Transient Simulation of Line-Focus Solar Thermal Power Plants

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Abstract

Concentrated Solar Power (CSP) is a utility scale technology that produces electricity using the thermal energy of the sun. Due to the varying intensity of the solar irradiation, there is a constant change in the operation point for solar thermal power plants. In order to optimize the process, a complex relation between irradiation intensity, fluid mass flow and collector focus must be considered and appropriate control strategies should take into account the transient situations. Therefore, detailed simulation tools are essential for the analysis and optimized operation of the power plant.

In this context, the German Aerospace Centre (DLR), as a pioneering research institution of CSP, developed a model to simulate line-focus solar fields with single-phase heat transfer medium: the Virtual Solar Field (VSF). This simulation tool considers the hydraulic and thermal aspects of the plant, enabling to model the thermal condition effect of the field on the flow distribution among the parallel loops. Accordingly, the goal of the master thesis is to validate VSF under certain conditions and improve its applications. In addition, VSF is also used as a tool to enhance the control and improve the outcome of solar thermal power plants.

The first phase of the project consisted of the validation of the simulation tool by the comparison of the VSF model results with data from a real power plant. For that, data preparation was realized and a validation method was developed, with further analysis of the results. The second phase of the project was based on the development of a broader use for the tool as an improvement for control. This was achieved by the application of a Fuzzy Logic Control (FLC) in MATLAB®. This FLC implementation includes loop mass flow and collector focusing mode in the same algorithm, aiming to decrease defocusing instances while still maintaining optimal temperature set-points. It considers control valves for each individual loop and also the period of the day, differentiating the phases of plant operation. The main advantage brought from fuzzy logic to this case is that the knowledge in the technology and in the expected behavior in transient situations could be fully applied in the control strategy.

Consequently, VSF was successfully validated and used as a good support for the development of FLC. The results of FLC application show that this unique approach can be very beneficial for the plant's operation, with a relative simple implementation. FLC performed as a robust and proactive controller, especially in transient situations, providing better energy performance and allowing less defocusing instances, with stable outlet fluid temperature. In conclusion, the FLC is considered to be a proper strategy to be applied in combination with VSF simulation tool to enhance the control of a solar thermal power plant. This implementation represents an additional value for VSF, characterizing an innovative approach that considers dynamic valve control and collector focusing mode in a single strategy.

Acknowledgements

This work is the accomplishment of a journey, which was only possible with the support of the people found on the way.

To my DLR colleagues, specially to Kareem Noureldin and Tobias Hirsch, thank you for the attention and patience that guided me to a great destination.

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To my ME3 friends, that gave music and colors for the way.

To my family, thank you for the constant love and care, supporting me to walk with firm steps.

That the destination is just a port and the journey keeps on going.

Contents

Acronyms

CSP Concentrated Solar Power. 1, 5, 8, 34, 35

DLR German Aerospace Centre. 1, 9, 10, 35

DNI Direct Normal Irradiation. 7, 8, 12, 14, 17, 22, 24, 26, 27, 30, 32, 34

FLC Fuzzy Logic Control. 1, 18–21, 23, 24, 26, 28, 30, 32, 34, 35

HTF Heat Transfer Fluid. 5, 6, 8, 11, 13, 21, 24, 27–29, 32, 34

PTC Parabolic Trough Collectors. 7, 34, 35

PV Photovoltaic Cells. 5

VSF Virtual Solar Field. 1, 10, 11, 15–17, 19, 28, 30, 34, 35

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1 Introduction

The continuous increase in world's economy predicts a consequent rise in energy demand of countries around the globe, even as great efforts are made in order to improve energy efficiency. Facing this scenario, the 2015 United Nations Climate Conference in Paris reinforced that a rapid and global transition to renewable energy technologies offers a realistic means to achieve sustainable development and avoid climate change. According to the Road-map for a Renewable Energy Future, developed by the International Renewable Agency (IRENA), renewable energy technologies can meet much of the growing demand at prices that are equal to or lower than those usually forecast for conventional energy[9].

In essence, the origin of all the forms of energy in the world as we know is the sun. Fossil fuels such as oil, coal, natural gas and wood were originally formed by photosynthetic processes, followed by complex chemical and physical reactions. Even the wind and tide behavior are related to the sun, as they are caused by differences in temperature in different regions of the Earth. Solar energy has been widely used by both nature and humankind throughout time, and deliberately harnessed for many applications, e.g. to heat and cool buildings, to heat water for domestic and industrial uses, to operate engines and pumps and to desalinate water for drinking purposes. There are many advantages on using solar power when comparing with other forms of energy, with the highlight that it is clean and can be supplied without environmental pollution.

Electricity can be generated from solar energy directly via Photovoltaic Cells (PV) or indirectly via Concentrated Solar Power (CSP). While PV technology is based on the photoelectric effect, CSP produces electricity using the thermal energy of the sun. The main innovation of solar thermal plants is the possibility of incorporating heat storage, which allows the system to be operational during cloudy weather or nighttime. This enables the compensation for short-term fluctuations in production and ensures a reliable electricity generation[10].

1.1 Concentrated Solar Power Characteristics

As a utility scale technology for renewable electricity generation, solar thermal power plants concentrate the solar radiation in order to reach the high temperature required for the process[1]. Mirrors are used to concentrate solar radiation on absorbers that transform it to heat energy in a fluid. The fluid at high temperature is used to boil water and the resulting steam drives turbines traditionally powered by conventional fossil fuels, therefore being an efficient sustainable alternative for large-scale systems. There is a range of available technologies of concentrating solar collectors, which are: Parabolic Trough Collectors, Linear Fresnel Collectors, Solar Tower Systems and Parabolic Dishes.

The great differential of CSP among other renewable energy systems is the possibility of efficient thermal storage, allowing the extension of solar electricity production to periods without solar irradiation. Furthermore, this enables the adaptation of electricity production in accordance with electricity demand. Figure 1 shows a schematic diagram of an example of a parabolic trough solar thermal power plant with integrated storage capacity and back-up boiler. The power plant consists of a collector field, storage system, auxiliary heater and power block. In the collector field, the Heat Transfer Fluid (HTF), represented in the red pipes in the scheme, is heated by the concentrated solar irradiation.

Then, the energy is transferred to the water/steam (represented in the blue pipes) via several heat exchangers. The steam is then used to drive the steam turbine in a Rankine cycle. In parallel to the solar field an auxiliary heater is installed. The heater is used to heat the HTF during cloudy periods, to prevent it from freezing or to speed up the start-up of the plant. The excess heat of the solar field can be used to charge the storage system of the power plant, which consists of a tank of molten salt represented in green in the scheme. During charging, the cold salt is pumped to the hot tank passing by a heat exchanger, where it is heated up by the excess energy of the solar field. During discharging, the hot salt is pumped to the cold tank transferring the heat back to the HTF, which will then drive the power block and generate electricity[13].

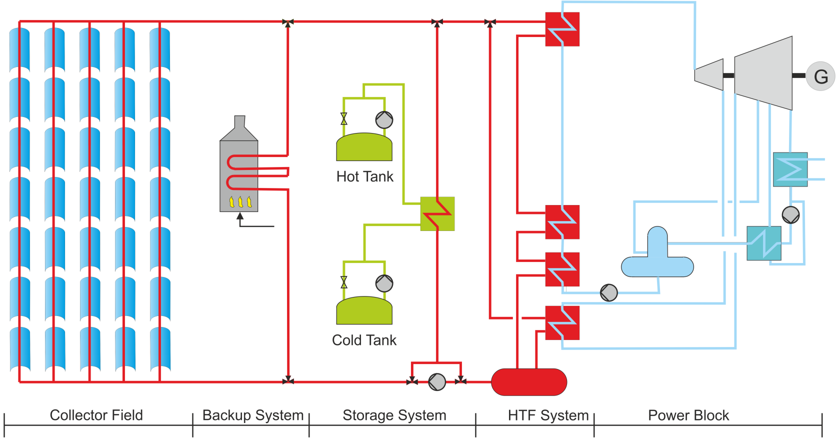


Figure 1: Scheme of a single-phase Line-Focus Solar Thermal Power Plant, with heat storage.

Due to the apparent movement of the sun across the sky, the concentrating collectors in the solar field must follow the sun's daily motion. By that, the mirrors can be efficiently used to concentrate the thermal energy, with a dynamic adaptation to the sun's position along the different periods of the year. Figure 2 shows the several angles that should be considered during the tracking analysis of the concentrating collectors.

The solar altitude angle (α) is the angle between the sun's rays and a horizontal plane, while the zenith angle (ϕ) is the one between the sun's rays and the vertical. The azimuth angle (z) is the angle of the sun's rays measured in the horizontal plane from due south for the Northern Hemisphere or due north for the Southern Hemisphere.

There are two tracking methods of concentrating collectors. The first one is called altazimuth method and it enables the collector to follow the exact sun position: the tracking device turns in both altitude and azimuth. The second method is a one-axis tracking, in which the collector tracks the sun only in one direction, either from east to west or north to south. Both systems require continuous and accurate adjustment to compensate the changes in the sun's orientation along the year[10]. The solar energy is then optically concentrated and transferred into heat, increasing the energy flux in the receiving target.

The tracking position is essential to determine the operational temperature

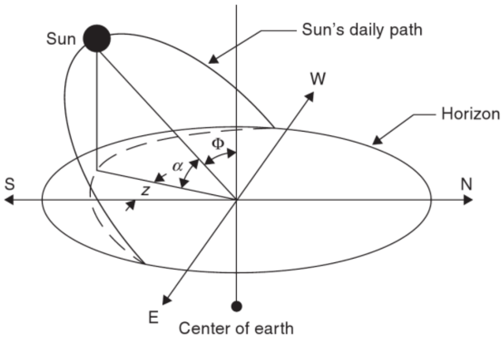


Figure 2: Apparent daily path of the sun across the sky from sunrise to sunset[10].

of the power plant, which can be adjusted by the focusing mode of the collectors. The collector angle can be set to exactly follow the sun track, being 100% focused, or to have a difference between the angle of the sun and its tracking angle, meaning that it can have a defocusing percentage. Figure 3 presents a schematic of both situations. This strategy is used mainly to avoid overheating of the fluid. Apart from that, a variable focusing mode is used to protect the collectors from hazardous environmental and working conditions, such as wind gusts and failure of the thermal fluid flow mechanism[10].

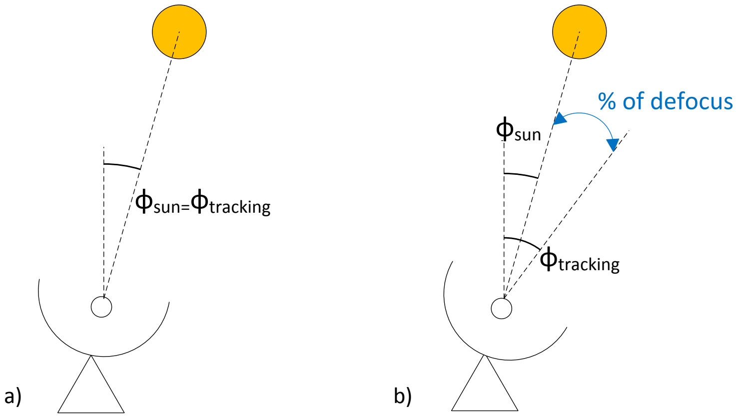


Figure 3: Scheme of the tracking position of a parabolic trough collector, with view from the normal to the mirror surface. In the left scheme, the collector is 100% focused, as its tracking angle is exactly the same as the zenith angle of the sun. The scheme on the right shows a situation of defocusing, when the tracking angle is different than the zenith angle of the sun.

1.2 Parabolic Trough Collector Systems

In Parabolic Trough Collectors (PTC), the Direct Normal Irradiation (DNI) is concentrated by a parabolic reflector on a linear receiver pipe located in the focal line of the mirrors, as shown in Figure 4. A Heat Transfer Fluid (HTF) is pumped through the receiver and heated up by the concentrated solar irradiance, which is used to boil water and generate steam to enable a Rankine cycle to operate for electricity generation. The optimum temperature of the HTF varies according to the type of fluid: molten salt, oil or water, typically. The one-axis tracking system is usually used by these collectors to track the sun along the day.

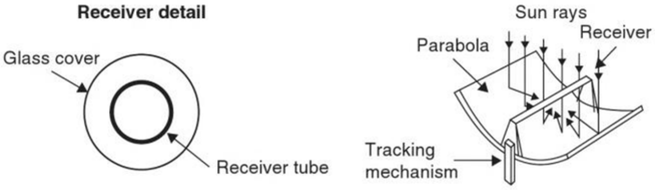


Figure 4: Schematic of a parabolic trough collector[10].

Several collectors are connected in series to form a collector loop and, depending on the capacity of the power plant, collector loops can be connected in parallel. So far, power plants with a capacity from 10 MW up to 300 MW are under operation[8]. At present, parabolic trough power plants are the most mature and commercially proven CSP systems[13].

The thermal performance of solar collectors can be determined by the detailed analysis of the optical and thermal characteristics of the collector material and design, apart from the intensity of the solar irradiation available. This study depends on the following parameters: Direct Normal Irradiation (DNI), fluid temperature at the collector inlet (T_i), fluid temperature at the collector outlet (T_o), fluid mass flow rate ($\dot{m}$) and gross collector aperture area (A_a). Also, the heat capacity (c_p) of the Heat Transfer Fluid (HTF) should be taken into account. By these measurements, it is possible to calculate the useful energy gain as [10]:

$$Q_u = \dot{m} c_p (T_o - T_i) \tag{1}$$

The performance of concentrating collectors will depend on DNI and the focusing mode of the collector, as the thermal energy reaching it will vary according to its angle in relation with the sun's position. Furthermore, in order to establish the DNI reaching the collector, it is essential to consider the concentrator geometry and optics. A more detailed study should take into account two important aspects: the concentrating acceptance angle and the incident angle modifier. The acceptance angle characterizes the effect of errors in the tracking mechanism on the angular orientation. The incident angle modifier is a correlation factor to be applied to the efficiency curve and is a function of the incident angle between the direct solar beam and the outward normal to the aperture plane of the collector.

