac{d}{dt}\dot{\varphi}_{kq1} \qquad \dot{\varphi}_{kq1} = \dot{L}_{kq1}\dot{i}_{kq1} + L_{mq} \ i_{kq} \tag{5.5}$$

$$\dot{V}_{kq2} = \dot{R}_{kq2} \ \dot{i}_{kd1} + \frac{d}{dt}\dot{\varphi}_{kq2} \qquad \dot{\varphi}_{kq2} = \dot{L}_{kq2}\dot{i}_{kq2} + L_{mq} \ i_{kq} \tag{5.6}$$

The used model assumes currents which flow into stator windings. Measured stator currents which are returned by Synchronous Machine Block (Ia , Ib , Ic , Id , Iq) are found to be the currents that flow out of the machine.

5.3. HYDRO TURBINE MODEL

In hydro turbine model, penstock is generally modelled through an assumption which assumes the flow to be incompressible when the flow rate changing in the penstock is acquired through equating the change of momentum rate in water flowing from the penstock, to net force being applied on the water at that particular instant in the penstock. The equation for the above-mentioned condition can be indicated as follows;

$$\rho L = \frac{dQ}{dt} = F_{net} \tag{5.7}$$

Where

- L is penstock length.
- Q is volumetric flow rate.
- $\rho$is mass density of the water.

By considering the pressure head, the net force being applied on the water may be obtained. On the penstock entry, the force applied on water is found to be simply proportional to static head, whereas, it is found to be proportional to head at the wicket gate. Because of the frictional effects in the turbine, a friction force is observed on the water which is represented by head loss and in the penstock, the net force on water is indicated by the equation given below:

$$F_{net} = (H_s - H_l - H)\, A\rho g \qquad (5.8)$$

Where:

- A is cross-sectional area of penstock
- g is gravitational acceleration
- ρ is mass density of the water

By substituting the net force in the Equation (3.8),

$$\rho L = \frac{dQ}{dt} = (H_s - H_l - H)A\rho g \qquad (5.9)$$

Usually, the equation is normalized to a convenient base. Despite the base system is found to be arbitrary, base head h_{base} in this equation is taken to be the static head above turbine. So, in this case, the base flow rate is q_{base} which is taken as flow rate in the turbine when the gates are fully open. The head in the turbine equals to h_{base} (IEEE Committee Report, 1992). By dividing both sides of the Equation (5.9) by q_{base}. h_{base}, we obtain;

$$\frac{dQ}{dt} = \left(1 - h_l - h\right)\frac{1}{T_w} \qquad (5.10)$$

Where:

- h, q are normalized flow rates and the pressure heads, respectively.

$$q = \frac{Q}{q_{base}} \qquad (5.11)$$

$$h = \frac{Q}{h_{base}} \qquad (5.12)$$

$$T_w = \frac{L_{qbase}}{Agh_{base}} \qquad (5.13)$$

Where:

- T_w is starting time of the water, which is defined theoretically as time taken for flow rate in penstock which changes by a value equal to q_{base} and the head in brackets changes in equal ratio as the value equal of h_{base} .
- Head loss is found to be proportional to square of the flow rate and it depends on the dimensions as well as the friction factor. We assume that $h_l = k_f q^2$, however, this assumption may often be neglected. The above equation gives us the penstock model.

While modelling the turbine, both the mechanical power output and the hydraulic characteristics must be modelled. Initially, the pressure head that is across the turbine, is observed to be related to flow rate by the assumption that the turbine could be represented using the valve characteristics which is denoted as follows;

$$Q = kG\sqrt{H} \qquad (5.14)$$

Where:

- G is gate position having a value between 0 and 1
- K is constant

G equals 1 when the gate is fully opened and a normalized equation can be derived by dividing both sides of the equation by;

$$Q = G\sqrt{H} \qquad (5.15)$$

Then, power generated by the turbine is calculated to be proportional to the product of head and the flowrate and is also found to be dependent on the efficiency. In order to account for turbine that is not 100% efficient, the no-load flow q_{nl} ought to be subtracted from actual flow to ensure the normalized parameters as shown below;

$$P_m = h\,(q - q_{nl}) \tag{5.16}$$

Unfortunately, the above expression differs in unit system used for the generator which has parameters that are normalized to generator in MVA base. Hence, the last equation can be written as follows;

$$P_m = A_t h\,(q - q_{nl}) \tag{5.17}$$

Where:

- A_t factor is introduced in order to account for base differences.

5.4. ELECTROHYDRAULIC GOVERNOR MODEL

Electrohydraulic governor (Controller and Servo motor) model is commonly used in the modern hydrospeed governors. The structure, dynamic behavior and the operation of this model are basically similar to that of mechanical hydraulic governor, but there are some exceptions which have been described below;

- Permanent droop, speed sensing, temporary droop and some other computer and measuring functions in this model are performed electrically.
- Electrical components provide better performance and more flexibility.

5.4.1. Modelling of controller

Proportion-integral-derivative (PID) operated three-term controllers are often implemented in the electro hydraulic governor models. This system calculates error values of a desired set point of $\Delta\omega$ and the measured process variable. The PID controller is used to minimize the error by the adjustment of the process control input. Proportional Integral Derivative regulator is a regulating process which is usually formulated [26] as shown below;

$$U(t) = K_p\, D(t) + K_i \int_0^t D(t) + K_d \frac{d}{d(t)}\, D(t) \tag{5.18}$$

Where:

- *U(t)* is the output signal of the system.
- *D(t)* is the deviation observed from the desired operating point.
- K_p is the proportional gain of the system.
- K_i is the integral gain.
- K_d is the derivative gain.

Taking the Laplace transformation on both sides of Equation (5.18), the resulting equation becomes;

$$U(s) = K_p D(s) + K_i \frac{D(s)}{s} + K_d\, s\, D(s) \quad (5.19)$$

Transfer function of PID controller is formulated to be;

$$G(s) = \frac{U(s)}{D(s)} = K_p + \frac{K_i}{s} + K_d\, s \quad (5.20)$$

The output signal found in this case is a superposition of three terms which are as follows;

Integral term corrects the droop through accounting for the duration of the previous deviation, and the magnitude. The obtained integral contribution hence increases as long as the deviation exists. Thus, the integral term is known to account for the accumulated deviation and multiply this by an integral gain denoted by K_i, and eventually adds this to proportional contribution.

Proportional in this case uses deviation D along the gain denoted as K_p in order to calculate the control signal output. Contribution obtained from proportional term is found to be only dependent on magnitude of deviation; therefore, there will be a small steady-state deviation in the system known as the droop.

Derivative in the system calculates the slope of the deviation or the rate of change, thus predicting the future deviations. The slope found is then multiplied by derivative gain denoted by K_d and the resulting value is added to other terms. The obtained derivative gain is generally small or in some cases even zero as this term is found to be highly sensitive against measurement noise.

5.4.2. Modelling of the Servo Motor

In the hydro turbine governor model, the servo motor is used in order to control the gate valve by the signals received from the controller. Controller nullifies any error detected in the speed signal through sending a signal to servo motor for controlling the valve.

The motor torque as mentioned below, is the function of error signal and the speed

$$T_m = f(\dot{\theta}, e) \tag{5.21}$$

The torque Equation (5.21) of servo motor is expanded using the Taylor`s series as depicted in Equation (5.22) [27] .

$$T_m = t_a(0) + \frac{dt_a}{de}\,[\mathrm{e}\,(\mathrm{t}) - \mathrm{e}\,(0)] + \ldots + \frac{dt_a}{d\dot{\theta}}\,\left[\dot{\theta}(t) - \dot{\theta}(0)\right] + \cdots \tag{5.22}$$

Neglecting the higher order terms and by considering the zero initial condition, Equation (5.22) is re-written as follows;

$$T_m = ke(t) - f\dot{\theta}(t) \tag{5.23}$$

Where $k = \frac{dT_m}{de}$, $f = \frac{dT_m}{d\dot{\theta}}$

As we know the mechanical relations in motors can be shown as,

$$T_m = J\ddot{\theta} + B\dot{\theta} \tag{5.24}$$

J and *B* are the friction co-efficients and the moment of inertia, respectively. Looking at the Equations (5.23) and (5.24) written above, we can write the following equation;

$$ke(t) - f\dot{\theta}(t) = J\ddot{\theta} + B\dot{\theta} \tag{5.25}$$

By taking the Laplace transform of both sides, we obtain the equation;

$$\frac{\theta(S)}{E(S)} = \frac{k}{Js^2+(B+f)s} = \frac{k}{s(Js+B+f)} \tag{5.26}$$

Where the $k_a = \frac{k}{B+f}$, $t_a = \frac{k}{B+f}$

Thus, the transfer function of servo motor is obtained to be;

$$G(S) = \frac{\theta(S)}{E(S)} = \frac{k_a}{s(t_a s+1)} \tag{5.27}$$

Servo motor in this condition controls the position of the gate opening in accordance with the change in speed at the shaft of generator in order to maintain constant speed over frequency [28].

5.4.3. Model of Excitation

The Model of Excitation can be described as the DC excitation system type, in the absence of saturation of exciter, which utilizes the direct current generator along with a commutator used as source for the excitation system power. This model can be used to generate excitation voltages that can be supplied to the synchronous generator. The feedback systems are used by the PID controllers in order to regulate both the mechanical power produced by turbine as well as the generated excitation voltage.

This presents the excitation system model that utilizes the direct current generator along with a commutator used as source for the excitation system power. Principal input to such a model is actually the output V_c, orginating from load compensator and terminal voltage transducer model. At the junction, the terminal voltage transducer, which is denoted by V_c, is thus subtracted from a set point reference of V_{REF}. And the stabilizing feedback denoted as V_F is also subtracted. Then the power system stabilizing signal denoted as V_S is added in order to produce the error voltage. At the steady-state, the last two signals are obtained to be zero, thus leaving the terminal voltage signal error only. The resulting signal goes through amplification in regulator. The time constant T_A generally rendered as major time constant and the gain K_A which is associated with voltage regulator, utilize the power sources which are unaffected essentially by the brief transients of auxiliaries buses or synchronous machine. Time constants denoted by T_C and T_B ought to be used in the modelling of the equivalent time constants that are inherent in voltage regulators, however these time constants can be frequently small enough and can be neglected. The provision of these should be made according to zero input data. Exciter is generally represented by following transfer function among regulator output E_{FD} and exciter voltage V_F. The signal derived in this case from field voltage is used in order to provide the stabilization of the excitation system V_F through the rate feedback along with the time constant T_F and the gain K_F

$$\frac{V_R}{E_{FD}} = \frac{1}{K_E + sT_E} \tag{5.28}$$

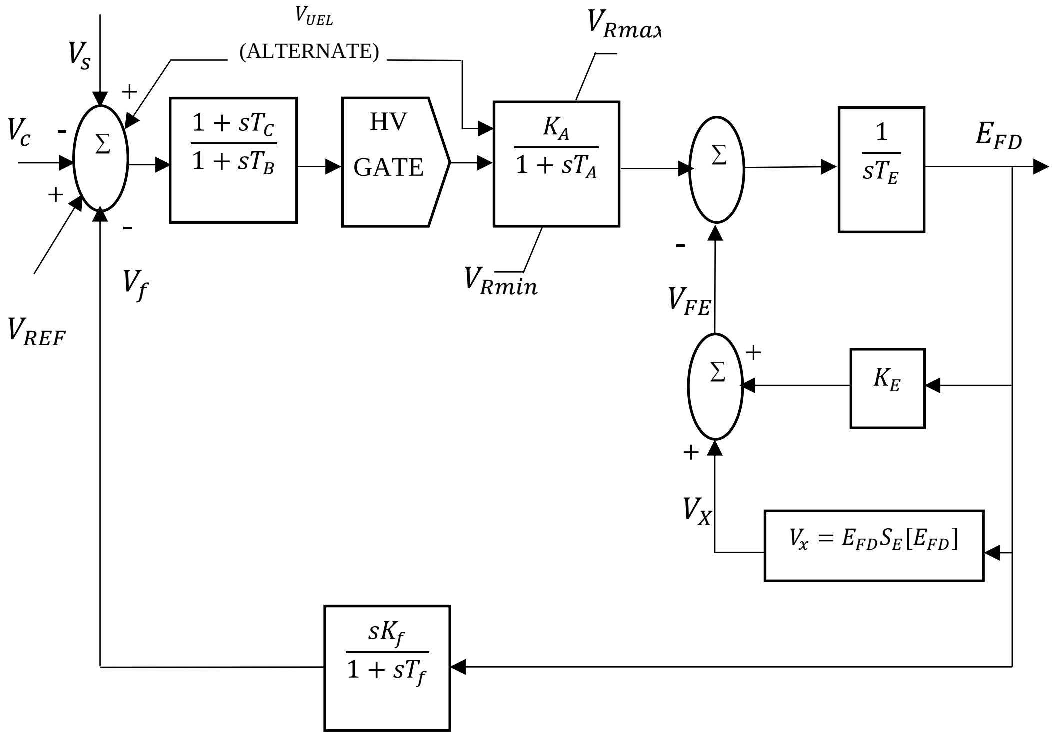


Figure 5.3. Excitation system along with the stabilizing circuit model [29].

5.5. HPP SIMULATION USING MATLAB SIMULINK

In this part, we used the Matlab software and being more specific, the Simulink Simscape PowerSystems tool, in order to represent the non-linear models which are analyzed in this chapter. The main purpose of this study is the modelling of Hydropower plant that is to be used in the study of the dynamic stability of Karabuk HPP.

In simulation models, the reference speed signal was obtained from the kinetic energy of falling water through the penstock of the HPP (see Figure 4.1). The synchronous machine speed measured was fed back in order to compare it with the reference speed signal. The speed deviation produced in this case by comparing the reference and the synchronous generator speed was used as an input for PID based speed governor. The PID was used as turbine governor because this control had stability, simple structure, strong robustness as well as non-steady state error. The governor produces the control signal, thus causing a change in the gate opening. In turn, the turbine produces the torque which drives the synchronous motor that generates the electrical power as an output. The speed governor checks the speed deviation constantly in order to take an action against it.

5.5.1. Simulation of Hydraulic Turbine and Governor

The block, used for the Hydro-turbine and the Governor, was the block that could operate a PID governor system, a non-linear hydraulic turbine model and a servomotor as well. The hydraulic turbine was modeled through the following non-linear system. The servomotor of the gate was modeled by a second-order system.

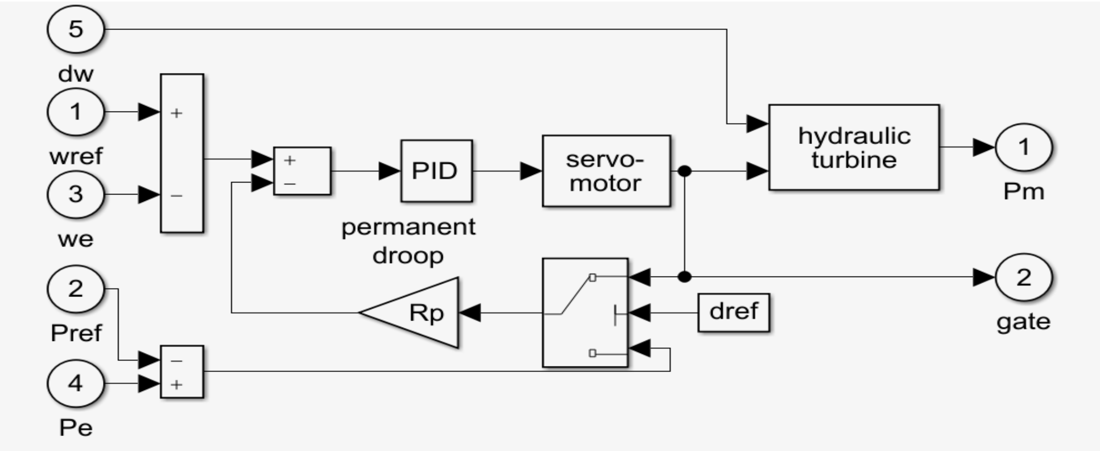


Figure 5.4. The HGT block that consist of a non-linear turbine, PID controller and Servomotor.

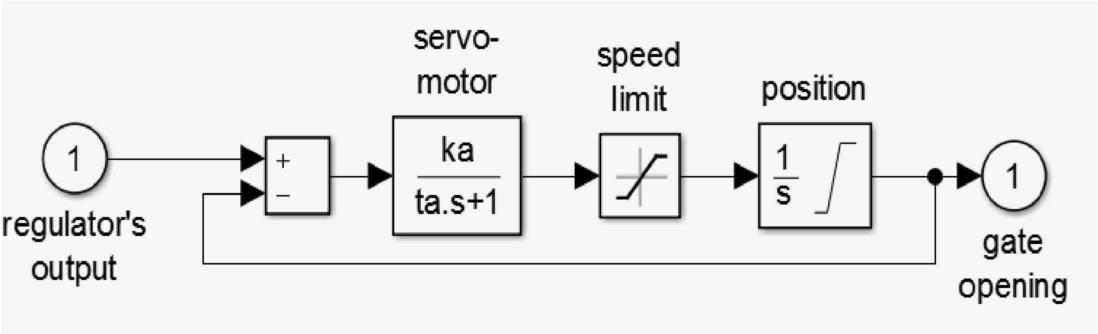


Figure 5.4. The servomotor block in the Simulink.

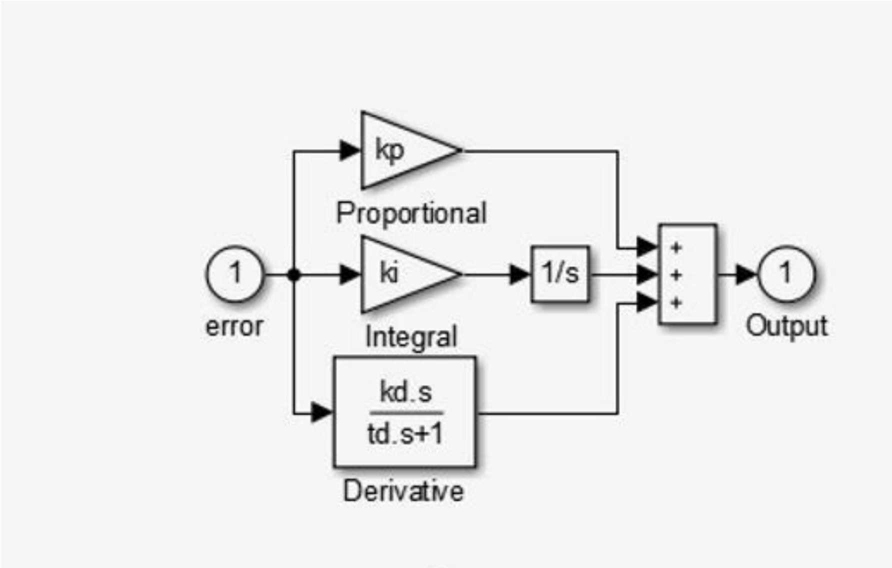


Figure 5.5. Simulink PID block.

