Control Strategy of Rectifier for a PV-Grid-Powered Electrolyser

by

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The people who are crazy enough to think they can change the world are the ones who do!

Steve Jobs

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Abstract

Green hydrogen can be produced from various renewable energy sources like PV, wind, geothermal and biomass. Especially PV or wind sourced hydrogen production systems are becoming more prevalent as a solution to produce green hydrogen, owing to their regional abundance. In this master thesis project, a PV-grid powered electrolyser shall be taken into consideration. The electrolyser is an equipment that produces hydrogen through electrolysis. Here, an alkaline electrolyser is taken into consideration, which is a DC load and hence, it requires a rectifier to convert the AC power from the grid and from the PV plant (DC PV power will be converted to AC through an inverter) into DC power. The amount of hydrogen produced is proportional to the amount of current flowing into the electrolyser. As the electrolyser operates, the process of electrolysis will, more often than not, produce heat. The heat produced during electrolysis, along with the ambient conditions, will result in variation of the temperature of the electrolyser. Some systems make use of a thermostat to control the temperature of the electrolyser whereas some employ a cooling system to extract heat and utilise it to perform useful work. If there is no system to control or maintain its temperature, the electrolyser is bound to have a varying temperature while it is operational. This research aims to develop a control strategy for a PV-grid powered electrolyser to ensure the optimal operation of the electrolyser despite its varying temperature. The need for such a control strategy for the electrolyser rises due to the dependence of the I-V characteristics of the electrolyser on the temperature. As the temperature of the electrolyser increases, the I-V curve shifts in such a way that a given current value will be produced at a lower value of voltage. Since the amount of hydrogen produced depends on the amount of current flowing into the electrolyser, the control strategy aims to maintain the input current to the electrolyser at the rated value irrespective of the change in the temperature of the electrolyser. The control strategy is tested on Simulink with the help of an electrolyser emulator into which data is fed through look-up tables. Real-time data for irradiance and ambient temperature has been used to perform day-long simulations. Based on the results obtained, the average efficiency of the converter was found to be 93.88%.

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Panneer Selvam Shivani
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Introduction

As the world is continuously moving towards making use of renewable energy in every sphere of life, the use of renewable energy sources has been incorporated into the process of producing hydrogen too. Green hydrogen can be produced from various renewable energy sources like PV, wind, geothermal and biomass. Especially PV or wind sourced hydrogen production systems are becoming more prevalent as a solution to produce green hydrogen, owing to their regional abundance. In this project, the focus is on an electrolyser - an equipment that facilitates the production of hydrogen through the process of electrolysis - that is powered by PV power and the grid (when PV power is insufficient to satisfy the electrolyser's demand).

1.1. Research Motivation

The electrolyser taken into consideration in this project does not employ any system or mechanism (like a thermostat or a cooling system) to control temperature, as mentioned in the previous section. In this research, throughout the operation time of the electrolyser and in turn the entire system, the temperature of the electrolyser is bound to change. Additionally, the amount of hydrogen produced is proportional to the current drawn by the electrolyser. Based on the above two main factors, the objective of this research has been formulated.

This research intends to find a way through which the optimal operation of the electrolyser can be ensured irrespective of the change in its temperature, following which, the goal is to develop a control strategy to regulate the output of the rectifier in order to ensure the optimal operation of the electrolyser. After having studied the working of the electrolyser, the amount of current flowing into the electrolyser was chosen as the deciding variable and the voltage across the electrolyser was chosen as the variable to be controlled. The control strategy works towards making the current stay at the rated value (based on the rating of the electrolyser) irrespective of the change in the temperature. Since the input for the electrolyser is a DC voltage which would be produced by a rectifier in this case, the research aims to regulate the voltage of the electrolyser (that is, the DC output voltage of the rectifier) to keep the current at the rated value despite the change in temperature. So, there must be a system that forms a link between the PV-grid powered rectifier and the electrolyser, to decide how the electrolyser can be made to work optimally.

Therefore, the objective of this research is to develop a control strategy for a PV-grid powered electrolyser for the optimal operation of the electrolyser.

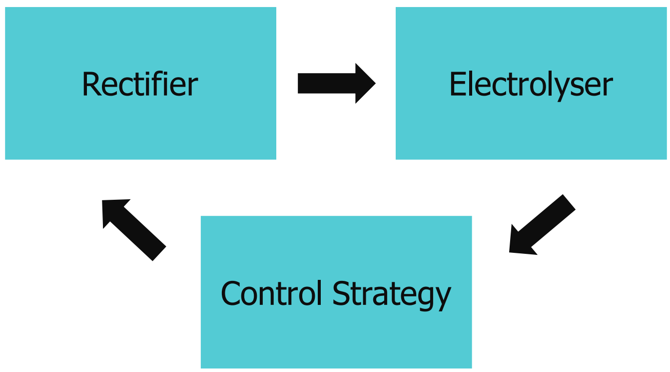

Figure 1.1: A simple representation of the objective of the research

1.2. RESEARCH QUESTIONS

This research aims to answer the following questions:

1. **What is the significance of change in temperature of the electrolyser with respect to the operation of the electrolyser?**
2. **What is the condition for optimal operation of the electrolyser as far as this research is concerned?**
3. **What are the quantities upon which the control strategy operates?**

4. **How does the control strategy work?**

5. **How would the control strategy be tested?**

1.3. Structure of the Thesis

This thesis report documents the above mentioned research and its structure is as follows.

- Chapter 1 gives the introduction, the background motivation and the scope of research of this thesis.

- Chapter 2 presents the information that was studied to understand the background of the research. A literature survey was carried out to study the recent work related to electrolysers. Based on the above information, the chapter 'Literature Review' has been written and it aims to provide the reader with appropriate information to understand the research.

- Chapter 3 intends to explain what are the various components that the system comprises of and how they are connected. It also explains the Simulink model and the function(s) of its components in detail, thereby enabling the reader to gain an understanding of how to interpret the Simulink model and how it works.

- Chapter 4 elucidates the need for such a control strategy and then presents the developed control strategy along with the phases of its development and a flowchart.

- Chapter 5 consists of the results of the research, which depict the successful working of the control strategy, in the form of plots obtained after having ran the model on Simulink (MATLAB R2019b) with a concise explanation for each case that was taken into consideration. This chapter also explains the various parameters in the results and the interpretation of the results.

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Literature Review

This chapter will provide the reader with relevant information that was studied in order to gain an understanding of the background of the research.

2.1. Recent Works

Though the hydrogen produced from water electrolysis constitutes only 4% of the total hydrogen produced, electrolysers are being used and studied in various researches and applications [1]. The research papers studied were either general in nature and dealt with the study and comparison of different converters for electrolyser applications [2], [3] or were specific in nature and dealt with the design of a power supply which is programmable for an electrolyser [4]. Some researches were solely performed to study the working of an electrolyser, for example under constant and variable input [5]. It was observed that addressing power quality issues [6], studying various methods of control [7], performing stability analysis [8] and performance analysis [9] for a system containing an electrolyser were some of the most commonly found research topics during the literature review. A key takeaway was that most of the research papers dealt with electrolysers integrated with renewable energy sources (PV and (or) wind) [10], some being grid connected and some being standalone. Optimisation being essential for any system, the optimization of power flow, electrolyser size, system elements' size and so on were studied [11]. Apart from the technical aspects, the economic side of an electrolyser application has also been dealt with in some researches [12].

2.2. FUNDAMENTALS OF ELECTROLYSERS

An electrolyser is a device used for producing hydrogen. As the name suggests, the underlying process for producing hydrogen is electrolysis. Electrolysers currently available in the market are of two types, namely, Alkaline and Proton Exchange Membrane (PEM) electrolysers, both of which function as DC loads [1]. In this project, the electrolyser taken into consideration is an alkaline electrolyser, which is a DC load. Electrolysers can be powered through conventional sources of energy as well. But in that case, the hydrogen which would be produced as the output would not be 'green hydrogen'. In this project, the renewable source of power for the electrolyser is PV power.

2.2.1. TYPES OF ELECTROLYSERS

As mentioned in the paragraph above, electrolysers are classified mainly into three types, namely:

- Alkaline Electrolysers
- Proton Exchange Membrane (PEM) Electrolysers
- Solid Oxide Electrolysers

Alkaline and PEM electrolysers are more widely used than the latter as the latter is still being studied. Nevertheless, the alkaline electrolyser technology is the oldest.

2.2.2. WORKING PRINCIPLE

An electrolyser converts electrical energy into chemical energy and the final end product of the electrolyser is hydrogen. The underlying process in an electrolyser is electrolysis, which is the process of splitting water molecules into hydrogen and oxygen in the presence of electricity. Since the type of electrolyser chosen for this project is alkaline electrolyser, the electrolyte used in this case is an aqueous solution of potassium hydroxide (KOH). The following equations depict the chemical reactions occurring at the cathode and anode respectively [13]:

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \tag{2.1}$$

$$4OH^- \rightarrow O_2 + 2H_2O + 4e^- \tag{2.2}$$

The overall reaction is:

$$2H_2O \rightarrow 2H_2 + O_2 \tag{2.3}$$

The electrolyser is responsible for carrying out the electrolysis of water, that is, it requires a DC voltage to be applied in order to split water into hydrogen and oxygen, therefore converting electrical energy into chemical energy. Some basic thermodynamics was studied in order to get a better understanding of the working of the electrolyser and it was found that the process involves some important parameters and are as follows [13]:

- U_{rev}: Reversible potential (V)
- U_{tn}: Thermoneutral voltage (V)

Since the reaction requires some amount of energy and heat to be supplied in order to split the water molecule into oxygen and hydrogen, the parameter U_{rev} indicates the minimum potential that is required for electrolysis to occur (at the cell level). This value holds good when the heat required to bring about the reaction is supplied by an external source. Whereas, if the heat required for the reaction to occur is supplied in the form of electricity, then the minimum voltage that is applied across the electrodes of the cell is called the thermoneutral voltage U_{tn} [13].

If the value of voltage applied is equal to the thermoneutral voltage, then there will be neither any heat emitted nor absorbed by the cell. Nevertheless there are other factors which have to be taken into account. The half-reactions have an activation energy which has to be overcome. The ohmic resistance of the cell should also be taken into account while deciding the amount of voltage to be applied across the cell to bring about the reaction. After having taken into consideration the above mentioned parameters, the actual cell voltage would be higher than the thermoneutral voltage. This implies that the reaction will result in the release of heat and hence the temperature of the electrolyser will not remain constant throughout the operation time of the electrolyser unless there is a system employed to regulate the temperature [13].

2.3. IMPORTANCE OF ELECTROLYSER TEMPERATURE

There are various ways in which the temperature of the electrolyser can be controlled or maintained at the desired level. Some systems make use of a thermostat to control the temperature of the electrolyser [14], whereas others employ a cooling system to extract the heat generated during the process and utilize it for other useful work like space and water heating (onshore) and for desalination (offshore) [13].

Electrolysers can be very promising when it comes to their contribution towards the production of hydrogen but the process involves various conditions to be satisfied in order to make it efficient. For an alkaline electrolyser, the equation relating voltage, current and temperature is [15]:

$$V = \left[a_o + a_1 T + b\ln(T) - \left(\frac{r_o}{T}\right) I\right] N_s \tag{2.4}$$

where, N_s refers to the number of electrolyser cells, a_o, a_1 and b are electrolyser parameters which will differ based on the characteristics of the electrolyser and r_o is the internal resistance of the cell.

The change in the temperature of the electrolyser has a significant impact on the I-V curve of the electrolyser. As the temperature of the electrolyser increases, the potential required to enable the water molecule to split, reduces. This in turn implies that as the temperature changes from T_1 to T_2, with $T_2 > T_1$, there will be a shift in the I-V curve of the electrolyser such that a particular value of current I with a corresponding voltage value of V_1 at T_1 would now be produced at a voltage value of V_2 at T_2, where $V_2 < V_1$ [16].

Given that the electrolyser taken into consideration in this research does not have its temperature maintained at a constant value, it is imperative that there is an alternate system responsible for ensuring the optimal operation of the electrolyser. This calls for the development of the control strategy, the objective of this research, which is explained in Chapter 4.

Moreover, it was also found that studies were carried out in order to see how the ambient conditions influence the operation of the electrolyser. Based on the data obtained through the research, the relationship between irradiance and the temperature of the electrolyser was understood and has been presented in Chapter 5.

The electrolyser is found to have a higher value of efficiency when the temperature of the electrolyser is increased [16]. Although electrolysis at elevated temperatures can result in higher efficiency, depending on the electrolyte and the type of diaphragm used, it comes with a price of resulting in the corrosion of the electrolyte and the diaphragm [17].

2.4. SYSTEM TOPOLOGY

Alkaline electrolysers with a power rating in the range of megawatts (MW) are also available and these types of electrolysers are being employed in industrial applications as well. Alkaline electrolysers are DC loads. Hence when an AC supply is used, it requires a rectifier or an AC-DC converter to convert the AC voltage to DC. Moreover, if required, the DC voltage level may have to be altered in order to suit the requirement of the electrolyser and hence the system may have to employ a DC-DC converter. The type of rectifiers mostly used for such applications are diode based or thyristor based rectifiers [1].

The electrolyser being a DC load, a direct connection between the PV plant and the electrolyser is possible but in this case the PV power cannot be controlled or conditioned. This calls for a topology that includes a power electronic interface between the PV plant and the electrolyser.

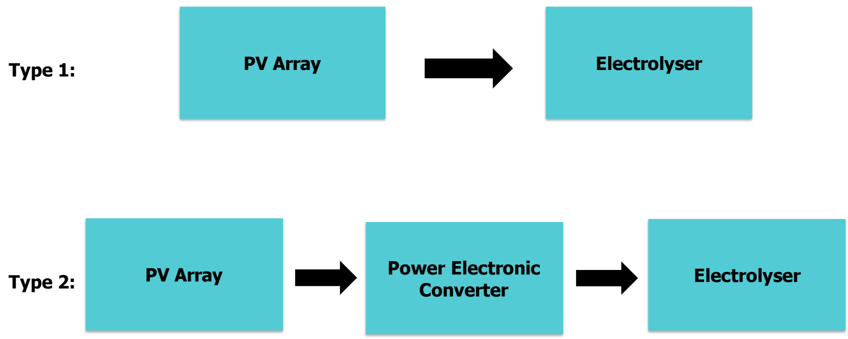

Figure 2.1: Topologies with and without a power electronic interface between the PV array and the electrolyser

2.4.1. POWER CONVERTER TOPOLOGY

There are two topologies which could be implemented, one with a DC-DC converter and another one that comprises of an inverter, transformer and a rectifier. The former would be better when the electrolyser is situated close to the PV plant. If the PV plant is located far away from the electrolyser, in order to avoid the losses that occur during the transmission of power, the topology comprising of an inverter, transformer and a rectifier could be used. The power from the PV plant, which is DC, will be given to the inverter as input which will convert it into AC power which in turn will be fed into the step-up transformer. If the power produced by the PV plant is insufficient to satisfy the demand of the electrolyser, power will be imported from the grid. If there is excess power being produced by the PV plant after having satisfied the electrolyser's demand, it will be exported to the grid. The transformer will step up the voltage to a higher value and it will be transmitted to the step-down transformer near the electrolyser's location. The voltage will then be stepped down to an appropriate value by this transformer. Now, the rectifier will convert the incoming AC voltage into DC so that it can be supplied to the electrolyser.

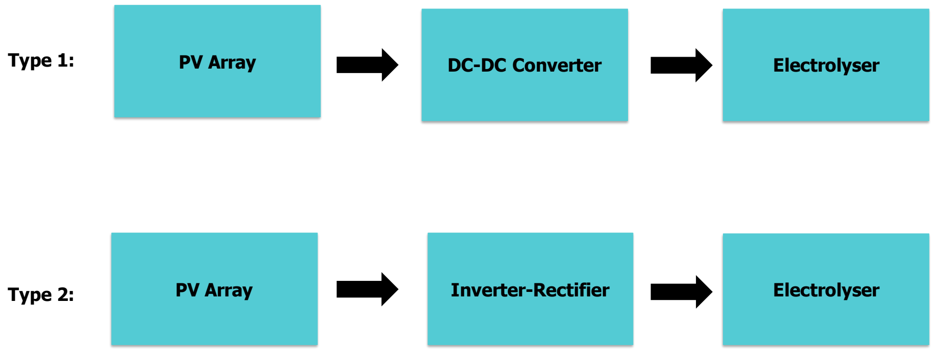

Figure 2.2: Different possible power electronic interfaces between the PV array and the electrolyser

2.4.2. TYPES OF RECTIFIERS

The rectifier being the most important component of this system with respect to the implementation of the control strategy, different types of rectifiers were studied, namely, diode-based rectifier, thyristor-based rectifier and IGBT-based rectifier.

A diode-based rectifier was studied first. A diode is a semiconductor device that conducts electricity when it is forward-biased. The value of the input voltage cannot be modified in order to produce a desired output voltage. In other words, the diode-based rectifier does not provide controllability, which means, the DC output voltage of the rectifier cannot be varied. Due to this reason, the thyristor and IGBT rectifiers, which provide controllability, were compared.

A thyristor-based rectifier offers controllability unlike the diode-based rectifier as it renders the output voltage based on the firing angle. If a lower output voltage in comparison with the input voltage is required to be produced, then the firing angle can be increased accordingly and vice-versa. The drawback of using a thyristor-based rectifier is that it requires a reverse voltage to be applied to turn it off [18]. Moreover, they also operate at low power factors [19]. On the other hand, IGBT-based rectifiers operate at comparatively higher power factors [19]. Additionally, IGBTs can be operated at higher switching frequencies as compared

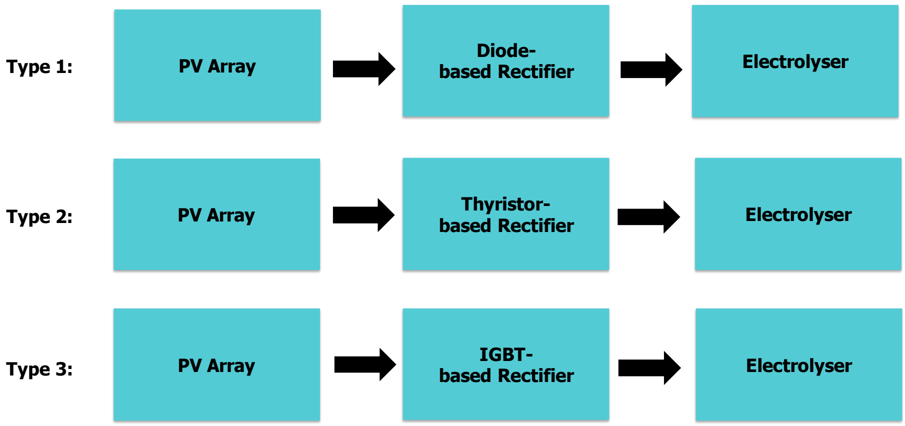

Figure 2.3: Different types of rectifiers which could be employed in the system

to thyristors [18]. Hence an IGBT-based rectifier was chosen for this research and a circuit diagram of a three-level converter is shown below.