A critical aspect of parabolic trough power plants is the control of its processes and outcome, as there is a constant change in the operation point due to the varying intensity of the solar irradiation. In order to optimize the operation, the transient processes must be considered, such as start-up and shutdown of the power plant, and also passing clouds during the normal operation. This imposes a big challenge, as it involves a complex relation between irradiation intensity, fluid mass flow and collector focus. Appropriate control schemes are developed taking into account the behaviour of the solar fields under these transient conditions, which should be improved by the reduction of defocusing instances and enhanced control of the field mass flow and temperature set-points. To increase the energy yield and optimize the power plant processes, detailed simulation tools are required to study the hydraulic and thermal interactions in the field[11]. Consequently, it is possible to reach a better outcome and increase the confidence in this new technology.

As most transient models for line focusing power plants investigate a single representative loop to model the whole field or assume equal mass flow distribution among the loops, it was not yet possible to achieve a realistic model of the mass flow distribution in collector loops arranged in parallel. Apart from that, the models that consider a varying hydraulic parameter for the different loops do not fully couple this behaviour with the thermal condition[11]. An improved model coupling the hydraulic and thermal parameters would improve the understanding of the transient behaviour of the loops and its effects in the outcome of the whole field.

1.3 Solar Energy and the German Aerospace Centre (DLR)

German Aerospace Centre (DLR) is the national aeronautics and space research centre of Germany, with extensive development work in aeronautics, space, energy, transport and security. DLR has approximately 8000 employees at 16 locations in Germany and some international offices (Brussels, Paris, Tokyo and Washington D.C.).

As its mission, DLR considers the exploration of Earth and the Solar System and research for protecting the environment. This includes the development of environment-friendly technologies for energy supply, mobility, communications and security. Therefore, DLR is a key contributor to scientific and technical expertise, enhancing Germany as an important location for industry and technology. DLR operates major research facilities for its own projects and as a service for clients and partners. It also fosters the development of the next generation of researchers, provides expert advisory services to government and is a driving force in the regions where its facilities are located.

In the context of one of the strongest countries performing energy transition, Germany's current policies focus in technological advances and a better understanding of the system, which is believed to deliver important contributions to transform the energy system into a sustainable form. Publicly funded energy research is especially committed to this goals and DLR considers itself an active and effective supporter, whose research is completely oriented towards these purposes. In this sense, DLR's energy research is focused on environmental friendly, efficient and low-cost energy supply and storage on a scale relevant to the energy industry.

The width and diversity of DLR institutes' competences offer a special competitive advantage, providing a multi-disciplinary work environment and exploiting various synergies. DLR's tasks in energy research are oriented along medium and long-term strategies, being followed in a coordinated way of division of work with its German, European, and international partners from research and industry.

As a pioneering research institution on concentrated solar power, the Institute of Solar Research of DLR is a prime mover of the development and qualification of solar power technologies in Europe and on a global scale. Its research activities focus on technical feasibility issues and on increasing the overall efficiency and lowering the cost of concentrating solar systems[6].

1.4 Objectives

In this context, the Virtual Solar Field (VSF) simulation tool has been developed by German Aerospace Centre (DLR). This model simulates a line-focus solar field with single-phase heat transfer medium, considering the hydraulic and thermal behaviors of the plant. The main advantage of VSF is that it enables a detailed modelling of the field's thermal condition effect on the flow distribution among the parallel loops. If combined with control algorithms, the model can be used to develop comprehensive control strategies and allow the controller to be proactive other than reactive to the changes, when considering the weather forecasts and the transient situations acting on the process.

The features of the tool are described on Section 2. Separate components of the VSF have been validated against experimental and other computational models. The goal of the thesis was to validate the model against real plant data and to use VSF for an application test case by coupling it with a controller and, consequently, improve the outcome of solar thermal power plants.

The first phase of the project consisted in the validation of the simulation tool by the comparison with real data from the solar thermal power plant Andasol 3, situated in Spain. For that, the preparation of the data was realized and a validation method was developed, with further analysis of the results.

The second phase of the project was based on the development of a broader use for the tool as an improvement for control. This was achieved by the application of a Fuzzy Logic Controller, which considered the mass flow in the loops and the focusing mode of the collectors, aiming to decrease defocusing instances while maintaining optimal temperature set-points. As a result, a process' improvement can be reached and an increased energy yield is achieved, together with the optimization of the power plant processes.

2 Virtual Solar Field Validation

2.1 Solar Thermal Power Plant Data

The solar thermal power plant Andasol 3 was the one considered for the validation of Virtual Solar Field (VSF). It is situated in the South of Spain and has an installed capacity of about 50 MW. Together with the neighbouring projects Andasol 1 and Andasol 2, which are almost identical in their construction, the site have a collector surface area of over 1.5 million square metres, making it the largest solar energy site in Europe. Figure 5 outlines the facility, which includes more than 210 thousand parabolic mirrors to capture the sunlight. It consists of a 4 subfield structure with 38 parallel loops per subfield, each one with 4 collectors, representing a total area of 497 thousand square metres. Apart from a conventional power station, Andasol 3 also has a thermal storage system, comprising of 30 thousand tonnes of a special salt mixture, which enables the plant to run the turbine for 8 hours at full load, therefore allowing electricity generation even after the sun has set[14].

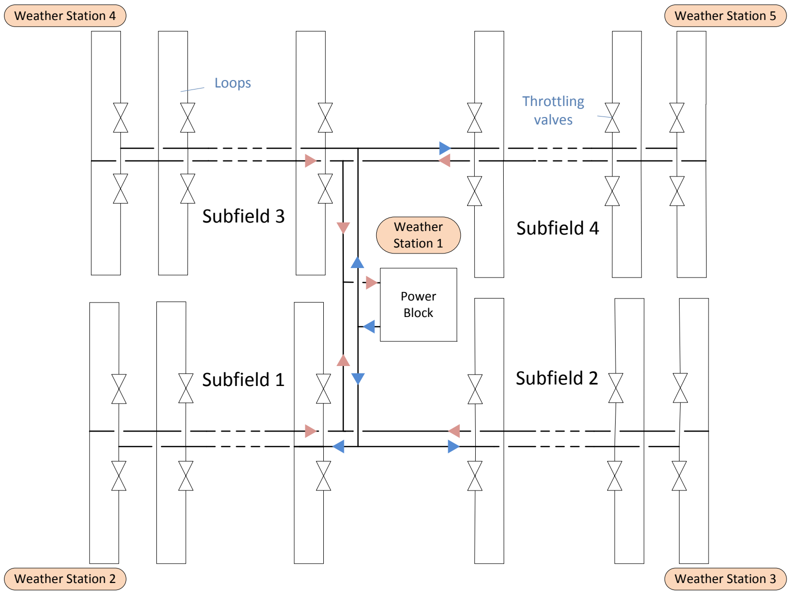


Figure 5: Schematic of Andasol 3 solar thermal power plant. The blue arrows indicate the low temperature oil going in the loops and coming out as hot temperature oil (red arrows). In the centre of the plant is situated the power block, briefly represented in this sketch. The power block includes the energy storage tank, the pump that controls the HTF flow through the solar field and the turbines for electricity generation. There are four reference points of DNI measurement situated in each corner of the field and one in the power block.

The first step for the validation of VSF was to prepare the raw data obtained from Andasol 3, composed of information of the thermal and hydraulic parameters of the field, and also the collector focus mode and weather data for several days. Data treatment was required in order to achieve the needed arrays to compare with the results obtained with VSF, making it possible to then perform the validation analysis. Data was processed for seven different dates, but the functions and procedure were developed in a way that it can be automatically repeated for as many dates as needed.

Initially, data was imported into a format in which it could be dealt in MATLAB®, which was the software used to perform the validation. The extraction was performed from Microsoft Excel tables and Microsoft Access data base files. The input variables were defined as: date, time step, maximum number of seconds of performed simulation, number of subfields, number of collectors, number of loops per subfield, number of collectors per loop, longitude and latitude of solar field location, length of pipe in one loop and diameter of loop's pipe.

The data was not provided in a regular time series, so it was linearly interpolated to obtain consistent values for every second of the day, enabling the time step input to be flexible for any value. Not only considering temporal constraints, also spatial interpolation of the DNI was performed linearly, such as the following equation, where y is the data to be obtained and t is the time or distance, depending on the specific case:

$$y = y_1 + \left[\frac{t - t_1}{t_2 - t_1}(y_2 - y_1)\right] \tag{2}$$

Each one of the outputs was obtained with a different methodology, as some required interpolation or extra treatment, as the following description:

Collector Angle It is the position of the collector in degrees, varying from -90° to 90°, with 0° facing up.

Focus Mode Considers the Focus Mode for each collector and assigns it a focused or defocused mode (1 or 0, respectively). The Focus Mode are established values of the control of the plant, which represents tracking modes, such as "on search", "track" or "follow".

Focus Signal From 0 to 1, varying from completely defocused to focused, respectively. Figure 6 shows the function used as basis for the Focus Signal calculation. It considers the acceptance angle curve for each collector, comparing the difference in position of the collector angle (Φ) with the collector tracking angle (p), which is the exact position that it should be to follow the sun. The tracking angle considers the collector azimuth angle (Z_s), the solar azimuth angle (z) and the solar altitude angle (α), such as shown in the following equation. These solar angles are calculated taking into account the solar time and its daily variation along the different periods of the year.

$$\tan(p) = \frac{\tan(\alpha)}{\cos(z - Z_s)} \tag{3}$$

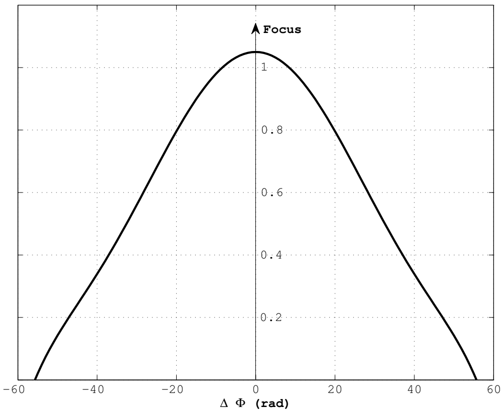


Figure 6: Focus Signal value determination according to the difference in position ($\Delta\Phi$) of the actual collector angle with the calculated collector tracking angle.

As seen in Figure 7, the Focus Mode loses many detailed information regarding the exact focusing status of the collector, e.g. after 8:30am, there is a significant defocusing of the collector, which is not shown in the Focus Mode data. Therefore, the processing of Focus Signal is of great value for the collector's behaviour analysis.

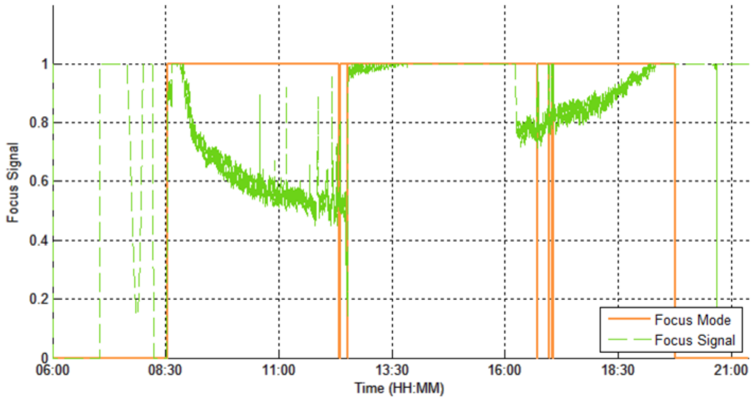


Figure 7: Focus Mode and Focus Signal of specific collector on specific date.

Pressure Difference in Power Block The difference of pressure across the inlet and outlet of the solar field.

Flow Rate Volume flow of the HTF into each subfield.

Inlet Field Temperature Inlet temperature of the whole solar field in each time step (TInField). This data was not provided by the solar plant, therefore it was estimated according to highest inlet temperature value of the four subfields ($\text{TInSubfield}_{\text{max}}$). Its calculation considers a time shift according to the velocity of the flow v, which changes for every time step t, and the length of the pipe L_p, as shown in the following equations:

$$\text{TInField}(t) = \text{TInSubfield}_{\text{max}}(t + t_{\text{shift}}) \tag{4}$$

$$t_{\text{shift}} = \frac{L_p}{v} \tag{5}$$

Outlet Field Temperature Outlet temperature of the whole solar field at each time step.

Inlet and Outlet Subfield Temperature Inlet and outlet temperature of each subfield at each time step.

Temperature in First Collector of each loop Temperature of the first collector of each loop at each time step.

Loop's Inlet, Middle and Outlet Temperature Inlet, middle and outlet temperature of each loop at each time step. The loop's middle temperature is the one from the middle of the third collector of each loop.

Direct Normal Irradiation (DNI) of Reference Measurement Points DNI value of the five reference points (DNI_i), located in the four corners of the solar field and the power block, as shown in Figure 5.

Direct Normal Irradiation (DNI) Reaching each Collector DNI value spatially interpolated from the three closest reference stations to each collector. The calculation was made through the inverse distance weighted and then corrected according to the cosine of the sun elevation angle ($\cos(\phi)$) and the incident angle modifier (IAM), according to the following equation, where d is the distance from the collector to the measurement point i:

$$\text{DNIcollector} = \left[\frac{\sum_{n=1}^{3} \left(\frac{1}{d_i} DNI_i \right)}{\sum_{n=1}^{3} \frac{1}{d_i}} \right] * \text{IAM} * \cos(\phi) \qquad (6)$$

An example of the estimation in comparison with the reference values can be seen in Figure 8.