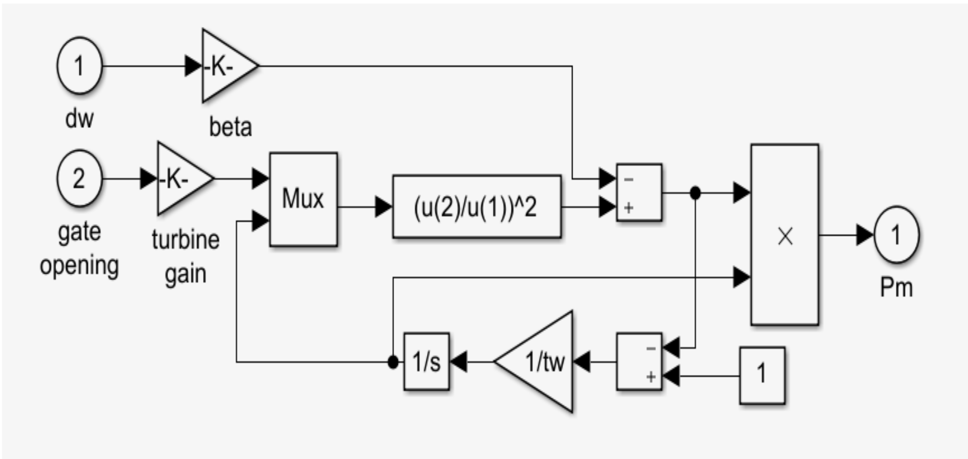


Figure 5.6. Hydraulic turbine block shown in Simulink.

The block parameters found in our study are shown below;

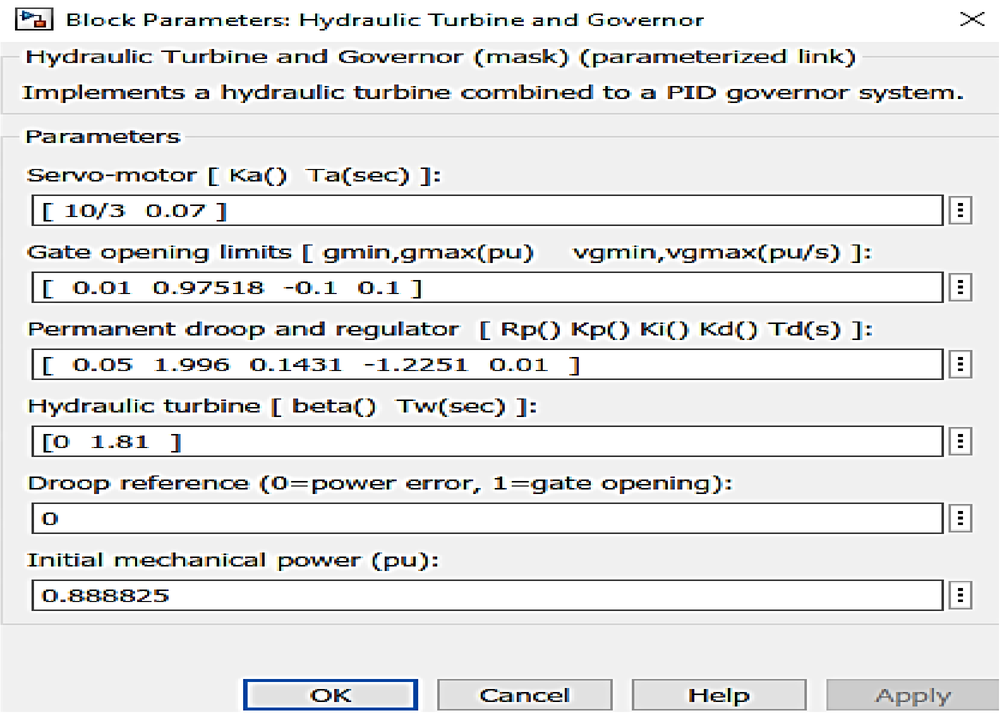


Figure 5.7. Parameters of HTG Block.

- ***Servo-motor:*** The gain denoted by *Ka* and the time constant denoted as *Ta*, in seconds (s), of first-order system represent the servomotor.
- ***Gate opening limits:*** The limits *gmin* and *gmax* (pu) were imposed on the gate opening, and *Vgmin* and *Vgmax* (pu/s) were imposed on the gate speed.
- ***Permanent droop and the regulator:*** The static gain of the governor was found to be equal to the inverse of permanent droop denoted as *Rp* in feedback loop. PID regulator had an integral gain *Ki*, a proportional gain as *Kp*, and a derivative gain as *Kd*. High-frequency gain of PID was limited by the first-order and low-pass filter with the time constant denoted as *Td* (s).
- ***Hydraulic turbine:*** The speed deviation had a damping coefficient β as well as the water starting time *Tw* (s).
- ***Droop reference:*** The input of the feedback loop was specified. The gate position was set to 1 or the electrical power deviation was set to 0.
- ***Initial mechanical power:*** The initial mechanical power was denoted as *Pm0* (pu) at the machine's shaft and was automatically updated by load flow utility of the Powergui block.

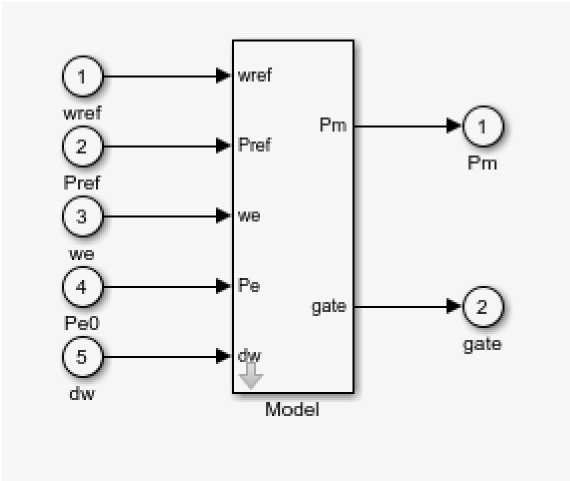


Figure 5.8. Summarized model of the Hydraulic Turbine using Simulink.

The Inputs and the Outputs are as follows.

- ***Wref*** is Reference speed, in pu.
- ***Pref*** is Reference mechanical power in pu. This input can be left unconnected if you want to use the gate position as input to the feedback loop instead of the power deviation.
- ***We*** is Machine actual speed, in pu.
- ***Pe0*** is Machine actual electrical power in pu. This input can be left unconnected if you want to use the gate position as input to the feedback loop instead of the power deviation.
- ***dw*** is Speed deviation, in pu.
- ***Pm*** is Mechanical power Pm for the Synchronous Machine block, in pu.
- ***gate*** is Gate opening, in pu.

5.5.2. Synchronous Machine Standard block (pu)

The block of the Synchronous Machine in pu Standard and the Synchronous Machine in pu Fundamental were set accordingly. In Configuration Tab of block, I, Mechanical Power Pm was selected in order to specify a mechanical power input, in W or in pu, and labeling of the block input was changed to Pm. In our study, the machine speed was determined by the machine Inertia J (constant inertia H for pu machine), the difference between mechanical torque denoted as Tm which results from applied mechanical power denoted as Pm, and last but not the least, the internal electromagnetic torque denoted as Te. Sign convention for the mechanical power was used when the speed was found to be positive. According to the model, a positive mechanical power signal indicated the generator mode and a negative signal indicated the motor mode.

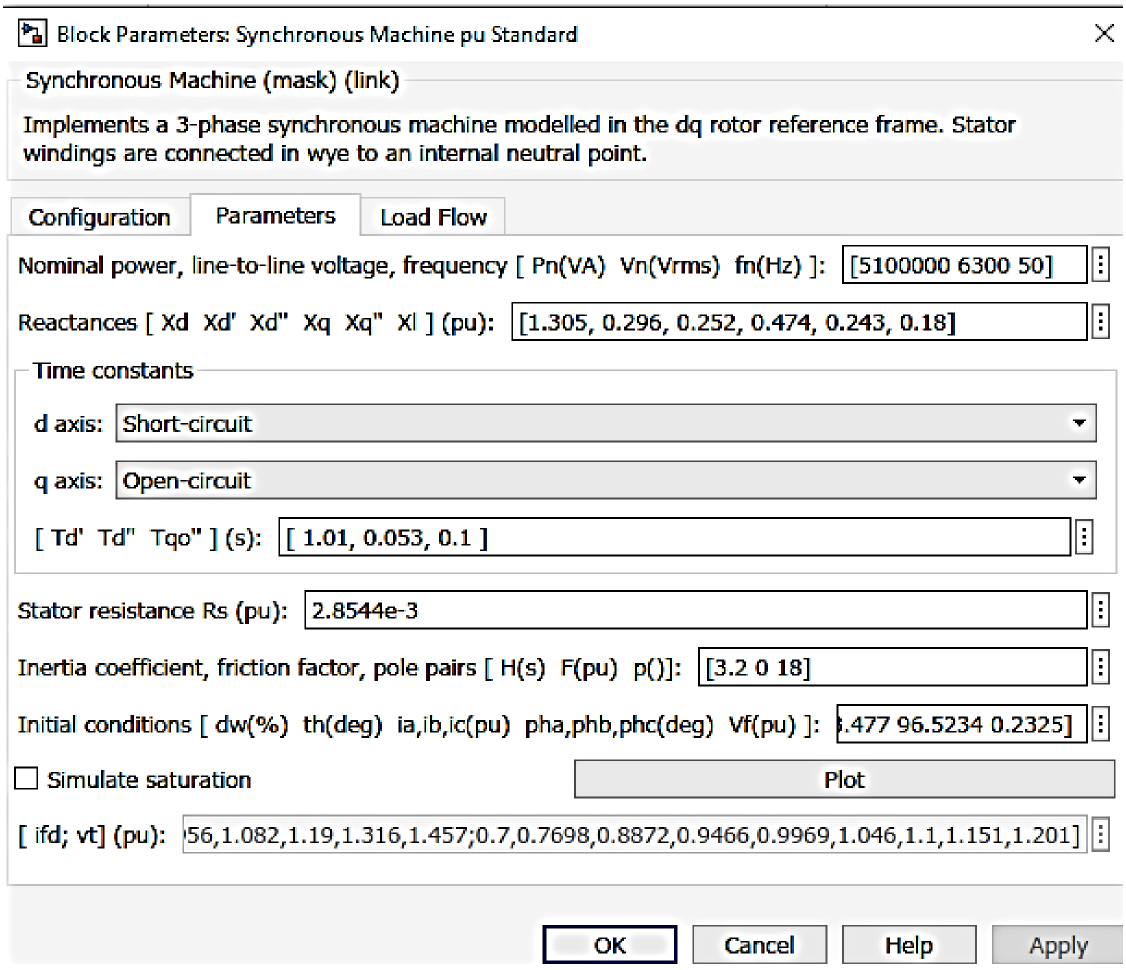


Figure 5.9. Parameters Tab of the Synchronous Machine Standard block (pu).

In the section Generator type parameter, we Selected PV in order to operate a generator controlling its output active power *P* and voltage magnitude *V*. *P* was specified by the Active power generation *P* parameter of the block. *V* was specified by the Swing bus or PV bus voltage parameter of the Load Flow Bus block that was connected to the machine terminals. The minimum and maximum reactive power generated by the block can be controlled by using the Minimum reactive power *Qmin* and Maximum reactive power *Qmax* parameters.

The units of the inputs and the outputs change according to the dialog box that are used in order to enter the block parameters. In case the fundamental parameters that are in SI units are used, the inputs and the outputs have to be in SI units. The exception includes the dw that is in vector of the internal variables and is always used in pu and the angle θ that is used always in radians. Otherwise, the inputs and outputs are in pu.

- ***Pm*** is the first Simulink input and is the mechanical power at shaft of the machine, and is used in pu or Watts. In the generating mode, the input is a function or positive constant or the output of the prime block (check the Steam Turbine and Governor or the Hydraulic Turbine and Governor blocks). Whereas, in the motoring mode, this input can be usually a negative function or a negative constant.
- ***w*** is the alternative block input that is used instead of the *Pm* and depends on value of parameters of Mechanical input. The machine speed is in rad/s.
- ***Vf*** is the second Simulink input of block and is called the field voltage. This can be supplied by voltage regulator in the generator mode (check Excitation System block). This voltage is usually constant in motor mode. In case used in SI fundamental units, the field voltage has to be entered in DC volts either nominal field current denoted as *Ifn* is specified or *Ifn* is not specified. In order to obtain *Vfd* producing the nominal voltage, Display nominal field current needs to be selected and the voltage producing stator havong a value of 1 pu checkbox needs to be selected in the Advanced tab. In case the model is in pu Fundamental units or in pu Standard, *Vf* ought to be entered in pu representing that 1 pu field voltage produces 1 pu terminal voltage at no load applied).
- ***m*** is the Simulink output of block and is a vector that contains the measurement signals. In order to demultiplex the signals, Bus Selector Block that is provided in Simulink library may be used. Depending on type of mask used, the units can be in SI or in pu units.

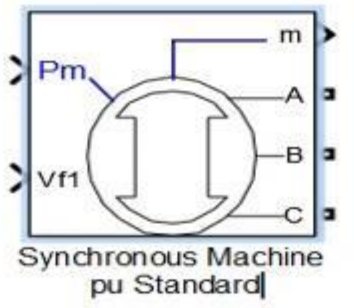


Figure 5.10. Synchronous machine Block in pu standard.

5.5.3. Excitation System

It provides the excitation system for the synchronous machine and then regulates its terminal voltage in the generating mode

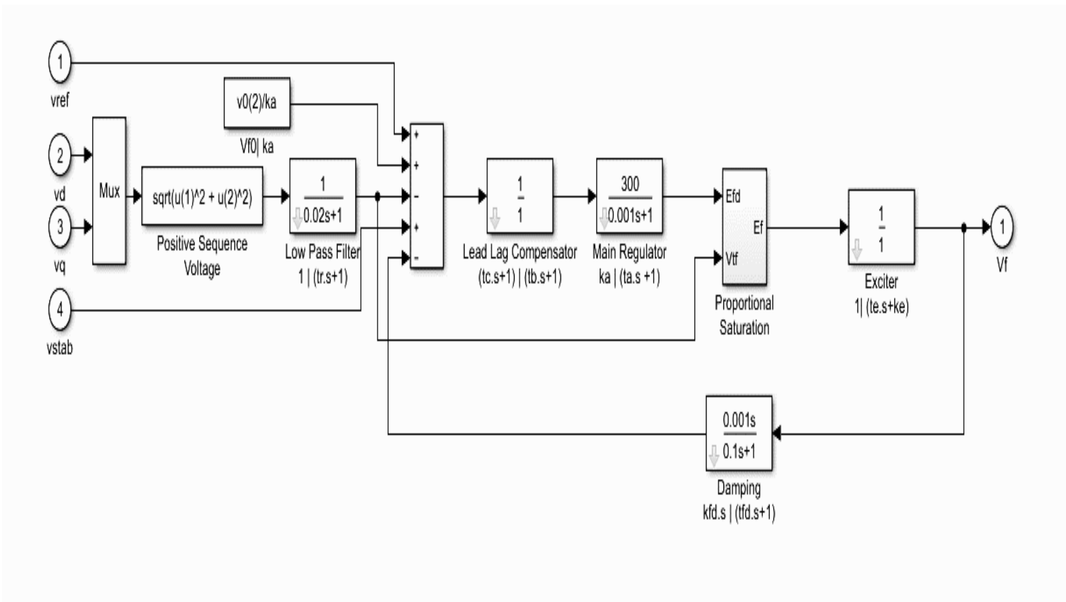


Figure 5.11. Exciter and voltage regulator of Excitation System block.

The parameters used in the Excitation System block are as follows;

- ***Low-pass filter time constant*** is denoted in seconds (s) of the first-order system which represents transducer of stator terminal voltage.

- ***Regulator gain and time constant*** denoted as *Ka* and *Ta* in seconds (s) of the first-order system and they represent the main regulator.
- ***Exciter*** is represented by the gain *Ke* and time constant *Te* denoted in seconds (s) of the first-order system.
- ***Transient gain reduction*** includes time constants *Tb* and *Tc* in seconds (s) of the first-order system and represents the lead-lag compensator.
- ***Damping filter gain and time constant*** are the gain *Kf* and time constant *Tf* denoted in seconds (s) of the first-order system and they represent a derivative feedback.
- ***Regulator output limits and gain*** are imposed on output of the voltage regulator as *Efmin* and *Efmax*. Upper limit may be constant and may be equal to *Efmax*, variable or may be equal to rectified stator terminal voltage *Vtf* multiplied by a proportional gain of *Kp*. When *Kp* is set to 0, former applies. When *Kp* is set to positive value, as expected, the latter applies.
- ***Initial values of the terminal voltage Vt0* (pu) *and the field voltage Vf0* (pu),** if set correctly, allow us to start simulation in the steady state. The initial terminal voltage ought to be normally set to 1 pu. The *Vt0* and the *Vf0* values are then automatically updated through load flow utility of Powergui block.

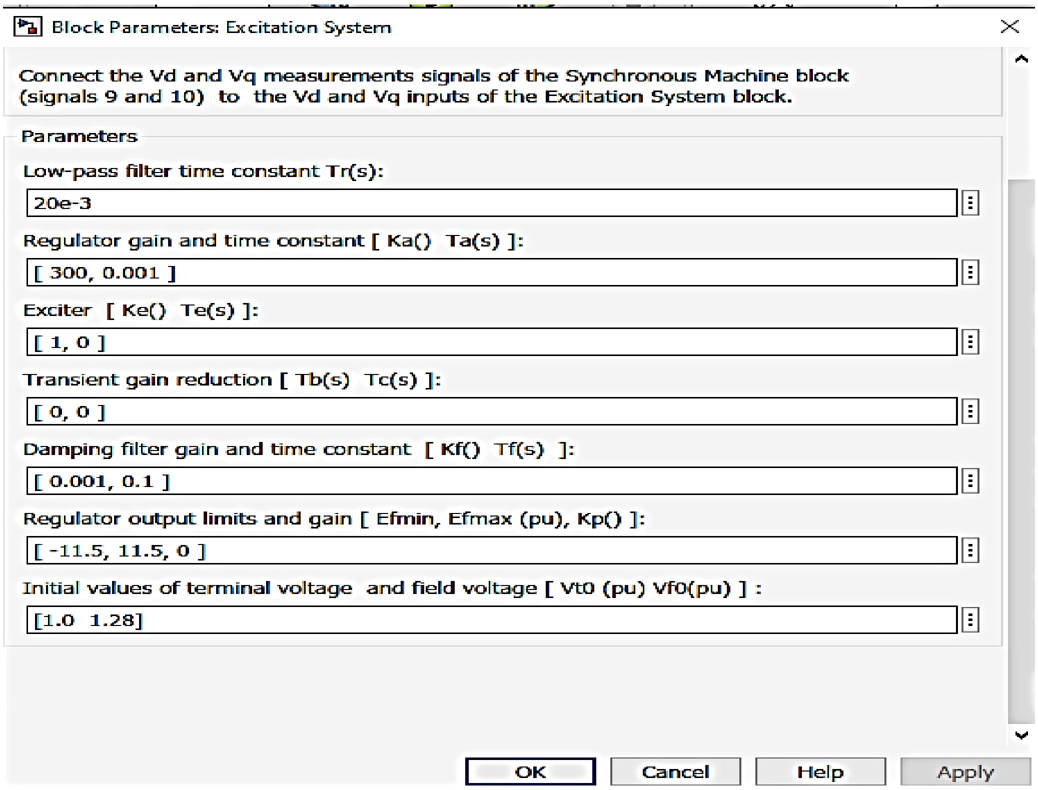


Figure 5.12. Parameters of excitation system block.