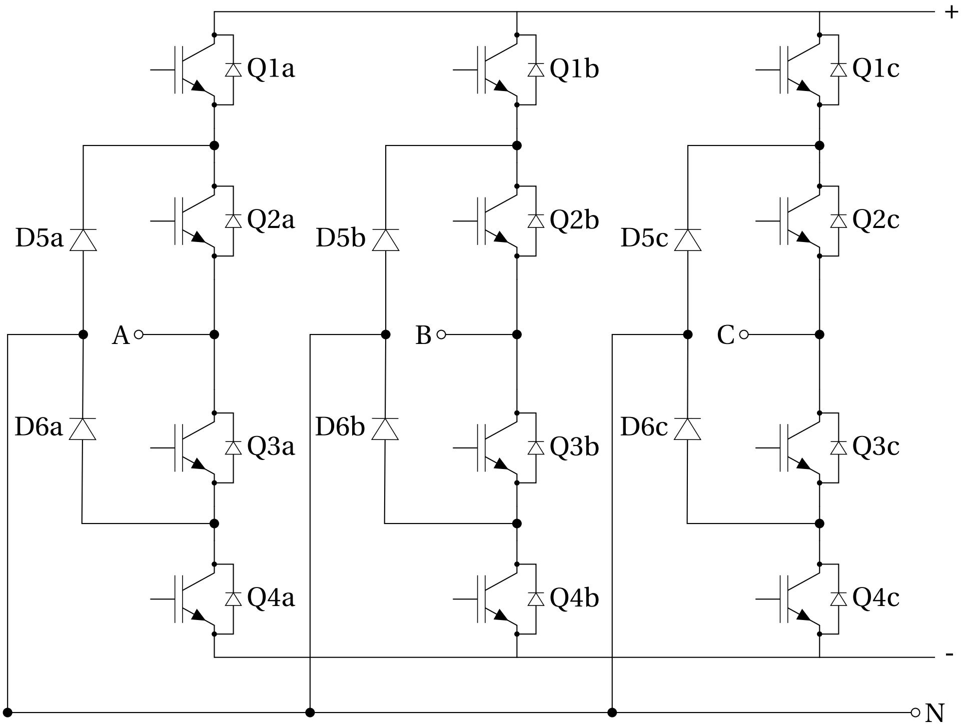

Figure 2.4: Three Level Converter

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THE SYSTEM

This chapter will help the reader understand the system and its model designed on Simulink. The system will be broken down into different parts and the functions and essential ratings will be discussed as well.

3.1. SYSTEM LAYOUT

Figure 3.1 is a simple representation of the entire system that has been taken into consideration in this research.

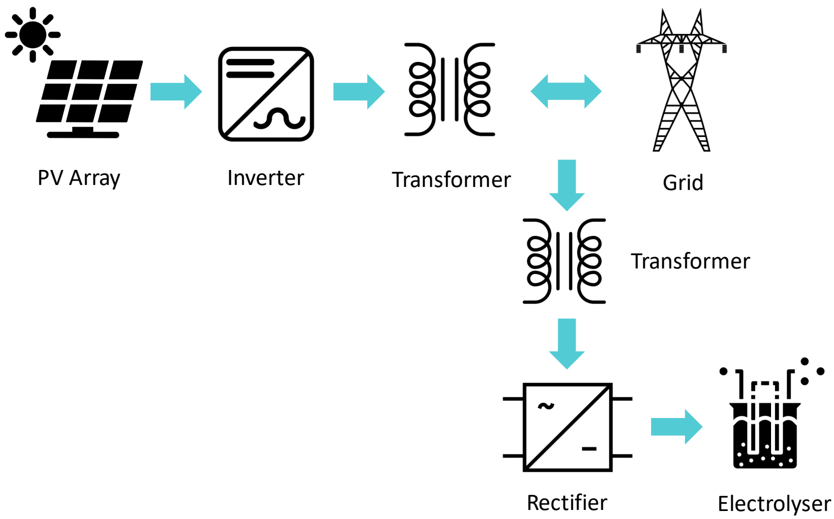

Figure 3.1: A visual representation of the system

This project deals with an electrolyser that intends to produce green hydrogen as the output and hence the source of the energy produced has to be a renewable energy source. Hence, the first block in this layout is the PV block. As discussed in Chapter 2, it is not necessary that the PV array has to be situated very close to the load, in this case, the electrolyser. Depending on the application, the geographic, technical and economical feasibility, the PV array may be located within the vicinity of the load (PV power would be directly supplied to the load after passing through the appropriate power conditioning devices) or it may be located far away from the load (PV power would have to be transmitted over long distances to supply the load). In this case, the PV array taken into consideration is located far away from the electrolyser.

The PV array is followed by the inverter that renders AC power as the output which is transferred over long distances by the transformer. The other end where the rectifier is located also has a transformer in order to step down the voltage to the desired level for the operation of the rectifier and hence the electrolyser.

The transformer is followed by the rectifier block. The input for the rectifier is taken from the transformer and the electrolyser is connected to the rectifier as a load. The voltage from the transformer is three phase AC voltage which will have to be converted into DC voltage to supply the electrolyser. The conversion of the three phase AC voltage into DC voltage takes place with the help of the rectifier.

The block that plays a crucial role and the most important one as far as this project is concerned is the control strategy. The control strategy forms a link between the rectifier and the electrolyser. This block, based on the algorithm will decide what should be its output, which is the DC voltage reference, which in turn should go as an input to the rectifier. For the control strategy block to produce the output, the inputs for the control strategy will have to be taken from the load side (electrolyser). They are:

- Current flowing into the electrolyser (A)
- Voltage across the electrolyser (V)

Based on the two inputs from the electrolyser, the control strategy will produce the output which in turn will aid the rectifier in producing the desired output DC voltage for the operation of the electrolyser.

Since this project deals with a PV-grid powered electrolyser, the final block shown in the figure is the grid. The rectifier is connected to the grid through the transformer. In many situations, the available PV power may not be sufficient to satisfy the demand of the electrolyser and in such cases, the grid compensates for the deficit power and satisfies the electrolyser's demand. On the other hand, if the power being produced by the PV array exceeds the demand of the electrolyser, the excess power will be sent to the grid. The exchange of power is also shown in the results.

3.2. THE SIMULINK MODEL

This project deals with a PV-grid powered electrolyser. The electrolyser being a DC load requires a rectifier and the aim of the project is to develop a control strategy to ensure that the electrolyser operates at the optimal condition, always. Hence the system can be broken down into the following parts:

- AC-DC Converter or Rectifier
- Control Strategy Model
- PV-Grid Interface
- Electrolyser

The overall Simulink model is presented in Figure 3.2.

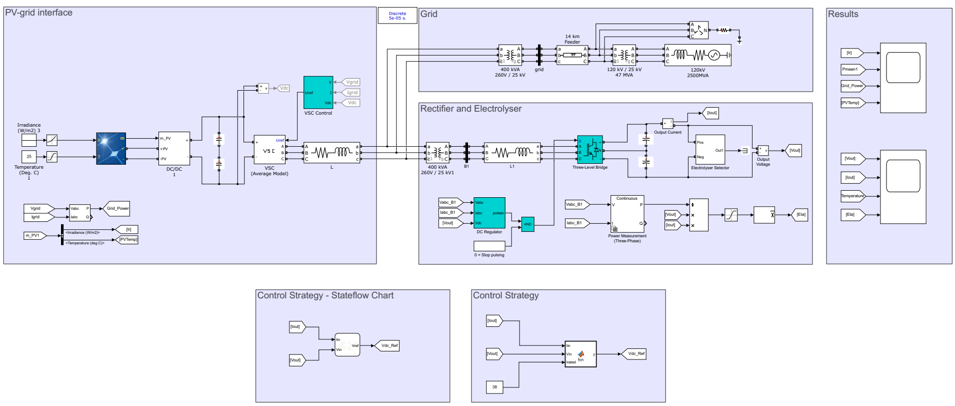

Figure 3.2: The Simulink Model

3.2.1. THE AVERAGE MODEL

The Simulink Library model used for building the final model consisting of the PV array, the grid, the rectifier, the electrolyser and the control strategy model is the 400 kW Average PV Farm Model. There were 4 PV arrays, each producing 100 kW of power connected to a DC-DC converter. The DC voltage passes through a Voltage Source Converter (VSC) and gets converted into three phase AC voltage. The VSC is followed by a transformer which steps up the voltage from 260 V to 25

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kV after which there are feeders and other loads connected to the grid. The grid has a rating of 120 kV, 2500 MVA.

The rating of the electrolyser chosen for this model is as given below:

- Rated voltage: 260 V
- Rated current: 38 A
- Rated power: 10 kW

THE PV ARRAY

As the average model had a PV power rating of 400 kW and since the electrolyser was rated for 10 kW, the average model was modified and only one PV array was used to provide a PV power in the range of 10 kW to 20 kW. This range was chosen in order to test the electrolyser's working in the presence of PV power below, equal to and above its own power rating, in other words, PV power in a range comparable with that of the electrolyser.

The module used in the model is SunPower SPR-315E-WHT-D whose specifications are as follows:

- Maximum power: 315.072 W
- Open Circuit Voltage (Voc): 64.6 V
- Voltage at maximum power point (Vmp): 54.7 V
- Short-circuit current (Isc): 6.14 A
- Current at maximum power point (Imp): 5.76 A
- Temperature coefficient of Voc: -0.27269 (%/°C)
- Temperature coefficient of Isc: 0.061694 (%/°C)
- Nominal Operating Cell Temperature (NOCT) [20]: 45°C

The PV array consists of 4 modules in a string and 16 such strings connected in parallel. This arrangement of panels produces PV power of about 20 kW. With the help of the block that controls the value of irradiance (W/m^2), the value of the PV power is made to vary from 10 kW to 20 kW. The PV array also takes temperature as an input. The module temperature plays a crucial role in deciding the amount of power produced by the PV array. Under the Standard Testing Conditions (STC), that is, an irradiance of 1000 W/m^2 irradiance and a module temperature of 25°C, the PV array would be able to produce the rated PV power. But if the irradiance is lower than that of the STC condition, then the PV power produced would decrease. If the module temperature increases beyond 25°C, the voltage of the module would decrease. As a result, the power from the PV array would decrease if the temperature of the module increases beyond 25°C [21]. To test the control strategy and in turn the entire model in different scenarios, results were collected under varying irradiance and varying ambient temperature conditions as well.

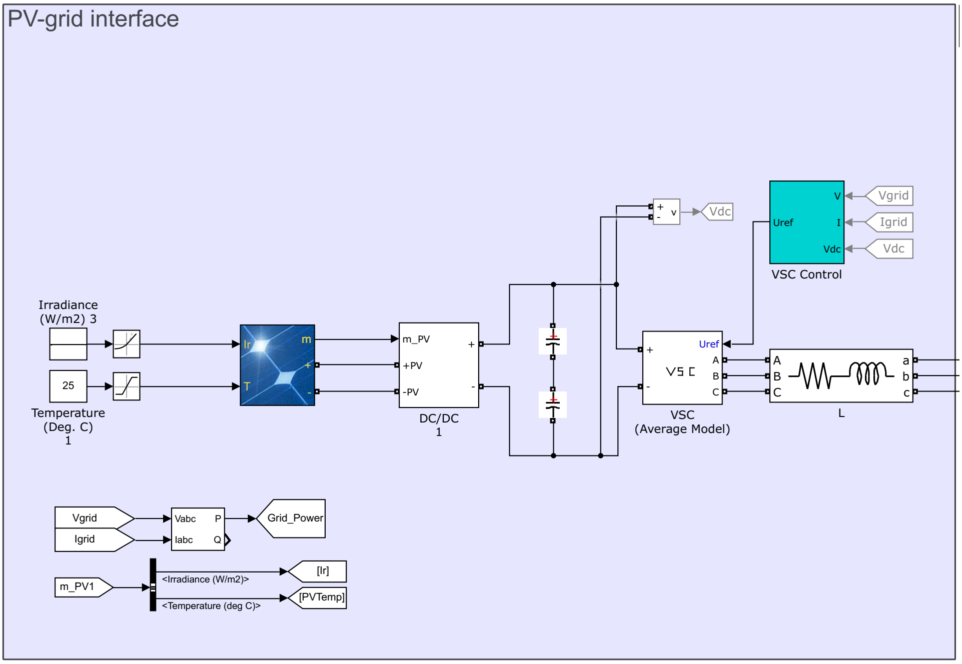

Figure 3.3: The PV-Grid Interface

3.2.2. THE AC-DC CONVERTER OR RECTIFIER

As explained in section 2.4, the rectifier used in this thesis is an IGBT based rectifier. The rectifier was considered as a separate entity (a separate Simulink Model) in order to understand how the control strategy and the rectifier should be linked with each other. The rectifier from the Simulink Library model, 'AC/DC Three-Level PWM Converter' was used.

The IGBT rectifier used here takes an ac input of 120 V. The electrolyser considered in this research operates between 210 - 260 V. Hence the input AC voltage of the rectifier was considered as 120 V in order to produce the required DC output voltage. The rectifier makes use of an inductor on the input side and split capacitor on the output side for the neutral point connection of the three-level converter. The block named DC Regulator is the main unit that is responsible for the production of the desired output of the rectifier. It takes the following inputs, 3 phase input voltage and current and the DC output voltage. This block comprises of the current regulators and the voltage regulators. Among the two blocks, the one that has prime importance as far as this research is concerned is the DC voltage regulator block. This block consists of two inputs namely:

- The DC output voltage of the rectifier (V)
- The DC voltage reference (V)

Since the control variable in this project is the DC output voltage of the rectifier, the second input, that is, the DC voltage reference plays the most crucial role. The value that reaches the rectifier as the DC voltage reference is generated by the control strategy, which will be explained in detail later. Based on the difference between the DC voltage reference and the DC output voltage of the rectifier, the voltage regulation will be performed and the desired output voltage will be produced by the rectifier.

3.2.3. THE ELECTROLYSER EMULATOR

The electrolyser emulator was integrated with the model at a later stage i.e., after having verified whether the logic of the control strategy was correct and whether the rectifier and the control strategy were working well in unison. The electrolyser emulator works with the help of a look-up table and the following variables were given as inputs to the electrolyser:

- Voltage across the electrolyser (V)
- Current flowing through the electrolyser (A)
- Temperature of the electrolyser (°C)

The above mentioned values were fed into the electrolyser through the look-up table and it consisted of 610 data points for current, 61 data points for voltage and 10 temperature values. The I-V curves (at different temperatures) of various electrolysers were studied to provide the electrolyser emulator with appropriate data to perform the simulations. Based on that information and the rating of the electrolyser taken into consideration, typical I-V curves at various temperatures, for the electrolyser were plotted by feeding values manually into the look-up table.

At each temperature, for every value of voltage, there would be a corresponding value of current. At a different temperature, the voltage values would have different values of current. In other words, since the I-V curve of the electrolyser shifts as the temperature changes, for each temperature value, a different I-V curve has been defined with the help of the look-up table. This can be explained with the help of the below data which was initially used to test the control strategy.

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Table 3.1: Look-up table for electrolyser current (A)

Temperature (°C) \ Voltage (V)	220	230	240	250	260
23	4	8	12	16	38
60	8	12	16	38	38
80	12	16	38	38	38

These values are interpreted in the following way. If the temperature is 60°C and if the voltage value is 240 V, then the corresponding value of current would be 16 A. Hence, depending on the values of the electrolyser's temperature and the output of the control strategy i.e. the DC voltage (which would also be the voltage value across the electrolyser), the value of the current flowing through the electrolyser will be picked from the look-up table.

The operating voltage range of the Enapter Electrolyser EL 2.1 found to be 220-240 V [22]. Hence the operating voltage values given to the electrolyser emulator for this research range from 210-260 V. A 10 kW electrolyser has been chosen for this research and therefore the rated current which has to be maintained by the control strategy is 38 A.

The temperature of the electrolyser can be modified manually with the help of a constant block. But, in order to check how the control strategy works when a change occurs in the temperature, a Signal Builder was used. It can be used to provide a user defined signal over a desired period of time as an input to a model.

The temperature was given as an input to the electrolyser. This was achieved by connecting the output of the Signal Builder to the electrolyser. Then the electrolyser was connected as a load to the rectifier. A voltage measurement block and a current measurement block were used to obtain the inputs (Vin and Iin respectively) for the control strategy.

3

3.2.4. INTEGRATION OF THE RECTIFIER AND ELECTROLYSER WITH THE AVERAGE MODEL

The average model consists of a transformer that steps up the voltage from 260 V to 25 kV. Since the electrolyser has an operating voltage range of 210 - 260 V, which would be produced by the rectifier, the rectifier was connected on the 260 V side through a transformer which steps down the voltage from 260 V to 120 V, which is the input to the rectifier. From here, the rectifier takes 120 V as input, obtains the 'Vdc_Ref' value from the control strategy and the output of the rectifier is regulated accordingly. This output voltage from the rectifier is given to the electrolyser as the input. A single line diagram of the system is shown below.