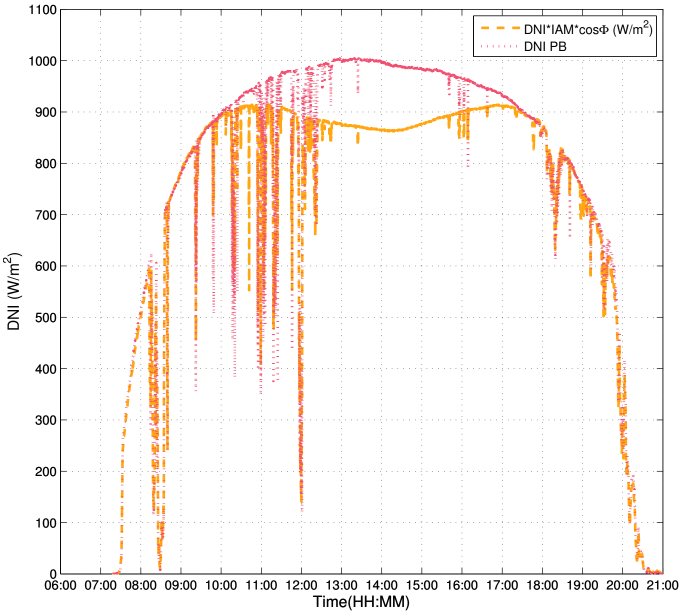


Figure 8: DNI reference value of Power Block measurement point and DNI estimated value for a individual loop on specific date.

Time Array Time of the measurements.

It is important to highlight that each output was acquired through a different function, but a general process was developed so that all of them are obtained in a single-run method. All the functions were elaborated to be as efficient as possible, in order to improve computational time. The arrays generated for the validation used a time step input of two seconds, and considered data from 6:00am until 9:22pm. Information from this period could be treated in one and a half hours, which means 9.76% of the real time interval.

2.2 Validation Methodology: post-processing tool development

After the data treatment, it was possible to perform the validation of VSF, through a comparison of the results from the model with the outputs of Andasol 3 data preparation. In order to analyze the outcomes, a data plotting tool was developed with a Graphical User Interface in MATLAB®. Figure 9 shows how the interface of the validation tool looks like. It enables the comparison of all the data treated and the simulations performed, for any required date and all the loops in the solar field.

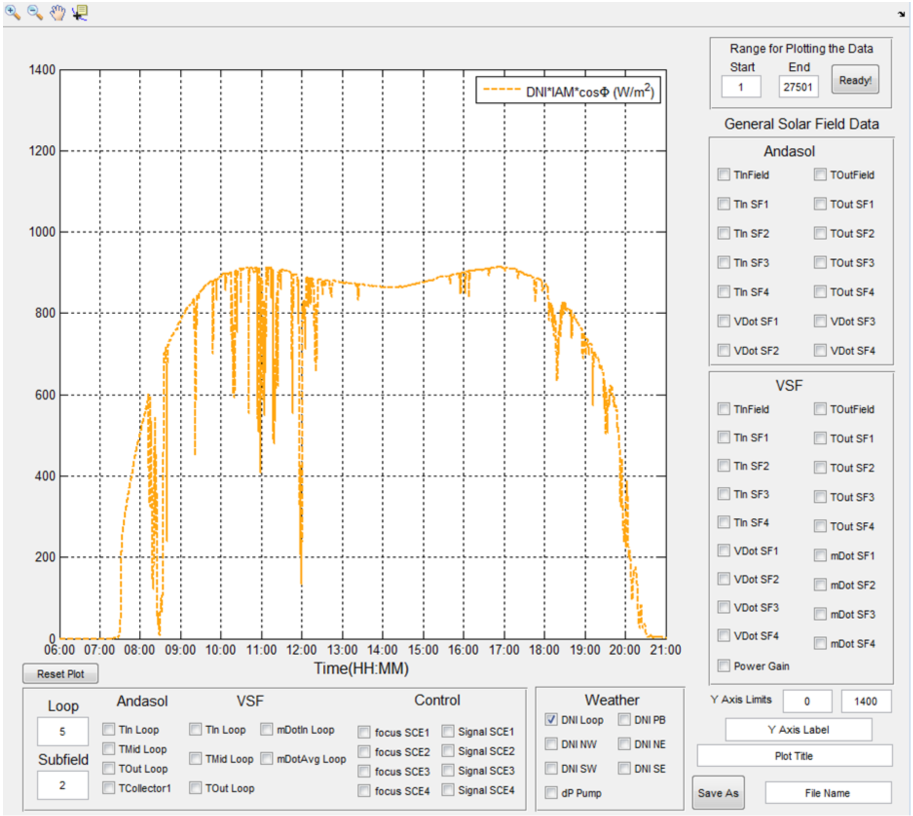

Range for Plotting the Data: Start 1, End 27501
Loop 5
Subfield 2
☑ DNI Loop
Y Axis Limits 0 1400

Figure 9: Interface of the Interactive Validation Tool, with the plot of the DNI value interpolated for Loop 5 of Subfield 2.

The advantages of this tool is that all the data obtained can be analyzed interactively, allowing a more rapid and simple evaluation of the differences and similarities of the outcomes from the real plant and VSF. With the tool, it is possible to compare all parameters from Andasol 3 and VSF results, from any date in which the data was produced. Moreover, it enables the selection of a time range in seconds in which the data will be plotted, so that only the hours of interested will be analyzed. General solar field data can be compared with plots from Andasol 3 and VSF simultaneously displayed. This tool also allows the selection of a specific loop from each subfield, for which plots from Andasol 3 data, VSF data and also control and weather data are presented. In order to export the plots performed, the validation tool permits to save them as high quality figures.

2.3 Virtual Solar Field Validation Analysis

The behaviour of VSF simulated parameters was compared with real Andasol data for several dates. Detailed analysis was performed with the data plotting tool, which allowed to investigate the exact aspects of the model that were accurate to reality, but also the ones that should be adapted in order to better fit the real conditions. The data plotting tool proved to be an efficient method for the validation of VSF, as it permitted a rapid investigation of parameters comparison. Apart from that, the analysis also showed that VSF is a well-developed tool that simulates accordingly a real solar field and helped the developers to more efficiently find and fix errors and bugs in the computations.

All the outputs of VSF were analyzed. Parameters that showed different behaviour than expected were taken into deeper consideration regarding its physical aspects of operation, as well as computational bugs in the code of the model. As an example, Figure 10 shows the inlet and outlet temperature of the whole solar field for a specific date, both real and simulated data, in an initial stage of the validation process. A very good coupling between the model and the plant data on the inlet temperature can be noticed. Although, the outlet temperature required more detailed studies, as it showed a slight difference during the shut down. After debugging the code and having a closer look in the thermal and hydraulic coupling of the model, VSF could be improved to better represent the reality.

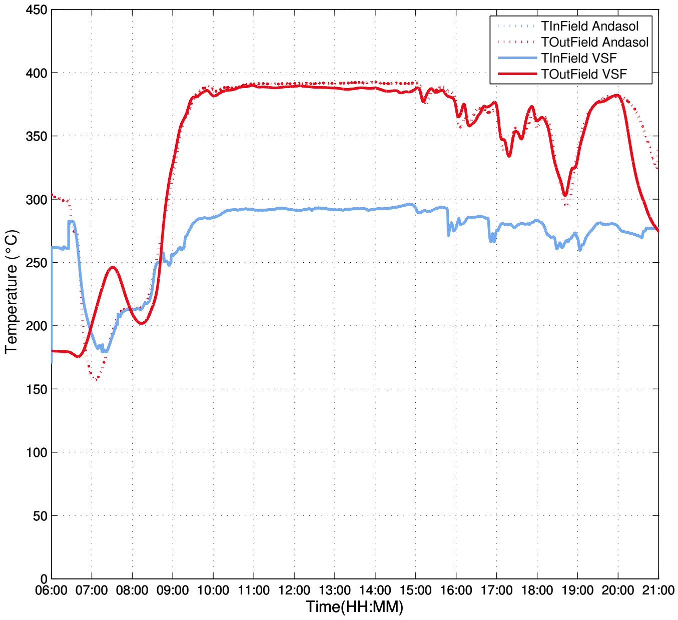


Figure 10: Field's Inlet and Outlet Temperatures obtained from Andasol 3 database and VSF simulation, on specific date.

Through the analysis of specific loops in different dates, some unusual behavior in the hydraulic and thermal aspects of the process were noticed, which were considered for further studies and for a better understanding of the general performance of the solar thermal power plant. Therefore, a sensible investigation of temperature and mass flow data was performed, relying on DNI data and specific collector parameters in the interest of obtaining the most reliable model for VSF. Moreover, the focusing control was analyzed in detail, in which some specific aspects were observed as a potential for additional improvements in VSF, such as instability in focusing mode at the end of the day.

The data preparation and validation phases were successfully performed, indicating the path for the next steps developed in the project. After these achievements, it was possible to consider VSF as a tool to enhance the power plant's operation, by taking into consideration the transient processes involved.

3 Control Strategy Application

As the second part of the project, it was thought that the VSF could be used as a tool to enhance the control of solar thermal power plants. As this model simulates the mass flow and thermal condition of the individual loops of the field, the idea of a controller that would combine these aspects came into place. In order to consider the transient situations, the DNI and period of operation were thought as important parameters to be taken into account. Therefore, a new control strategy based on Fuzzy Logic was developed, as further explained in the next sections.

3.1 Challenges and Perspectives of Control Strategies

The control of a solar thermal power plant is of high importance as its primary energy source, the solar radiation, cannot be manipulated. Besides, the solar radiation intensity depends on daily and seasonal cycle variations and temporary disturbances, such as passing clouds, atmospheric humidity and air transparency[7]. According to Camacho et al. [3], the purpose of this control is not to maintain a constant supply of produced energy, as it is not a cost effective strategy, but rather to regulate the outlet temperature of the collector field by suitably adjusting the oil flow rate. A good control strategy should aim to maintain the outlet fluid temperature of the loop at a desired level in spite of disturbances such as changes in the solar irradiance level, mirror reflectivity or inlet fluid temperature. This desired outlet temperature should correspond to the design point of the turbine and Rankine cycle. A strategy carried on with this goal shows the following benefits:

- It furnishes any available thermal energy in a usable form, improving the overall system efficiency and reducing the demands placed on auxiliary equipment, such as the storage tank;
- The solar field is maintained ready for the resumption of full scale operation when the intensity of sunlight rises once again, avoiding unnecessary shutdowns and start-up procedures, which are neither energetic nor time effective;

- An efficient, fast and well damped control allows the plant to be operated close to design limits, improving the productivity.

The methods available for achieving this is via the adjustment of the fluid flow, through the control of valve opening of the loops, and focusing mode of the collectors. Although, for better performance, it is recommended to use defocusing just as an alternative, which means that the hydraulic control should be preferred than the collector tracking. This fact combined with the daily solar power cycle characteristics leads to an operation in which the fluid flow has to change substantially, causing significant variations in the dynamic characteristics of the field. Therefore, the control of solar thermal power plants present important challenges, especially due to the nonlinear and complex characteristics of the system. This leads to the requirement of modelling simplifications and control adaptations, apart from the need to take into account the dynamics and environmental conditions changes, such as the solar radiation as a disturbance of the process and the time varying input/output transport delay due to the fluid flow rate.

Nevertheless, improvements in performance of solar thermal systems gained through the use of advanced control techniques would help to present this technology as a viable alternative to conventional energy sources, or even place them as a top choice among the renewable energy options. Moreover, a solar collector is essentially a very large heat exchanger and as these types of systems are common in process industry, any gained experience with the control of solar collector fields can be also used for other industrial processes[3].

3.2 Introduction to Fuzzy Logic Control

Conventional control algorithms based on a simplified model of the process proves to have significant drawbacks as a strategy for solar thermal systems, especially due to the nonlinear and dynamics characteristics of these type of power plants[7].

The methodology of Fuzzy Logic Control (FLC) is considered to be very adequate in cases where the process is difficult to control and there is wide experience in the operation, as it allows the incorporation of such knowledge in terms of qualitative rules. Nonlinearities are introduced to the system by membership definitions that correspond to membership functions used in FLC [4]. In addition, FLC seems to be appropriate when working with a certain level of imprecision and uncertainty, apart from dealing well with cases where the process knowledge can be translated into a control strategy that improves the results reached by other classical strategies[7].

A FLC is based on a set of fuzzy rules that interconnects relationships between measurable variables and control variables. There are three main parts that constitute the FLC strategy, as shown in Figure 11: the block fuzzifier, the control block (fuzzy rule base and inference procedure) and the block defuzzifier.

The fuzzification phase converts the numerical values of the input variables into linguistic variables, forming the fuzzy sets. The rule-based fuzzy control algorithm provides definitions of linguistic control rules which characterize the control strategy, taking into consideration the decision making logic, fuzzy control actions and the inference rules. The defuzzification block converts the

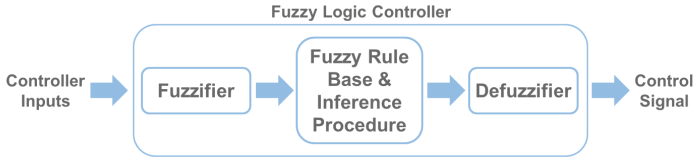


Figure 11: Fuzzy Inference System.

inferred control action, by interpolating between rules that are applied simultaneously, to a classical control signal[4].

Fuzzy applications were already performed in solar thermal systems. Alata et al. [2] demonstrated the design and simulation of a controlled sun tracking system. One axis sun tracking with the tilted aperture equal to the latitude angle was considered. Camacho et al. [3] used the error between the output of the plant and the set-point signal of fluid outlet temperature and its increment as inputs for a FLC. The output variable of the FLC was applied as the increment in the control signal of a feed-forward controller. Rubio et al. [12] analyzed with more detail the application of fuzzy logic in an incremental form, considering the signal obtained from FLC as an increment needed in the control signal to provide a desired behavior. In this approach, a series feed-forward controller was calculated from steady-state relationships, aiming to stabilize the outlet fluid temperature by adjusting the flow input. In both last cases the single control signal used was the fluid flow.