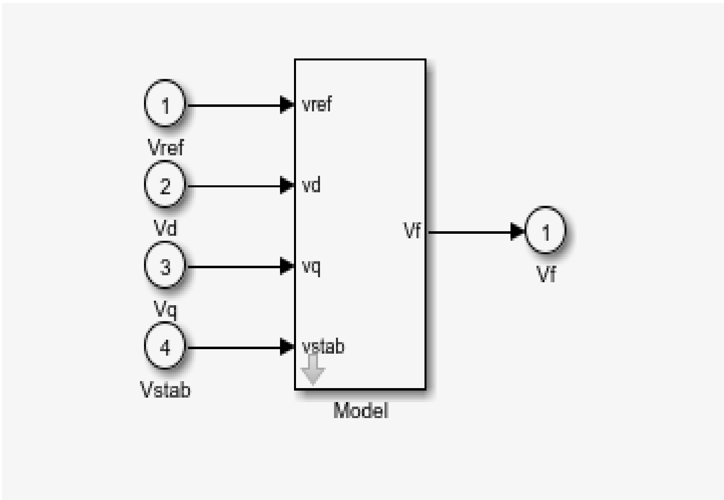


Figure 5.13. The summarized model of the excitation system.

The Inputs and the Outputs are as follows

- ***Vref*** which is the desired value in pu unit of stator terminal voltage.
- ***Vd*** is the component in pu unit of terminal voltage.
- ***Vq*** is the component in pu unit of terminal voltage.
- ***Vstab*** connects the input to the power system stabilizer in order to provide the additional stabilization for the power system oscillations.
- ***Vf*** in pu is used for Synchronous Machine block.

Figure 5.15. demonstrates a complete Model for hydropower plant in Karabuk, and we will review the obtained results with detailed explanation of Electric power P_e, three-phase current I_{abc} and three-phase voltage V_{abc}.

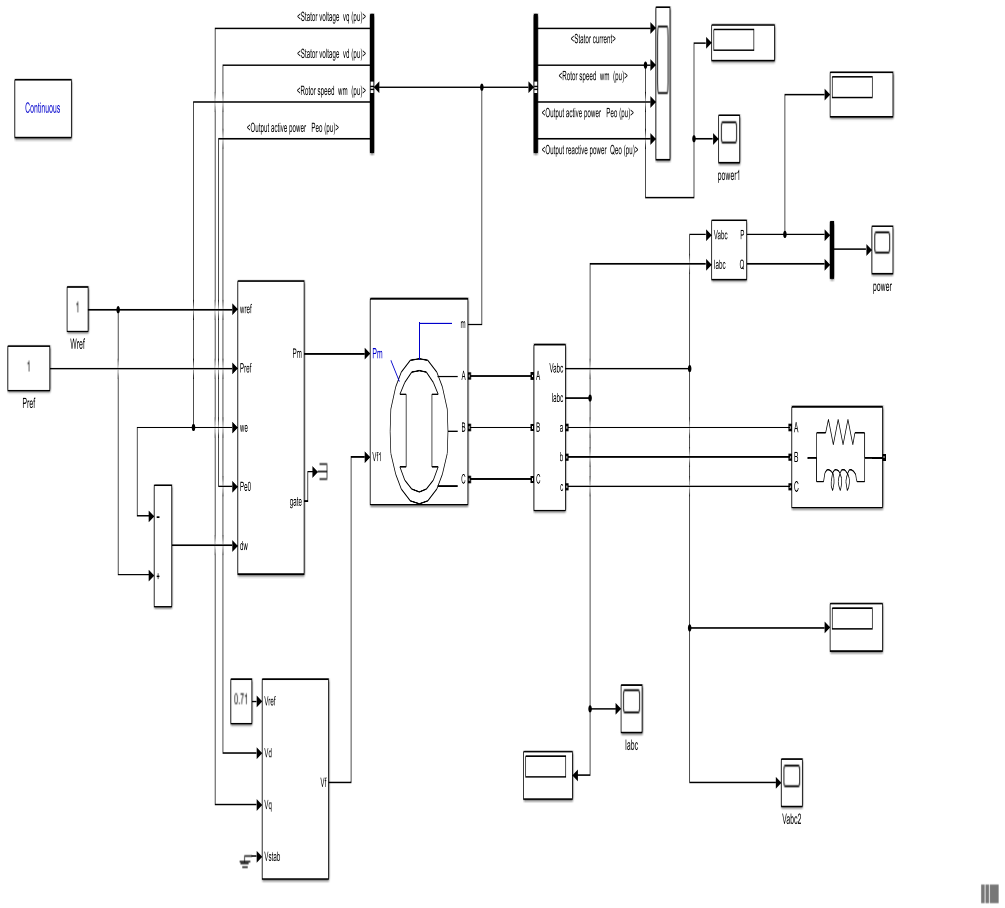


Figure 5.14. Complete model of the RRHPP.

5.6. SIMULATION RESULTS

The simulation program was run, and it was found that the obtained results were good and acceptable, especially in terms of power and the three-phase voltage.

Figure 5.16 shows the power signal obtained by the simulation program, and the power value = 5.025 MW with an error of 0.075 MW as compared to the design value of the generator (error = 1.47%), and this indicates how accurate the simulation system is.

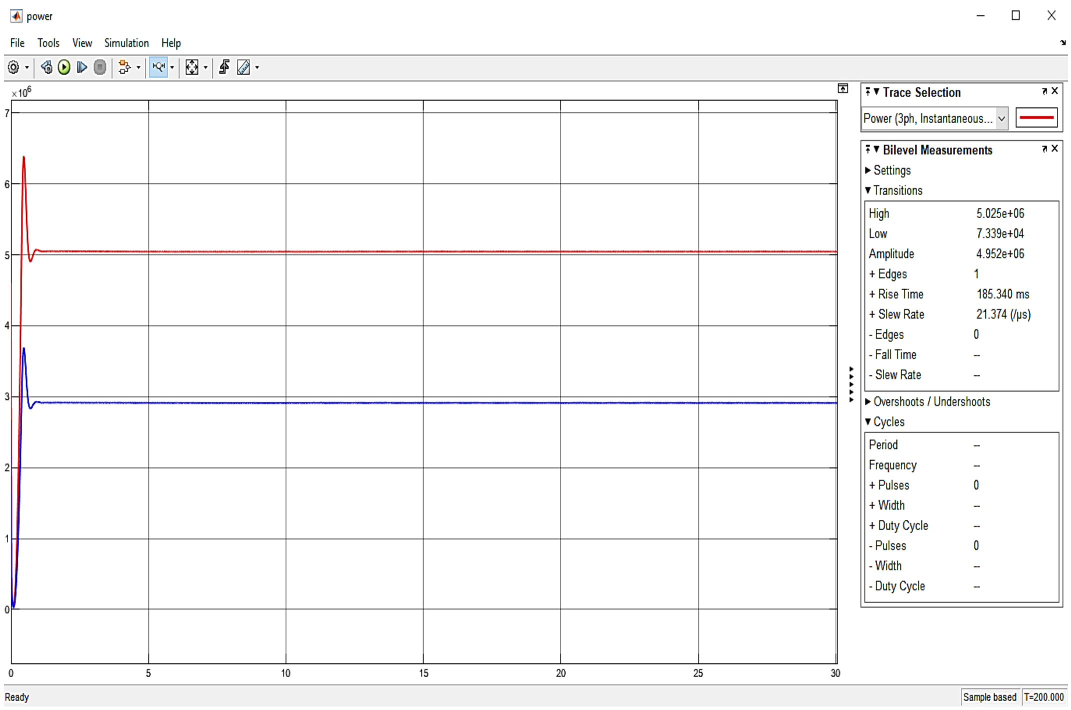


Figure 5.15. Electric power of synchronous generator.

Figure 5.17 shows the generated voltage signal obtained from the simulation results. The output sine wave signal has the following characteristics:

Amplitude = 12528V, with high current output=6264V, and low current output =-6264V

Frequency = 50.85 Hz, with percentage error = 1.7%

Time Period =19.665 m Sec,

Duty Cycle= 50%

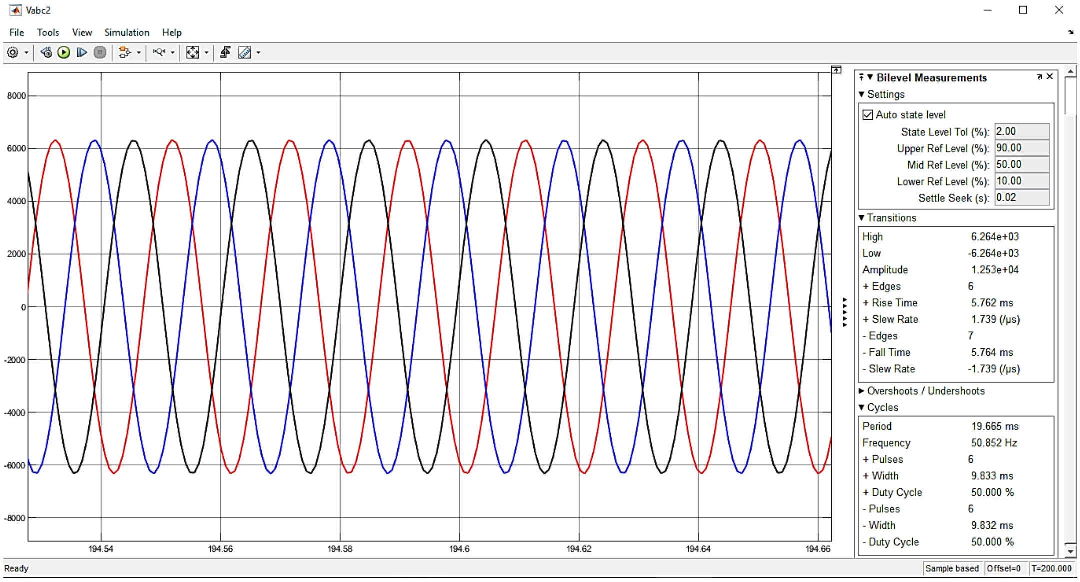


Figure 5.16. Stator three phase voltage characteristics of RRHPP.

Figure 5.18 shows the generated current signal obtained from the simulation results. The output sine wave signal had the following characteristics:

Amplitude = 1215A, with high current output = 607.5A, and low current output = -607.6A

Frequency = 50.85 Hz, with Error percentage = 1.7%

Time Period = 19.67mSec,

Duty Cycle = 50%

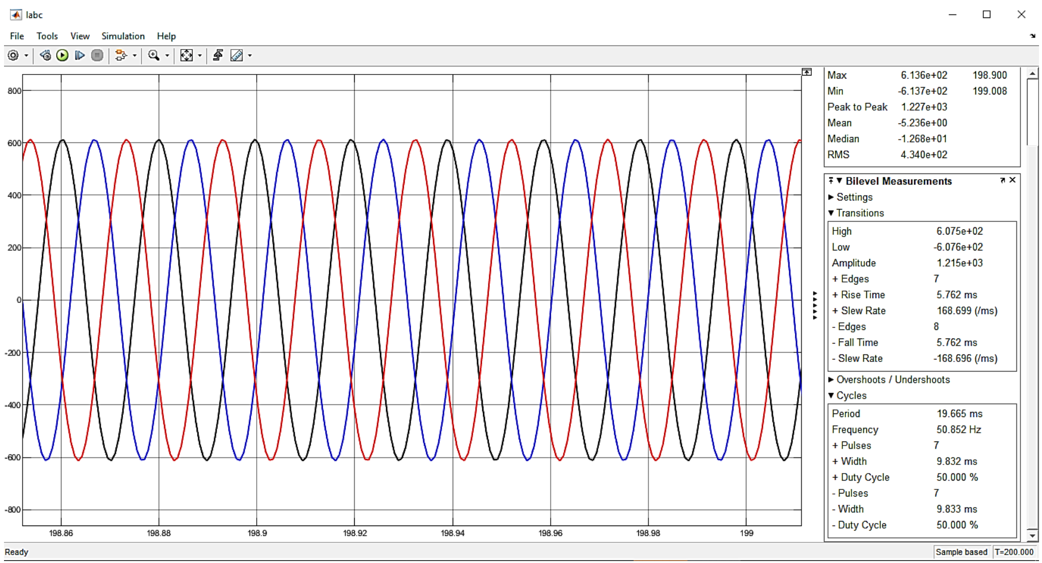


Figure 5.17. Stator three phase current characteristics of RRHPP.

SIMULINK programm is an efficient and powerful software package for the study of dynamic and non-linear systems. Using SIMULINK software, the simulation model can be created systematically starting from the simple sub-models. The hydro power plant model developed can be used alone, as in direct-on-line starting example presented above, or it may be incorporated in an advanced drive system. Numerous tests and operating conditions can be performed on the model. We believe that the SIMULINK software will become an indispensable tool soon for the teaching as well as the research of electrical machine drives.

CHAPTER 6

AUTOMATION OF THE RRHPP

Yalnızca RRHPP is being operated fully automated. The control and monitoring of the system is performed from the control room. The basic parameters of the generators such as voltage, current, active power and reactive power and values such as the height of the system above sea level etc. can be monitored on the SCADA main screen. The start-stop processes of the units (generators) can also be started from this screen. Figure 6.1 shows the main screen of the plant.

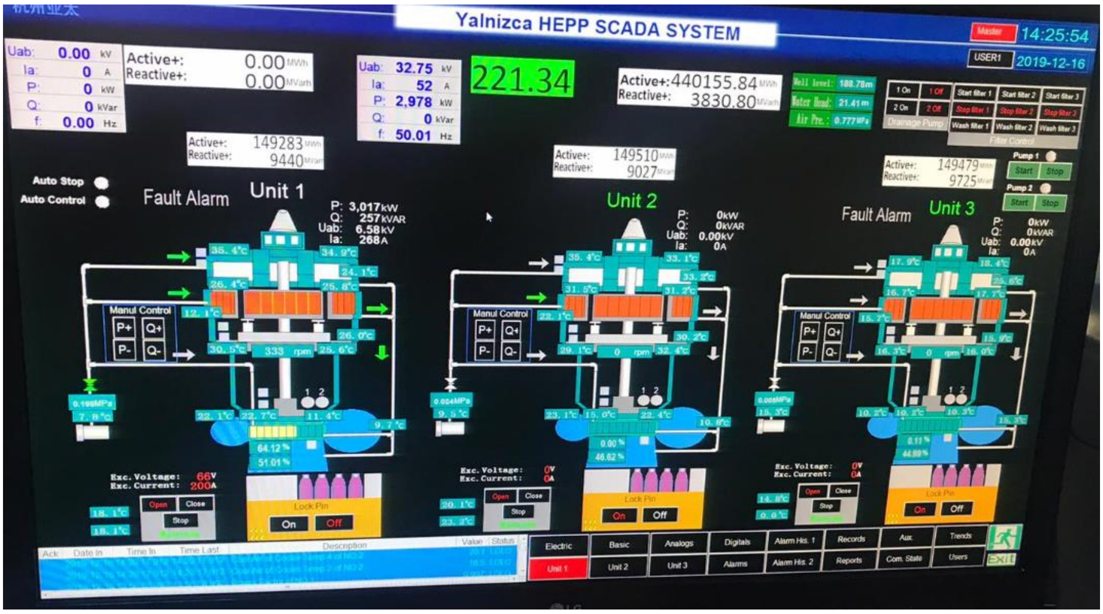


Figure 6.1. Yalnızca RRHPP main SCADA screen.

The synchronization of 3 units with each other and with the network can be carried out and monitored on the SCADA screen. The open-closed states of the disconnectors and circuit breakers, information regarding energization of the busbars and the basic electrical parameters can be seen on the Electric Single Line SCADA screen. Figure 6.2 shows the Electric Single Line SCADA screen.

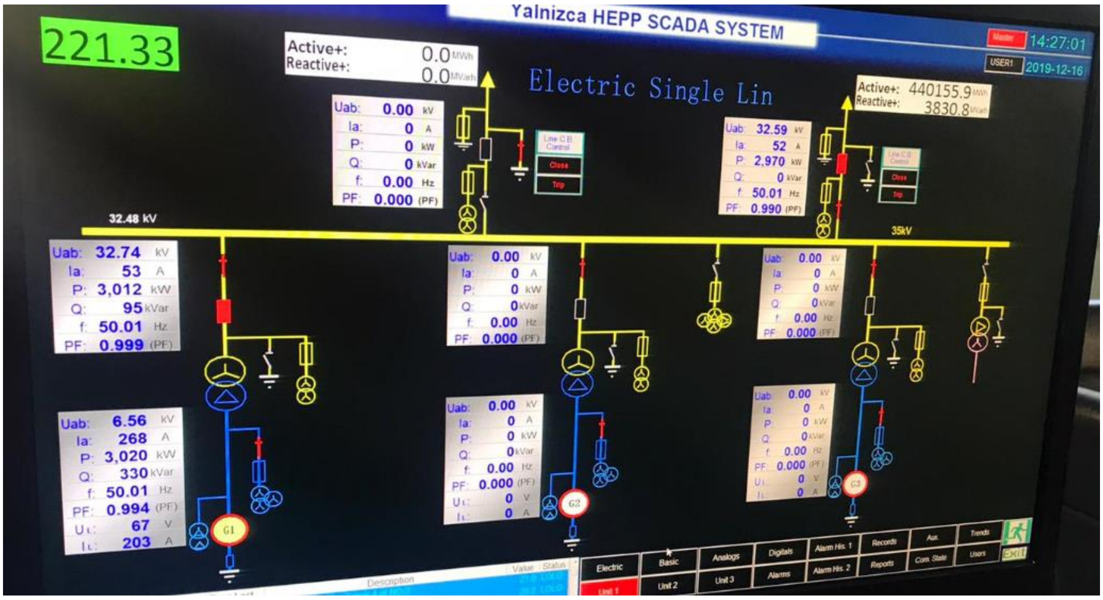


Figure 6.2. Yalnızca RRHPP Electric Single Line SCADA screen.

On the SCADA screen given in Figure 6.3, the state and values of fore bay and weir intake can be monitored.

Figure 6.3. Yalnızca RRHPP forebay SCADA screen

The alarms from the system are displayed on the SCADA screen shown in Figure 6.4. Alarms are divided into three groups as fault alarm, accident alarm and over limit alarm.