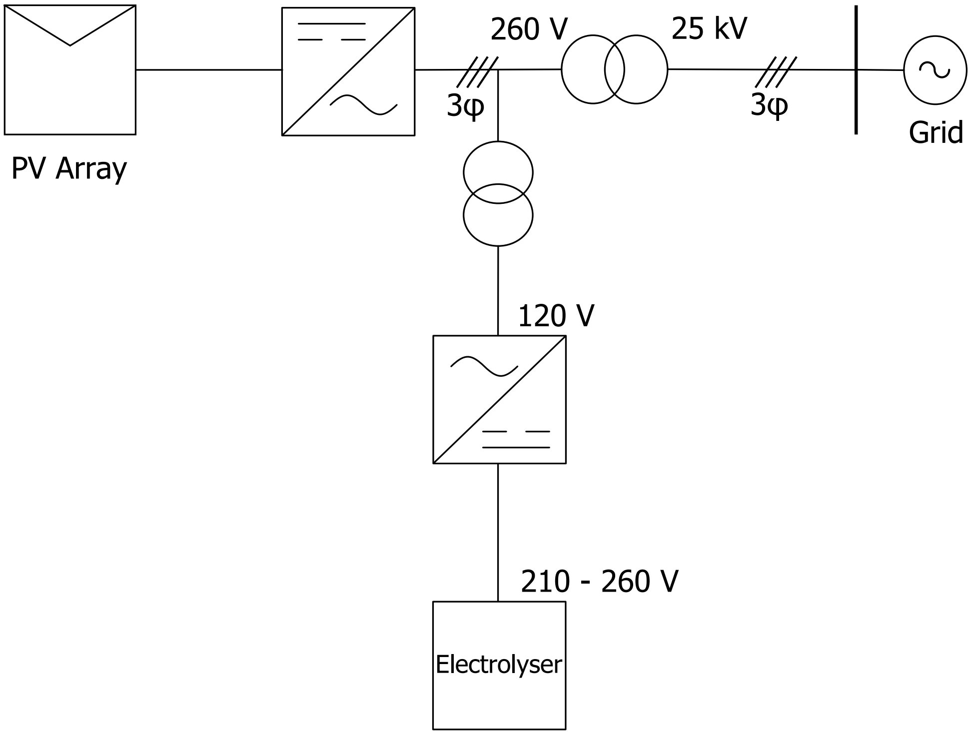

Figure 3.4: A single line diagram of the system

3.2.5. CONTROL STRATEGY

The control strategy is the prime area of focus as far as this project is concerned. This control strategy is meant to govern the way in which the rectifier and in turn the electrolyser will function. The control strategy was simulated on MATLAB R2019b Simulink.

For the initial phase, when the control strategy was being formulated, the

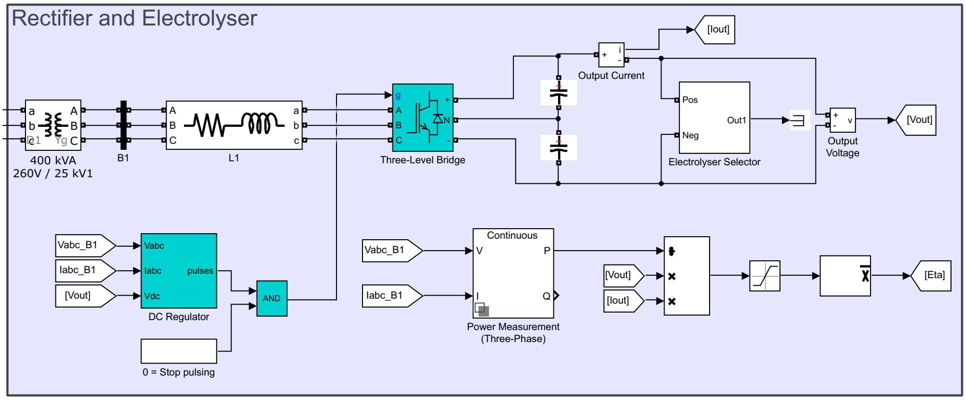

Figure 3.5: Integration of the Rectifier and Electrolyser with the Average Model

algorithm was drawn on paper for making corrections with ease. After having made a first draft of the control strategy on paper, a flowchart of the algorithm was made. The flowchart has been modified according to the final version of the control strategy and is presented in Chapter 4.

3.2.6. CONTROL STRATEGY MODEL

The next step was to make a Simulink model of the control strategy. The main features of the control strategy would be to make decisions based on the value of the incoming voltage and current values from the rectifier. This implies that the model would have to have multiple if-else loops and the hence the model comprised of various components, namely, the 'If-Else' block, the 'If Action' block, the 'Constant' block, the 'Compare to Constant' block and the 'MATLAB Function' block.

Following the initial draft of the control strategy, as changes were made to the model, simultaneously, different tools or features which could be used for simulating the model were searched for and studied.

STATEFLOW CHART

After having searched for various methods to incorporate an algorithm into a Simulink Model, without using the most common and convenient technique of using the 'If-Else' block, the 'If Action' block, the 'Constant' block and other components from the Simulink Library to build the model, a feature called a 'Stateflow Chart' was discovered in the process. It is a feature available on MATLAB Simulink and is also known as 'Chart'. Further explanation regarding the Stateflow Chart is given in Appendix A.

After having gained an understanding of how the Stateflow Chart works, the flowchart was implemented in the chart. The initial version of the control strategy model was tested with the help of 'Constant Blocks' being given as inputs to check if the algorithm was functioning as desired. One main reason to have chosen the Stateflow Chart for implementing the algorithm is the fact that when the model is running and when the control comes into the Stateflow Chart, the flow of the algorithm is indicated by highlighting the connections between the states in blue. This is indeed very helpful as it enables the user to understand whether the algorithm is working in the desired manner or not. This feature was extremely helpful to identify errors and debug the algorithm. Constant Blocks helped in testing the control strategy model in one iteration only. As the intention of the project is to control the working of the electrolyser throughout its operational period, the control strategy was required to be tested with continuous inputs. In order to do that, a MATLAB Function Block was used to continuously generate variables to test the working of the control strategy over a period of time. The MATLAB Function Block initially comprised of a linear function to generate inputs for testing the control strategy followed by a non-linear function. In this manner, the initial basic testing of the control strategy was performed.

MATLAB FUNCTION BLOCK

The MATLAB Function Block was simple to use and the same function that was constructed with the help of states, connecting arrows and conditions in the Stateflow Chart with was written into the function block as well.

3.2.7. INTEGRATION OF THE CONTROL STRATEGY WITH THE RECTIFIER

Following the basic testing, the Stateflow Chart was integrated with the rectifier or AC-DC converter. This was done by using a tag called 'Vdc_Ref' which would go to the DC Regulator and would be taken as the reference for the rectifier to produce the desired output DC voltage. While running the model, some issues were faced with respect to the simulation time due to the usage of the Stateflow Chart. Though it did help in producing the desired result, as the value of the current and voltage had to be given as inputs to the Chart and the DC voltage regulation had to take place throughout the operation of the electrolyser, the process of producing the output became time-consuming. In an attempt to find an alternate solution, the control strategy was written into the MATLAB Function block and then, the model was simulated. On running the model, it was found that the MATLAB Function Block consumed much lesser time than the Stateflow Chart to produce the output.

On the whole, though the Stateflow Chart was extremely helpful in aiding to visualize and understand the working of the control strategy, to debug it and to validate it, since it was slower than the MATLAB Function Block in terms of producing the result, the MATLAB Function Block was used to collect the results quicker.

4

The Control Strategy

This chapter intends to give the reader an understanding of why a control strategy is required for the optimal operation of the electrolyser, how the algorithm was formulated and a description of the control strategy in detail.

4.1. The Need for a Control Strategy

The electrolyser described in Chapter 2 is a device used to produce hydrogen. When it comes to any process, it is imperative that we take into account the amount of output produced by it. If the output produced by the process is maximum throughout its period of operation, then the process would be an efficient one. Likewise, here hydrogen is the end product of the process and hence the intention is to maximize the output of the electrolyser, that is, to ensure that the rated amount of hydrogen is produced throughout its operation. This is considered as the optimal operating condition in this research. In order to do that, it is necessary to identify which variable or which condition is to be satisfied to ensure that maximum amount of hydrogen is produced by the electrolyser. As mentioned in the Chapter 2, the amount of hydrogen produced by the electrolyser is dependent on the amount of current flowing into the electrolyser. Thus, for optimal operation of the electrolyser, it needs to be operated such that it draws the rated current.

As explained in Chapter 2, the temperature of the electrolyser does not remain constant throughout its operation. For an alkaline electrolyser, the relationship between the current, voltage and temperature is [15]:

$$V = \left[a_0 + a_1 T + b\ln(T) - \left(\frac{r_0}{T}\right) I\right] N_s \tag{4.1}$$

where, N_s refers to the number of electrolyser cells, a_o, a_1 and b are electrolyser parameters which will differ based on the characteristics of the electrolyser and r_o is the internal resistance of the cell.

Temperature plays an important role in the working of an electrolyser and as shown in the above equation, both current and voltage are dependent on it. As the temperature of the electrolyser increases, a particular value of current can be produced at a lower value of voltage. That is, as the temperature increases, the potential required to bring about the reaction reduces [16]. Hence, the electrolyser behaves similar to a variable resistor [15]. So increasing the temperature of the electrolyser can help in increasing the amount of current flowing through the electrolyser. In addition to this, the amount of hydrogen produced is proportional to the amount of current flowing through the electrolyser [15]. It can be concluded that, increasing the input current to the electrolyser would result in increased hydrogen production.

4.2. THE CONTROL STRATEGY

The need for this control strategy rose due to the varying temperature of the electrolyser and its impact on the I-V curve of the electrolyser. The aim of the control strategy is to maintain the rated current throughout the operation of the electrolyser, despite the fluctuation of its temperature. The value of current flowing through the electrolyser is taken as the deciding variable for the algorithm. The inputs given to the algorithm are as follows:

- Current flowing into the electrolyser (A)
- Voltage across the electrolyser (V)

Both of the above values are measured on the load side. The algorithm takes the input current value and compares it with the rated current value. If the former is greater, since the algorithm intends to maintain the rated current value, it calculates the difference between the input current value and the rated current value of the electrolyser. Based on this difference, the DC voltage reference for the rectifier is generated by the control strategy. If the input current value is lesser than the rated current value then the voltage is incremented in order to make the current reach the rated value. If the input current is equal to the rated current, then the voltage value will remain the same.

Through this method, the value of the temperature of the electrolyser is not given as an input to the control strategy, but when a change occurs in the temperature, the algorithm will continue to monitor the value of the current and check whether it is at the rated value or not. If it is not at the rated value, then the value of the voltage corresponding to the rated current value at that particular temperature will be found and the DC voltage reference will be generated accordingly by the control strategy which will then be sent to the rectifier. Finally, the desired output voltage will be produced by the rectifier and thus, the optimal operating condition of the electrolyser is achieved.

When the input current value is greater than the rated current value, the difference between the input current value and the rated current value of the electrolyser is calculated and then, based on the difference, the voltage is decremented. Initially, the values used as step sizes for decreasing the voltage value were discrete and were chosen based on the voltage range of the data that was used to test the electrolyser for this research. Different sets of values were compared to study which one of them would be most appropriate for the electrolyser taken into consideration. Based on the comparison, a set of values were used and the control strategy produced the expected results. In the next iteration, a factor was calculated to replace the discrete value. The control strategy was tested with these factors being used and it rendered the expected results. These factors were found to work well for this case, with the chosen voltage and current ranges.

When the input current value is greater than the rated current, the control strategy further provides three conditions to decide what action should be performed on the voltage, based on the difference between the input current and the rated current. If the difference is lesser than 5 V, then the output of the control strategy is the incoming voltage minus 3 V. If the difference lies between 5 V and 10 V, then the voltage is decremented by 5 V and for a difference greater than 10 V, the voltage is decremented by 10 V. Hence the first set of values for the step size was 3 V, 5 V and 10 V. After having tested the control strategy with the above mentioned set of values, in an attempt to study the behaviour of the control strategy and to improve the algorithm, 2 more sets of values (5 V, 7 V, 10 V and 7 V, 10 V, 15 V) were taken and a comparison was drawn. Finally, a factor was calculated to replace the discrete value. The calculation of the factor is explained in Appendix B.

The equation to obtain the output of the control strategy, V_{ref}, is:

$$V_{\text{ref}} = V_{\text{in}} - \left[factor \times (I_{\text{in}} - I_{\text{rated}})\right] \tag{4.2}$$

where, I_{in} is the input current to the electrolyser, I_{rated} is the rated current of the electrolsyer and V_{in} is the voltage across the electrolyser.

For every value of difference and every value of step size, the factor was calculated. Out of all the values, the factors that rendered the most promising results (0.6 V/A, 0.5 V/A and 0.67 V/A) were incorporated into the control strategy.

On having observed that the control strategy was successful in producing the desired results, a general version of the control strategy for an electrolyser was formulated and is presented in Appendix B.

4.3. THE CONTROL STRATEGY IN THE STATEFLOW CHART

Though the control strategy was implemented using the stateflow chart only during the initial phase, it proved to be immensely helpful in debugging the code. Shown below is a figure of the control strategy's Stateflow Chart in the Simulink model followed by a figure showing the definition of the initial version of the control strategy in the Stateflow Chart.

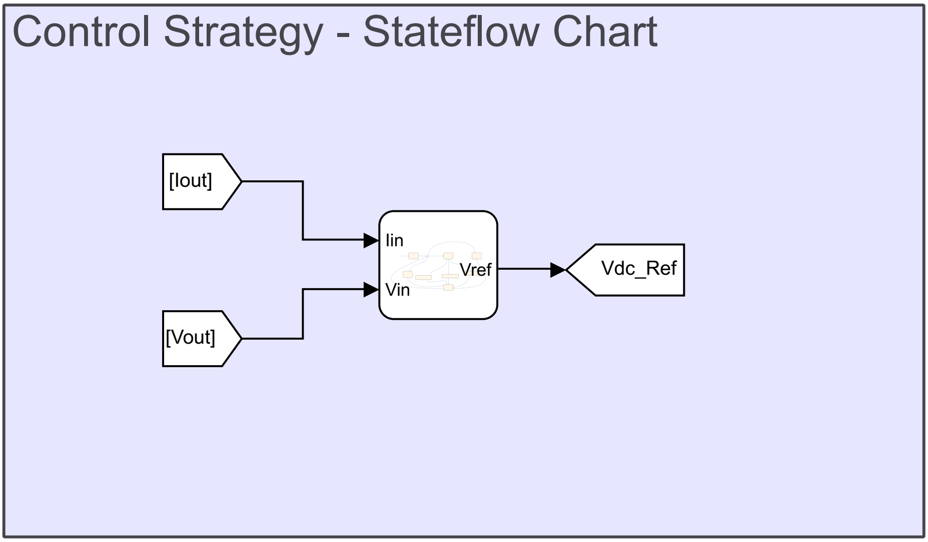

Figure 4.1: The control strategy's Stateflow Chart in the Simulink model

The parameters I_{out} and V_{out} refer to the input current to the electrolyser and the voltage across the electrolyser respectively, in the Simulink model.

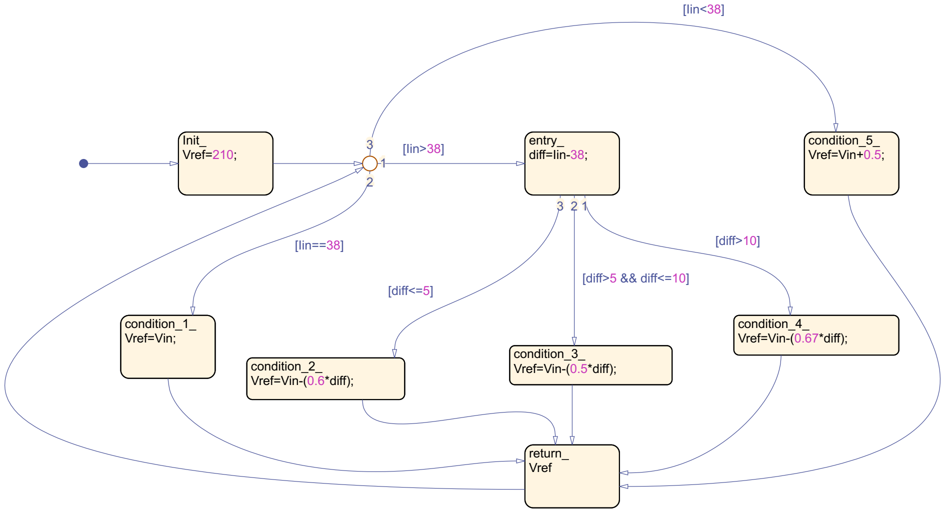

Figure 4.2: The control strategy defined in the Stateflow Chart

4.4. THE FLOWCHART

Shown below is a flowchart depicting the final version of the control strategy.

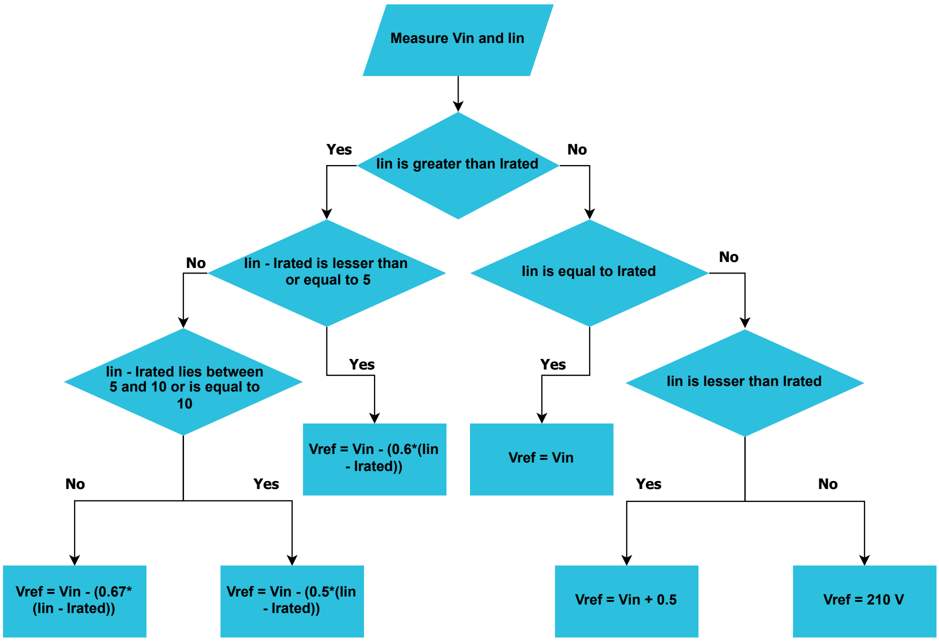

Figure 4.3: A flowchart of the control strategy

4.5. THE CONTROL STRATEGY IN THE MATLAB FUNCTION BLOCK

Shown below is a figure of the control strategy's MATLAB Function Block in the Simulink model followed by a figure showing the definition of the control strategy in the MATLAB Function Block.