3.3 Methodology of Fuzzy Logic Control Application

As noticed during data analysis and validation previously performed, the controllers decision either to vary the fluid flow or the collectors focusing, for a certain aimed outlet temperature, is a determining aspect for the plant's efficiency and optimal operation. Apart from that, the focus signal of the collectors appeared to respond with significant instabilities in some cases. This is not recommended for good performance and maintenance of the plant.

In this context, the Fuzzy Logic Control (FLC) was considered to be a proper strategy to be applied in combination with VSF simulation tool to enhance the control of a solar thermal power plant. This implementation represents an application for VSF, considering dynamic valve control and collector focusing mode. The main advantage brought from fuzzy sets to this case is that the knowledge in the technology and in the expected behavior in transient situations can be fully applied in the control strategy.

Figure 12 shows the inputs and outputs of the proposed control strategy. This presents itself as an innovative approach as it combines both flow and collector's position control in a single control strategy.

This approach was developed with the following main goals:

- To simultaneously control fluid flow, through valve opening/closing, and focusing status;
- To integrate in the control of one specific collector, the focus signal of the other collectors in the same loop;

- To enable gradual changes in the reaction of controller parameters;
- To obtain more stability in collectors focusing in transient conditions.

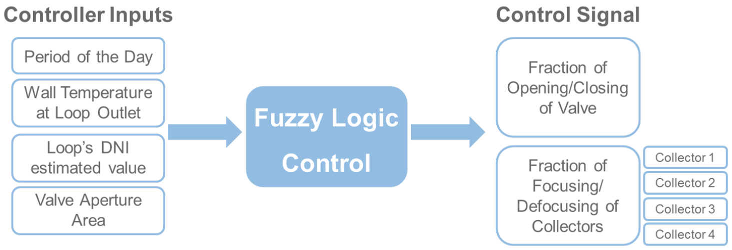


Figure 12: Inputs and Outputs of the proposed Fuzzy Control Strategy.

The FLC strategy was developed to be applied in every single loop of the solar field. Figure 13 shows a schematic where the controlled valve is situated. The proposed control strategy considers that the valve placed in the inlet of each loop can be dynamically controlled in every time step.

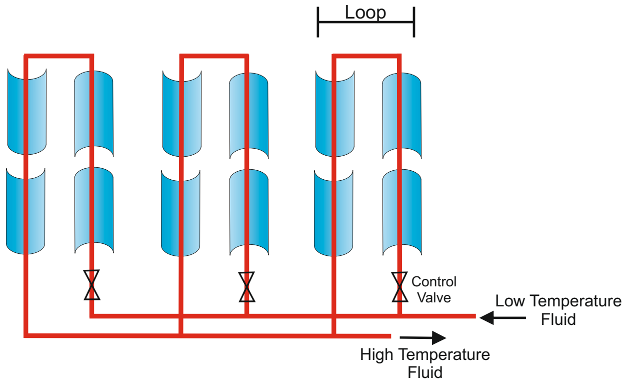


Figure 13: Schematic of the valve's position in loops in parallel.

Although the overall mass flow control also relies on the pump pressure difference in the power block, the application performed in this study considered it as the real values of Andasol 3. Therefore, the pump is not controlled but it is taken into account, as the simulations react to pressure changes, such as dumping i.e. abrupt drops in its value.

The methodology for the development of this control considered the three main steps of the Fuzzy Logic scheme previously presented in Figure 11: fuzzification, inference procedure and defuzzification. Both knowledge in the solar thermal power plant operation and data were used together in developing this proposed strategy.

The Mamdani Linguistic fuzzy model was used, combining the non-linear behaviour of the system in the rules development and design of membership functions, both based on domain expertise. The application of the control and its simulation was performed with the Fuzzy Logic Toolbox in MATLAB®. In the following sections, the elaboration of the proposed control strategy is explained in detail.

3.3.1 Fuzzification: creating the Membership Functions

A fuzzy set is characterized by a membership function, which gives to a variable a degree of belonging (from 0 to 1) to a set of a linguistic expression. One single variable can belong with different degrees to more than one set. The determination of the membership functions' limits and linguistic expressions is essential to incorporate the knowledge base approach in the strategy and to build a robust control. By definition, the shape of the membership function is chosen arbitrarily by following the advice of an expert in the theme or by statistical studies.

In this case, the membership functions were designed as triangular or trapezoidal, as according to the fuzzy theory, those shapes provide faster computational time when applied in control. The characterization of the fuzzy sets aims not to exhaustively define the linguistic variables, but to identify main fuzzy subsets that will be used later in definition of the rule base[5]. Each of the categories were established combining the expertise in optimal systems operation and the studies of the data provided by Andasol 3.

The first input of the controller is the period of the day, which is divided into three membership functions: start-up, normal operation and shutdown, as shown in Figure 14. This categorization is essential to consider the impact of transient situations on the operation of the plant.

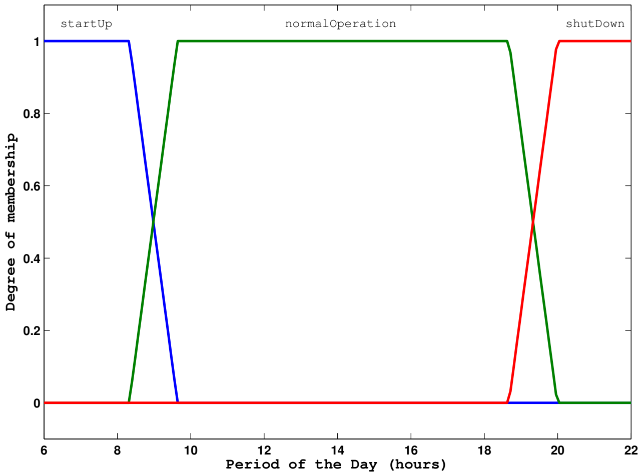


Figure 14: Membership functions of input period of the day of specific date.

Due to the variation of the Earth's position in relation to the sun, the length of the day differ and, thus, the start-up and shutdown times. This FLC approach takes this into account, therefore adapting the limits for the membership functions according to the the sun's azimuth and altitude angles for each day. This means that the start-up and shutdown of the plant will always respect the position of the sun, while the time when those periods will happen differ according to the day of the year. The angle used as base to calculate the limits for the membership functions was the collector tracking angle. Considering that the tracking angle varies from -90° to 90°, with 0° facing up, the operation is considered to be fully in start-up until this angle is 75°. Normal operation fully starts when the tracking angle is 60°. Accordingly, for shutdown, the limits considered were -75° and -60°. These values were determined by the study of Andasol 3 data and the behaviour of collectors regarding operation.

The membership functions of the input wall temperature at the loop outlet were developed considering the value 393°C to be the optimal loop fluid outlet temperature during operation and 400°C as the exceeding limit. Five membership functions were created (low, medium, high, very high and limit exceeded), as shown in Figure 15.

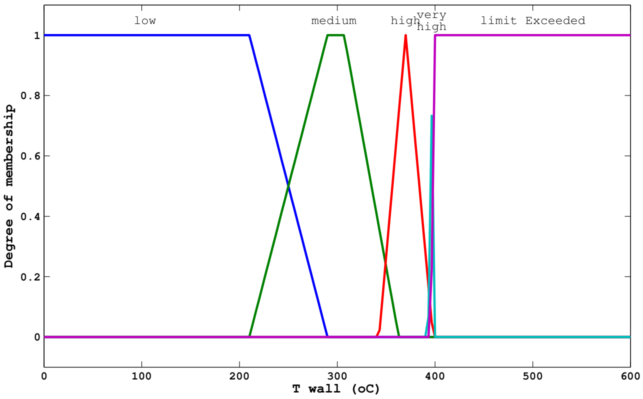


Figure 15: Membership functions of input wall temperature at the loop outlet.

As previously mentioned, a good control strategy of a power plant is based on aiming a constant HTF outlet temperature. The temperature of the pipe wall is considered as an input, instead of the fluid outlet temperature as a predictive measure: if the controller reacts to the wall temperature, due to the time that the heat takes to be transferred to the fluid, the controller's decision is taken in advance of the actual fluid heating, avoiding overheating and behaving as a proactive control.

For the input of loop's DNI estimated value, four membership functions were created (low, medium, high and very high), as shown in Figure 16. In order to improve the pro-activeness of this control, the DNI reaching the specific loop is an essential information for the controller's decision. The input loop's DNI estimated value is the one obtained in the previous phase of this project during the data preparation. By interpolation, it was possible to estimate the DNI value reaching each loop for the days analyzed. The behavior of the DNI in each of the three periods of the day is known: increase during start up, relative stability during normal operation and decrease during shut down. Any variation in that behavior means that there is an unexpected event, such as a passing cloud. Because of this expertise, the rule base of the control strategy was further developed in order to perform proactively to these changes.

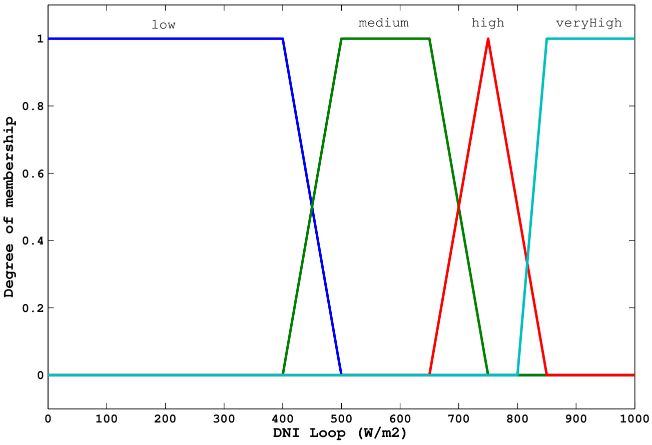


Figure 16: Membership functions of input estimated DNI value for the loop.

To include the mass flow control, it is important to consider the current valve aperture area for each selected time step. This input has five membership functions (almost closed, little opened, middle opened, almost opened and opened), in accordance with Figure 17. The aperture limits were established as the valve could be fully opened, but not allowing complete closing. The nominal valve aperture area was calculated taking into account the nominal mass flow of the plant during operation. In the case of the examined loop in Andasol 3, it is considered a valve aperture diameter of around 4.37 cm for a nominal flow of 6.5 kg/s.

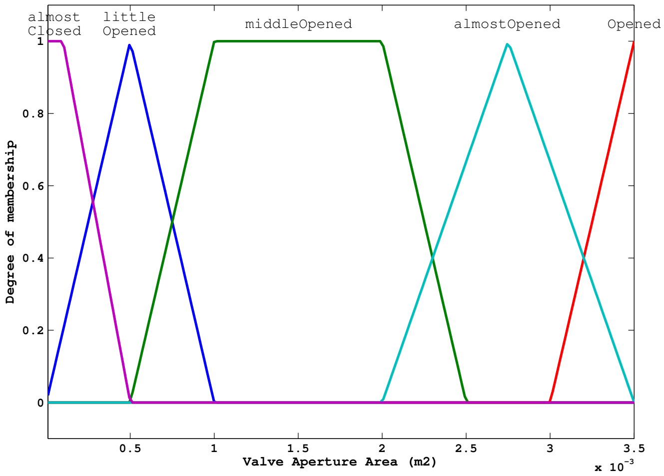


Figure 17: Membership functions of input current valve aperture area.

3.3.2 Rule Base and Inference Procedure

In order to easily manipulate fuzzy sets, the operators of the classical set theory are redefined to the specific membership functions for values between 0 and 1 [5]. The operators on fuzzy sets are established by manners of complement (NOT), intersection (AND) and union (OR). In consideration of that, fuzzy rules are developed, that express with linguistic variables the relations between inputs and outputs. A fuzzy rule has the following form, where A, B and C are fuzzy sets, x and y are input values and z is the output:

$$\text{If} \quad x \in / \notin A \quad \text{and/or} \quad y \in / \notin B \quad \text{then} \quad z \in / \notin C.$$

The FLC proposed is comprised of 71 rules, in which the intersection operator was used to relate all the inputs. Appendix A shows all the rules included in this control strategy. It is important to emphasize that the rules were developed prioritizing the fluid outlet temperature regulation through mass flow control, by valve opening or closing, rather than collector defocusing. This means that the collectors focus control is secondary, and only applied when it is considered that the valve is already opened, for overheating situations for example.

The designed rules do not cover all the possible combinations of inputs' evaluation, but they were developed in an effective way in order to contemplate all the possible scenarios of the system. This reduction in the number of rules is intrinsic in the the knowledge base approach of fuzzy logic in control. Before the final rules set establishment, many others were developed and applied in simulations: some with a significant additional amount of rules, taking into account more inputs' combinations, which didn't show improved results, as it will be outlined in the next section. Hence, the final rule set of 71 rules is chosen for this investigation to be the most effective one for a good control of a single loop.

Following the knowledge base approach, the rules were developed mainly based on the three different periods of the day: start-up, normal operation and shutdown. For start-up, as it is known that the DNI is increasing and there is the need to heat up the HTF, all the collectors are expected to be completely focused. Due to the characteristics of this period of the day, there is no risk of overheating due to focusing, and this risk is completely controlled by the valve's reaction.

During normal operation, the collectors are defocused only in situations when the wall temperature is exceeding the temperature limit. Due to the time buffer of heat exchange between the wall and the fluid, this strategy is enough to ensure that the system will act properly and no fluid overheating will occur.

The shutdown is a more sensible period of the day, as although the DNI is decreasing, some overheating can be expected. This can happen due to the reduction of the flow by the main pump in the solar field, preparing the operation to be finished. Consequently, the fuzzy rules are set up to establish some defocusing factors if the wall temperature is very high or exceeds the limit.