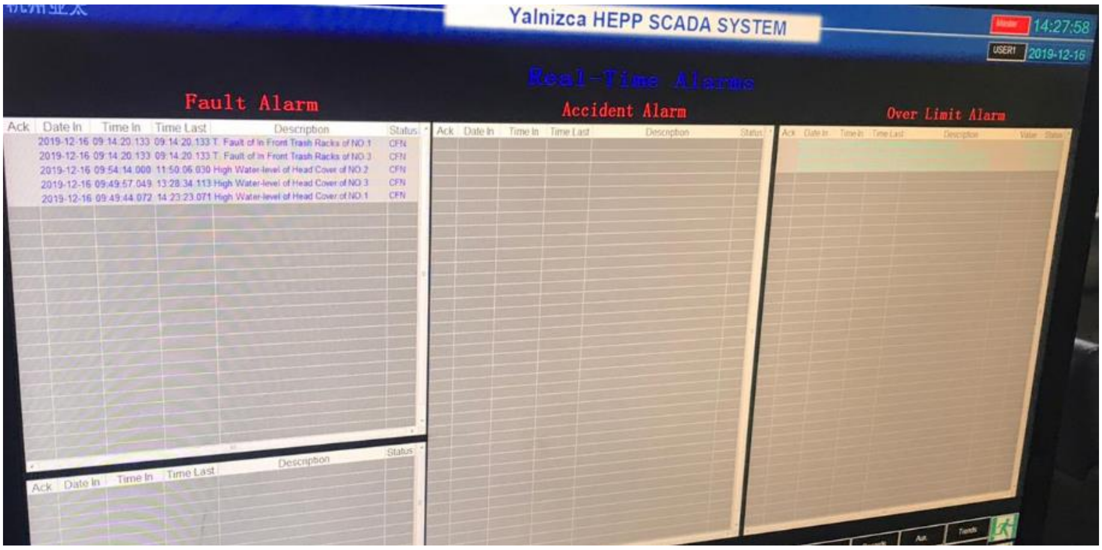


Figure 6.4. Yalnızca RRHPP alarm SCADA screen

Furthermore, the energy amounts generated on daily basis by the RRHPP and some other values are continuously reported and recorded on the SCADA screen in Figure 6.5.

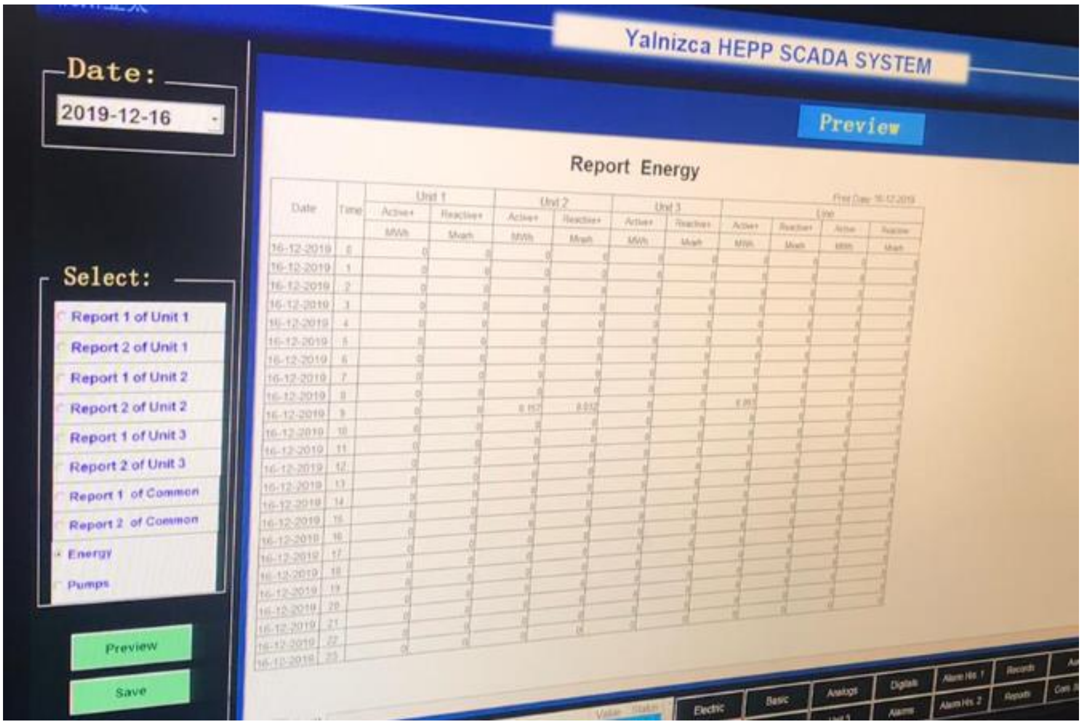


Figure 6.5. Yalnızca RRHPP report SCADA screen

6.1. PLC AND SCADA SOFTWARE AND SIMULATION OF RRHPP

In this section, the software implemented on the TIA Portal interface will be explained in order to allow the conduction of tests on some scenarios that are very risky and/or impossible to test on the running system and also to ensure that the parts which need improvements are pre-tested in the PLC simulation environment and loaded into the system without risk.

PLC and SCADA software was implemented using Simatic Step 7 TIA Portal V15 interface. Siemens S7-1500 1518-4 PN/DP brand/model PLC was used. The ladder programming language has been preferred for programming. Instead of a real (physical) HMI panel, the computer (PC) screen was used as an operator panel via the SIMATIC HMI Application/WinCC RT Advanced. "Device&Networks" and "Portal View" of the created TIA Portal project have been shown in Figures 6.6 and 6.7, respectively.

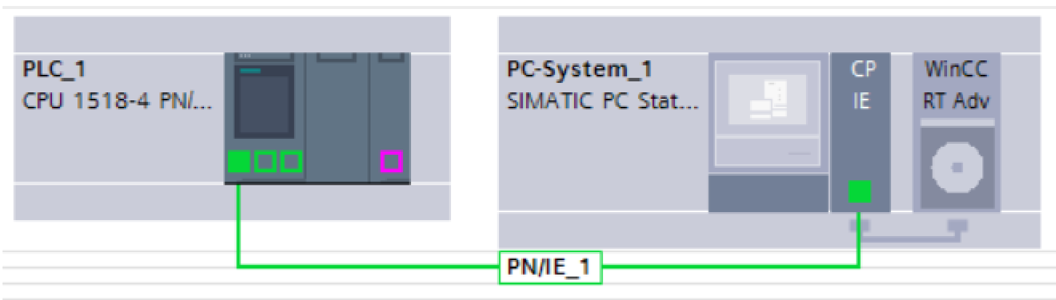


Figure 6.6. Device&Networks view of the project.

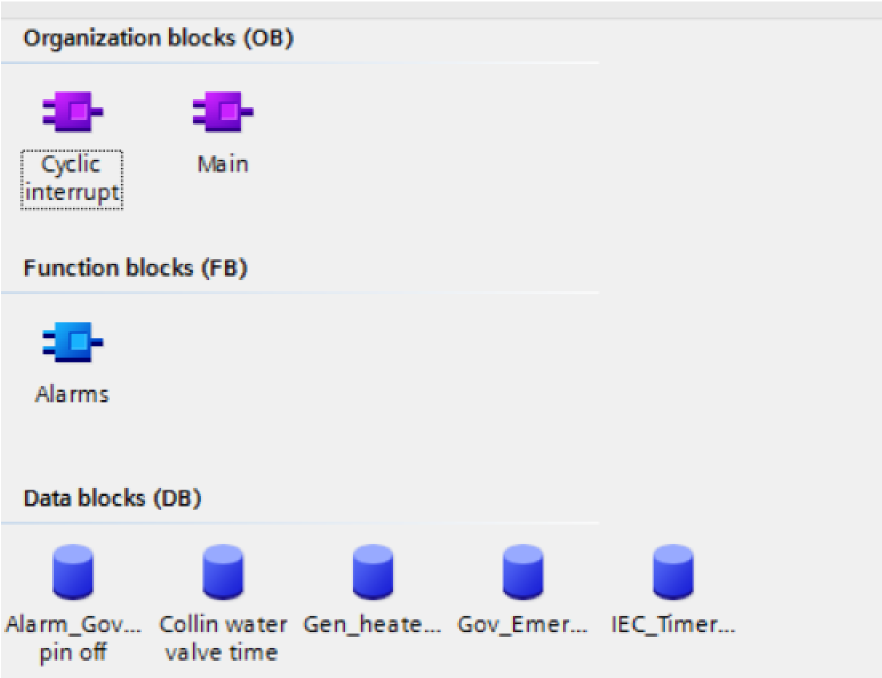


Figure 6.7. Portal View of the project.

Considering the working scenario of the system and the flow chart given in Figure 6.8, 3 DI 32x24V DC BA modules, 3 DQ 32x24V DC 0.5A BA modules, 7 AI 8xU/I/RTD/TC ST modules and 5 AQ 8x U/I HS module were added in the Device Configuration section of the TIA Portal project. By doing this, 96 digital inputs (DI), 96 digital outputs (DQ), 56 analog inputs (AI) and 40 analog outputs (AQ) were obtained. The device configuration of the project can be seen in Figure 6.8.

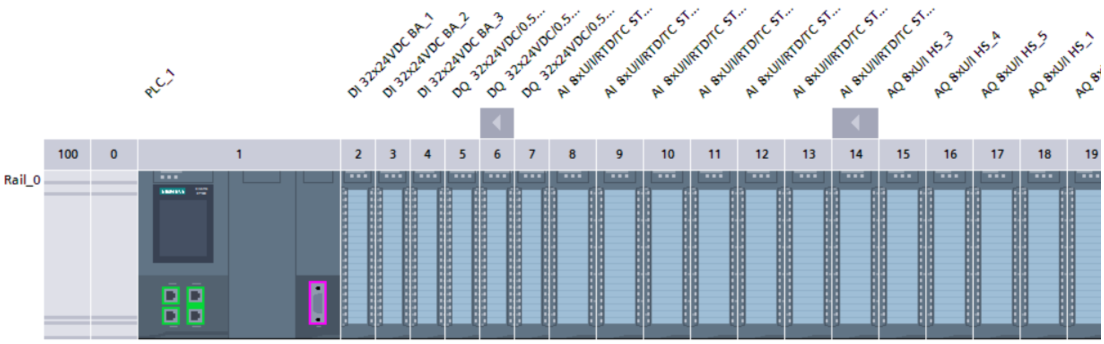


Figure 6.8. Device Configuration view of the project

DIs and DQs were used for processing the digital signals from the field to the PLC and from the PLC to the field. AI modules were used to measure the values such as voltage, current, pressure, temperature and then display them on the SCADA screen. AQ modules were used for controlling the equipments such as valves controlled proportionally in the field and values such as excitation current.

Once the digital and analog hardware connections described above were made, the hardware and software configurations required for the project were carried out on the TIA Portal interface. The software was implemented according to the flow chart given in Figure 6.8.

First of all; in order to start the system, the prerequisites must be fulfilled. These prerequisites can be grouped into six groups: Running State Condition, Unit Start Ready Condition, Stop Generator Heater, Governor Locking Pin Off, Open Cooling Water Valve, and Cooling Water OK. Each group has its own sub-conditions.

Once these conditions are met, start order can be sent to the governor. After sending the start order to the governor, no load or online order or local start is selected. The difference between the active power that is set and the real value must be at least 50 kW. The excitation switch is closed. If the excitation current is less than 30A, excitation is activated. Then, if the excitation current is less than 60A, synchronization processes are started. If the excitation current is greater than 60A, manual excitation operations are performed and the current is checked again.

In the synchronization process, firstly, online or auto synchronization is selected. The positions of the circuit breakers and disconnectors (open-closed) are checked. If the positions are suitable, the generator speed is checked to be within normal limits (>110%, <90%). If the speed is normal, the power regulator is checked to be in auto position, the difference between the set active power and real power is checked to be greater than 50 KW and the governor is checked to be in auto channel. If the difference between active power and real power is less than 50 KW, active power is increased from the SCADA screen (Increase/Decrease Power Active Pulse). Then, the difference between the set reactive power and the real reactive power is checked to find out whether or not it is greater than 100 KVA. If not, reactive power is increased from the SCADA screen (Increase/Decrease Power Reactive Pulse).

If shutdown, fault and alarm signals are not received from the system, the process is completed by switching to synchronization with other generators and the network.

The PLC ladder diagram was drawn and SCADA screens were designed in accordance with the process of the system described above concisely and in accordance with the flow chart given in Figure 6.9. Parts of ladder diagrams and tag table are given in Appendix A and B respectively.

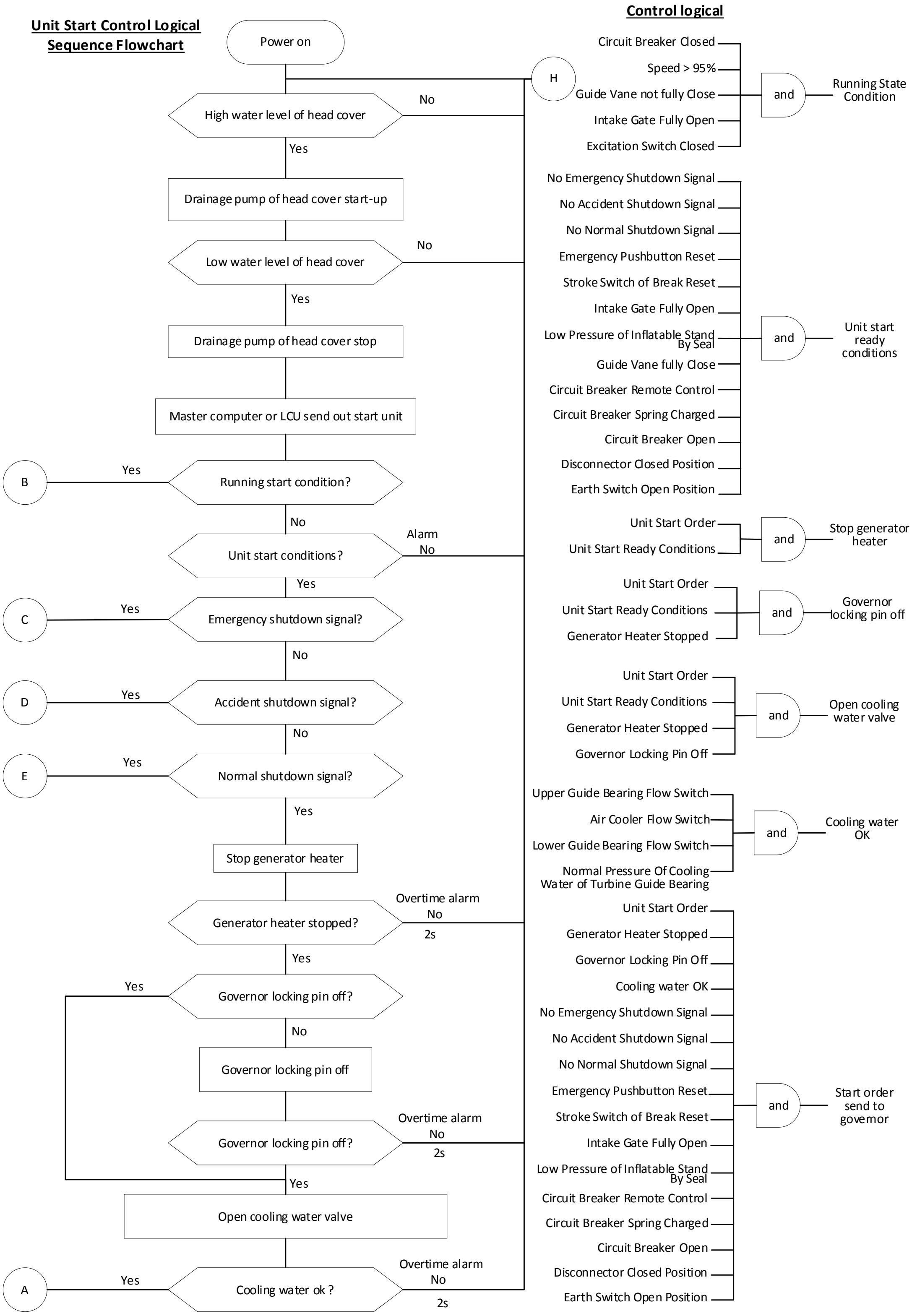


Figure 6.9. Flow chart of the RRHHP.