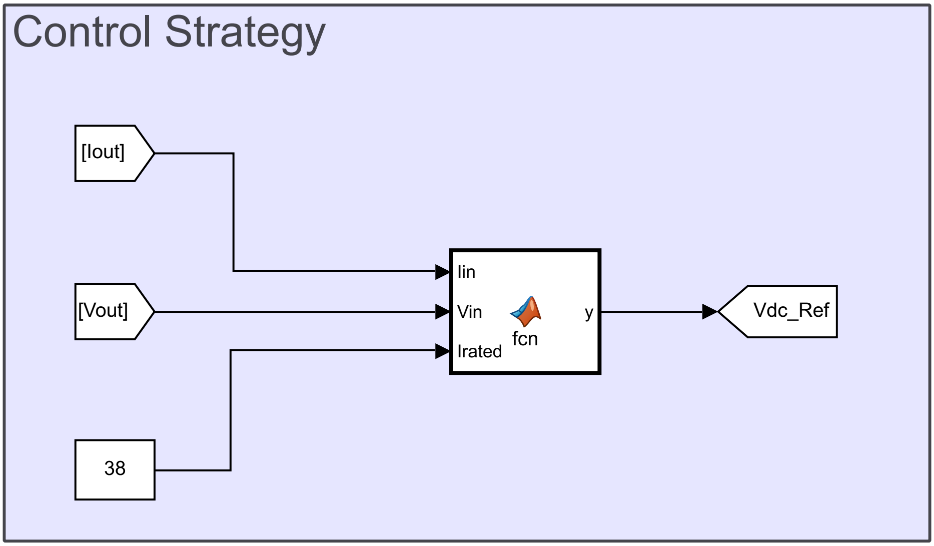

Figure 4.4: The control strategy's MATLAB Function Block in the Simulink model

The parameters Iout and Vout refer to the input current to the electrolyser and the voltage across the electrolyser respectively, in the Simulink model.

4

```
function Vref = fcn(Iin, Vin, Irated)

if(Iin > Irated)

    if (Iin-Irated<=5)
        Vref = Vin- (0.6*(Iin-Irated));
    elseif (Iin-Irated>5 && Iin-Irated<=10)
        Vref = Vin -(0.5*(Iin-Irated));
    else
        Vref = Vin-(0.67*(Iin-Irated));
    end

elseif ( Iin == Irated)
            Vref = Vin;
elseif ( Iin < Irated)
            Vref = Vin+(0.5);
else
            Vref = 210;
end
```

Figure 4.5: The control strategy defined in the MATLAB Function Block

5

Results

This section presents the results of the simulations of the model on Simulink with appropriate explanation in order to understand and interpret the results.

5.1. The Approach

This research focuses on a PV-grid powered electrolyser application whose temperature is bound to change during its operation. The change in temperature of the electrolyser has an effect on its I-V curve. The electrolyser converts electrical energy into chemical energy and its end product is hydrogen. The amount of hydrogen produced is proportional to the amount of current flowing into the electrolyser. Hence, the control strategy aims to keep the amount of current flowing into the electrolyser at the rated value, irrespective of the change in temperature. Simulations of the model comprising of the control strategy were performed. Along with the simulation results of the control strategy, the results of other significant parameters which are important to study the working of the developed control strategy have been presented as well. Besides having performed simulations under various ambient conditions, the model was also tested with real-time data for irradiance and ambient temperature for an entire day (1440 minutes). In addition to this, data was obtained to find a correlation between the irradiance and the temperature of the electrolyser and the performance of the electrolyser was recorded under this condition as well.

5.1.1. Irradiance

This application being PV-grid powered, the amount of irradiance available for the PV array plays a crucial role in determining the amount of PV power produced by it. At the STC condition (irradiance: 1000 W/m^2, module temperature:

25°C), the PV array used in this model will produce 20 kW.

5.1.2. PV POWER

Based on the irradiance and the module temperature, the amount of PV power (measured in kW) produced is also presented in the results.

5.1.3. GRID POWER

Owing to the intermittent nature of PV, the model is connected to the grid in order to ensure that power is supplied continuously to the electrolyser. When there is excess PV power available after having satisfied the electrolyser's demand, the excess power is sent to the grid. Similarly, when there is a deficit of PV power, power from the grid is imported to satisfy the electrolyser's demand. The amount of power imported from or exported to the grid is shown in the results.

5.1.4. VOLTAGE

The voltage across the electrolyser is recorded in the results mainly to test the working of the control strategy. The control strategy produces the DC voltage reference that is given to the rectifier. As the temperature of the electrolyser changes, the voltage across the electrolyser will change, while maintaining the rated current, which is shown in the results.

5.1.5. CURRENT

The control strategy aims to maintain the input current to the electrolyser at its rated value. The result shows the current being maintained at 38 A, which is the rated current for the electrolyser taken into consideration in this project and hence proves that the control strategy works well.

5.1.6. TEMPERATURE

The temperature of the electrolyser is the most crucial parameter used to study and test the working of the control strategy. The module temperature has an effect on the amount of PV power produced and hence, it has been recorded as well.

5.1.7. EFFICIENCY

For every system it is imperative that the efficiency is calculated. In this project, the efficiency of the rectifier after having employed the control strategy is calculated and presented in the results.

5.2. INTERPRETATION OF THE GRAPHS

The results are broadly classified into two figures, one where the irradiance, PV power, import/export of grid power and module temperature are shown and the other where the voltage across the electrolyser, the input current to the electrolyser, the temperature of the electrolyser and the efficiency of the converter are depicted. A brief explanation of how to interpret the results is given below.

5.2.1. IRRADIANCE, PV POWER, IMPORT/EXPORT OF GRID POWER AND MODULE TEMPERATURE

The irradiance, PV power, grid power and module temperature are shown simultaneously. The import/export of grid power has to be interpreted in the following way:

- Since the rating of the electrolyser taken into consideration is 10 kW, if the available PV power exceeds 10 kW, the excess power will be exported to the grid, which will be indicated by positive power in the result.
- If the available PV power is below 10 kW, it will be completely used up by the electrolyser and the rest will be imported from the grid to satisfy the electrolyser's demand, which is depicted by negative power in the result.
- If the available PV power is equal to 10 kW,the electrolyser's demand will be completely satisfied by PV power and hence the result will show that the power is neither being exported to nor being imported from the grid, in other words, the grid power will be equal to 0.

5.2.2. VOLTAGE, CURRENT, ELECTROLYSER TEMPERATURE AND EFFICIENCY

The figure containing the voltage across the electrolyser, the input current to the electrolyser, the temperature of the electrolyser and the efficiency of the converter intends to present the performance of the control strategy. With the control strategy in place, as the temperature of the electrolyser changes, the current must remain at 38 A and this should happen by altering the voltage across the electrolyser at that temperature, based on whether the temperature is increasing or decreasing. This can be observed through this figure. Moreover, the efficiency of the rectifier with the control strategy is also presented along with the above mentioned parameters.

5.3. SIMULATION RESULTS

5.3.1. TEMPERATURE OF THE ELECTROLYSER IS CONSTANT (25°C)

In this result, the temperature of the electrolyser is 25°C. The PV array produces 20 kW of power as the irradiance is 1000 W/m^2 and the module temperature is 25°C (STC condition). The voltage across the electrolyser is 260 V and the input current to the electrolyser is 38 A.

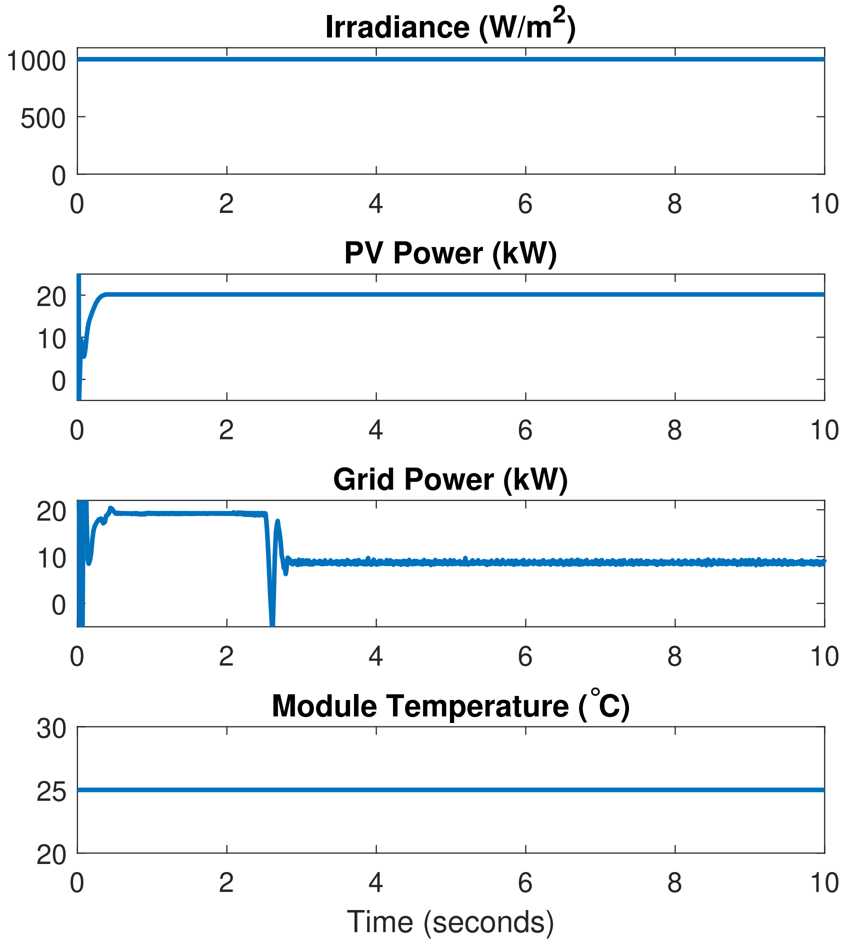

Figure 5.1: Irradiance, PV Power, Import/Export of Grid Power and Module Temperature when the temperature of the electrolyser is constant at 25°C

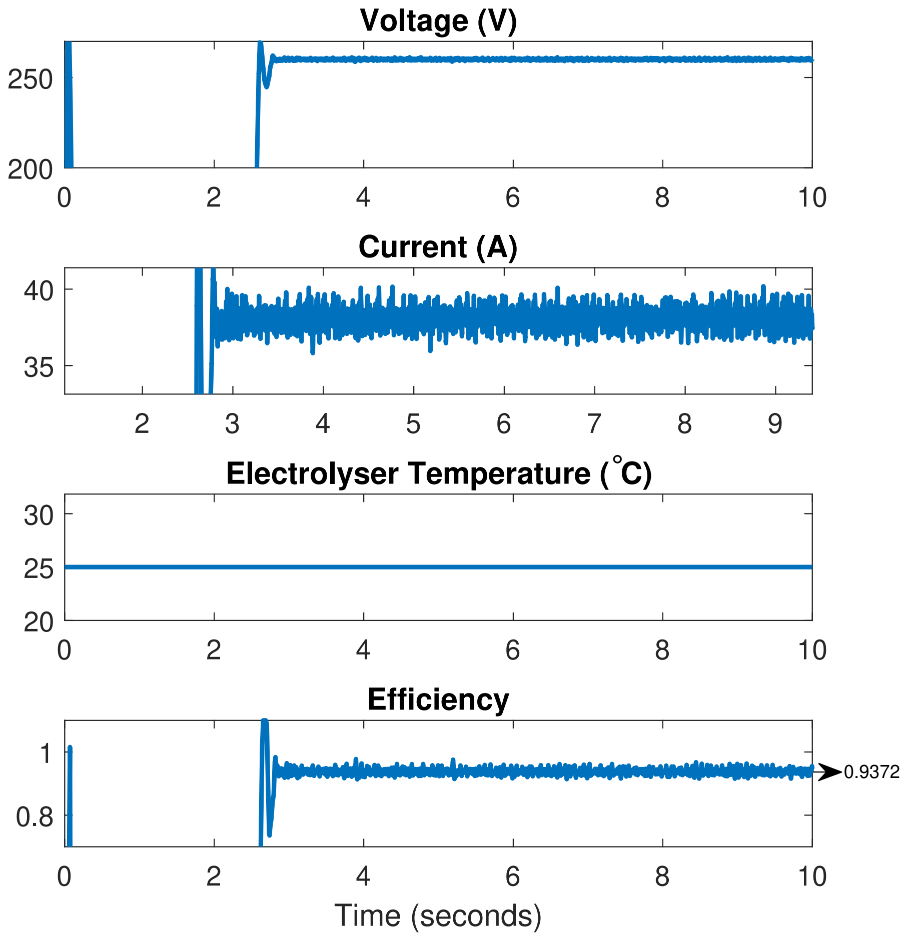

Figure 5.2: Voltage, Current, Electrolyser Temperature and Efficiency when the temperature of the electrolyser is constant at 25°C

5.3.2. TEMPERATURE OF THE ELECTROLYSER IS CONSTANT (35°C)

Here, the temperature of the electrolyser is 35°C. The PV array produces 20 kW of power as the irradiance is 1000 W/m^2 and the module temperature is 25°C (STC condition). The voltage across the electrolyser is 250 V and the input current to the electrolyser is 38 A.

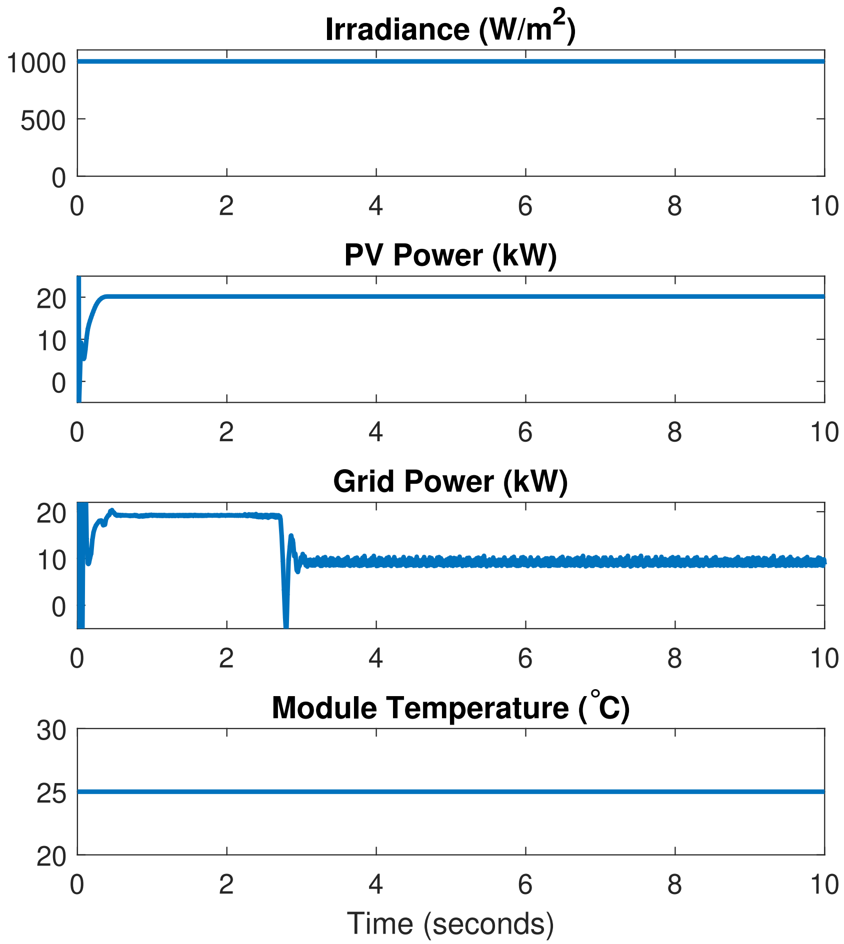

Figure 5.3: Irradiance, PV Power, Import/Export of Grid Power and Module Temperature when the temperature of the electrolyser is constant at 35°C

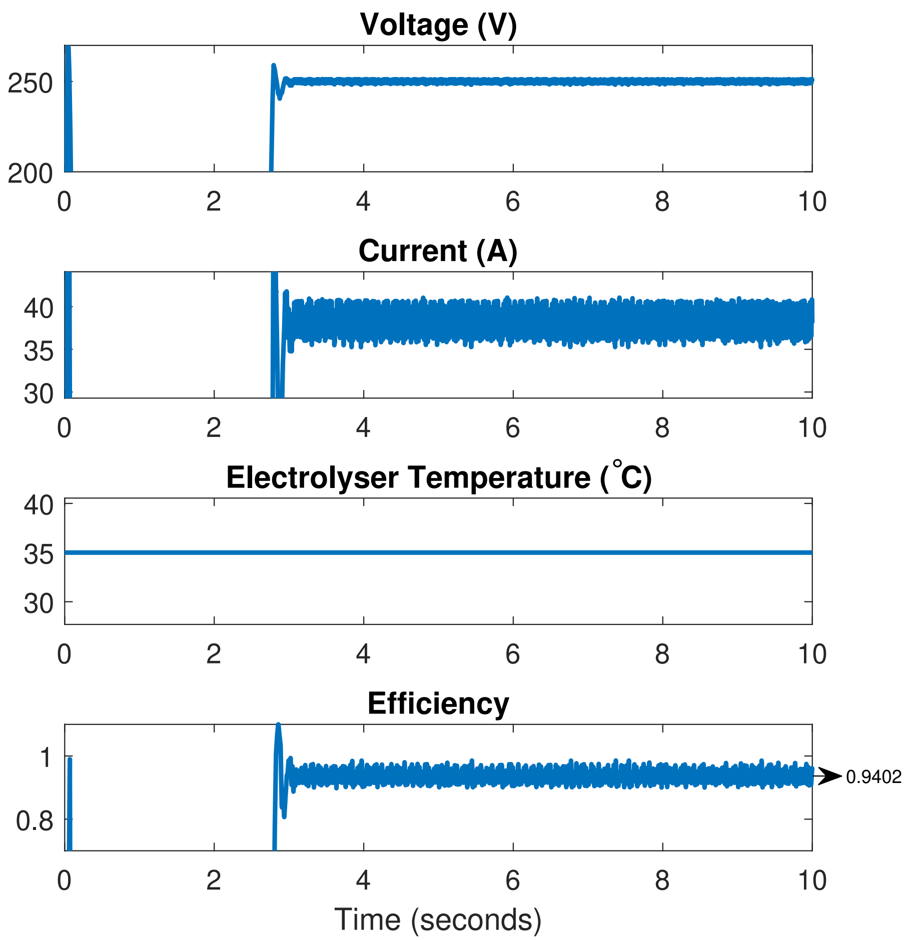

Figure 5.4: Voltage, Current, Electrolyser Temperature and Efficiency when the temperature of the electrolyser is constant at 35°C

5.3.3. TEMPERATURE OF THE ELECTROLYSER CHANGES FROM 25°C TO 35°C

This result is a combination of the previous two results to indicate working of the control strategy when the temperature of the electrolyser changes from 25°C to 35°C. The PV array produces 20 kW of power as the irradiance is 1000 W/m^2 and the module temperature is 25°C (STC condition). It can be seen that the voltage across the electrolyser reduces from 260 V to 250 V as the temperature of the electrolyser increases from 25°C to 35°C, thereby maintaining the input current at the desired value of 38 A.