All the rules implement the focusing control respecting a collector-wise defocusing: the forth and last collector of the loop is the first one to be defocused, followed by the third one, then the second one and by last, defocusing the first collector of the loop. According to Wittmann et al. [16], collector-wise defocusing is more interesting in comparison with a loop-wise defocusing strategy in order to mitigate the temperature drop. Also, the same authors stated that when adding additional control valves the deviations to the temperature reference can be decreased or even eliminated, e.g. with the installation of a control valve at the beginning of each loop, which is the idea behind the proposed control strategy in this project.

3.3.3 Defuzzification: obtaining the Control Signals

The last step of the FLC is the defuzzification, which gives the output signals of the system. There are five control signals given by the FLC: a fraction of opening/closing the valve and a fraction of focusing/defocusing for each of the four collectors of a single loop. Figures 18 and 19 expose the functions to defuzzify the values into classical controls signals.

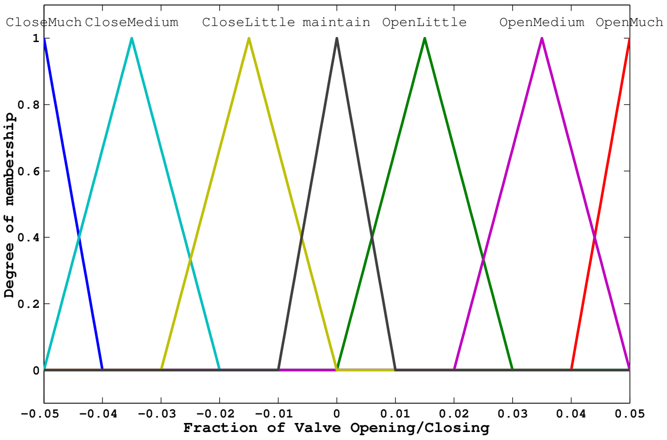


Figure 18: Output functions of control signal: fraction of valve opening/closing.

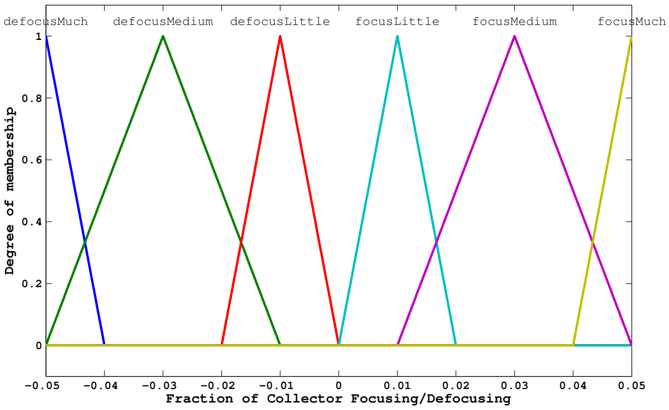


Figure 19: Output functions of control signal: fraction of collector focusing/defocusing.

For both types of control signals, the limit of 5% variation was considered to be the maximum, i.e. the maximum opening of the valve in each time step is 5% of its previous value, as well as the maximum focusing fraction of the collector. Thus, the speed of the actuators could be considered. The great advantage of having both types of signals included in the same control strategy is that it was possible to prioritize the mass flow control rather then focusing control. The decrease of defocusing instances reduces the wasted solar irradiation.

Among the several existing deffuzification methods, the one chosen for this application was the method of the mean of maximum. It sets the output as the average of the maximum abscissas of the fuzzy set resulting from the aggregation of the implication results, which is the combination of the outputs of the rules called. The mean of maximum was chosen to enable the valve to be fully opened and the collectors completely focused.

The result of the application of the fuzzy rules is a combination between the rules themselves and the membership functions previously developed[5]. A single classical variable can belong to different sets and, therefore, call several rules. In the following, three different example cases are outlined: Expected Normal Operation Behavior, Transient Situation of a Passing Cloud and Transient Situation from Start-Up to Normal Operation. Each scenario has a different set of inputs, therefore reacting in a distinct way.

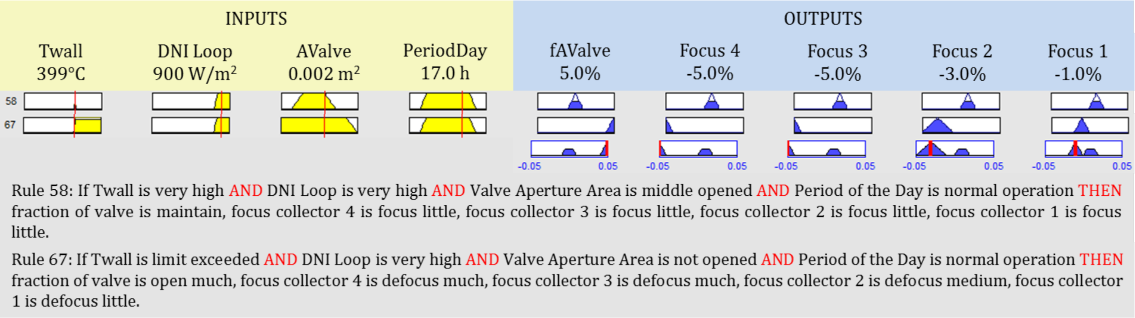
Expected Normal Operation Behavior

This situation considers inputs that simulates an overheating risk during normal operation. The wall temperature at loop outlet measured is 399°C and the current valve aperture area is 0.002 m^2. The estimated DNI for the loop is 900 W/m^2, at 17h. This scenario calls two rules, that establish a relation between a very high temperature and limit exceeding of the wall during normal operation. Figure 20 shows the rules called and the membership functions evaluated in MATLAB®.

This scenario represents a case with high DNI value and a critical temperature of the wall. The outputs are then combined according to the outcome of the rules and the defuzzification method selected[5]. The evaluation of rule 58 gives as output of fraction of valve opening a degree of membership of around 0.5 in the fuzzy set "maintain", and approximately the same membership value for the other four outputs in the fuzzy set "focus little". The evaluation of the other called rule results in a degree of membership of 1 for all the outputs, but in different fuzzy sets for each output parameter: "open much" for fraction of valve opening, "defocus much" for collectors 3 and 4, "defocus medium" for collector 2 and "defocus little" for collector 1.

Combining the values of membership in all sets and applying the mean of maximum defuzzification method, the control signal generated is that the valve should open much: 5% of its current aperture area, which is the maximum signal value that can be obtained. It can be noticed that even if one of the rules implicate in maintaining the valve aperture area, the combination of both results in a maximum signal for opening, as the knowledge base approach leads the controller to know that this is a risky situation.

Apart from that, the collectors are also signalized to be defocused: 5% of collectors 3 and 4, 3% of collector 2 and 1% of collector 1, respecting the collector-wise defocusing of the loop. This also shows that even though one of the rules states the collectors to focus a little, the strategy recognizes the hazard of overheating and applies the most suitable control signal for this situation.



Rule 58: If Twall is very high AND DNI Loop is very high AND Valve Aperture Area is middle opened AND Period of the Day is normal operation THEN fraction of valve is maintain, focus collector 4 is focus little, focus collector 3 is focus little, focus collector 2 is focus little, focus collector 1 is focus little.

Rule 67: If Twall is limit exceeded AND DNI Loop is very high AND Valve Aperture Area is not opened AND Period of the Day is normal operation THEN fraction of valve is open much, focus collector 4 is defocus much, focus collector 3 is defocus much, focus collector 2 is defocus medium, focus collector 1 is defocus little.

Figure 20: Rule evaluation and defuzzification at expected normal operation scenario.

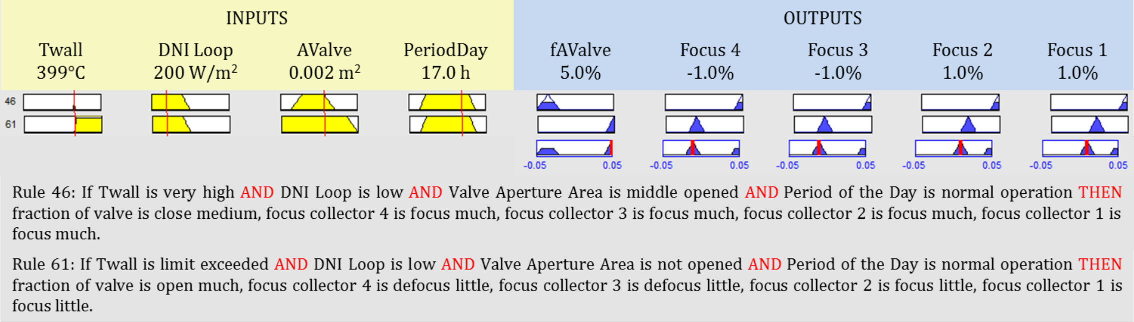
Transient Situation: Passing Cloud

This scenario simulates a passing cloud during normal operation, which is one of the transient situations that the FLC proposed tries to improve in operation. The inputs are similar to the previously studied scenario: the temperature of the wall at loop outlet is 399°C and the current valve aperture area is 0.002 m^2, at 17h. Although, the estimated DNI for the loop is 200 W/m^2, which is not expected for the time of the measurement, meaning that there is a cloud passing by. This scenario calls two rules, different ones from the previous situation, that establish a relation between a very high temperature and limit exceeding of the wall during normal operation, when the DNI is low. Figure 21 outlines the called rules and the evaluated membership functions in MATLAB®.

The outputs are obtained through the fuzzy inference of the rules, membership functions and deffuzification method selected[5]. The output fraction of valve opening has membership degrees in two different sets: around 0.5 in "close medium" and 1 in "open much". All collectors get as membership degree the same value from rule 46: approximately 0.5 in set "focus much". Although, the other rule give as fuzzy value 1 for collectors 3 and 4 in set "defocus little" and in set "focus little" for the other two collectors.

Even though this scenario represents a case of critical temperature of the wall, the combination of rules called and membership degrees shows the reaction of the controller according to a low DNI situation with temperature almost exceeding the limit of 400°C.

Therefore, the control signal generated is that the collector's shouldn't defocus much: there is no defocusing in collectors 1 and 2, while collectors 3 and 4 should defocus only 1%. This happens as it is known that the DNI shouldn't be that low, so then the controller knows that there is a passing cloud and that this will generate a thermal energy drop in the system. The focusing signal acts as a proactive strategy, respecting also the collector-wise defocusing for the loop. The risk of over heating is then tackled by the valve control signal: 5% of opening of its current aperture area, which is the maximum signal value that can be obtained.



INPUTS				OUTPUTS				
Twall	DNI Loop	AValve	PeriodDay	fAValve	Focus 4	Focus 3	Focus 2	Focus 1
399°C	200 W/m^2	0.002 m^2	17.0 h	5.0%	-1.0%	-1.0%	1.0%	1.0%

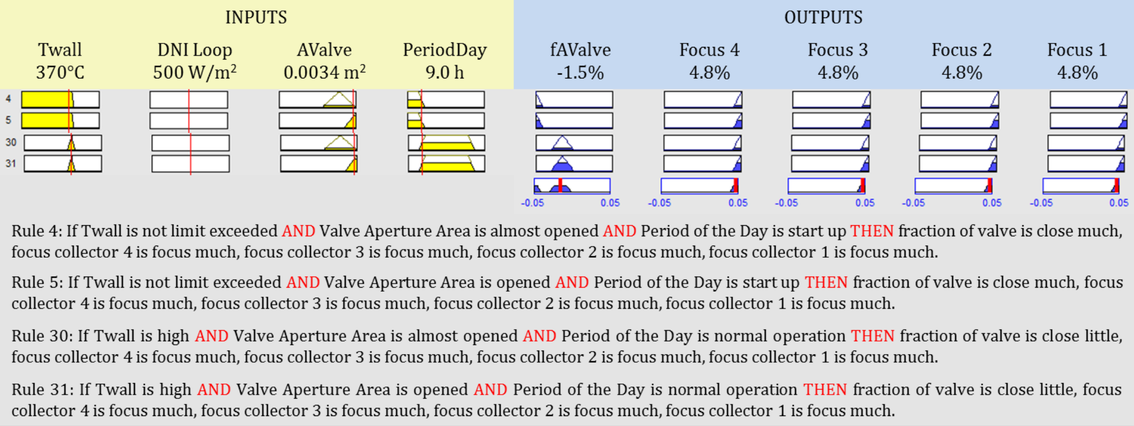
Rule 46: If Twall is very high AND DNI Loop is low AND Valve Aperture Area is middle opened AND Period of the Day is normal operation THEN fraction of valve is close medium, focus collector 4 is focus much, focus collector 3 is focus much, focus collector 2 is focus much, focus collector 1 is focus much.

Rule 61: If Twall is limit exceeded AND DNI Loop is low AND Valve Aperture Area is not opened AND Period of the Day is normal operation THEN fraction of valve is open much, focus collector 4 is defocus little, focus collector 3 is defocus little, focus collector 2 is focus little, focus collector 1 is focus little.

Figure 21: Rule evaluation and defuzzification for passing cloud transient situation.

Transient Situation: from Start-Up to Normal Operation

The last situation outlined here considers inputs that simulates the transition between start-up and normal operation. Figure 22 shows the rules called and the membership functions evaluated in MATLAB®. The HTF is still being heated up and the temperature of the wall at loop outlet measured is 370°C. The valve aperture area is almost fully opened, with a value of 0.0034 m^2. The estimated DNI for the loop is 500 W/m^2, at 9h. This scenario calls four rules, that establish a relation between a not limit exceeding temperature of the wall during normal operation and start-up. As the DNI behavior is known (it will be increasing as the sun is rising), the DNI input is not taken into account for any of the rules during start-up. Although, this situation is considered to belong in both periods of the day: start-up and normal operation, with different values of membership for each of them. As the valve is considerably opened and the temperature is not yet close to the optimal, the control signal for the valve is to close 1.5%, while all the collectors should be focusing 4.8%, which means that they can be completely focused in a short period of time.