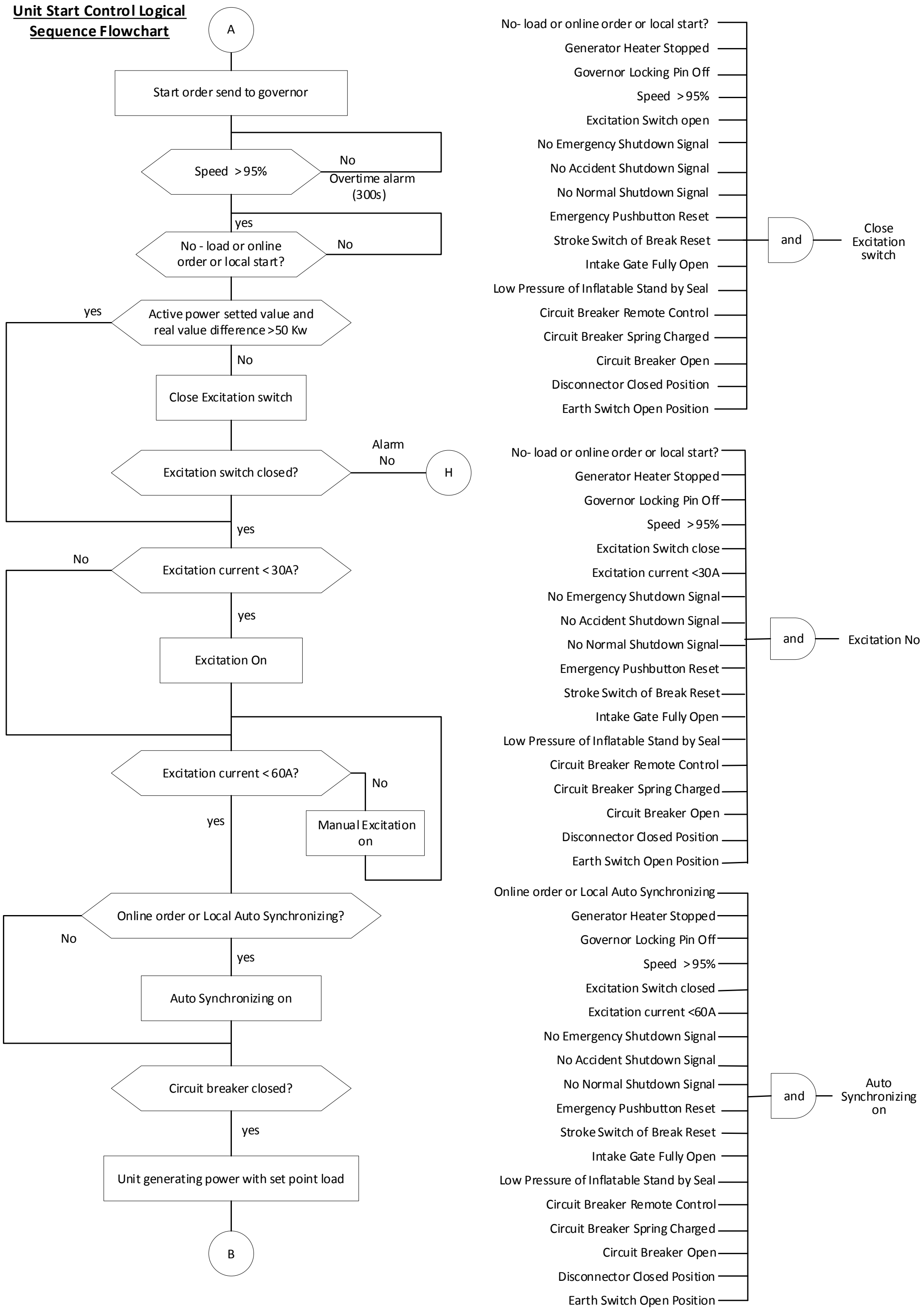
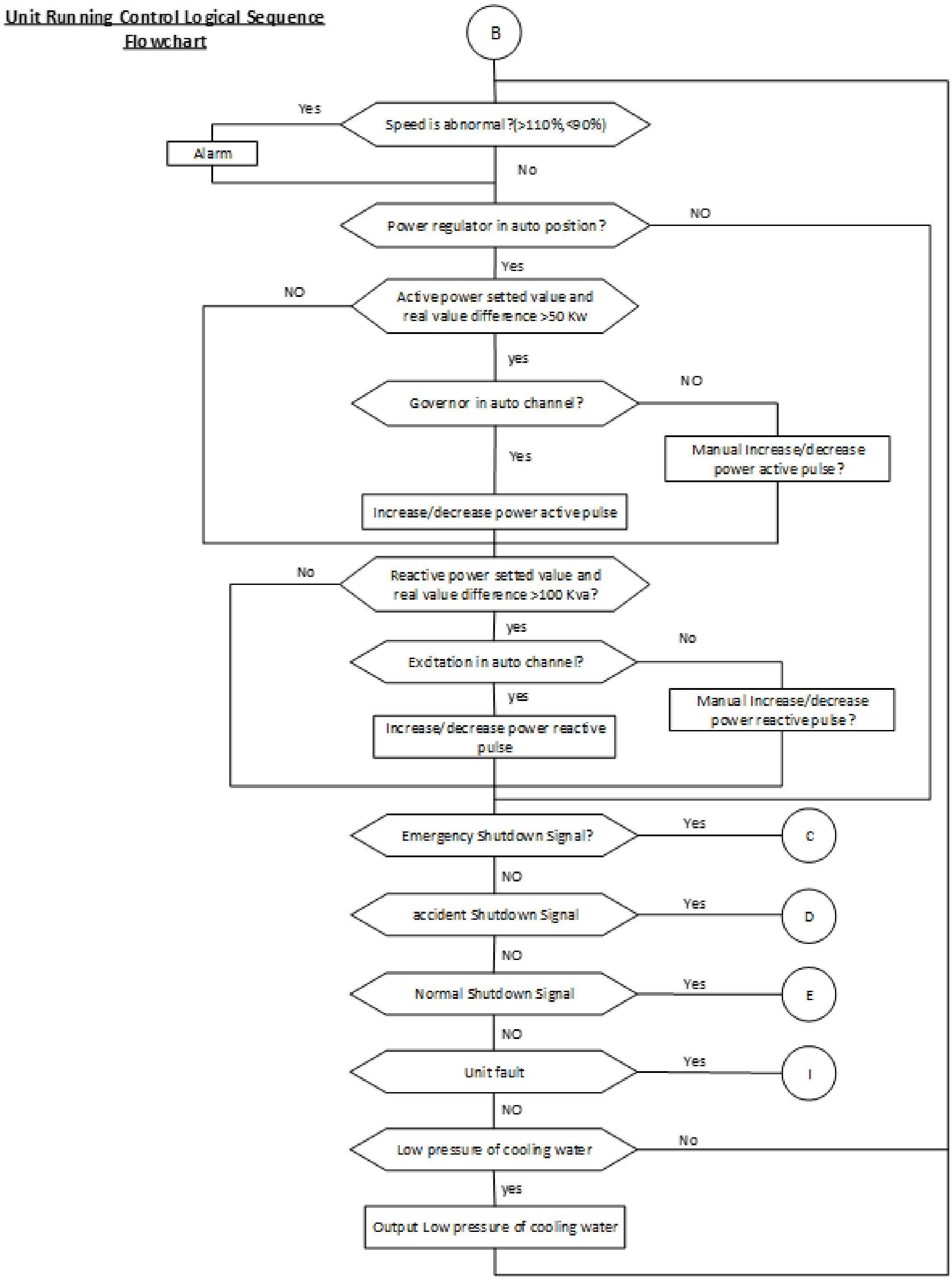


Figure 6.10. (Continuing).



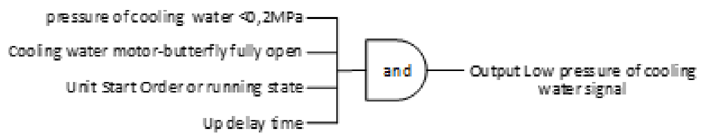
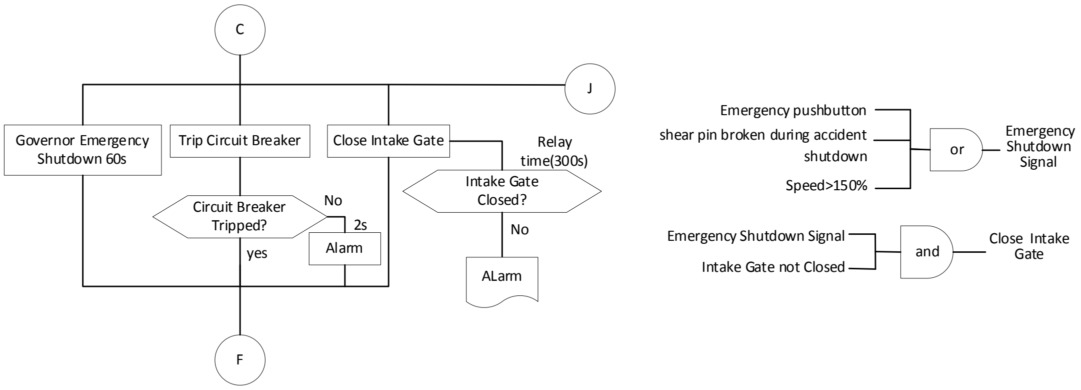


Figure 6.11. (Continuing).

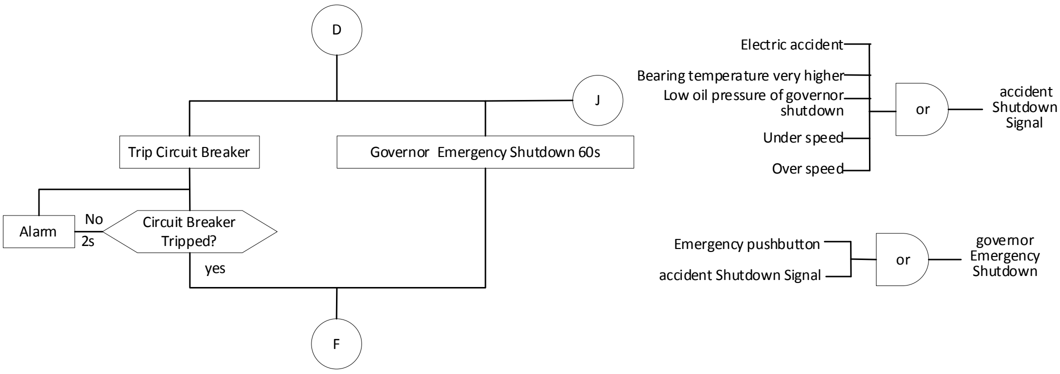
Abnormal Logical Sequence Flowchart

A-Emergency shutdwon



B-Accident shutdwon signal

1- Electric accident



2- Mechanical accident

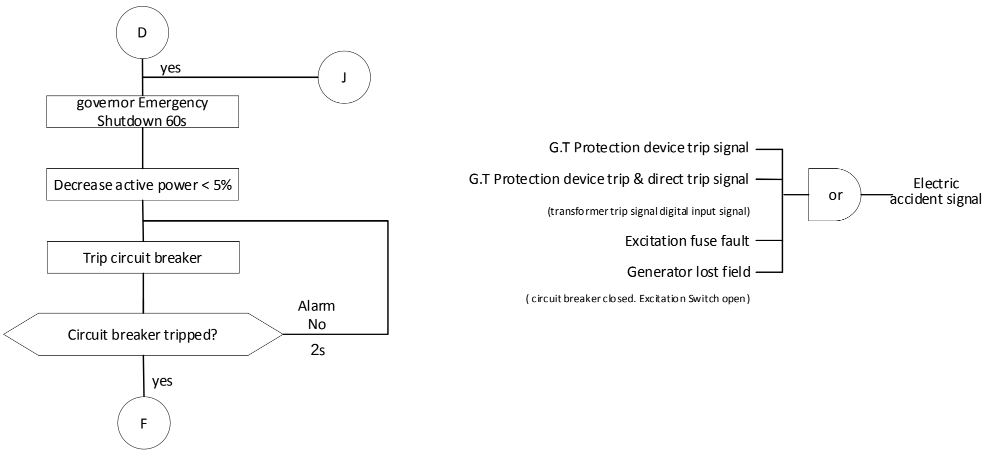


Figure 6.12. (Continuing).

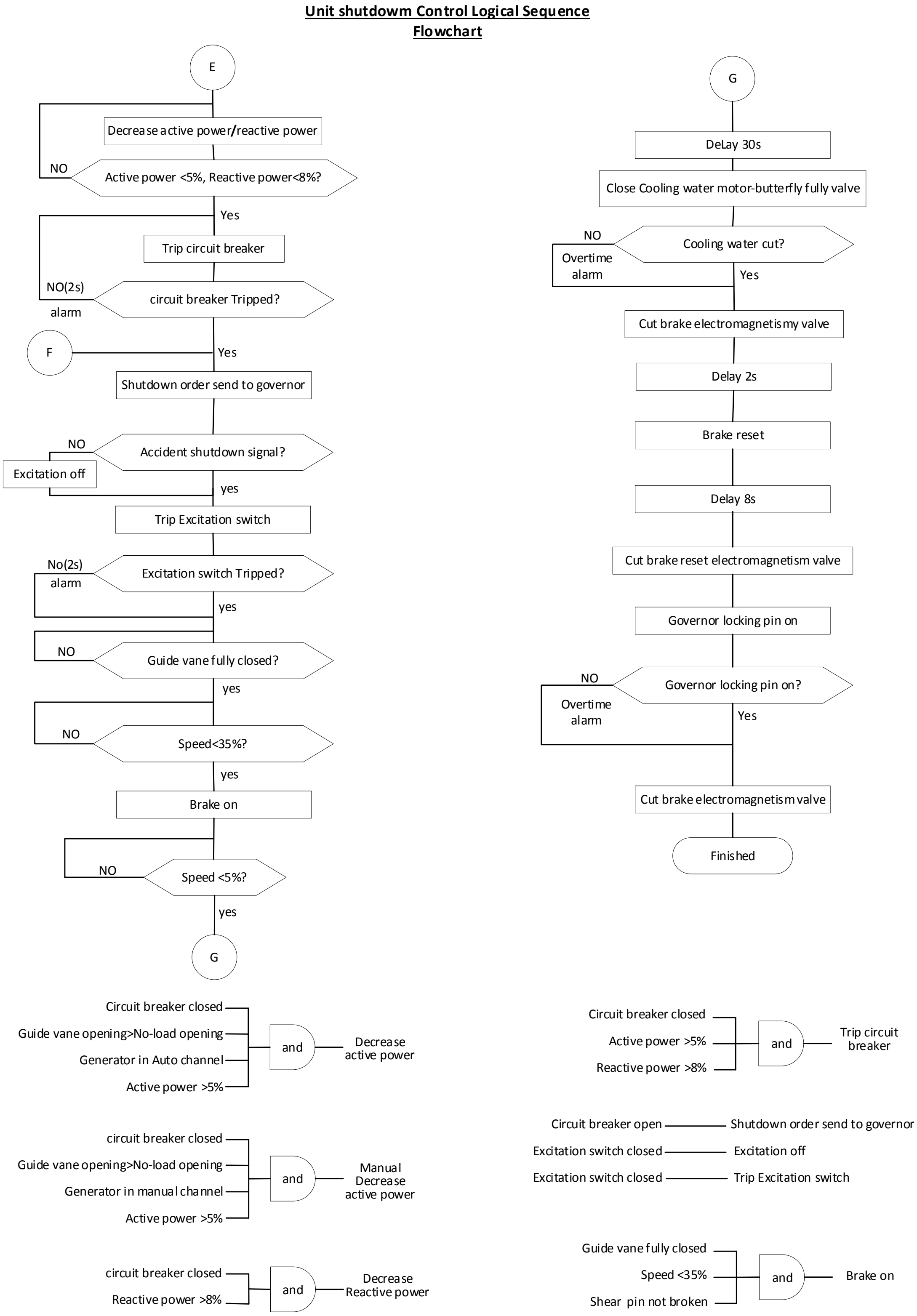


Figure 6.13. (Continuing).

Alarm voice& fault indecator Control Logical Sequence Flowchart

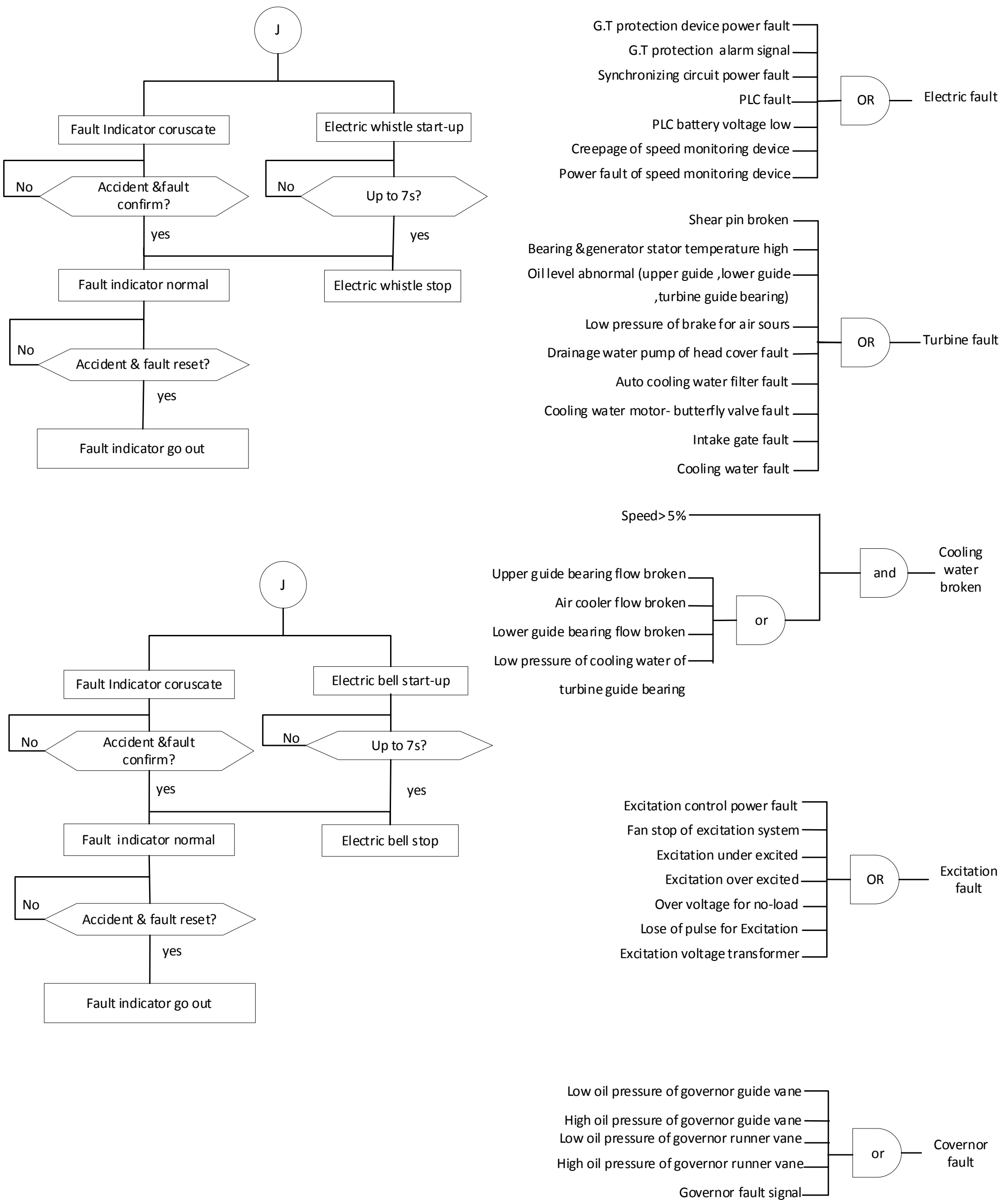


Figure 6.14. (Continuing).

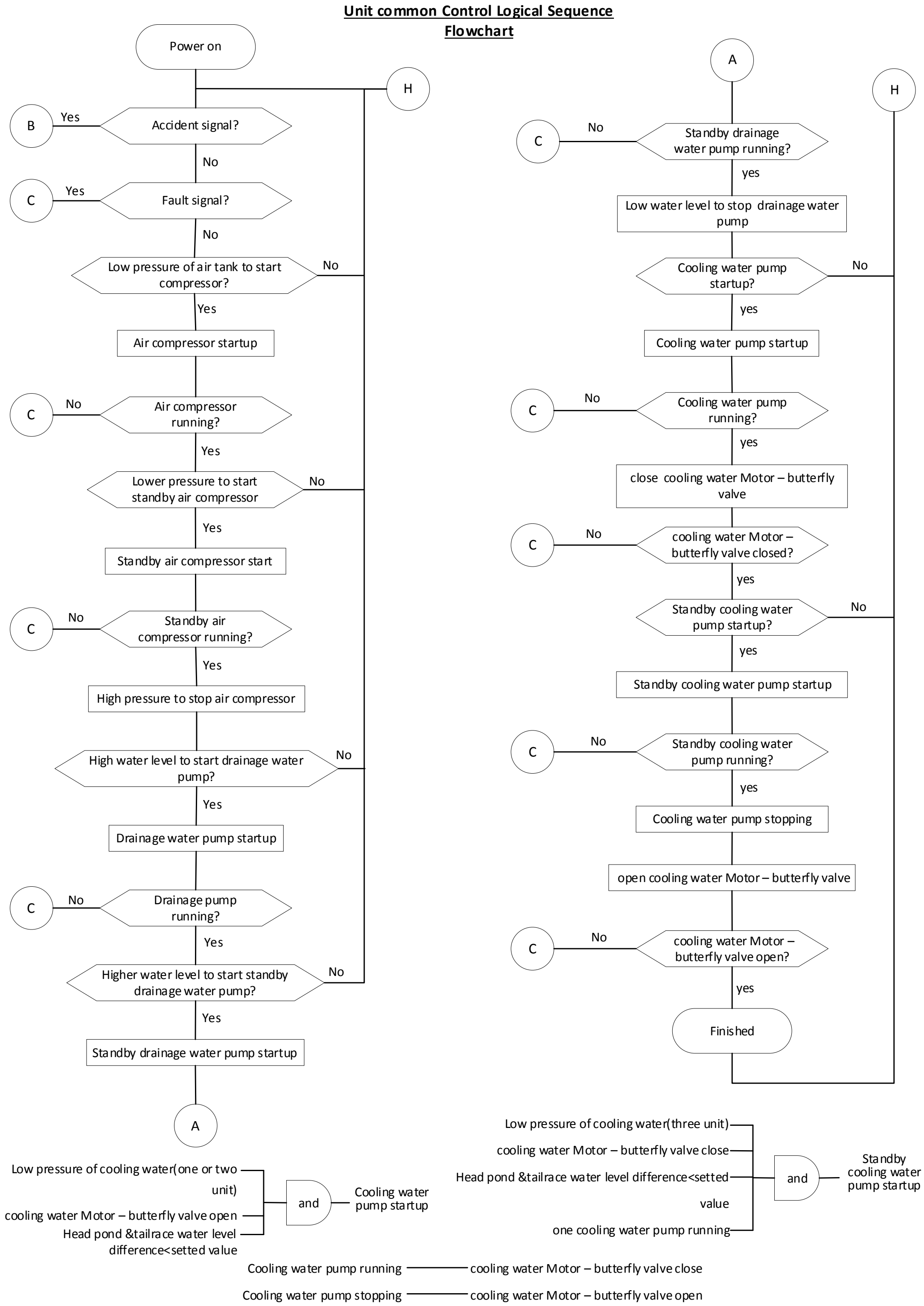


Figure 6.15. (Continuing).