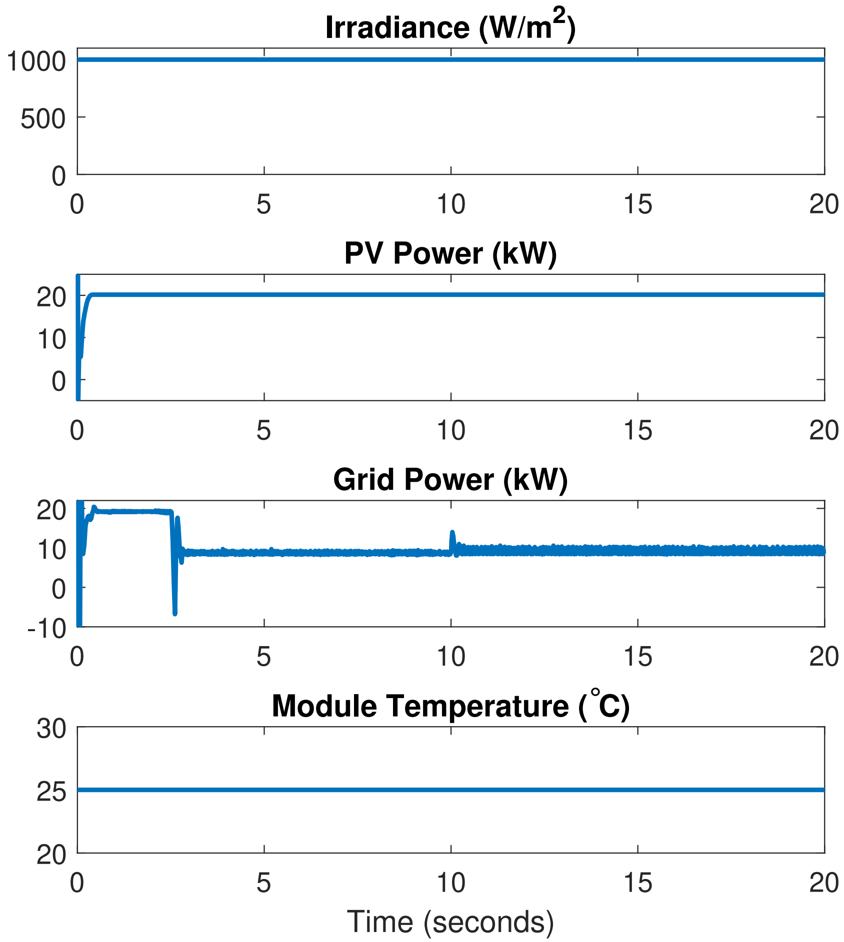

Figure 5.5: Irradiance, PV Power, Import/Export of Grid Power and Module Temperature when the temperature of the electrolyser changes from 25°C to 35°C

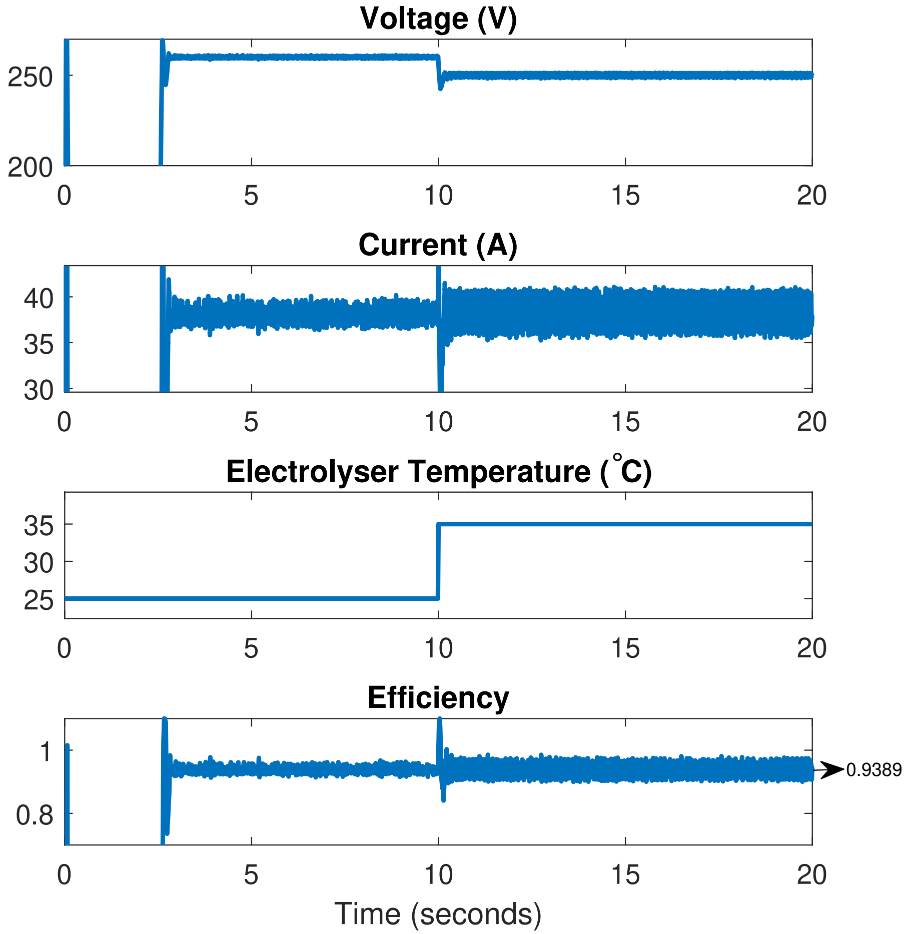

Figure 5.6: Irradiance, PV Power, Import/Export of Grid Power and Module Temperature when the temperature of the electrolyser changes from 25°C to 35°C

5.3.4. TEMPERATURE OF THE ELECTROLYSER RANGES FROM 25°C UP TO 70°C

In this case, the temperature of the electrolyser is made to vary with time and the working of the control strategy is observed. The PV array produces 20 kW of power as the irradiance is 1000 W/m^2 and the module temperature is 25°C (STC condition). As the temperature of the electrolyser changes, the voltage across the electrolyser changes in such a way that the desired value of 38 A is given as input current to the electrolyser.

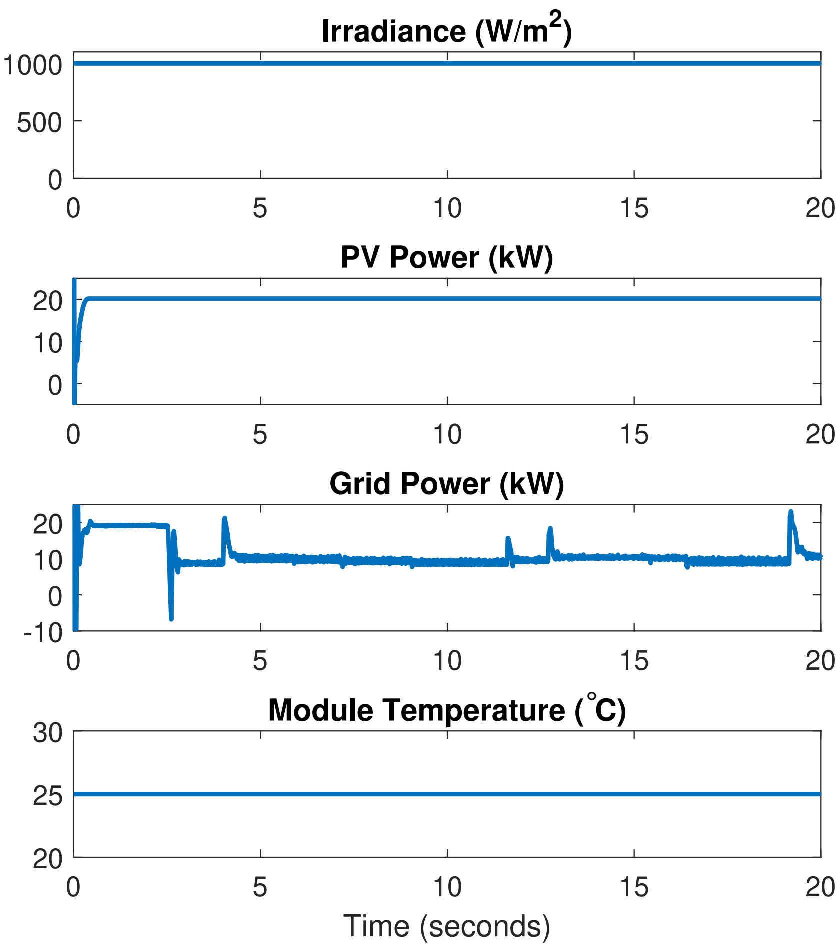

Figure 5.7: Irradiance, PV Power, Import/Export of Grid Power and Module Temperature when the temperature of the electrolyser ranges from 25°C to 70°C

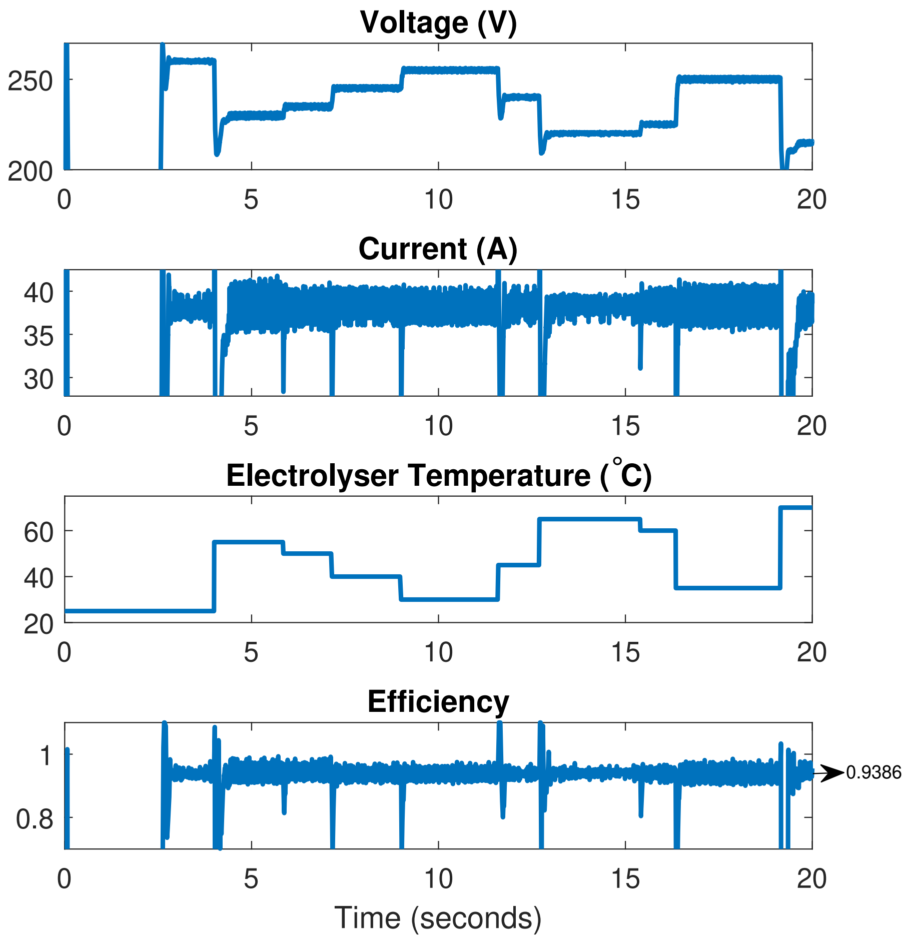

Figure 5.8: Voltage, Current, Electrolyser Temperature and Efficiency when the temperature of the electrolyser ranges from 25°C to 70°C

For all four cases discussed above, since the PV power produced (20 kW) is above the demand of the electrolyser (10 kW), it can be seen that the remaining power is exported to the grid (indicated by positive power in the figure).

5.3.5. TEMPERATURE OF THE ELECTROLYSER CHANGING THROUGHOUT, VARYING IRRADIANCE AND CONSTANT MODULE TEMPERATURE

Similar to the previous result, this result shows that the temperature of the electrolyser changes but the control strategy ensures that the input current to the electrolyser is maintained at 38 A. Unlike the previous cases, the irradiance does not remain constant whereas the module temperature remains constant at 25°C. In this case, since the irradiance is varying, the amount of power exported to the grid or imported from the grid depends on the amount of PV power produced by the PV array and the result shows positive power or negative power accordingly.

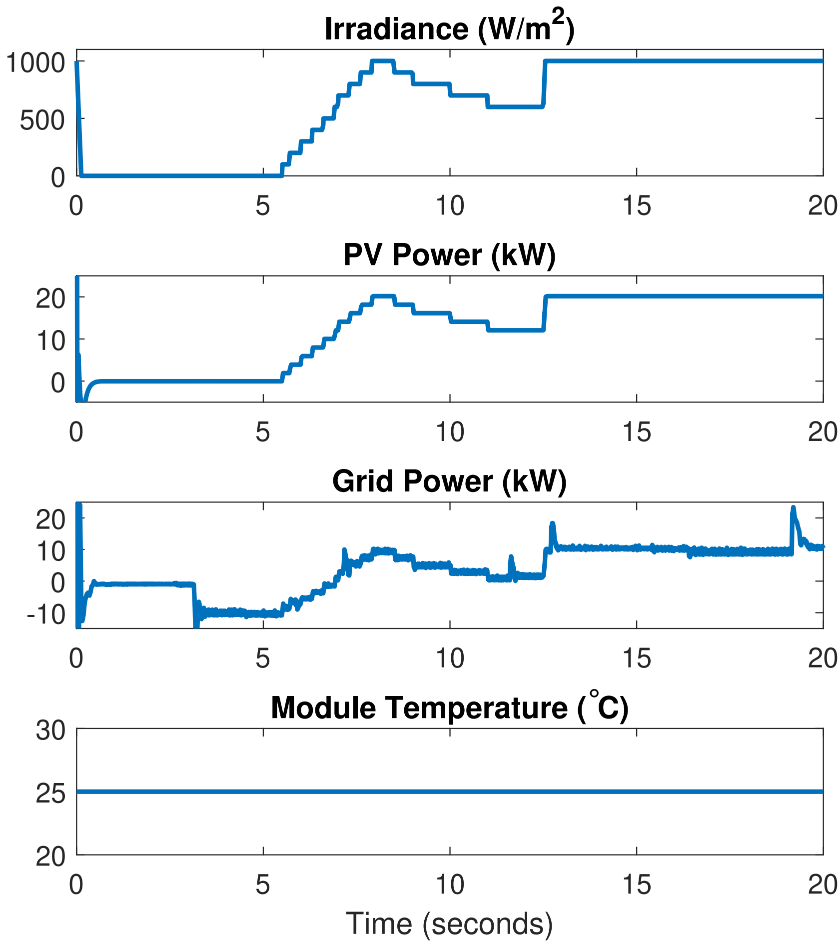

Figure 5.9: Irradiance, PV Power, Import/Export of Grid Power and Module Temperature with varying electrolyser temperature, varying irradiance and constant module temperature

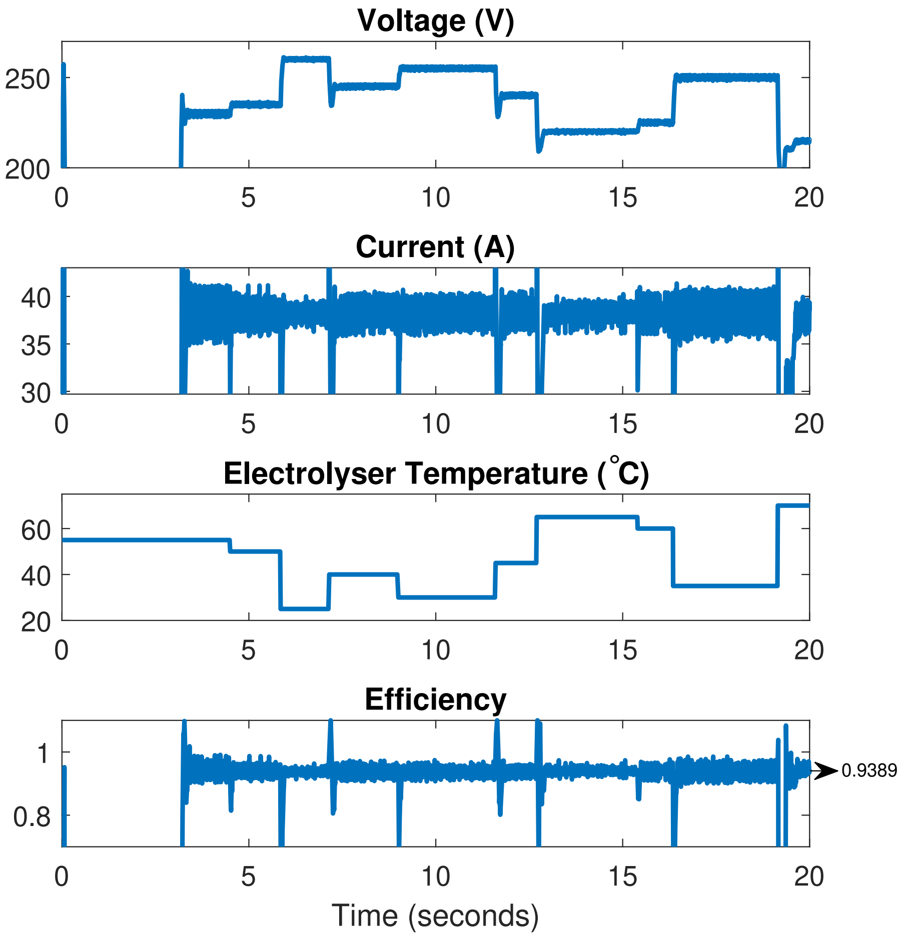

Figure 5.10: Voltage, Current, Electrolyser Temperature and Efficiency with varying electrolyser temperature, varying irradiance and constant module temperature

5.3.6. Temperature of the electrolyser is constant (25°C), varying irradiance and constant module temperature

Here, the temperature of the electrolyser remains constant at 25°C while there is a change in the irradiance. The module temperature remains constant at 25°C. It can be seen that the control strategy makes sure that the input current to the electrolyser is maintained at 38 A.