INPUTS				OUTPUTS				
Twall	DNI Loop	AValve	PeriodDay	fAValve	Focus 4	Focus 3	Focus 2	Focus 1
370°C	500 W/m^2	0.0034 m^2	9.0 h	-1.5%	4.8%	4.8%	4.8%	4.8%

Rule 4: If Twall is not limit exceeded AND Valve Aperture Area is almost opened AND Period of the Day is start up THEN fraction of valve is close much, focus collector 4 is focus much, focus collector 3 is focus much, focus collector 2 is focus much, focus collector 1 is focus much.

Rule 5: If Twall is not limit exceeded AND Valve Aperture Area is opened AND Period of the Day is start up THEN fraction of valve is close much, focus collector 4 is focus much, focus collector 3 is focus much, focus collector 2 is focus much, focus collector 1 is focus much.

Rule 30: If Twall is high AND Valve Aperture Area is almost opened AND Period of the Day is normal operation THEN fraction of valve is close little, focus collector 4 is focus much, focus collector 3 is focus much, focus collector 2 is focus much, focus collector 1 is focus much.

Rule 31: If Twall is high AND Valve Aperture Area is opened AND Period of the Day is normal operation THEN fraction of valve is close little, focus collector 4 is focus much, focus collector 3 is focus much, focus collector 2 is focus much, focus collector 1 is focus much.

Figure 22: Rule evaluation and defuzzification in a start-up scenario.

3.4 Fuzzy Logic Control Results and Discussion

To test the application of the proposed control strategy, the Fuzzy Logic Control (FLC) was applied to a virtual loop simulated by Virtual Solar Field (VSF). Real weather data from several days of Andasol 3 was used as inputs to the controller and its outputs were used as inputs in VSF, in order to model the behavior of the loop. The time step used for the simulations was of two seconds and the maximum valve aperture area of 0.0035 m^2. The presented controller was then evaluated according to three main aspects: improvements in operation, energy gain and possibility of real implementation.

In order to evaluate the improvements in operation and energy gain obtained with the proposed control, several dates were simulated in detail with Andasol 3 and VSF data, from April and May of 2015. Here, it will be outlined three main date results: one sunny day, one cloudy day and one day that was sunny and cloudy.

Figures 23, 24 and 25 show the comparison of the outlet temperature of the HTF between Andasol 3 power plant data and simulated VSF data obtained with FLC.

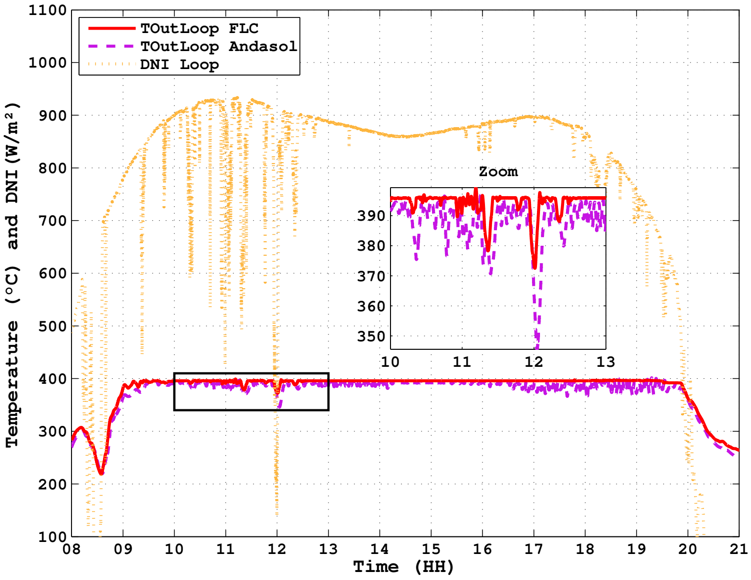


Figure 23: DNI and HTF outlet temperature profile of real and simulated data for specific loop in a sunny day.

The first main aspect that can be observed is the temperature stability obtained with the proposed control. While in the real case of Andasol 3 significant outlet temperatures oscillations can be noticed along the day, the simulation performed with VSF applying FLC presents itself as an effective control strategy in order to reach a stable value during operation.

Another important aspect regarding the outlet temperature, is the reaction to passing clouds. It is seen that with a classical control, when there is a drop in DNI, the outlet temperature also has a relevant reduction. With the proposed control application, this temperature drop is significantly reduced or almost

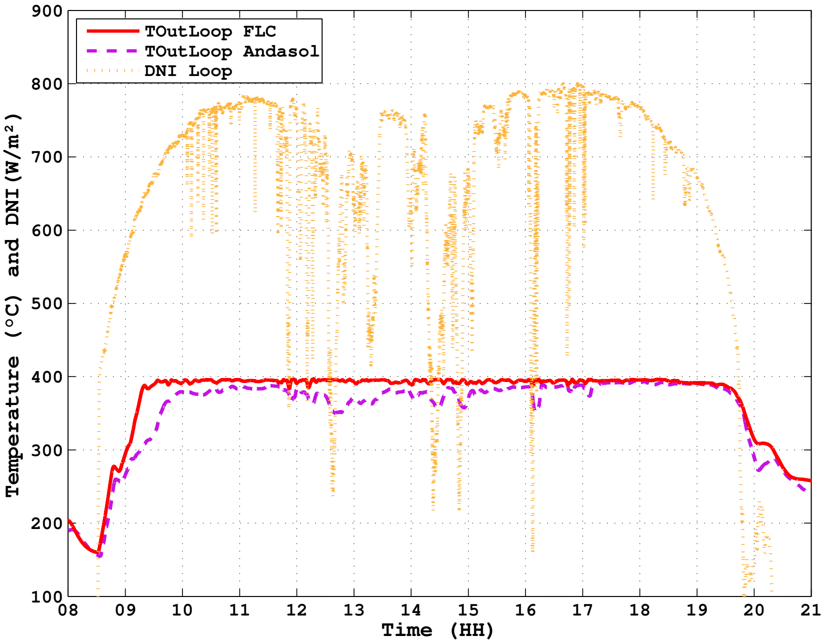


Figure 24: DNI and HTF outlet temperature profile of real and simulated data for specific loop in a cloudy day.

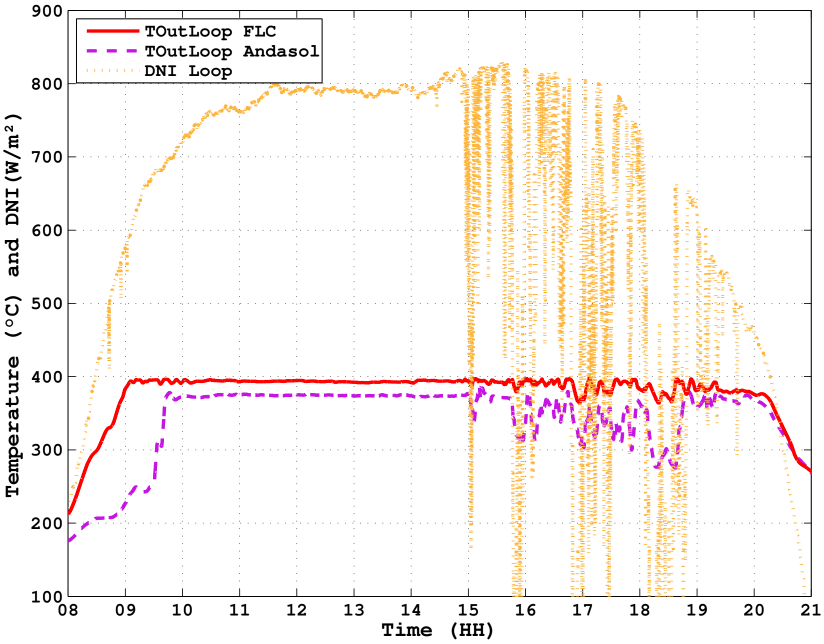


Figure 25: DNI and HTF outlet temperature profile of real and simulated data for specific loop in a sunny and cloudy day.

eliminated, in most of the cases, as shown in the zoomed box in Figure 23.

Apart from that, the energy loss is also diminished, specially on days that the DNI profile is not very high, such as seen in Figure 25. The outlet temperature obtained with the application of FLC is higher than with the classical control, without the risk of exceeding the maximum allowable temperature for the oil, 400°C.

Regarding the focus signal of the collectors, the proposed control proves to be very efficient in terms of not wasting the incident solar radiation. Figures 26, 27 and 28 show the comparison of the real and simulated focus signal of the four collectors in a specific loop, from Andasol 3 data and VSF simulation performed with FLC, for the three days analyzed.

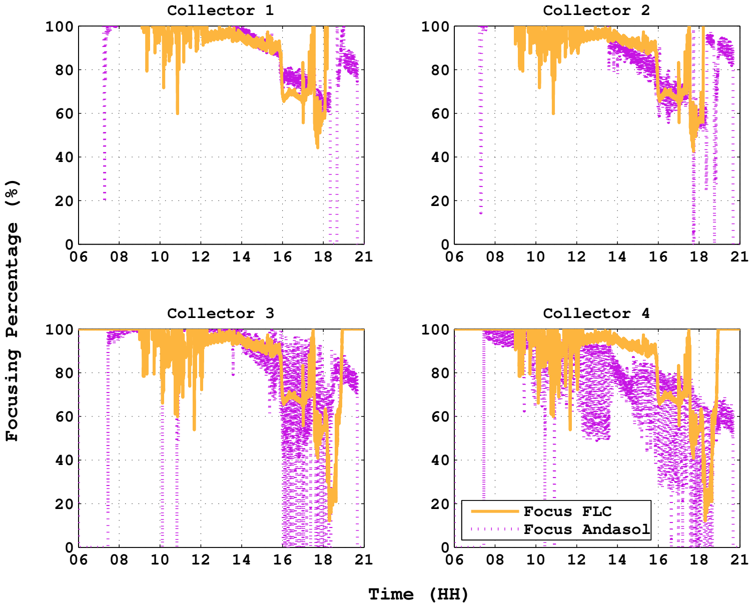


Figure 26: Real and simulated focus signal of the four collectors for specific loop in a sunny day.

It can be noticed that FLC results in less defocusing instances along the day, apart from a smoother change in focus, with less oscillations in comparison to real data. Also, due to the rules developed and the inference procedure applied, the collector-wise defocusing strategy is respected: the forth collector is the first one to be defocused when needed, followed by the third one, then the second one and for last the first collector, if necessary.

The results show that with the application of FLC, during the analyzed sunny day, the collectors are not completely focused 11.01% of the time, for this specific date and loop. For days with more DNI drops, the defocusing instances can be almost eliminated: 0.46% for this specific simulated loop in the cloudy day and 0.42% for the sunny and cloudy day. This behavior on the results was obtained for all simulations performed, with other dates and loops in the four subfields.

To analyze the energy performance of the control, the comparison of heat transfer rate $\dot{Q}_{\text{out}}$ in the real plant and FLC simulation was performed. Figures

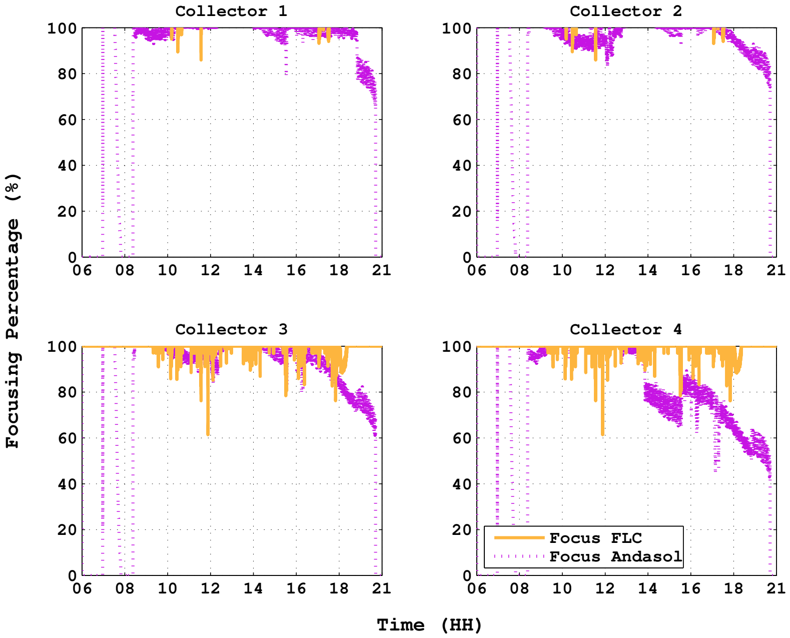


Figure 27: Real and simulated focus signal of the four collectors for specific loop in a cloudy day.

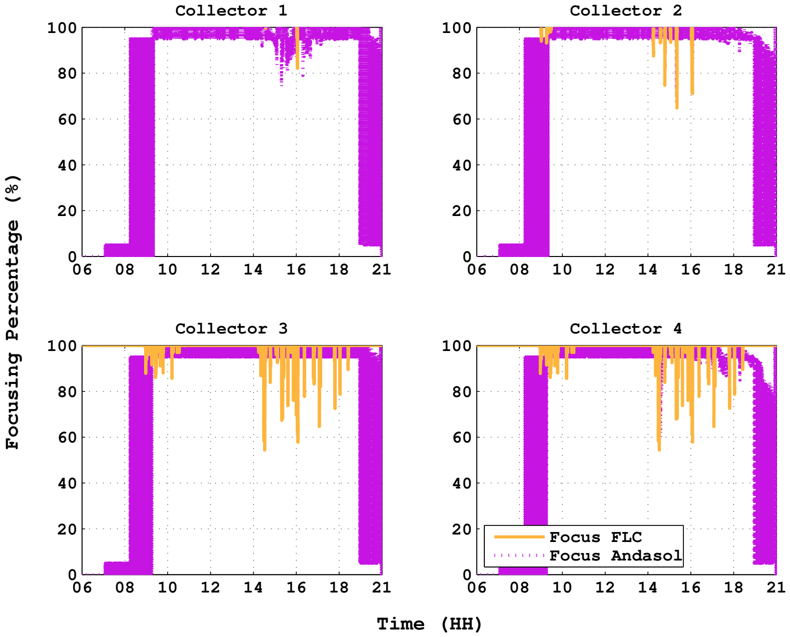


Figure 28: Real and simulated focus signal of the four collectors for specific loop in a sunny and cloudy day.