Alarm voice& fault indecator Control Logical Sequence Flowchart

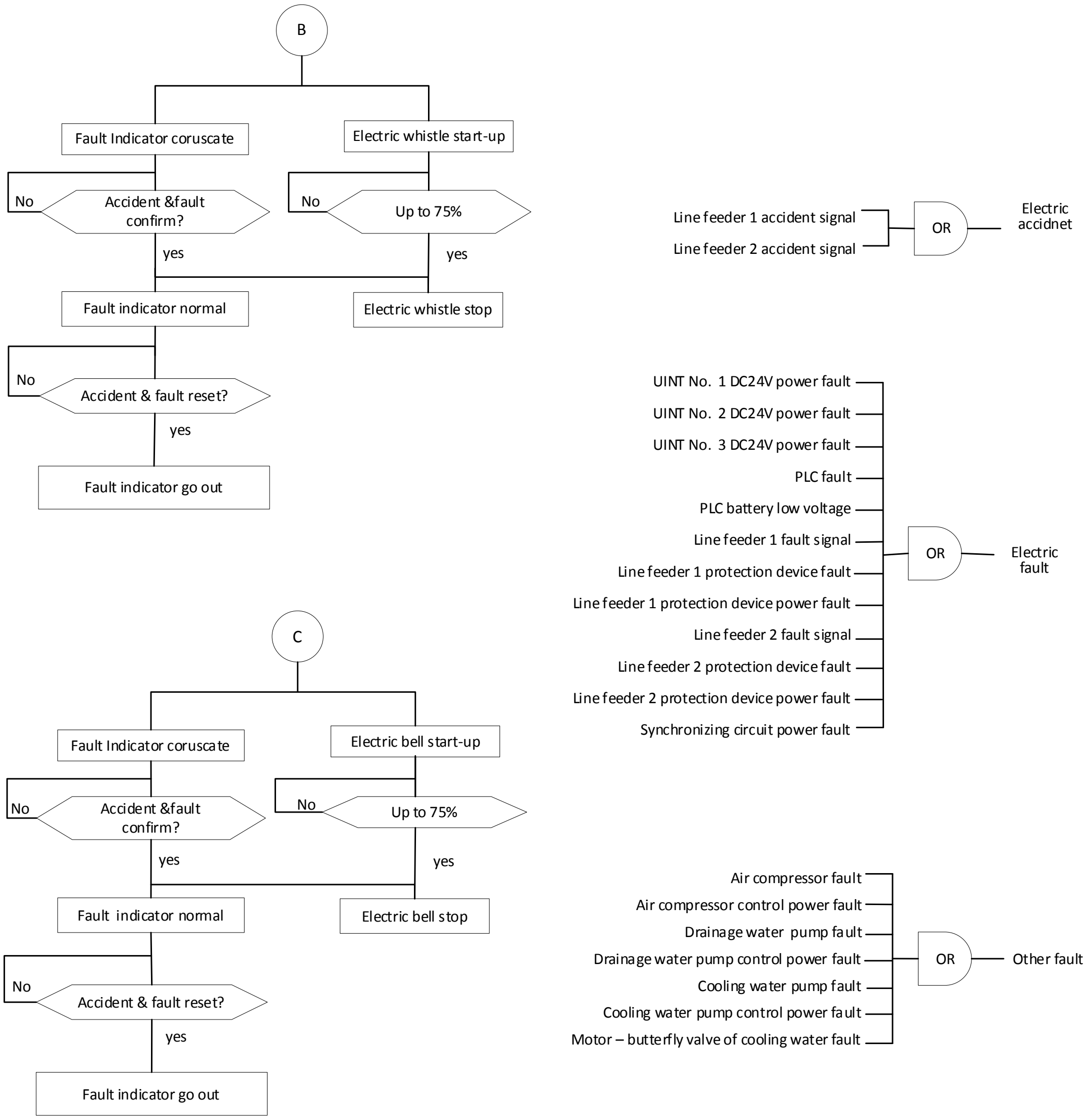


Figure 6.16. (Continuing).

6.2. SCADA SCREENS

Four SCADA screens were designed in accordance with the working scenario of the process. These are main, single line, alarms and values SCADA screens. As shown in Figure 6.10, on the Main SCADA screen, the values of basic parameters such as current, voltage, active power, reactive power of the generators and the general state of the system can be monitored.

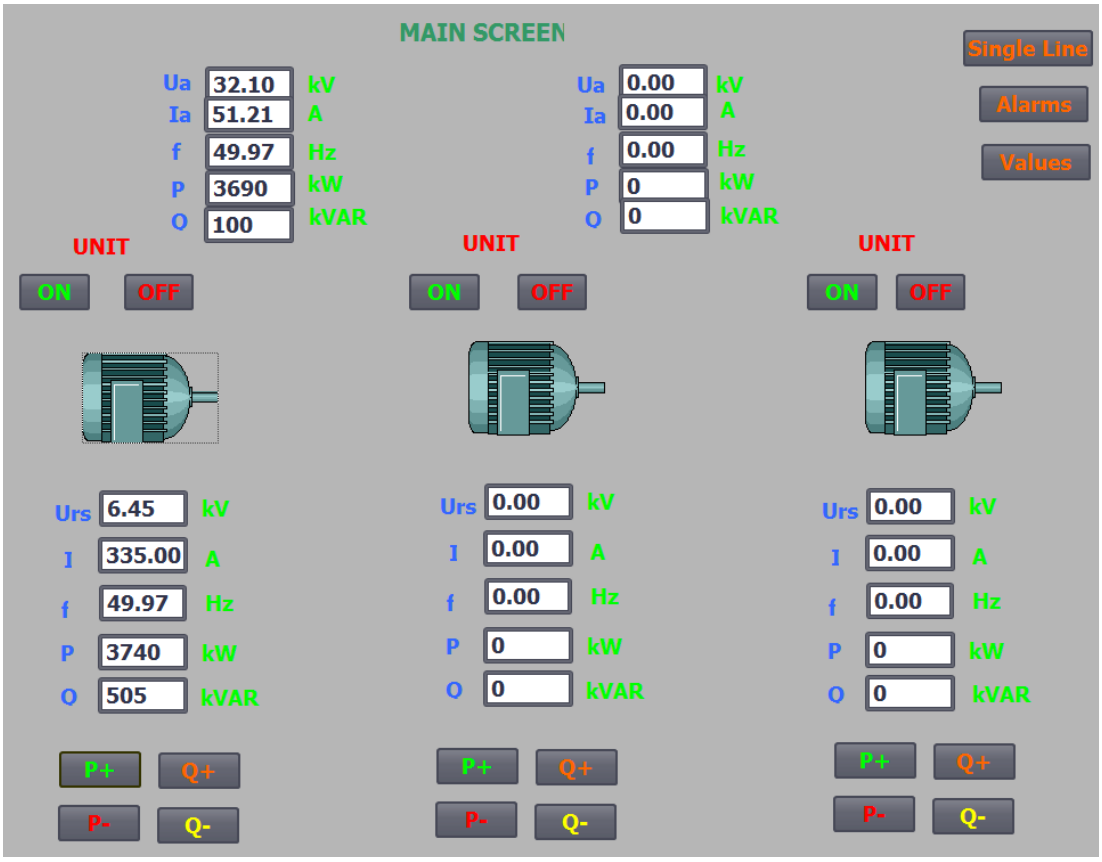


Figure 6.17. Main SCADA screen.

On the Single Line SCADA screen, the positions of the circuit breakers and disconnectors on the single line diagram of the system drawn and the information regarding the energization of the busbars can be monitored, and synchronization processes can be performed. Figure 6.11 show single line SCADA screen.

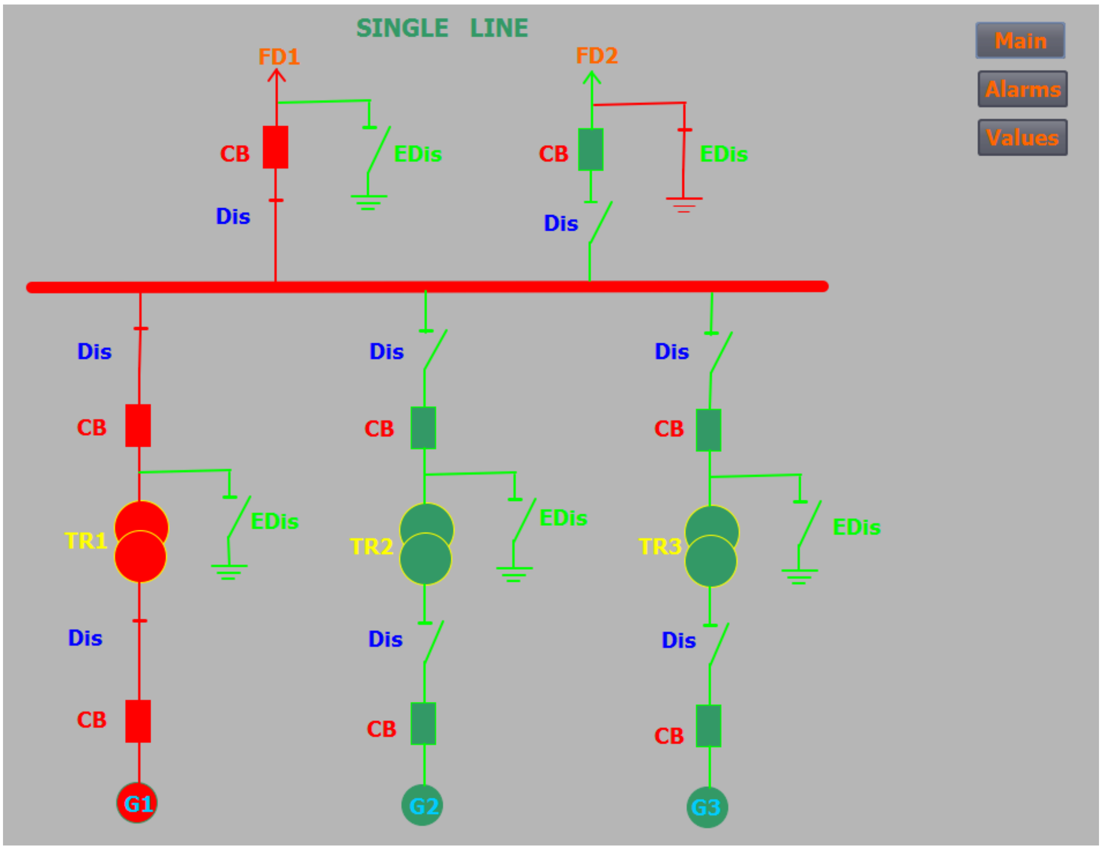


Figure 6.18. Single line SCADA screen.

On the Alarm SCADA screen, all faults and warning alarms coming from the system are displayed. Alarms SCADA screen is shown in Figure 6.12.

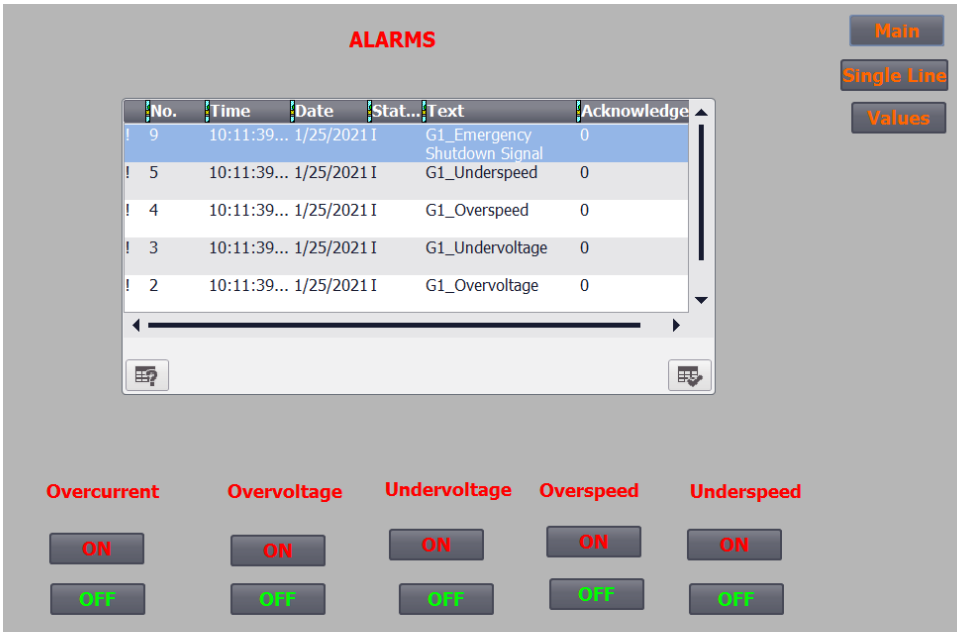


Figure 6.19. Alarms SCADA screen.

Since the system is very complex and large, a prototype has not been made and therefore real (physical) equipment has not been used. For this reason, the values coming from the field to the real system are sent from the SCADA screen.

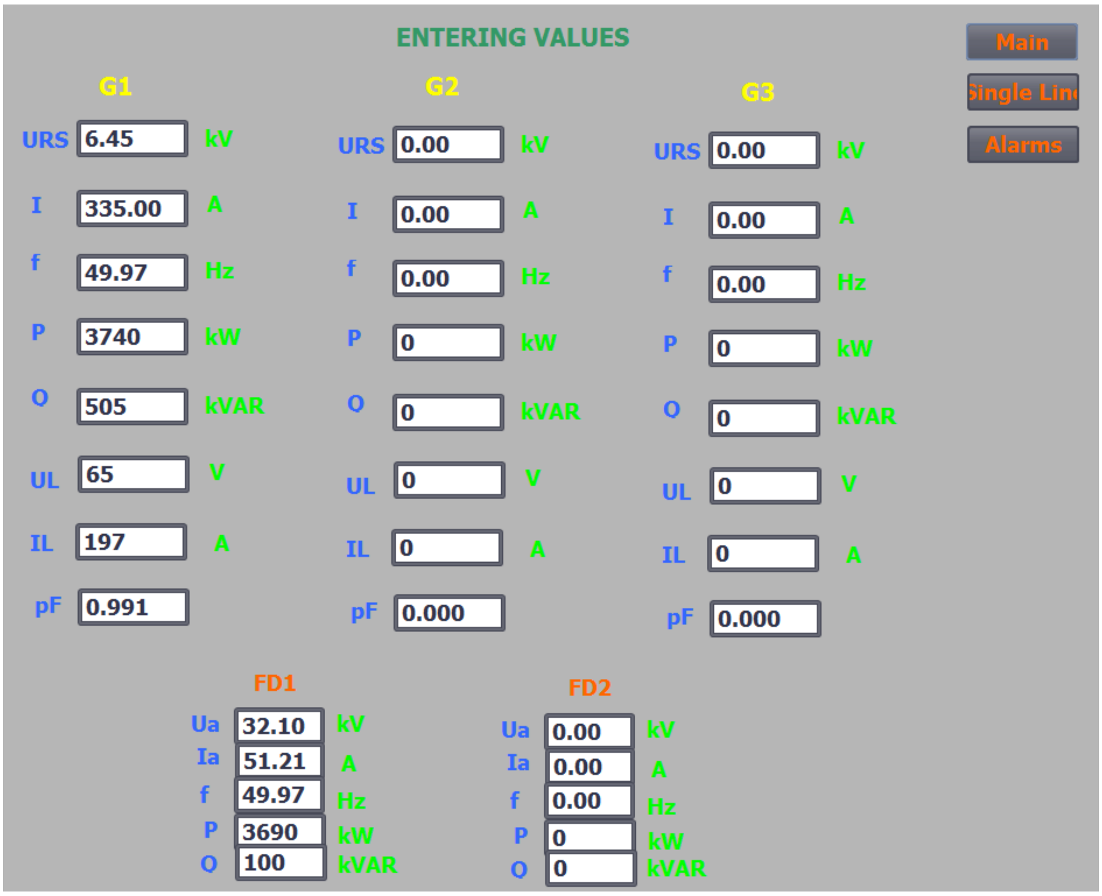


Figure 6.20. Values SCADA screen.

CHAPTER 7

CONCLUSION AND SUGGESTION

In this thesis, simulation of RRHPP with 15 MVA power production capacity was performed in Matlab environment and PLC ladder diagram was drawn on TIA Portal interface and SCADA screens were created. Satisfactory results with reasonable errors were obtained from Simulink simulations presented in Chapter 5. It has been shown that non-linear and very complex systems such as RRHPP can be modeled and that such systems can benefit from these models during the design and projecting stages.

With PLC/SCADA software, the use of applications which are very risky and/or impossible to test on the real system is made possible in order to improve the system. Different scenarios can be tried in the PLC simulation environment, and its applicability to the real system can be considered accordingly.

Two of the most studied subjects in HPPs are the regulation/stability of voltage and frequency (rpm) according to the load. PID control is usually implemented for these. Using artificial intelligence techniques such as the artificial neural network, genetic algorithm and fuzzy logic alongside traditional PID control can help improve the PID control. Artificial intelligence techniques can be used in future studies.

Since RRHPPs do not have dams, their production capacities are affected much more by rainfall as compared to HPPs with dams. Especially in the summer months and when rainfall is low, the production capacity can be reduced to half or even a quarter. Depending on the amount of rainfall, there may be times when only one of the three units is operating, or even when all three units are disabled. For this reason, geographical data of the region and annual and ten-year weather data can be obtained and energy production amount can be estimated for the coming years from the geographical weather data using ANN.

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APPENDIX A.