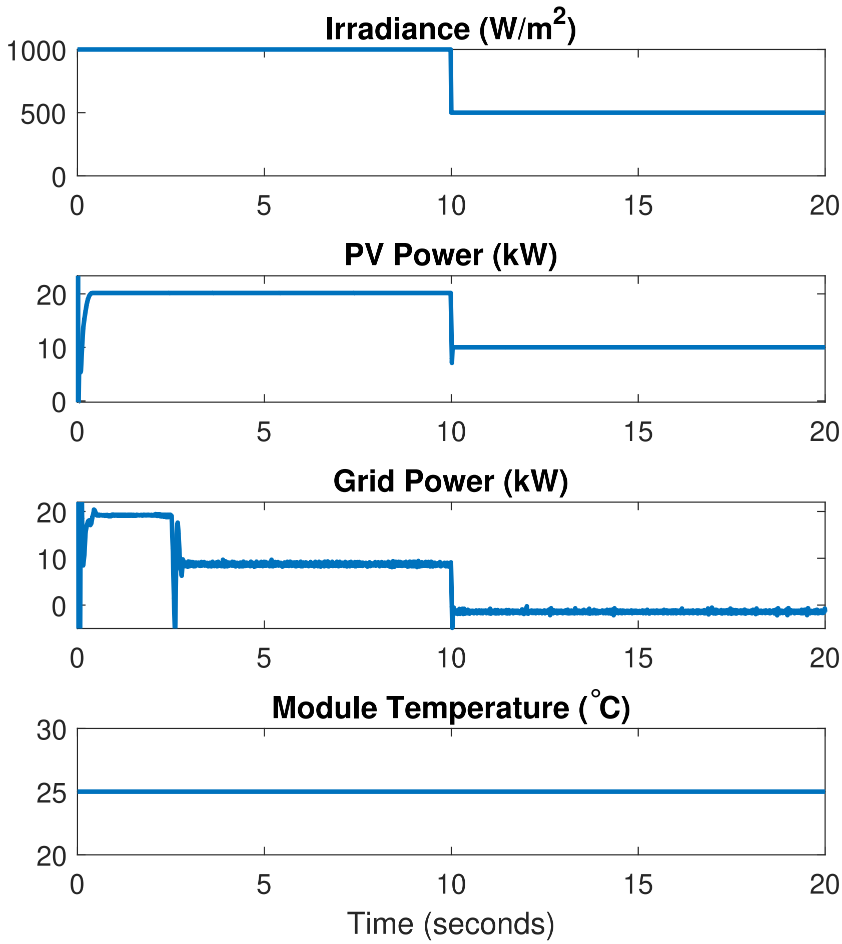

Figure 5.11: Irradiance, PV Power, Import/Export of Grid Power and Module Temperature with constant electrolyser temperature, varying irradiance and constant module temperature

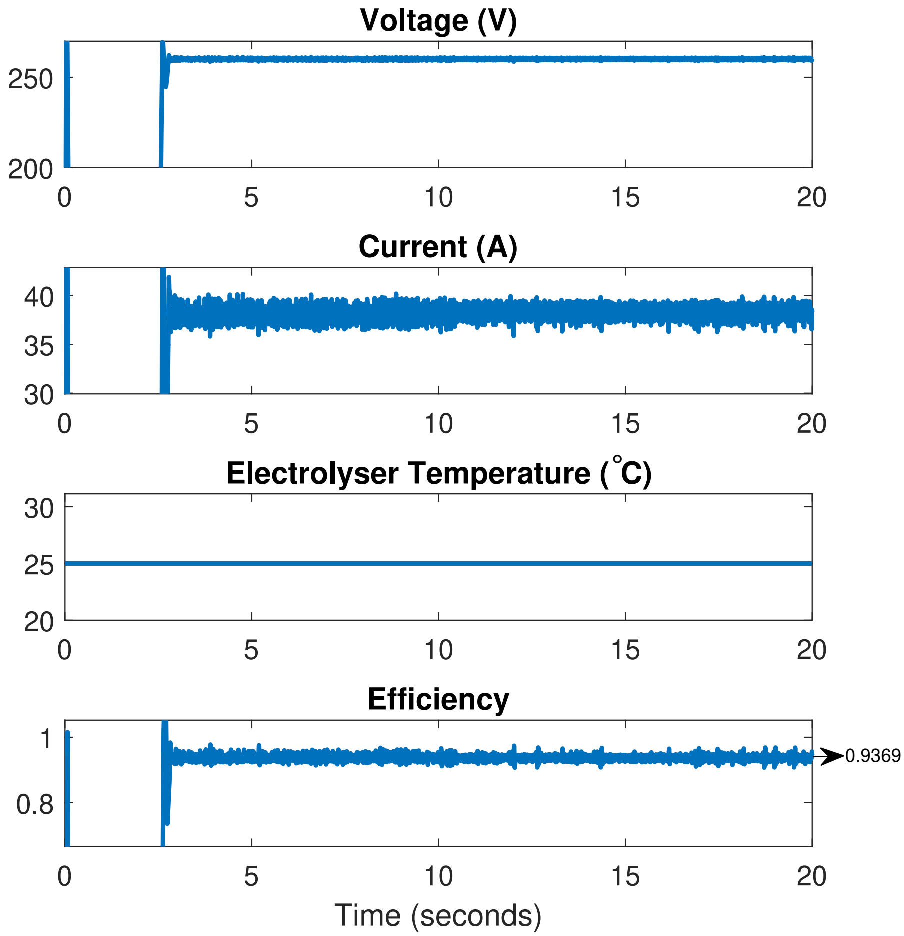

Figure 5.12: Voltage, Current, Electrolyser Temperature and Efficiency with constant electrolyser temperature, varying irradiance and constant module temperature

5.3.7. TEMPERATURE OF THE ELECTROLYSER CHANGING THROUGHOUT, CONSTANT IRRADIANCE AND VARYING MODULE TEMPERATURE

This case represents a situation where the irradiance is constant but the module temperature is varying. The module temperature has an effect on the PV array's output. As the module temperature increases beyond 25°C, the PV power produced tends to decrease, which can be observed in the results. The irradiance is considered to be constant at 1000 W/m^2 and the control strategy maintains the input current to the electrolyser at 38 A despite the varying temperature of the electrolyser.

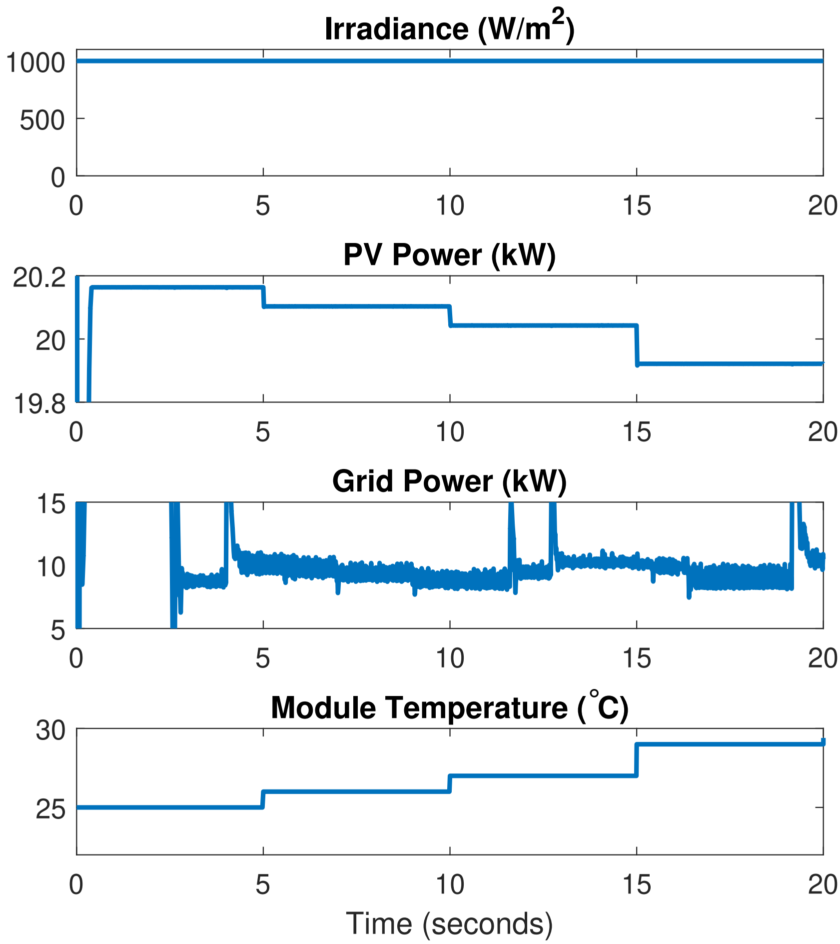

Figure 5.13: Irradiance, PV Power, Import/Export of Grid Power and Module Temperature with varying electrolyser temperature, constant irradiance and varying module temperature

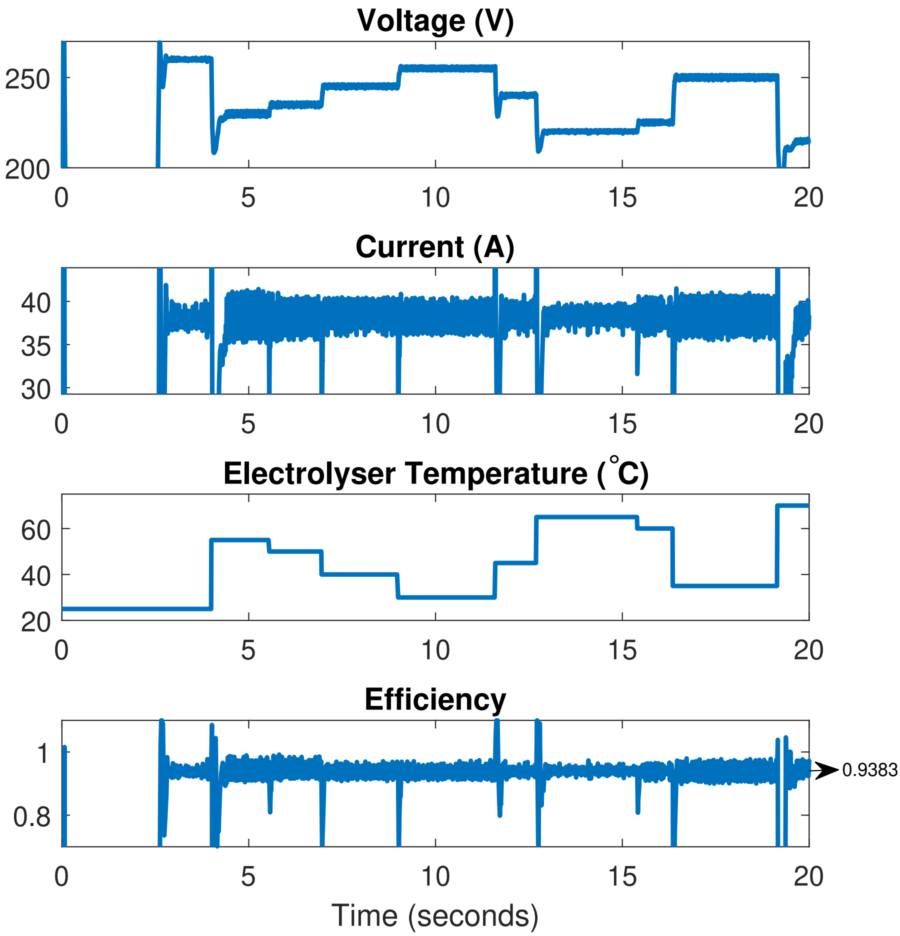

Figure 5.14: Voltage, Current, Electrolyser Temperature and Efficiency with varying electrolyser temperature, constant irradiance and varying module temperature

5.3.8. TEMPERATURE OF THE ELECTROLYSER CHANGING THROUGHOUT, VARYING IRRADIANCE AND VARYING MODULE TEMPERATURE

This case is a combination of all of the above cases, with varying irradiance, varying module temperature and varying electrolyser temperature. Even in this case, the electrolyser is supplied with 38 A of input current although the temperature of the electrolyser is varying, which indicates that the control strategy works successfully.

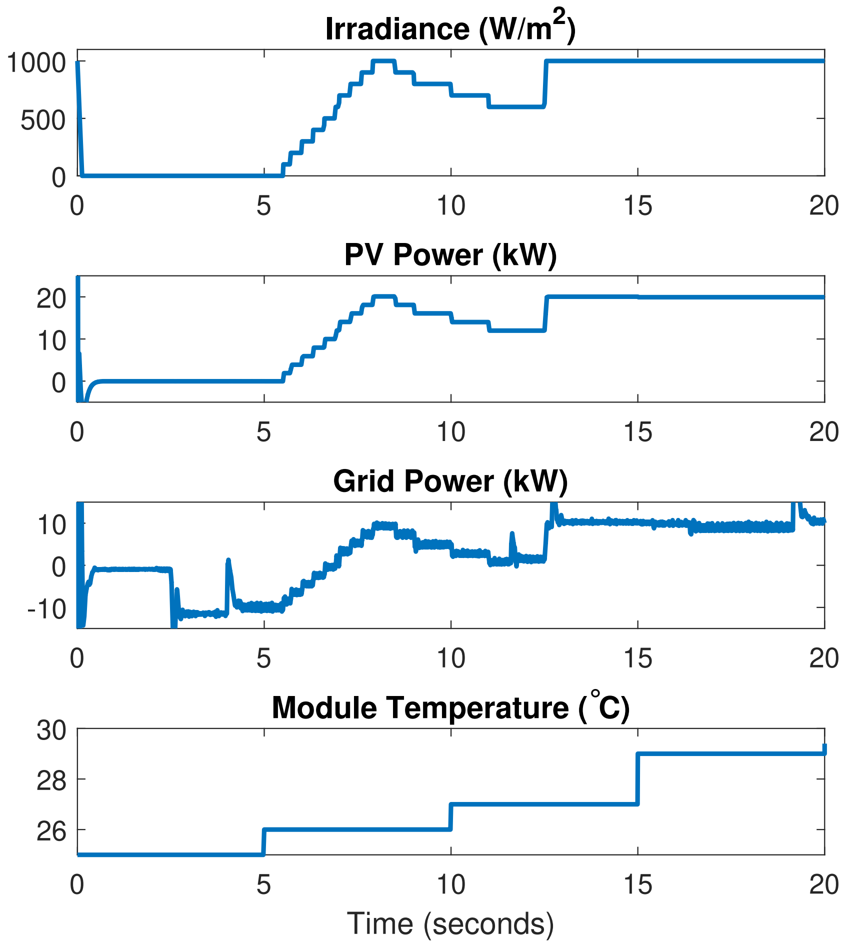

Figure 5.15: Irradiance, PV Power, Import/Export of Grid Power and Module Temperature with varying electrolyser temperature, varying irradiance and varying module temperature

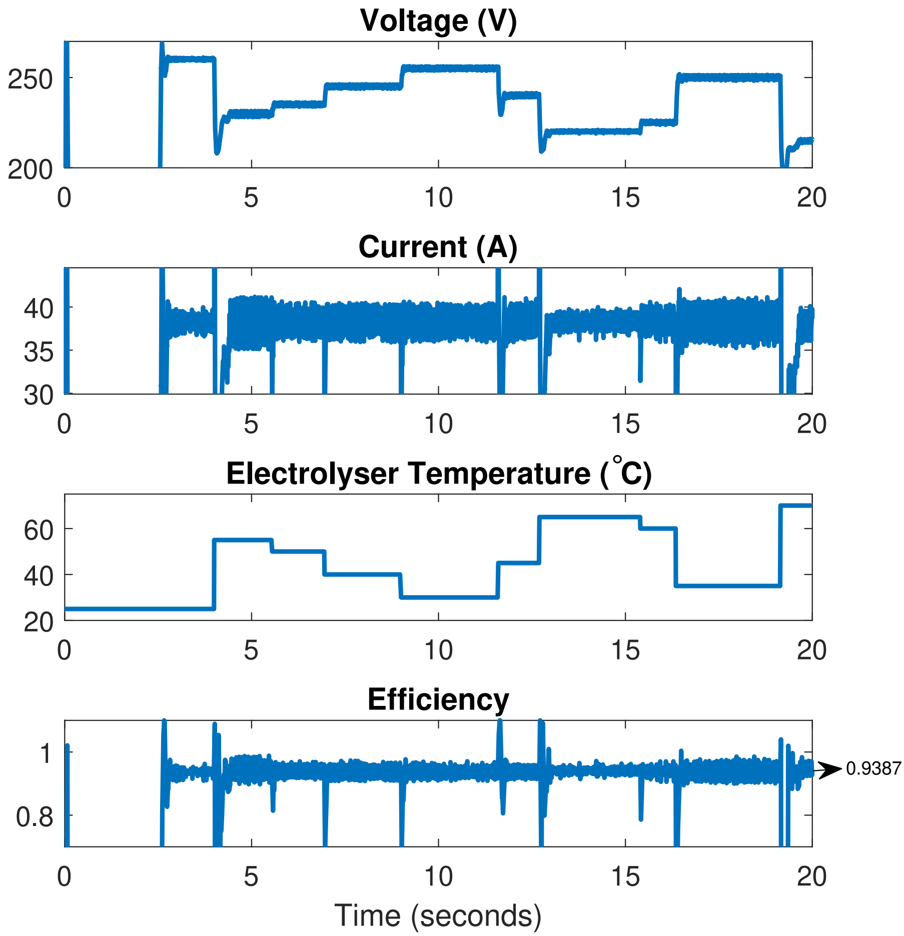

Figure 5.16: Voltage, Current, Electrolyser Temperature and Efficiency with varying electrolyser temperature, varying irradiance and varying module temperature

5.3.9. IRRADIANCE AND ELECTROLYSER TEMPERATURE

The ambient conditions influence the temperature of the electrolyser [23]. It was found that as the irradiance increases through the course of the day, the temperature of the electrolyser also increases. Based on the data obtained from [24], the curves for irradiance and the temperature of the electrolyser were plotted and fed as inputs to the model to observe the output of the control strategy, that is, whether 38 A is maintained throughout the operation time of the electrolyser. The result proves that the control strategy is successful in producing the desired result.