29, 30 and 31 show the obtained results for the simulated days. Apart from improvements in operation, the proposed control strategy proves to be more energy efficient. By integrating $\dot{Q}_{\text{out}}$ for the whole day, it is possible to know the total gained heat during the operation. The results of the three days analyzed here show that the proposed control is beneficial in all the situations.

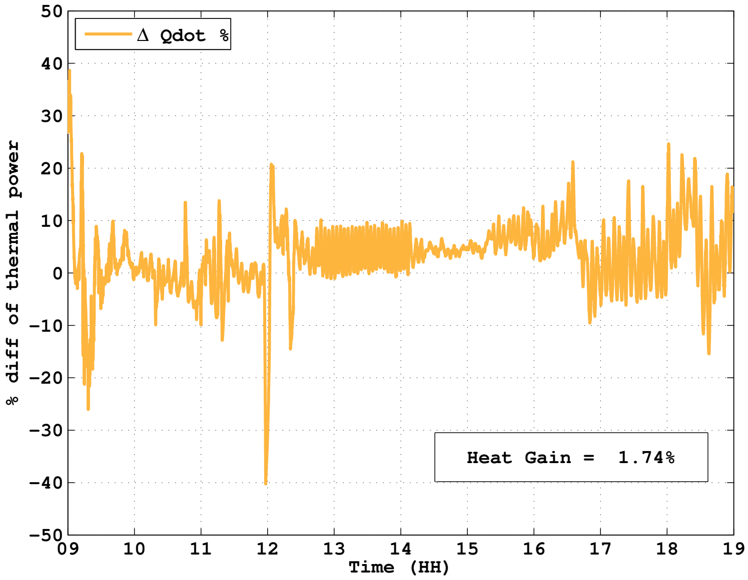


Figure 29: Real and simulated heat transfer rate of specific loop in a sunny day.

During the sunny day, the extra gained heat obtained was of 1.15 GJ, which means 1.74% of increase when compared to the real power plant operation for that date. Similar results were obtained for the cloudy day: 1.77% of increase in the extra gained heat, with an absolute value of 1.02 GJ. The main advantage is on days when there are many clouds and the DNI profile is not very high, such as the sunny and cloudy day outlined in this analysis. The extra gained heat obtained with FLC application is of 5.77 GJ in this case, which represents an increase of 10.54%.

It can be noticed that in this last case, great gain is obtained during start-up. Even though the proposed controller reacts better to this transient situation, it can happen that a slow start-up is forced, due to specific operation requirements. It is not known if this happened in this specific date in the real plant, therefore it is believed that such a high energy gain depends on the conditions needed for operation. Nevertheless, the implemented control strategy proves to be more effective even in this type of event, yet with possible lower energy gain than the one obtained in this simulation.

Due to the reduced thermal losses and consequent increase in HTF outlet temperature, the proposed control strategy reacted with similar improved behavior for the several days studied, especially for situations when the operation was not expected to be optimal in consequence of low DNI profiles.

Appendix B presents the graphs of simulated valve aperture area for the

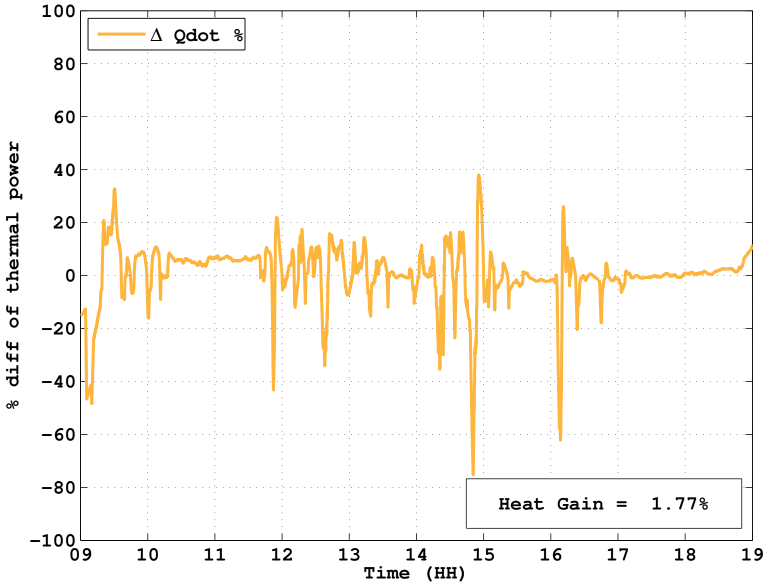


Figure 30: Real and simulated heat transfer rate of specific loop in a cloudy day.

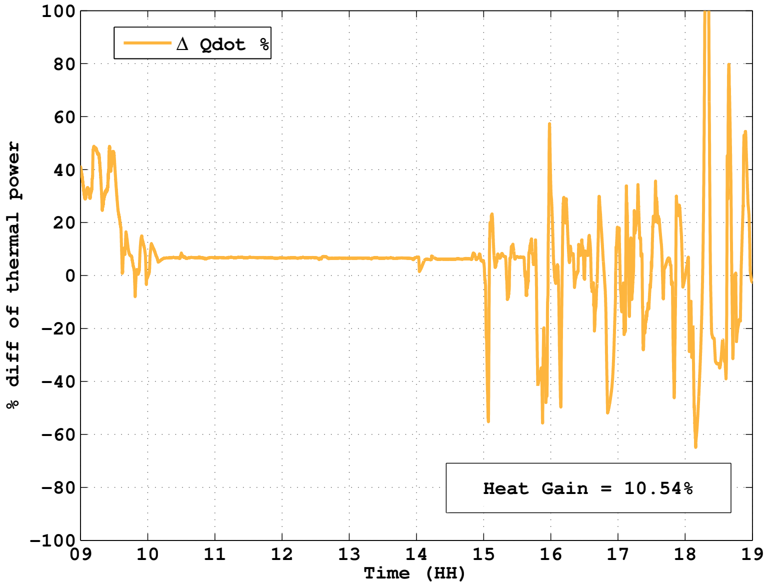


Figure 31: Real and simulated heat transfer rate of specific loop in a sunny and cloudy day.

selected loops in the three days studied. The response time from fully closed to fully opened or vice-versa depend on the valve size and operating mode, apart from the type of fluid, temperature and pressure. Usually, the response time for valves used in this type of control is in the magnitude of milliseconds. Therefore, the proposed strategy respects the allowed response time expected for this type of operation.

The proposed control strategy was studied in order to analyze the possibility of a real implementation. According to Wang et al. [15], the structure and relative simplicity of fuzzy logic processing algorithms naturally lead to straight forward implementation in dedicated hardware structures. Different approaches have to be chosen based on the features of the application, but it is already possible to directly implement a fuzzy controller developed in MATLAB®. Existing Open Platform Communications (OPCs) can specify the communication of a real-time plant data between the MATLAB® controller and a Programmable Logic Controller (PLC), which is a digital computer used for automation. Therefore, it can be stated that the proposed control strategy is feasible to be implemented in reality, fulfilling the third mentioned evaluation criteria.

The suggested fuzzy system methodology is the final one obtained after several trials. Other membership functions shapes and limits were tested, as well as some alternative defuzzification methods. Apart from that, initially the temperature input used was the HTF outlet temperature, but as previously mentioned, the behavior of the system with wall temperature as input was improved, due to the time buffer obtained.

Moreover, an extra input was tested: DNI change. This input was calculated according to the difference of the DNI value of the current and previous time step, either increasing or decreasing. Although this input was thought to ameliorate passing clouds situations, the outcome was similar to the one of the final FLC. As the rules are set up to deal with this transient situation, this extra input was superfluous, with the unwanted constraint of increased computational time.

Several rule bases were developed, in order to try different inference procedures. By a diverse range of rules trials, it could be stated that a higher number of rules is not connected to a higher efficacy of the controller. A set of rules that would combine much more possible situations were tested and the results were not improved. In consideration of that, based on the knowledge of the system and the expected behavior of the controller, the final 71 rules are considered within this thesis to be the most efficient and effective ones for a proactive control of the plant.

The implemented strategy assumed perfect inputs and did not consider any restrictions from the power block, such as temperature gradient or overload. Although these parameters could be of influence, the proposed controller proves to be already robust, with possible improvements if taking those into consideration.

4 Conclusions

The first part of the presented project was successfully concluded, as it supported the validation of the Virtual Solar Field (VSF) simulation tool with a practical methodology. The data plotting tool provided a valuable analysis, with the dynamic examination of the data. Apart from that, the Andasol 3 data preparation allowed a deep investigation of PTC power plants operation and consequently provided enhanced knowledge in CSP technologies in general. Greater computational skills were also obtained after the performance of this first phase.

Considering the obtained results of the second part of the project, it can be concluded that the proposed Fuzzy Logic Control (FLC) is a comprehensive control strategy for line-focus solar thermal systems. The main goal of dynamic flow and focus control was reached, with the advantage of a proactive controller, with better performance specially during transient situations. With a relatively simple implementation, the proposed strategy allows energy gain and improvements in operation, proving to be a robust control that can be applied in operational solar thermal power plants.

Accordingly, VSF is presented as a valuable tool for the study and further improvements of PTC power plants. The innovative FLC strategy confirms the possibility of advanced operation, representing a significant added value for VSF.

Regarding personal and professional conclusions, the experience of this master thesis brought deeper knowledge and increased the interest in CSP technologies. To work closely with simulations was a great chance to ensure future career path engagements. Apart from that, the collaborative environment at German Aerospace Centre (DLR) was a decision point to confirm the following steps in a research career. The acceptance and support for the implementation of a new control strategy based on background knowledge in Fuzzy Logic was a prominent opportunity to build up next steps.

5 Outlooks

As further recommendations for this work, some aspects were identified and studied to broaden the application of the proposed Fuzzy Logic Control (FLC). First of all, it is important to consider that the developed controller can be applied not only to Parabolic Trough Collectors (PTC) solar thermal power plants, but also to other CSP technologies. An application for a Linear Fresnel plant could be almost immediate, while the control system would need some adaptations in order to fit a point focusing system, such as the Solar Tower Systems. Although, only the type of inputs and outputs would have to be adapted, but the strategy of the inference procedure used could be the same.

Another important aspect that could be further developed is related to the linguistic variables associated with the fuzzy control. This can easily allow the inclusion of an operator in the strategy, whose inputs could be used to improve the control even more. It is known that there is a progressing learning curve of the operators, from the starting of a plant along its period of operation. This interaction could be used to optimize the process being considered, for example, as an adaptation mechanism for the controller.

The controller implemented in combination with the simulations assumed no errors in measurement for the inputs and did not consider any restrictions from the power block, such as temperature gradient or overload. Those are refinements that can be performed in further studies. To contemplate signal noise or delay can improve even more the robustness of the developed controller.

The input of the pump pressure difference on the power block was considered as the real one from Andasol 3 data. A more detailed analysis can be done taking into account the dumping as a pressure release of the system, with direct influence in mass flow control. As last suggestion, trials with an extra input considering the dumping as low or high is believed to be valuable for the strategy. As the applied control and simulation was done based in a main pump pressure difference controlled in the power block, a dumping value could represent an important measure to be taken into account if the controller is further developed.