PARTS OF THE LADDER DIAGRAM

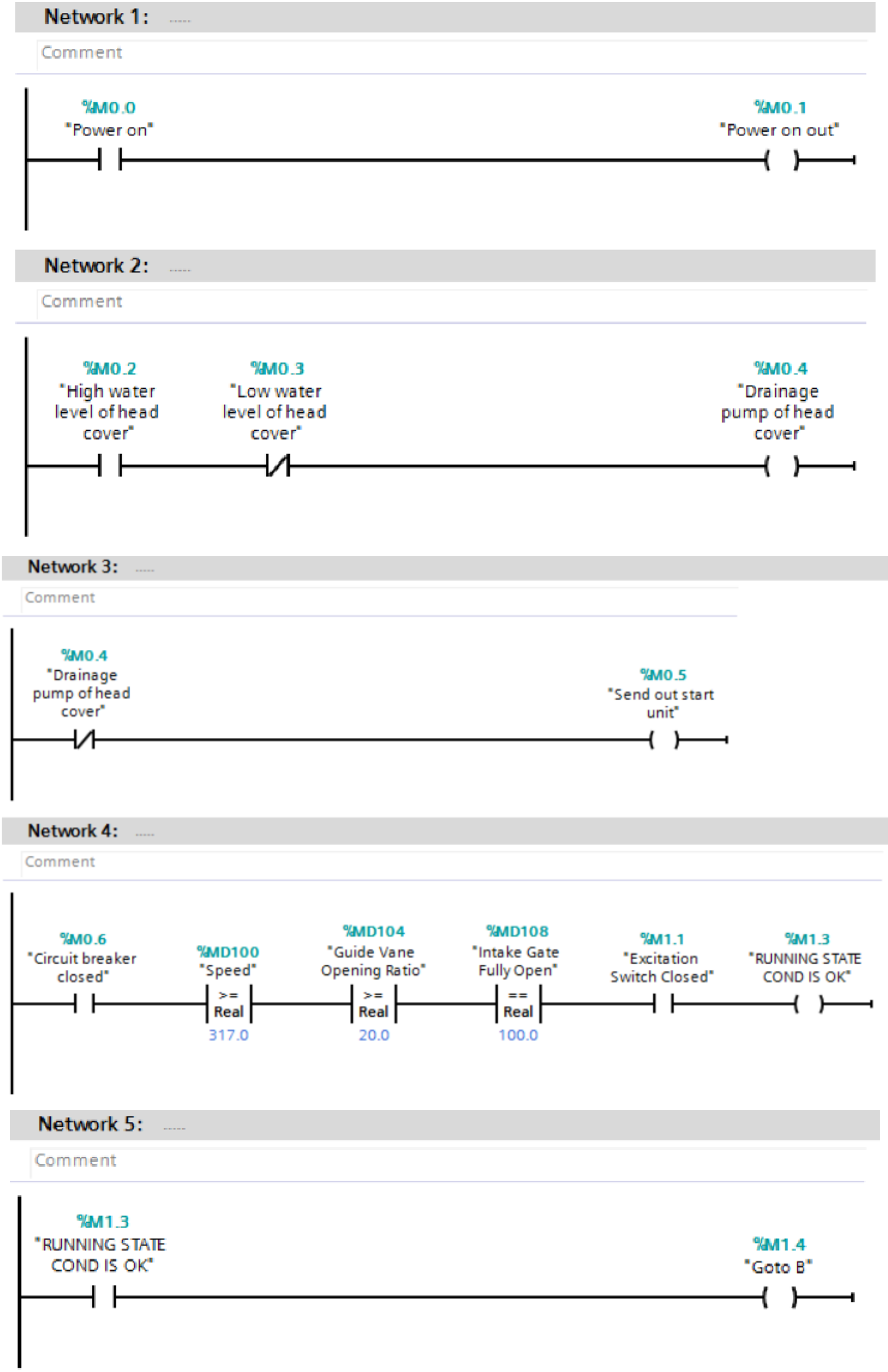


Figure Appendix A. Parts of the ladder diagram.

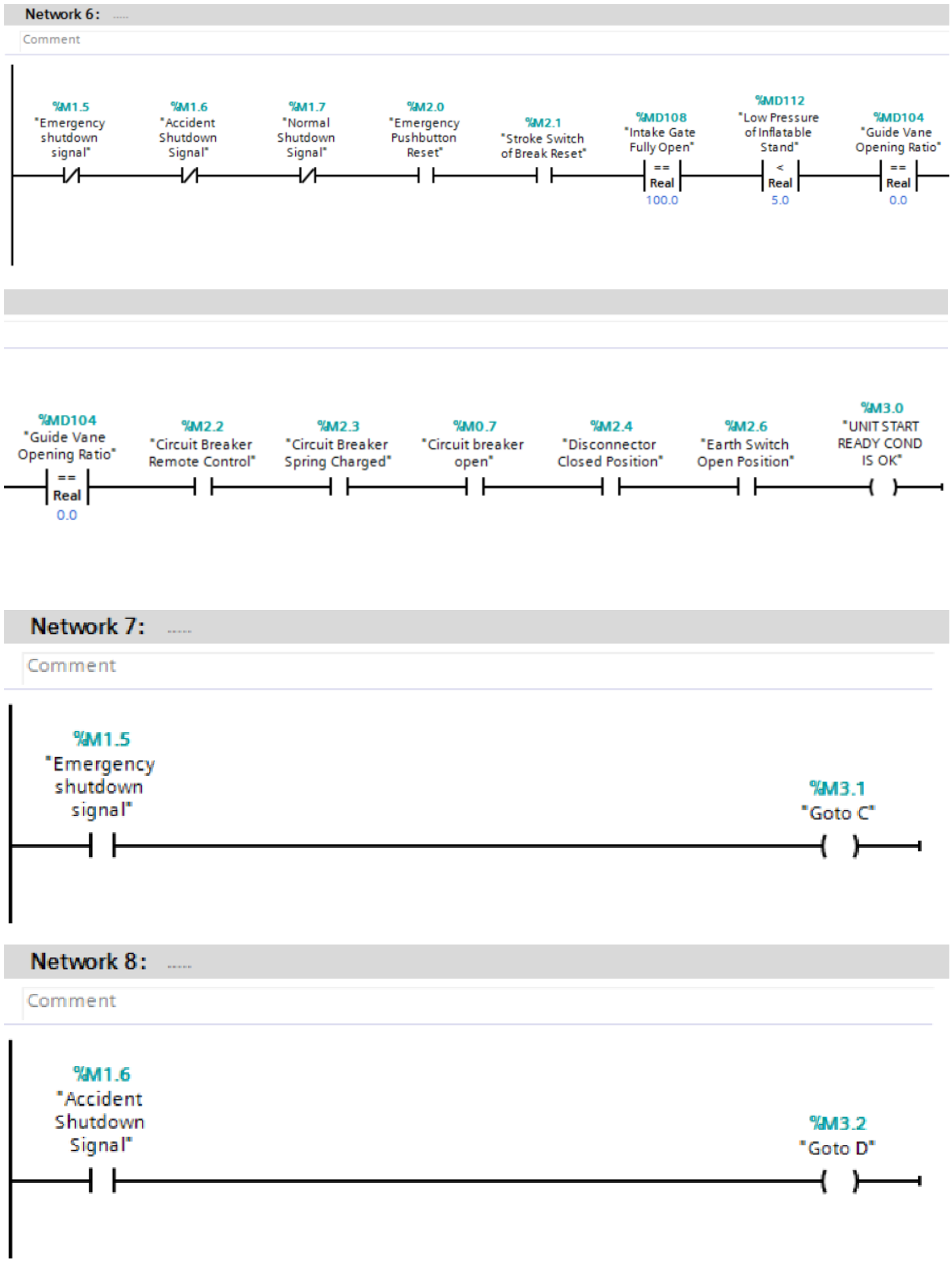


Figure Appendix A. (Continuing).

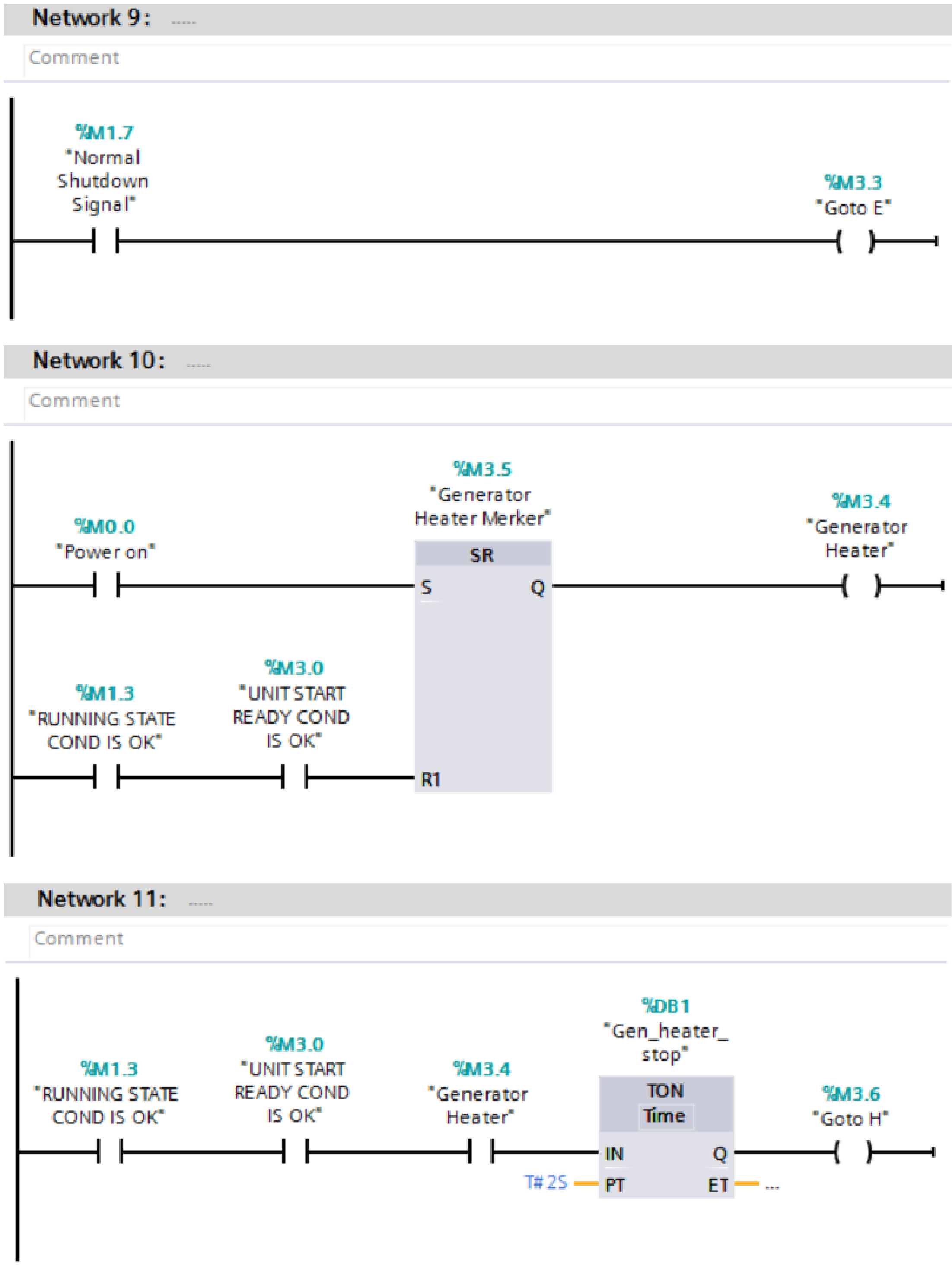


Figure Appendix A. (Continuing).

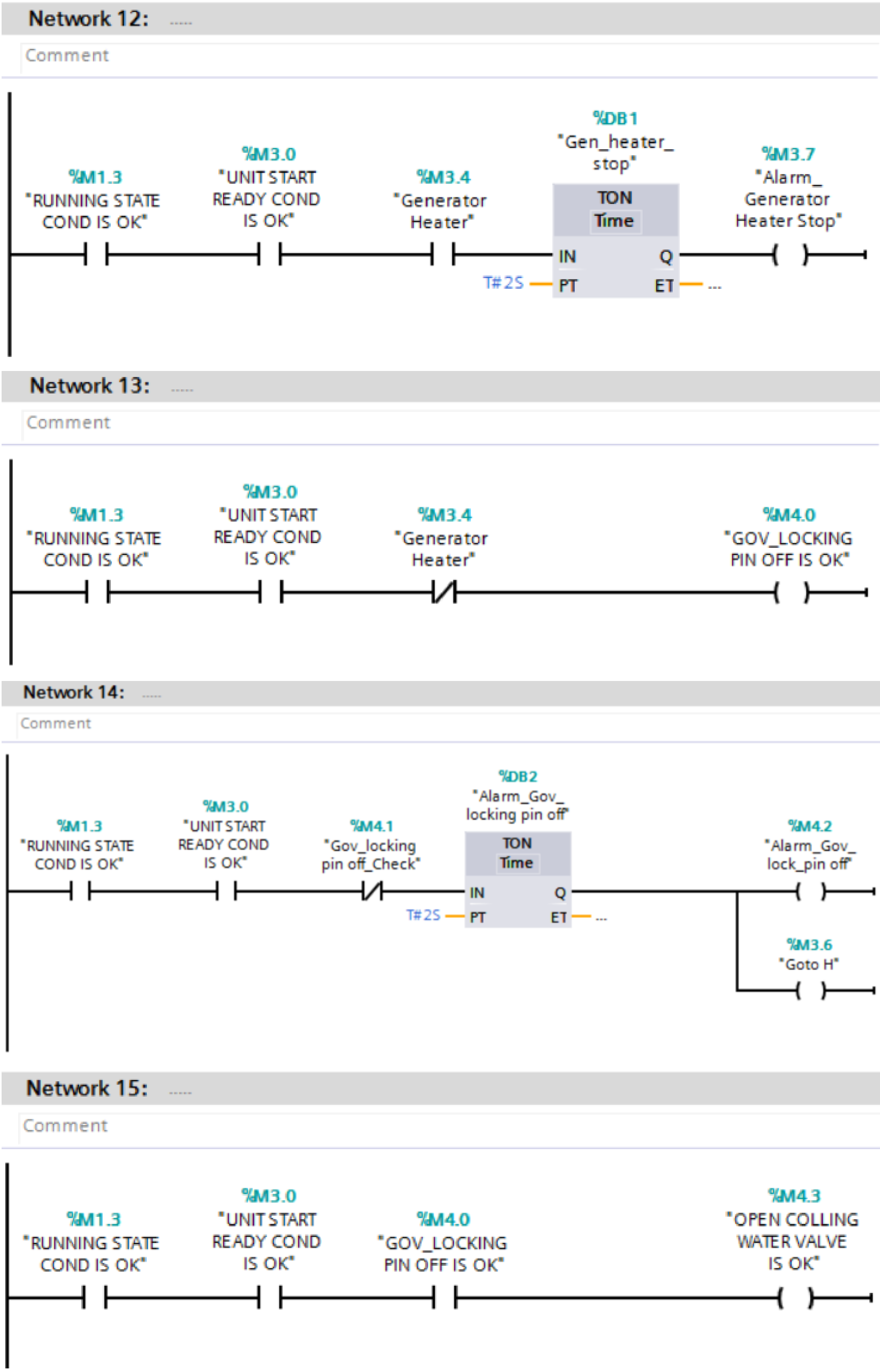


Figure Appendix A. (Continuing).

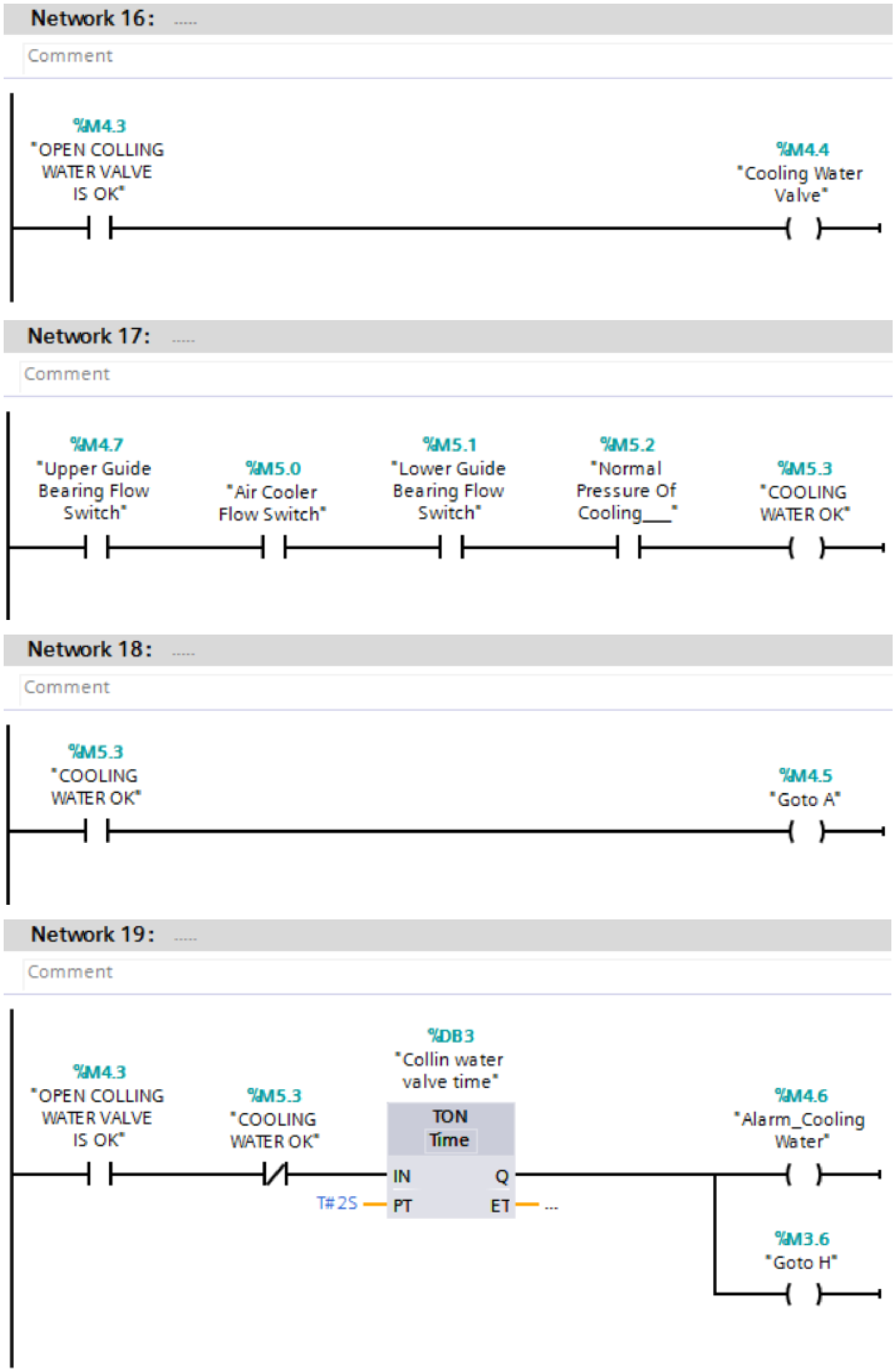


Figure Appendix A. (Continuing).