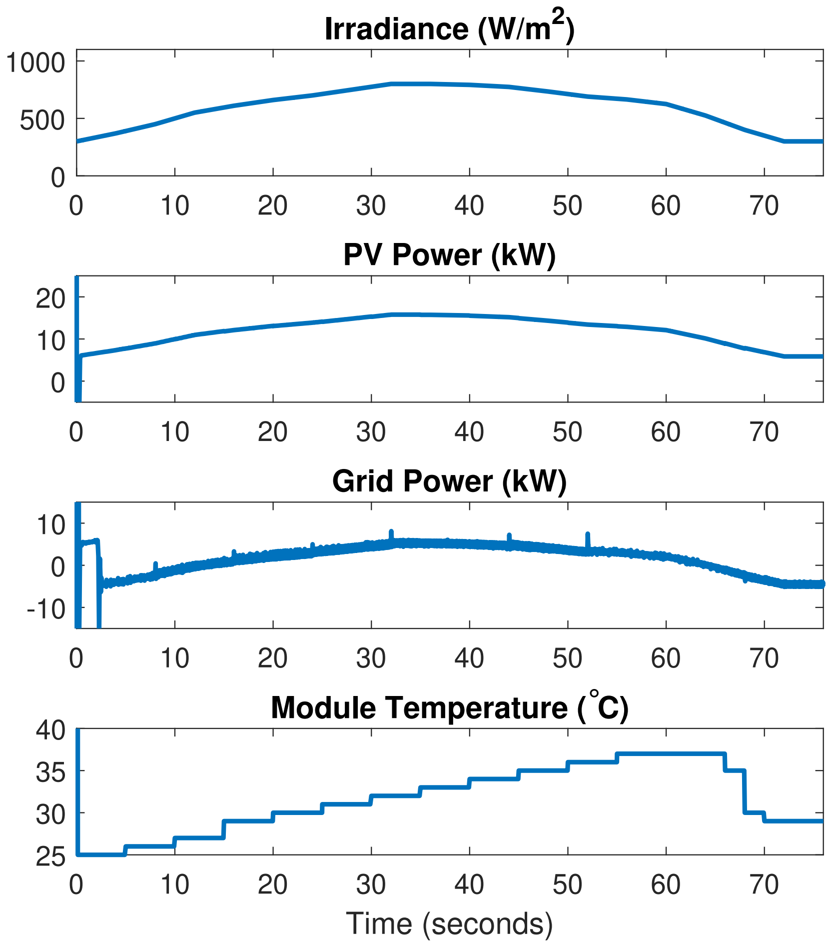

Figure 5.17: Irradiance, PV Power, Import/Export of Grid Power and Module Temperature with varying electrolyser temperature, varying irradiance and varying module temperature

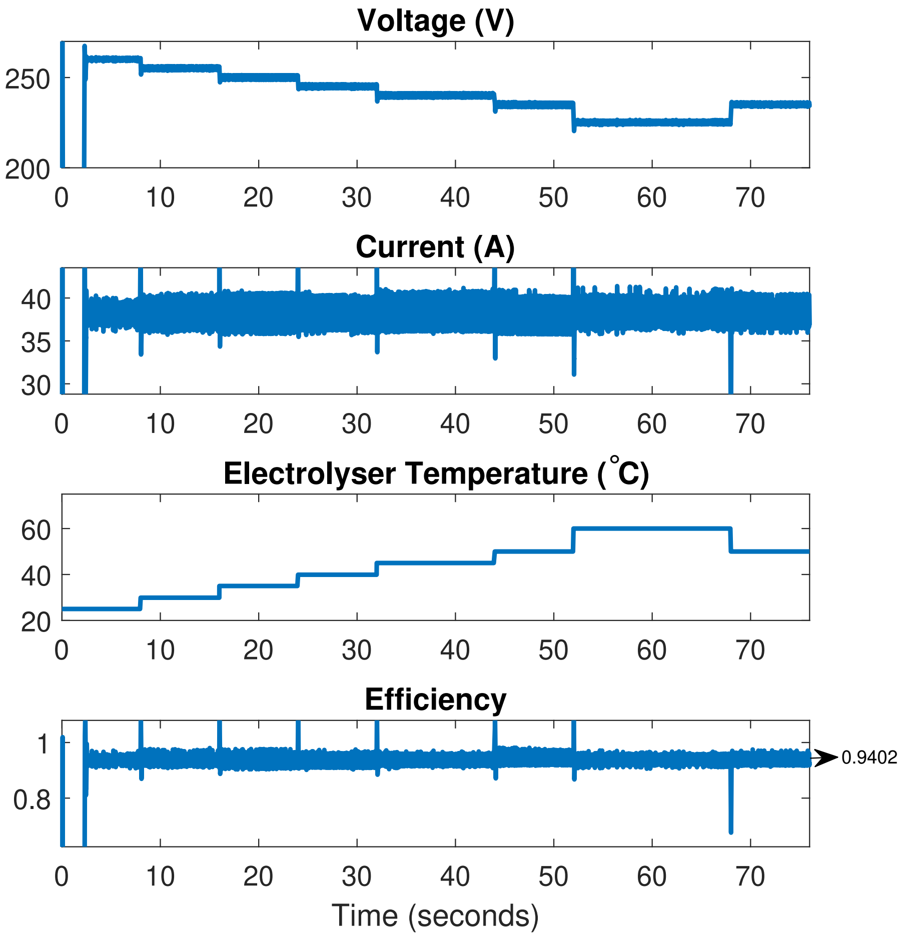

Figure 5.18: Voltage, Current, Electrolyser Temperature and Efficiency with varying electrolyser temperature, varying irradiance and varying module temperature

5.4. RESULTS USING REAL-TIME DATA

Although the data points fed into the look-up table of the electrolyser emulator remain the same, in order to observe how the model works when real-time data is given as input, simulations were performed to test the data for a clear day and a highly variable day. Real-data for irradiance and ambient temperature were fed as inputs for 1440 minutes. In order to calculate the module temperature to be given as the input to the PV array, the following formula was used:

$$T_{\mathrm{M}} = T_{\mathrm{a}} + \left(\frac{T_{\mathrm{NOCT}} - 20°C}{800} \times G_{\mathrm{M}} \right) \tag{5.1}$$

where T_M is the module temperature, T_a is the ambient temperature, T_{NOCT} is the nominal operating cell temperature (NOCT) and G_M is the solar irradiance [21].

The results of the simulations are shown below.

5

5.4.1. CLEAR DAY RESULT

Here, real-time data for a clear day was used to run the simulation. Data for the entire day starting at 00:00 hrs to 23:59 hrs (1440 minutes and hence 1440 data points) for irradiance and ambient temperature were fed to the model as inputs. The temperature of the electrolyser was taken as random values varying between 25°C and 70°C. The results of this day long simulation are shown below through which it is observed that the control strategy manages to maintain 38 A as the input current to the electrolyser, throughout the day. The average efficiency of the converter on a clear day is 93.97%. For the initial and last hours, when the irradiance is 0 W/m^2, the electrolyser's demand is completely satisfied by the grid and this is indicated by negative power in the result. For the rest of the hours, depending on the amount of PV power produced, the exchange of power with the grid is depicted accordingly. It can be seen that on the clear day, only for approximately 4.5 continuous hours power is exported to the grid after having satisfied the electrolyser's demand.

5

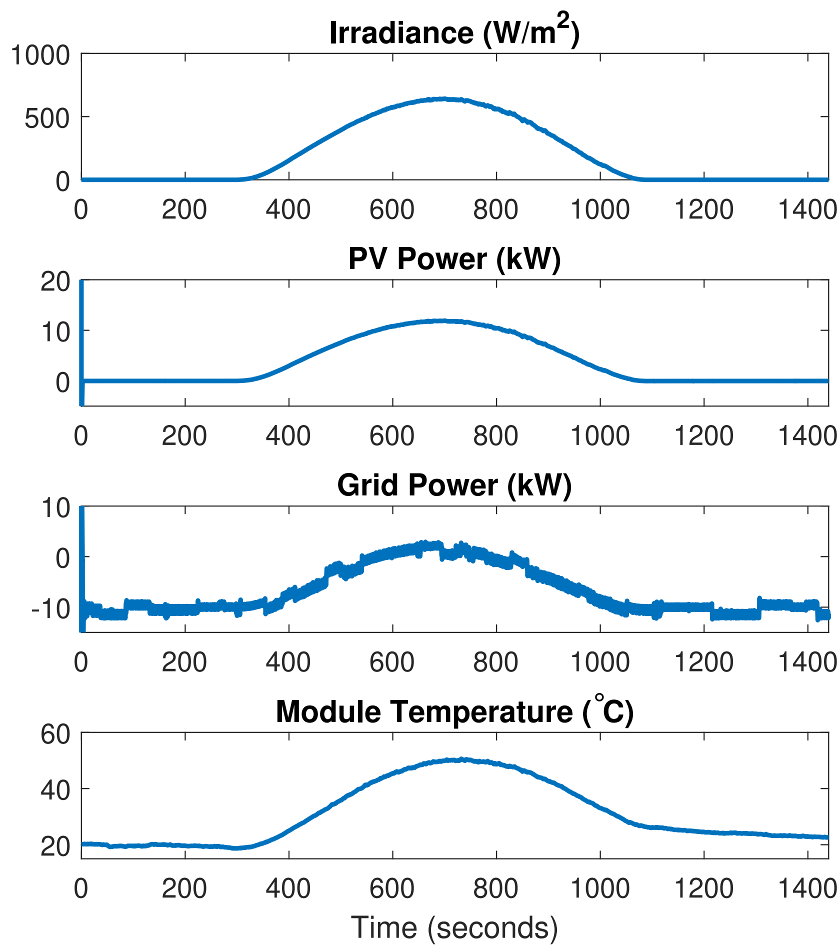

Figure 5.19: Irradiance, PV Power, Import/Export of Grid Power and Module Temperature on a clear day

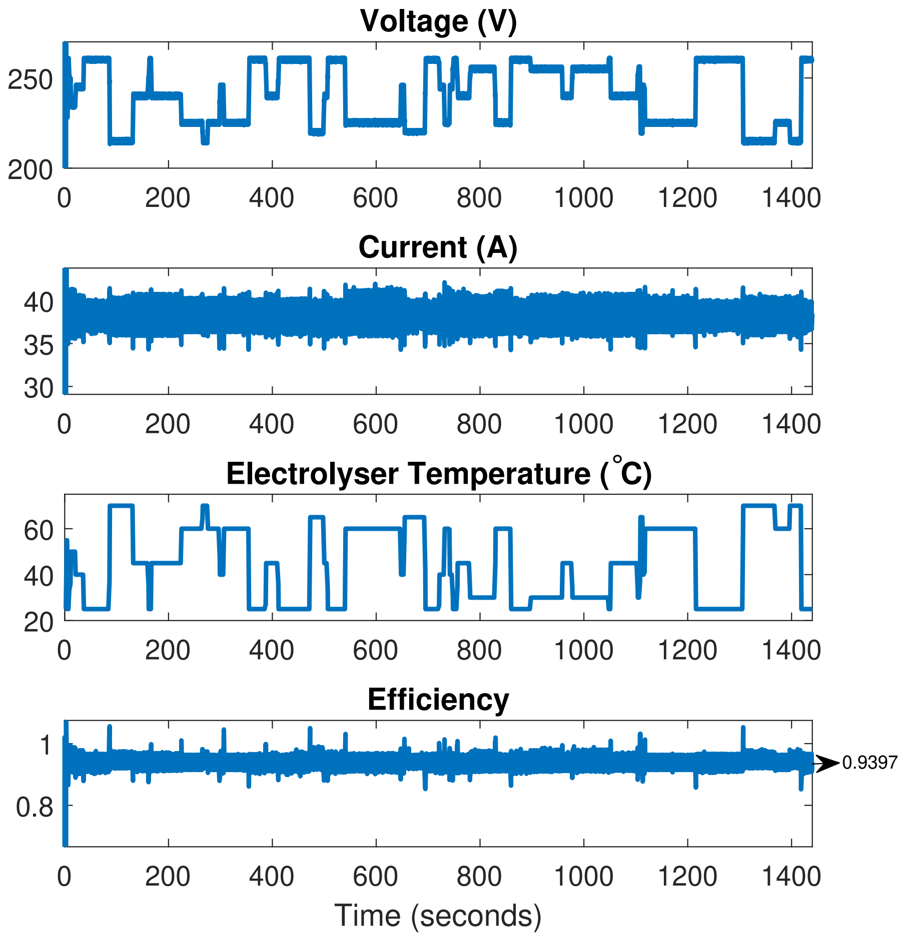

Figure 5.20: Voltage, Current, Electrolyser Temperature and Efficiency on a clear day

5.4.2. HIGHLY VARIABLE DAY RESULT

Here, real-time data for a highly variable day was used to run the simulation. Data for the entire day starting at 00:00 hrs to 23:59 hrs (1440 minutes and hence 1440 data points) for irradiance and ambient temperature were fed to the model as inputs. The temperature of the electrolyser was taken as random values varying between 25°C and 70°C. The results of this day long simulation are shown below through which it is observed that the control strategy manages to maintain 38 A as the input current to the electrolyser, throughout the day. The average efficiency of the converter on a day with highly varying ambient conditions is 93.97%. For the initial and last hours, when the irradiance is 0 W/m^2, the electrolyser's demand is completely satisfied by the grid and this is indicated by negative power in the result. For the rest of the hours, depending on the amount of PV power produced, the exchange of power with the grid is depicted accordingly. Unlike the clear day, in this case, the export of excess power to the grid is interspersed with import of power from the grid.

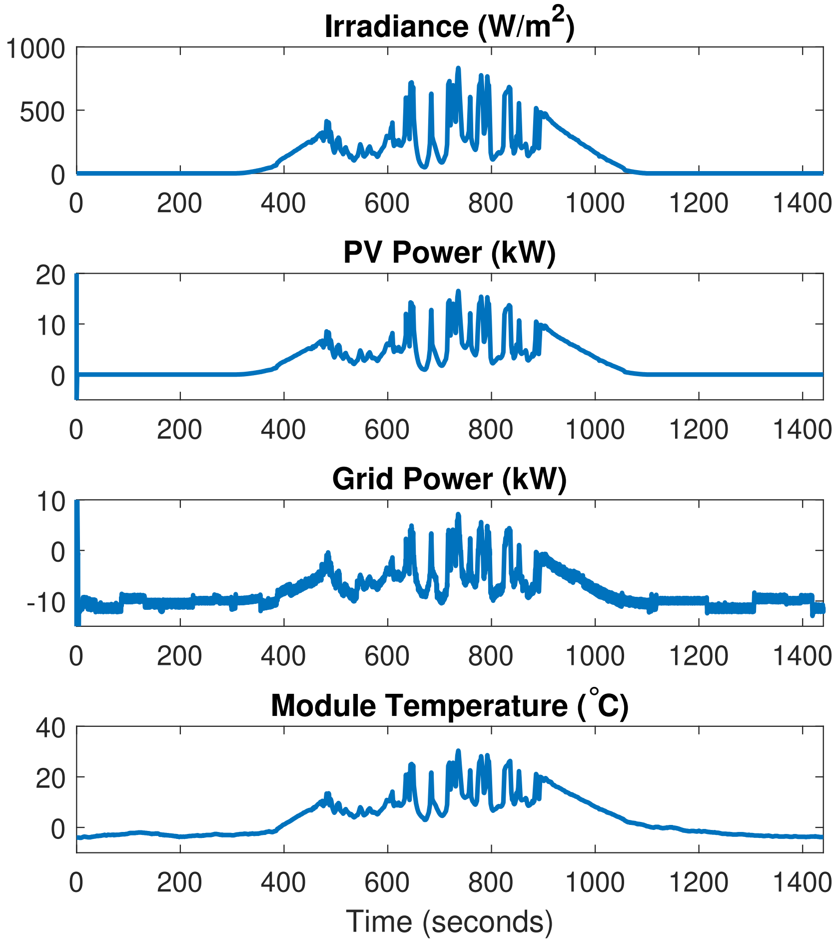

Figure 5.21: Irradiance, PV Power, Import/Export of Grid Power and Module Temperature on a day with highly varying ambient conditions

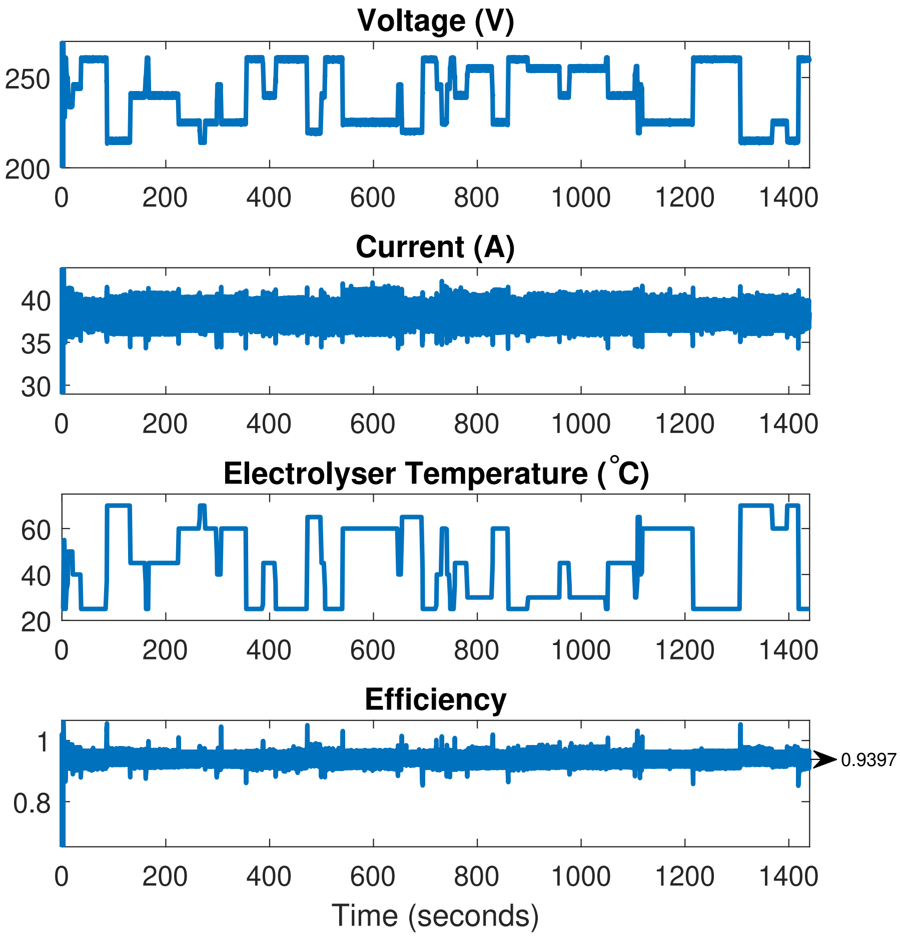

Figure 5.22: Voltage, Current, Electrolyser Temperature and Efficiency on a day with highly varying ambient conditions

5.5. DISCUSSION

Given below are a few points of discussion with respect to this research.