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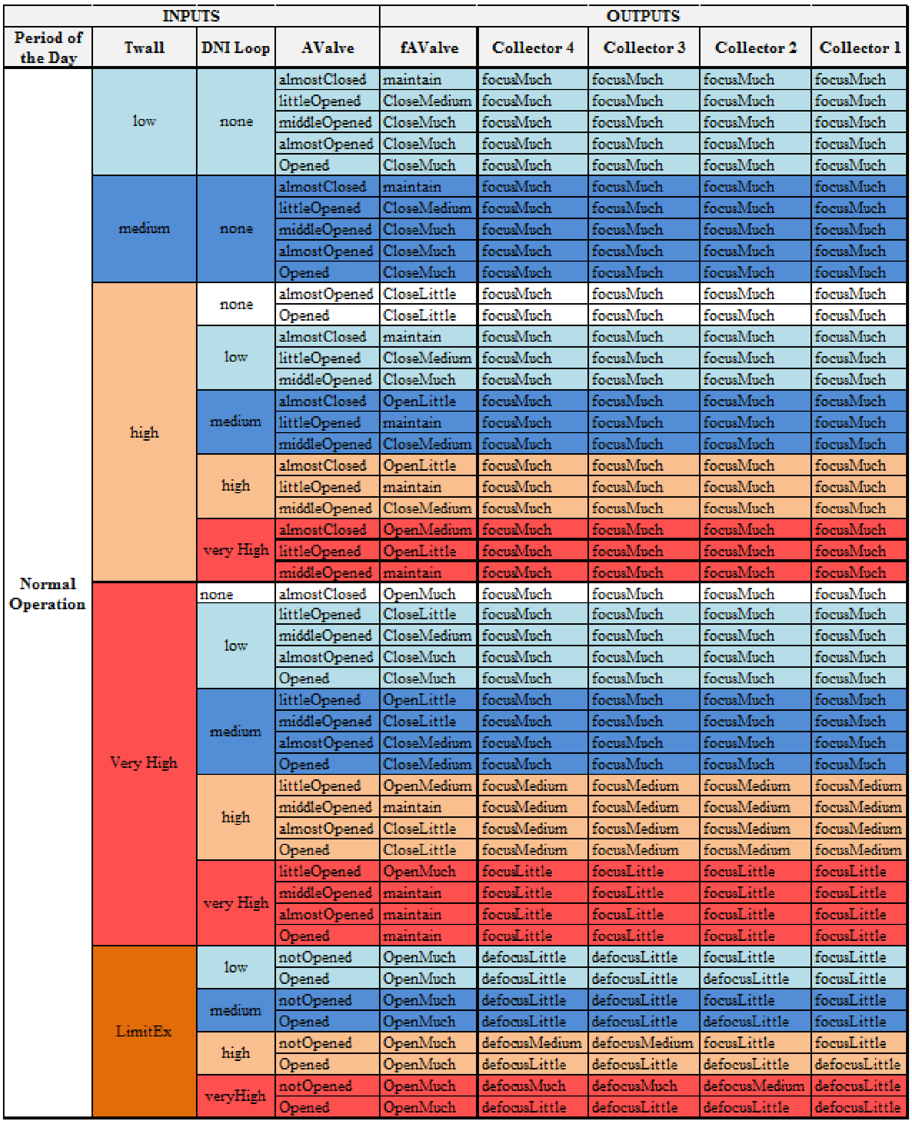
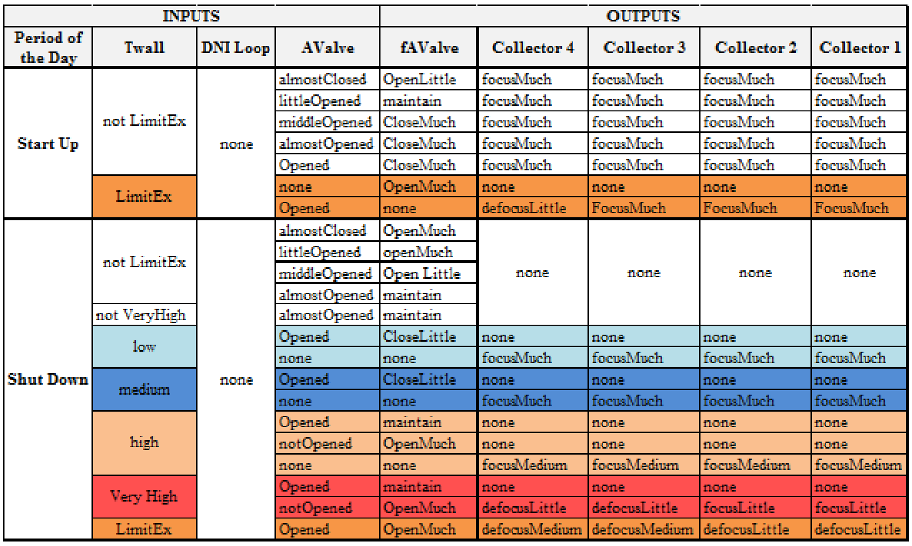
Appendices

A Fuzzy Rule Base



INPUTS				OUTPUTS				
Period of the Day	**Twall**	**DNI Loop**	**AValve**	**fAValve**	**Collector 4**	**Collector 3**	**Collector 2**	**Collector 1**
Normal Operation	low	none	almostClosed	maintain	focusMuch	focusMuch	focusMuch	focusMuch
			littleOpened	CloseMedium	focusMuch	focusMuch	focusMuch	focusMuch
			middleOpened	CloseMuch	focusMuch	focusMuch	focusMuch	focusMuch
			almostOpened	CloseMuch	focusMuch	focusMuch	focusMuch	focusMuch
			Opened	CloseMuch	focusMuch	focusMuch	focusMuch	focusMuch
	medium	none	almostClosed	maintain	focusMuch	focusMuch	focusMuch	focusMuch
			littleOpened	CloseMedium	focusMuch	focusMuch	focusMuch	focusMuch
			middleOpened	CloseMuch	focusMuch	focusMuch	focusMuch	focusMuch
			almostOpened	CloseMuch	focusMuch	focusMuch	focusMuch	focusMuch
			Opened	CloseMuch	focusMuch	focusMuch	focusMuch	focusMuch
	high	none	almostOpened	CloseLittle	focusMuch	focusMuch	focusMuch	focusMuch
			Opened	CloseLittle	focusMuch	focusMuch	focusMuch	focusMuch
		low	almostClosed	maintain	focusMuch	focusMuch	focusMuch	focusMuch
			littleOpened	CloseMedium	focusMuch	focusMuch	focusMuch	focusMuch
			middleOpened	CloseMuch	focusMuch	focusMuch	focusMuch	focusMuch
		medium	almostClosed	OpenLittle	focusMuch	focusMuch	focusMuch	focusMuch
			littleOpened	maintain	focusMuch	focusMuch	focusMuch	focusMuch
			middleOpened	CloseMedium	focusMuch	focusMuch	focusMuch	focusMuch
		high	almostClosed	OpenLittle	focusMuch	focusMuch	focusMuch	focusMuch
			littleOpened	maintain	focusMuch	focusMuch	focusMuch	focusMuch
			middleOpened	CloseMedium	focusMuch	focusMuch	focusMuch	focusMuch
		very High	almostClosed	OpenMedium	focusMuch	focusMuch	focusMuch	focusMuch
			littleOpened	OpenLittle	focusMuch	focusMuch	focusMuch	focusMuch
			middleOpened	maintain	focusMuch	focusMuch	focusMuch	focusMuch
	Very High	none	almostClosed	OpenMuch	focusMuch	focusMuch	focusMuch	focusMuch
		low	littleOpened	CloseLittle	focusMuch	focusMuch	focusMuch	focusMuch
			middleOpened	CloseMedium	focusMuch	focusMuch	focusMuch	focusMuch
			almostOpened	CloseMuch	focusMuch	focusMuch	focusMuch	focusMuch
			Opened	CloseMuch	focusMuch	focusMuch	focusMuch	focusMuch
		medium	littleOpened	OpenLittle	focusMuch	focusMuch	focusMuch	focusMuch
			middleOpened	CloseLittle	focusMuch	focusMuch	focusMuch	focusMuch
			almostOpened	CloseMedium	focusMuch	focusMuch	focusMuch	focusMuch
			Opened	CloseMedium	focusMuch	focusMuch	focusMuch	focusMuch
		high	littleOpened	OpenMedium	focusMedium	focusMedium	focusMedium	focusMedium
			middleOpened	maintain	focusMedium	focusMedium	focusMedium	focusMedium
			almostOpened	CloseLittle	focusMedium	focusMedium	focusMedium	focusMedium
			Opened	CloseLittle	focusMedium	focusMedium	focusMedium	focusMedium
		very High	littleOpened	OpenMuch	focusLittle	focusLittle	focusLittle	focusLittle
			middleOpened	maintain	focusLittle	focusLittle	focusLittle	focusLittle
			almostOpened	maintain	focusLittle	focusLittle	focusLittle	focusLittle
			Opened	maintain	focusLittle	focusLittle	focusLittle	focusLittle
	LimitEx	low	notOpened	OpenMuch	defocusLittle	defocusLittle	focusLittle	focusLittle
			Opened	OpenMuch	defocusLittle	defocusLittle	defocusLittle	focusLittle
		medium	notOpened	OpenMuch	defocusLittle	defocusLittle	focusLittle	focusLittle
			Opened	OpenMuch	defocusLittle	defocusLittle	defocusLittle	focusLittle
		high	notOpened	OpenMuch	defocusMedium	defocusMedium	focusLittle	focusLittle
			Opened	OpenMuch	defocusLittle	defocusLittle	defocusLittle	defocusLittle
		veryHigh	notOpened	OpenMuch	defocusMuch	defocusMuch	defocusMedium	defocusLittle
			Opened	OpenMuch	defocusLittle	defocusLittle	defocusLittle	defocusLittle

Figure A.1: Rule base used to build the Fuzzy Control Strategy for normal operation.



INPUTS				OUTPUTS				
Period of the Day	**Twall**	**DNI Loop**	**AValve**	**fAValve**	**Collector 4**	**Collector 3**	**Collector 2**	**Collector 1**
Start Up	not LimitEx	none	almostClosed	OpenLittle	focusMuch	focusMuch	focusMuch	focusMuch
			littleOpened	maintain	focusMuch	focusMuch	focusMuch	focusMuch
			middleOpened	CloseMuch	focusMuch	focusMuch	focusMuch	focusMuch
			almostOpened	CloseMuch	focusMuch	focusMuch	focusMuch	focusMuch
			Opened	CloseMuch	focusMuch	focusMuch	focusMuch	focusMuch
	LimitEx		none	OpenMuch	none	none	none	none
			Opened	none	defocusLittle	FocusMuch	FocusMuch	FocusMuch
Shut Down	not LimitEx	none	almostClosed	OpenMuch	none	none	none	none
			littleOpened	openMuch				
			middleOpened	Open Little				
			almostOpened	maintain				
	not VeryHigh		almostOpened	maintain				
	low		Opened	CloseLittle	none	none	none	none
			none	none	focusMuch	focusMuch	focusMuch	focusMuch
	medium		Opened	CloseLittle	none	none	none	none
			none	none	focusMuch	focusMuch	focusMuch	focusMuch
	high		Opened	maintain	none	none	none	none
			notOpened	OpenMuch	none	none	none	none
			none	none	focusMedium	focusMedium	focusMedium	focusMedium
	Very High		Opened	maintain	none	none	none	none
			notOpened	OpenMuch	defocusLittle	defocusLittle	focusLittle	focusLittle
	LimitEx		Opened	OpenMuch	defocusMedium	defocusMedium	defocusLittle	defocusLittle

Figure A.2: Rule base used to build the Fuzzy Control Strategy for start-up and shutdown.

B Valve Aperture Area Plots

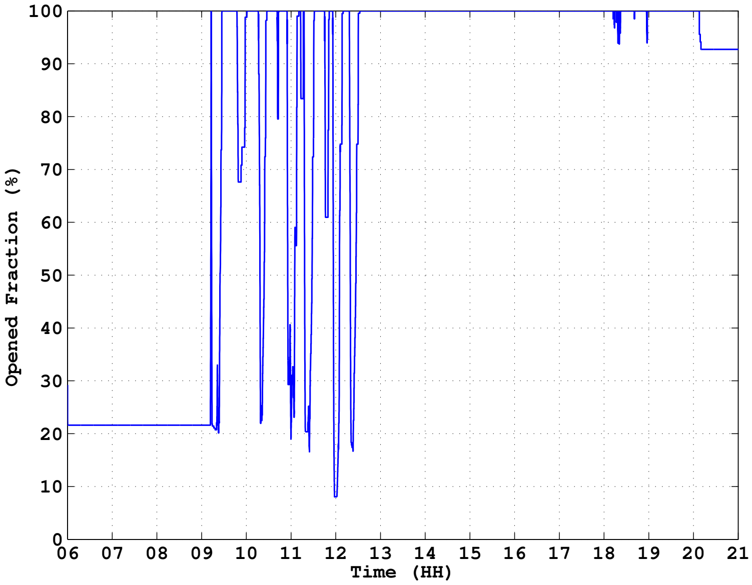


Figure B.1: Valve aperture area of simulated data for specific loop in a sunny day.

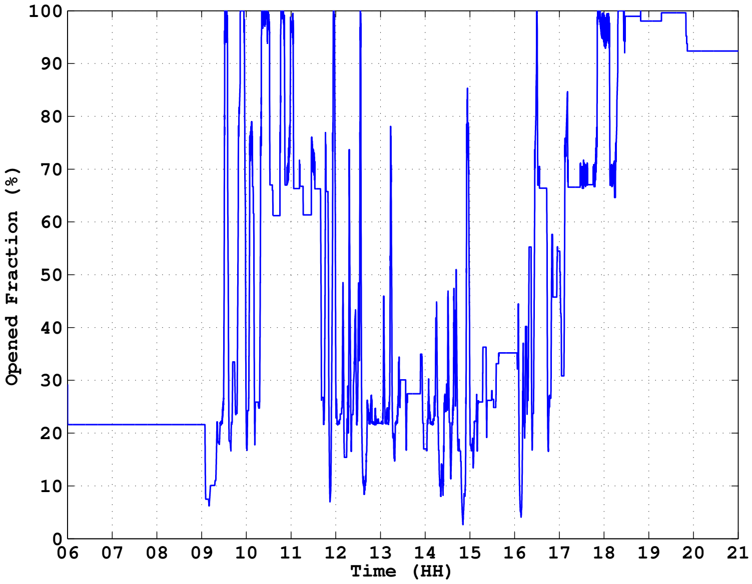


Figure B.2: Valve aperture area of simulated data for specific loop in a cloudy day.

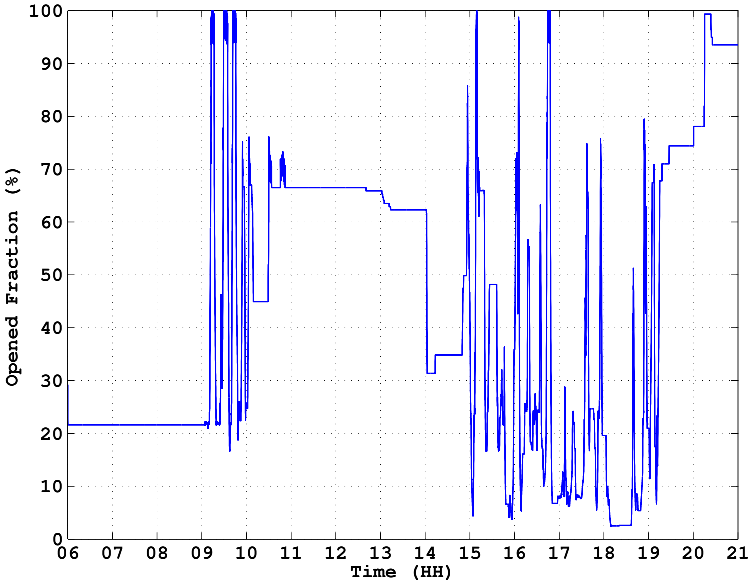


Figure B.3: Valve aperture area of simulated data for specific loop in a sunny and cloudy day.