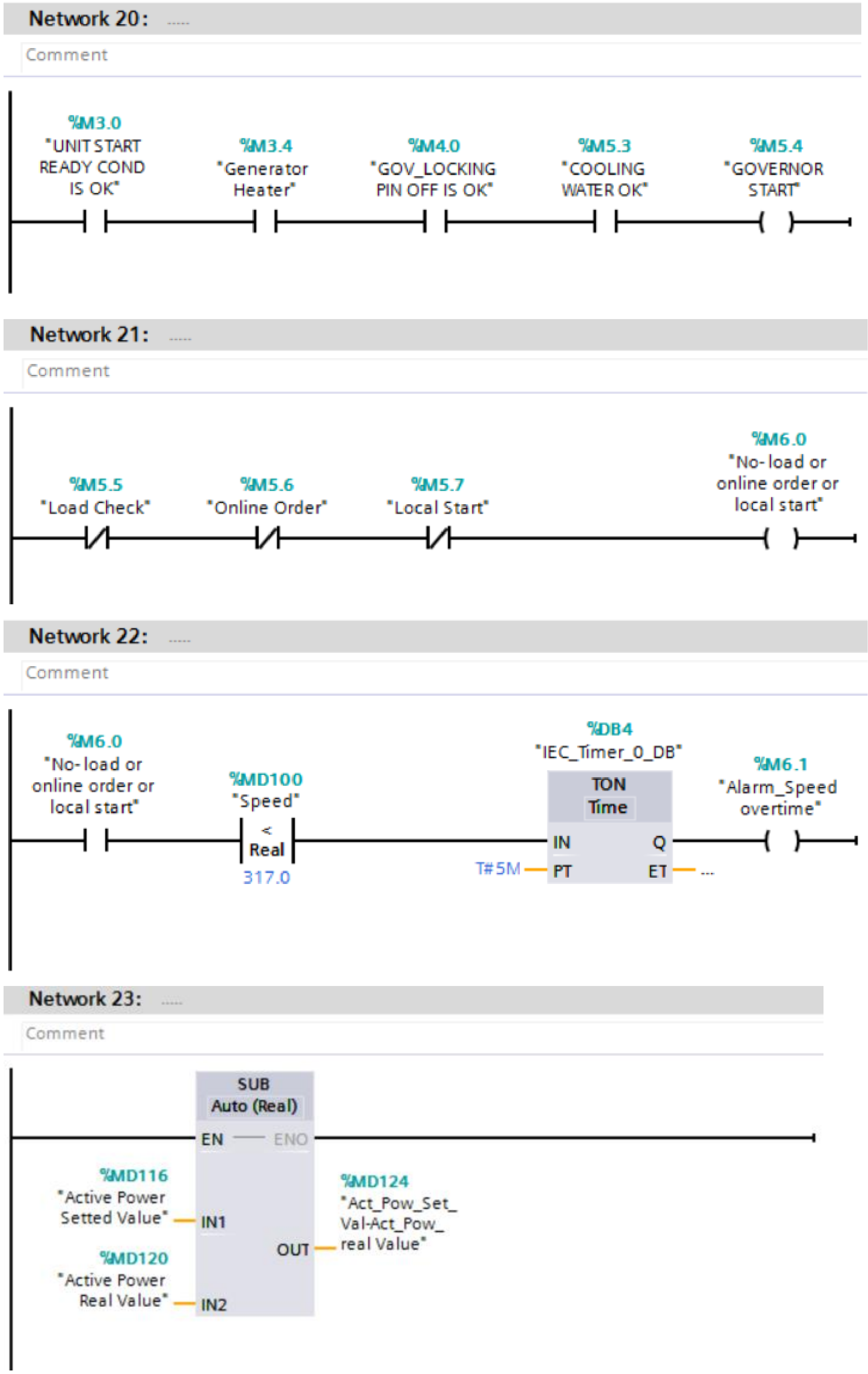
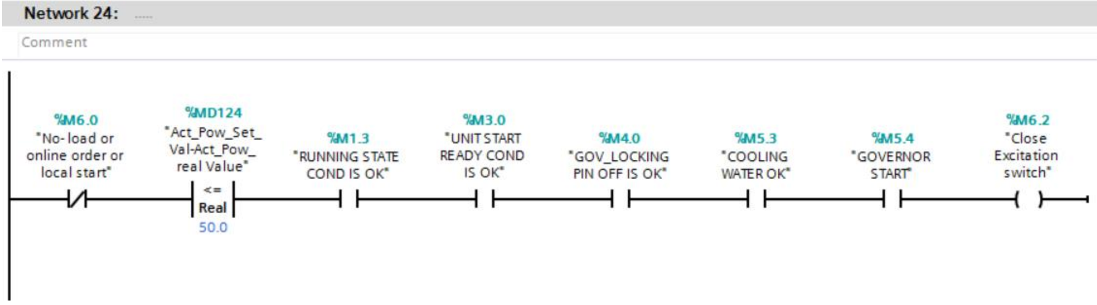
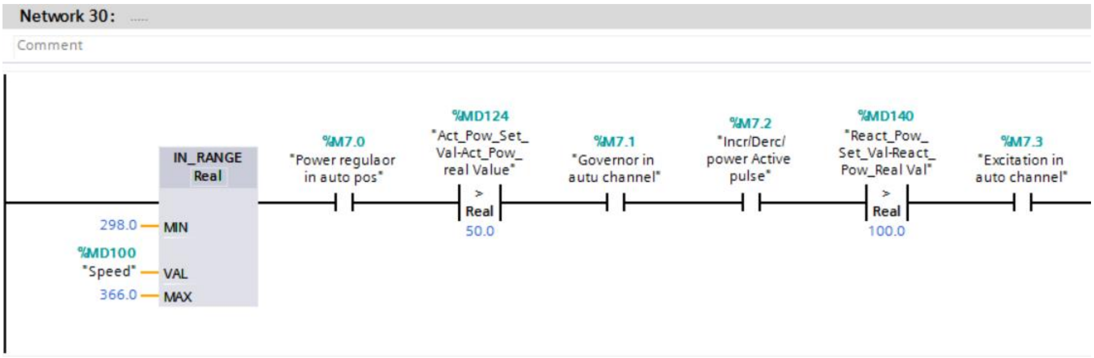
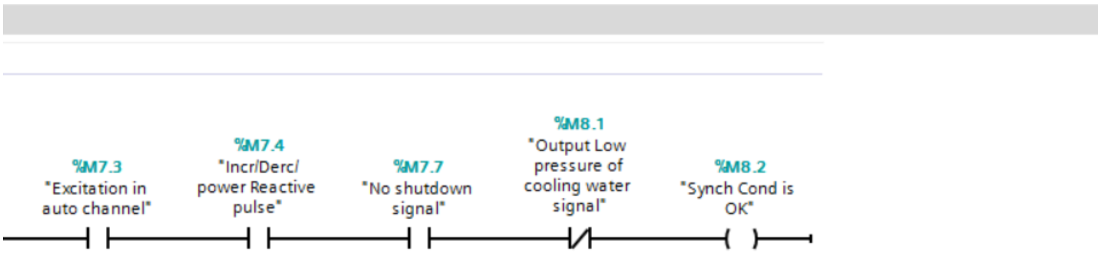


Figure Appendix A. (Continuing).







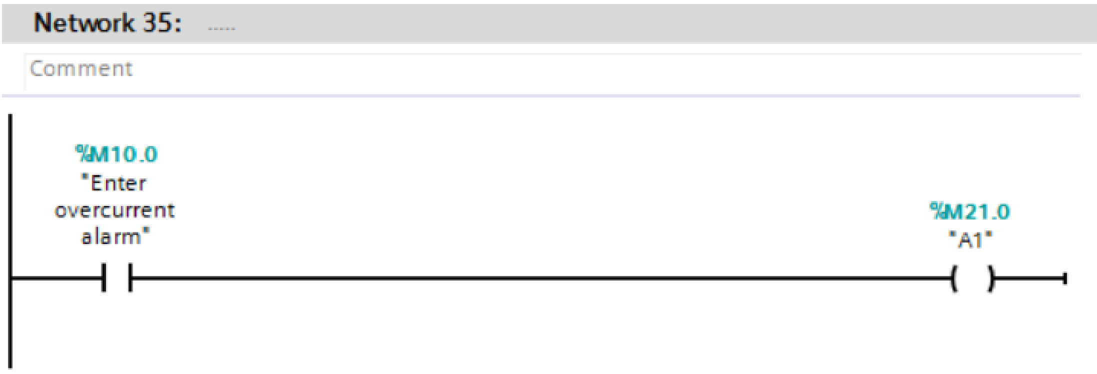


Figure Appendix A. (Continuing).

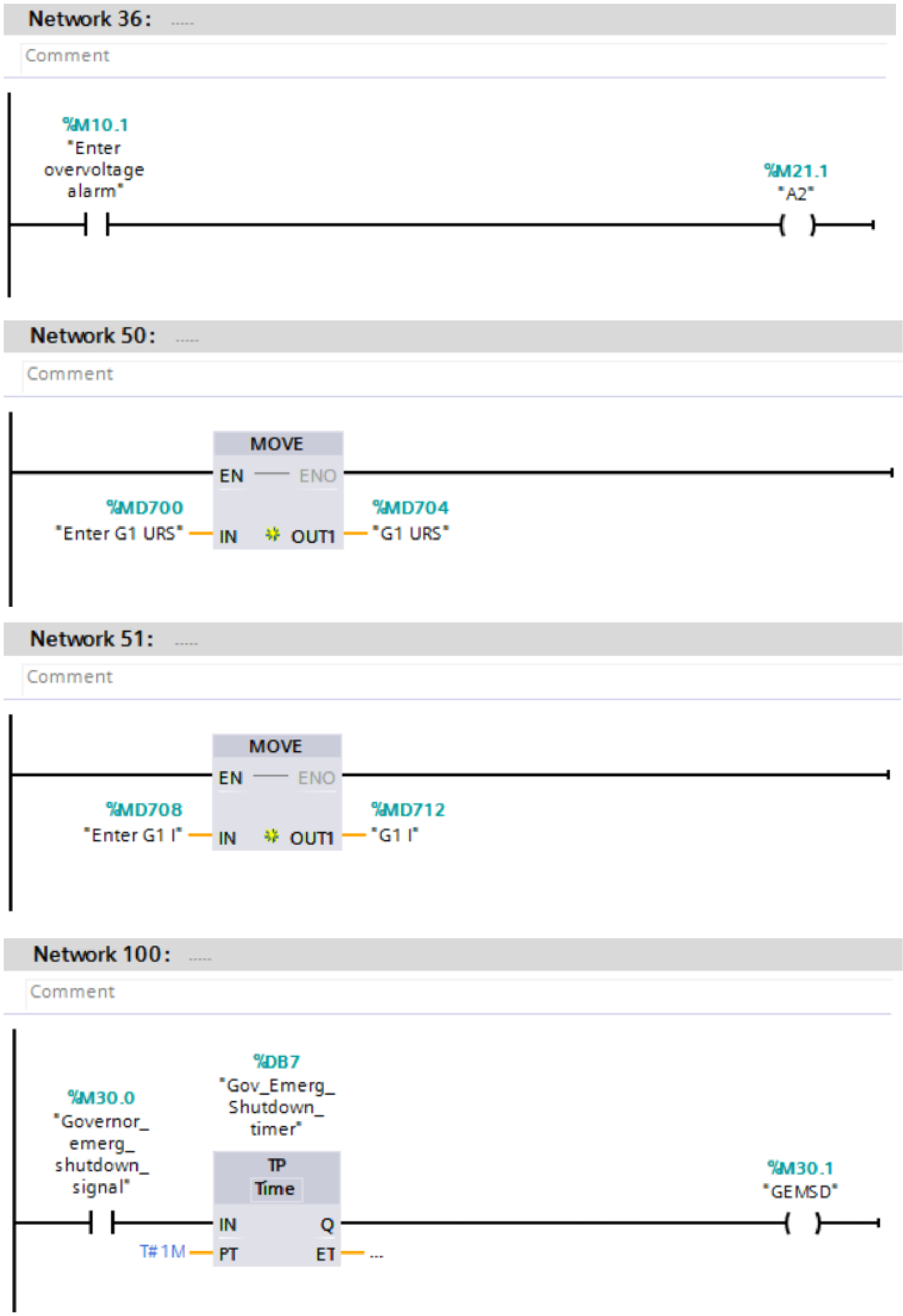


Figure Appendix A. (Continuing).

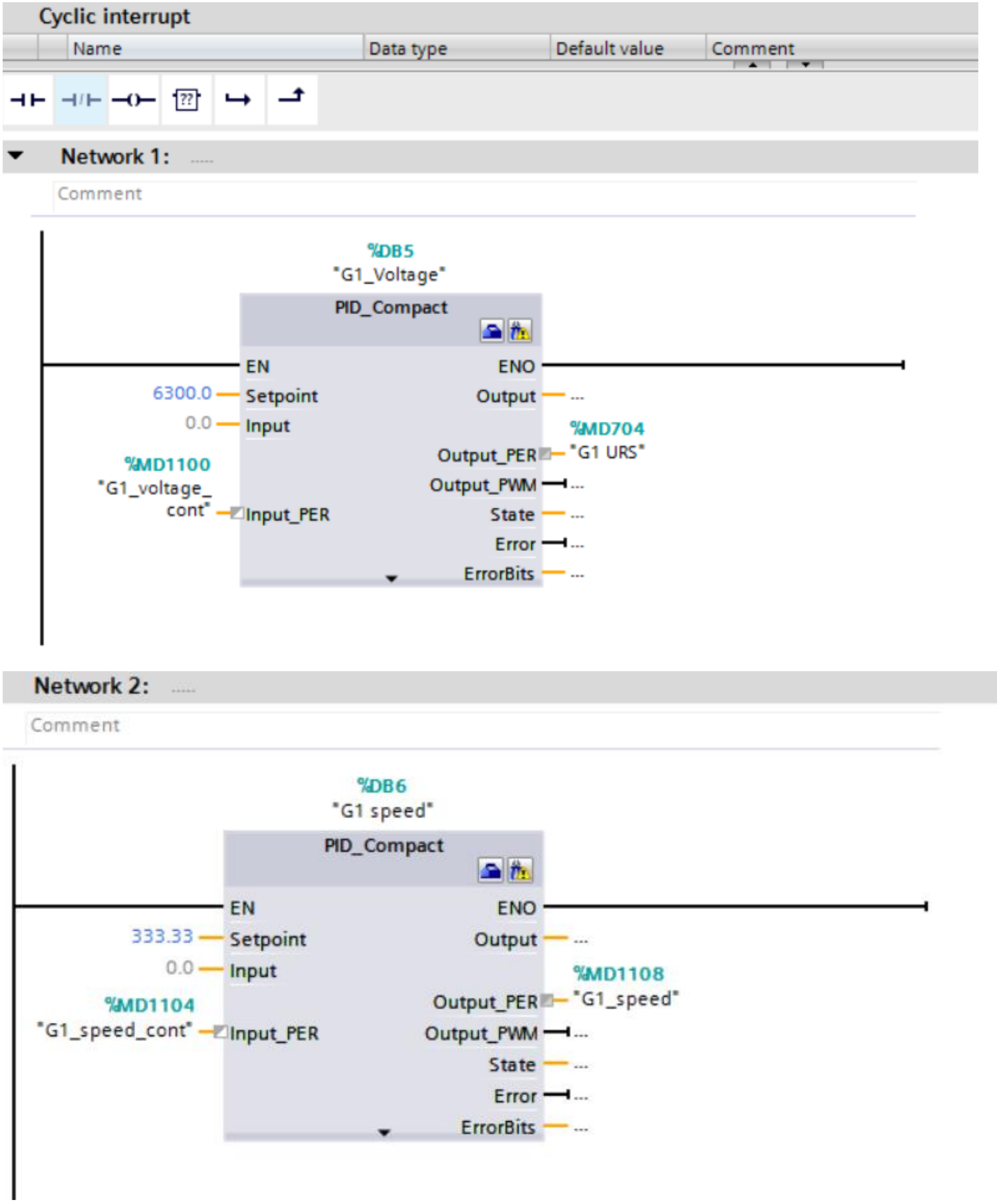


Figure Appendix A. (Continuing).

APPENDIX B.

PARTS OF THE TAG TABLE

PLC tags

Name	Data type	Address
Power on	Bool	%M0.0
Power on out	Bool	%M0.1
High water level of head cover	Bool	%M0.2
Low water level of head cover	Bool	%M0.3
Drainage pump of head cover	Bool	%M0.4
Send out start unit	Bool	%M0.5
Circuit breaker closed	Bool	%M0.6
Circuit breaker open	Bool	%M0.7
Speed	Real	%MD100
Guide Vane Opening Ratio	Real	%MD104
Intake Gate Fully Open	Real	%MD108
Excitation Switch Closed	Bool	%M1.1
Excitation Switch Open	Bool	%M1.2
RUNNING STATE COND IS OK	Bool	%M1.3
Goto B	Bool	%M1.4
Emergency shutdown signal	Bool	%M1.5
Accident Shutdown Signal	Bool	%M1.6
Normal Shutdown Signal	Bool	%M1.7
Emergency Pushbutton Reset	Bool	%M2.0
Stroke Switch of Break Reset	Bool	%M2.1
Low Pressure of Inflatable Stand	Real	%MD112
Circuit Breaker Remote Control	Bool	%M2.2
Circuit Breaker Spring Charged	Bool	%M2.3
Disconnector Closed Position	Bool	%M2.4
Disconnector Open Position	Bool	%M2.5
Earth Switch Open Position	Bool	%M2.6
Earth Switch Closed Position	Bool	%M2.7
UNIT START READY COND IS OK	Bool	%M3.0

Figure Appendix B. Parts of the tag table.

	Name	Data type	Address
	G1 I	Real	%MD712
	Enter G1 f	Real	%MD716
	G1 f	Real	%MD720
	Enter G1 P	DInt	%MD724
	G1 P	DInt	%MD728
	Enter G1 Q	DInt	%MD732
	G1 Q	DInt	%MD736
	Enter G1 UL	Real	%MD740
	G1 UL	Real	%MD744
	Enter G1 IL	Real	%MD748
	G1 IL	Real	%MD752
	Enter G1 pF	Real	%MD756
	G1 pF	Real	%MD760
	Enter FD1 Uab	Real	%MD764
	FD1 Uab	Real	%MD768
	Enter FD1 Ia	Real	%MD772
	FD1 Ia	Real	%MD776
	Enter FD1 f	Real	%MD780
	FD1 f	Real	%MD784
	Enter FD1 P	DInt	%MD788
	FD1 P	DInt	%MD792

Figure Appendix B. (Continuing).

RESUME

Abdurraouf Otman Elmiladi was born in Tripoli -Libya in 1969 and graduated from elementary school in the same city. He completed his high school education in Suq Aljumea High School and then pursued his undergraduate degree in The Bright Star of Technology -Albrega University Department of Electrical and Electronics in 1991. Then in 2000, he started working as an Instrument Engineer in Akakus oil company, Department of Instrumentation & control. As of 2018, he is pursuing his master degree at Karabuk university.

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