- In the figures presenting irradiance, PV power, grid power and module temperature, it can be seen that the grid power tends to drop/shoot up at some points. This is due to the change in the temperature of the electrolyser at those corresponding points, shown in the figure consisting of voltage, current, electrolyser temperature and efficiency. When a change in the temperature of the electrolyser occurs, the system takes some time to stabilize and produce the desired output. During that short period of time, since the system is unstable, the grid power deviates from the desired value and hence it drops/shoots up at those points.

- The simulation results shows that the system takes approximately 2.8 s to stabilize and render the desired output of the control strategy i.e. the DC voltage reference. Once the control strategy produces the DC voltage reference for the rectifier, it produces the requisite DC output voltage. The calculations involved in the control strategy is the reason behind the time taken for the system to stabilize. The parameters that have an effect on the time taken for the system to stabilize are voltage across the electrolyser, rated current of the electrolyser and the step size values. Since the control strategy takes a small step size value to increment the voltage, it takes about 2.8 s to stabilize at the desired value. Hence, the control strategy provides enough time to the rectifier to produce the desired DC output voltage.

- When the temperature of the electrolyser is 25°C, the average efficiency of the converter is 93.72%. At an electrolyser temperature of 35°C, the average efficiency of the converter is 94.02%. When the temperature of the electrolyser changes from 25°C to 35°C, Figure 5.6 depicts a change in the efficiency and the average efficiency is 93.89%. When the temperature of the electrolyser increases, as explained in Chapter 2, the voltage decreases. Since the input current to the electrolyser is maintained at the rated value with the help of the control strategy, the power consumption of the electrolyser reduces. Hence, the efficiency of the converter increases as the temperature of the electrolyser increases. On the other hand, when the irradiance changes, the average efficiency of the converter is 93.69%. Although ambient conditions have an impact on the temperature of the electrolyser [23], it can be seen in Figure 5.12 that the change in the efficiency of the converter caused by the change in the irradiance is comparatively lower than in the above mentioned case due to the fact that the input power is not influenced by the PV power as a result of the grid connection. Therefore, the change in the temperature of the electrolyser is found to influence the efficiency of the converter more than the change in the irradiance.

6

Conclusions and Recommendations

This thesis documented the above mentioned research with the following chapters:

- Chapter 1 gave the introduction, the background motivation and the scope of research of this thesis.
- Chapter 2 presented the information that was studied to understand the background of the research. A literature survey was carried out to study the recent work related to electrolysers. Based on the above information, the chapter 'Literature Review' was written and it aimed to provide the reader with appropriate information to understand the research.
- Chapter 3 intended to explain what components the system comprises of and how they are connected. It also explained the Simulink model and the function(s) of its components in detail and thereby enabled the reader to gain an understanding of how to interpret the Simulink model and how it works.
- Chapter 4 elucidated the need for such a control strategy and then presented the developed control strategy along with the phases of its development and a flowchart.
- Chapter 5 consisted of the results of the research, which depict the successful working of the control strategy, in the form of plots obtained after

having ran the model on Simulink (MATLAB R2019b) with a concise explanation for each case that was taken into consideration. It also explained the various parameters in the results and the interpretation of the graphs.

The following research questions were answered in the thesis and are presented below:

1. **What is the significance of change in temperature of the electrolyser with respect to the operation of the electrolyser?**

   The change in the temperature of the electrolyser has an effect on its I-V curve. As the temperature of the electrolyser increases, a particular value of current can be produced at a lower value of voltage. That is, as the temperature increases, the potential required to bring about the reaction reduces [16]. Hence, the electrolyser behaves similar to a variable resistor [15]. So increasing the temperature of the electrolyser can help in increasing the amount of current flowing into the electrolyser.

2. **What is the condition for optimal operation of the electrolyser as far as this research is concerned?**

   In this research, the optimal operating condition of the electrolyser is when it produces the rated amount of hydrogen.

3. **What are the quantities upon which the control strategy operates?**

   The amount of hydrogen produced is proportional to the amount of current flowing through the electrolyser [15]. Increasing the input current to the electrolyser will result in an increase in the hydrogen production. Therefore, if the rated current is maintained throughout the operation time of the electrolyser, then the rated amount of hydrogen would be produced by the electrolyser. Moreover, as mentioned above, the change in the temperature influences the I-V curve of the electrolyser. Hence, the parameters taken into account to develop the control strategy are input current to the electrolyser, voltage across the electrolyser and rated current of the electrolyser. Although the control strategy does not take the temperature of the electrolyser as an input, it plays an important role in the implementation of the control strategy. The developed control strategy, how it was formulated and the stages of its development were explained in detail in the thesis.

4. **How does the control strategy work?**

   Based on the input current value, the control strategy generates the output which is the DC voltage reference to the rectifier and finally the rectifier generates the DC output voltage accordingly. Initially the control strategy made use of discrete step size values which were replaced with a factor, for each case, that was calculated with the help of rated voltage, input current and rated current of the electrolyser.

5. **How would the control strategy be tested?**

   For the initial phase, a MATLAB Function block which generated values continuously with the help of a linear function followed by a non-linear function was used to test the control strategy. Later, an electrolyser emulator which functions with the help of look-up tables, was integrated with the model. Data for voltage across the electrolyser, current flowing into the electrolyser and the temperature of the electrolyser were given to the electrolyser emulator through look-up tables. A Signal Builder was used to vary the temperature of the electrolyser to test the control strategy. Finally, real-time data was also used to perform day-long simulations and the results were presented and explained.

6.1. RECOMMENDATIONS FOR FUTURE RESEARCH

The results of the simulations performed proved that the control strategy was successful in achieving the objective of the research. However, there are some recommendations for future research which are listed below:

- In this thesis, day long simulations were performed for a clear day and for a day with highly variable weather. In the future, data for various other weather conditions and different geographical regions could be utilised to perform simulations to test the control strategy.

- The control strategy developed and presented in this thesis could be validated on a hardware setup that would mainly comprise of an electrolyser emulator, a PV simulator, a rectifier, transformers and a computer which will behave as the control centre to access the Simulink model to implement the control strategy. Moreover, the general version of the control strategy presented in this research could be validated.

- From the results it is clear that since the regulation of voltage is taking place continuously throughout the operation time of the electrolyser, there exist a significant amount of ripple in the DC output voltage of the rectifier. Further research could be carried out to reduce the ripple in the DC output voltage of the rectifier which will aid in increasing the accuracy of the control strategy.

- Furthermore, the voltage values used in this research ranged from 210-260 V based on a real electrolyser available on the market [22]. Some electrolysers' operating voltage ranges are significantly different from the one considered in this research. Hence an interesting line of research would be to develop a DC-DC converter to cater to the needs of such electrolysers, to implement the general version of the control strategy and test it, or a combination of both.

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A

STATEFLOW CHART

The Chart behaves like a separate entity, similar to a MATLAB Function Block. It is capable of taking inputs from the Simulink model into it, processing the information, making decisions, producing the required output and returning the value to the Simulink model for the rest of the operations to take place. It gets its name from the way it functions, i.e., different 'states' which could possibly be found in the chart/algorithm being written into the Chart, can be defined using this feature and hence the name, 'Stateflow Chart'. A stateflow chart containing a simple function is shown below.

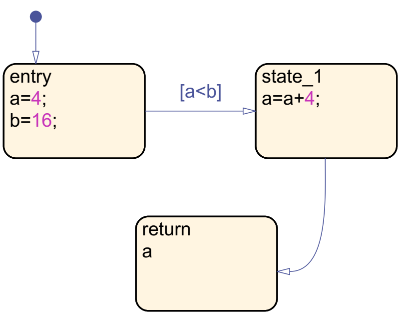

Figure A.1: A Stateflow Chart containing a simple function

Each curved rectangle indicates a 'state' in the algorithm. Connections between various states of the algorithm are established with the help of arrows as shown in the above figure. The 'flow' of the algorithm is logic-based and that

A

would be decided by the condition that can be defined on the arrow that points to a state or connects two states. A few examples of conditions are:

- a==10
- a>17
- a<=98
- a≅56
- a>=b

Each of the above conditions enclosed within square brackets '[]' indicates a condition and with the help of such conditions, the algorithm can be made to flow in the desired manner. The connecting arrow can also have an 'Action' defined or an 'Event name or Message name' specified.

As shown in Figure A.1, each rectangle has its own state label, namely, 'entry' and 'exit', and state names, namely 'state_1'. Entry and exit follow a general format whereas state names can depend on the application and user's convenience. As shown in the figure, when 'return' is specified in the state, the values of the variables which were used in the algorithm or function will be returned to the main Simulink model of which the Stateflow Chart is a part. 'Init' is used to indicate that, that particular state will be used to give initial values or to initialise the values of the variables being used in the function. Moreover, the chart also provides a 'Symbols Pane' where the type of the data can be selected. For example, the data can be classified as Input Data, Output Data, Local Data and so on.

B

A General Version of the Control Strategy

The control strategy implemented and the flowchart shown in Chapter 4, pertain to the 10 kW (rated current: 38 A, operating voltage range: 210 - 260 V) electrolyser that was taken into consideration in this research. Since the control strategy worked successfully, a general version of the control strategy for an electrolyser was made and is presented below.

B.1. Calculation of the Factor

The calculation of the factor used in the control strategy requires the following values:

- ΔV_{step}
- ΔI
- ΔT

Based on the above mentioned values, a value, 'k', is calculated to aid in the process of calculating the factor for the control strategy, with the help of the following equation:

$$k = \frac{\Delta V_{\text{step}} \times \Delta T}{\Delta I} \tag{B.1}$$

where the value of ΔT is the sampling time, (in this research 5×10^{-5} s was used), the value of ΔI is the difference between the input current and the rated current rounded up to the nearest percentage of rated current (10%, 25%, 40%, 50%, 80%, 105% and 115%) and the value of ΔV_{step} corresponds to the voltage step size to decrement the voltage.

The output of the control strategy, Vref is calculated using the following equation:

$$V_{\text{ref}} = V_{\text{in}} - \Delta V_{\text{step}} \tag{B.2}$$

But,

$$\Delta V_{\text{step}} = \frac{k \times (I_{\text{in}} - I_{\text{rated}})}{\Delta T} \tag{B.3}$$

After substituting for ΔV_{step}, the equation becomes:

$$V_{\text{ref}} = V_{\text{in}} - \left[\frac{k \times (I_{\text{in}} - I_{\text{rated}})}{\Delta T}\right] \tag{B.4}$$

On substituting Equation (B.1) in (B.4), the resulting equation is:

$$V_{\text{ref}} = V_{\text{in}} - \left[\frac{\Delta V_{\text{step}}}{\Delta I} \times (I_{\text{in}} - I_{\text{rated}})\right] \tag{B.5}$$

On incorporating a value, 'factor' (V/A) into the above equation, the equation for the output of the control strategy is obtained and is as follows:

$$V_{\text{ref}} = V_{\text{in}} - \left[factor \times (I_{\text{in}} - I_{\text{rated}})\right] \tag{B.6}$$

where,

$$factor = \frac{\Delta V_{\text{step}}}{\Delta I} \tag{B.7}$$

With the help of Equation (B.6) and (B.7), the flowchart of the general version of the control strategy has been made and is presented below in Figure B.1.

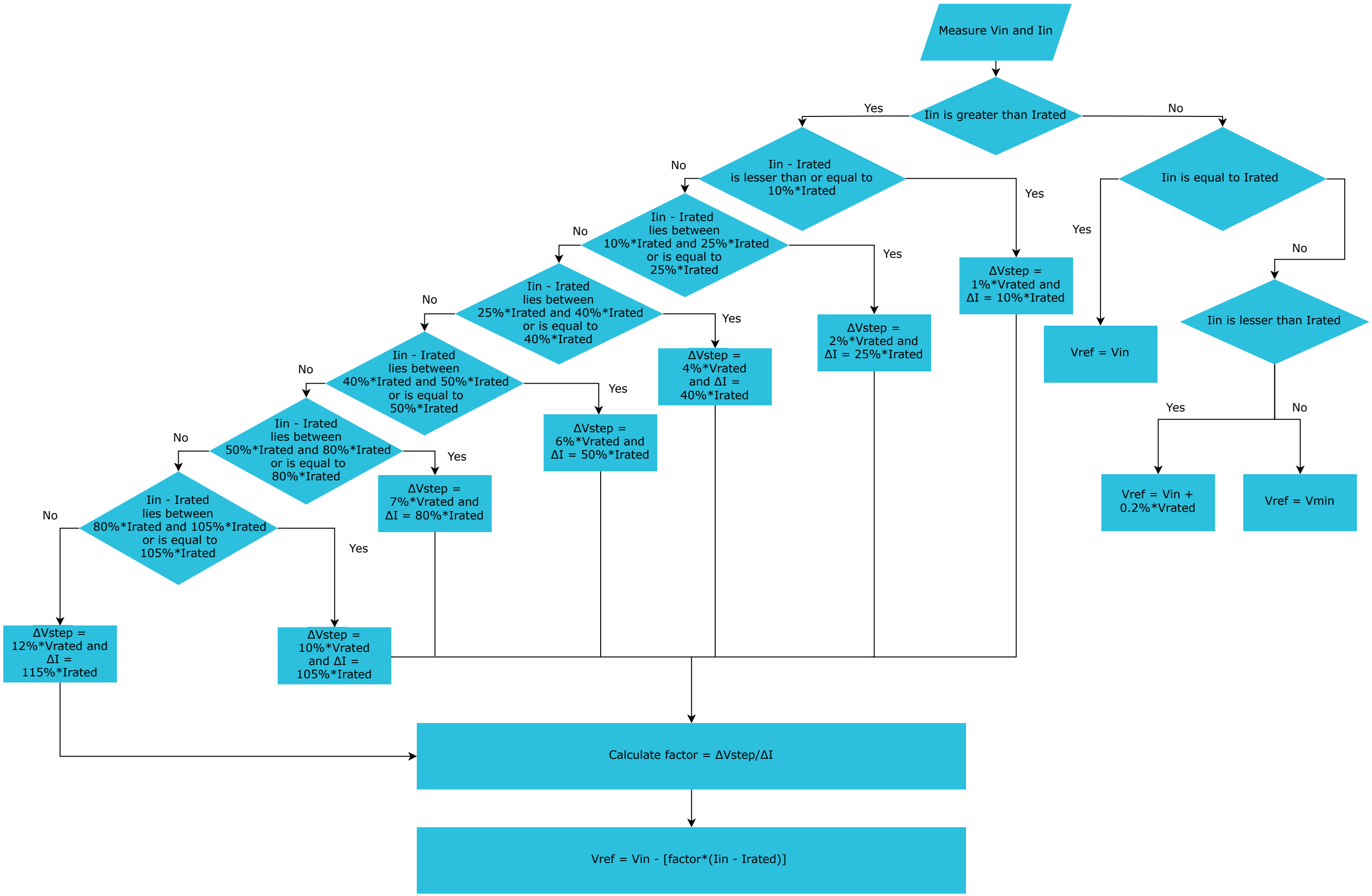

Figure B.1: A flowchart of the general version of the control strategy

Unlike the control strategy used in this research, the general version of the control strategy requires two additional inputs, namely, V_{rated} (the rated voltage of the electrolyser) and V_{min}, (the minimum voltage required for the operation of the electrolsyer).

The implementation of the control strategy is demonstrated with the help of an electrolyser rated 360 kW [25]. The rated voltage of the electrolyser is 480 V and the rated current is 750 A. If the input current to the electrolyser is 900 A, the value of I_{in} - I_{rated} would be 150 A. 150 A being 20% of the rated current of the electrolyser, based on the flowchart, the value of V_{step} should be 2% of V_{rated}, which is, 9.6 V. The value of I_{in} - I_{rated} lies between 10% of I_{rated} and 25% of I_{rated}. Hence, the value of ΔI to be used for the calculation of the factor would be, 25% of I_{rated}, which is 187.5 A. The value of the factor is calculated as shown below:

$$factor = \frac{9.6V}{187.5A} = 0.0512V/A \tag{B.8}$$

Therefore, the output of the control strategy would be calculated by making use of the factor, 0.0512 V/A with the help of the below equation:

$$V_{\text{ref}} = V_{\text{in}} - [0.0512 \times (I_{\text{in}} - I_{\text{rated}})] \tag{B.9}$$