Proposed design of a Micro-inverter for an integrated Photovoltaic-Battery Module in Grid and Off-Grid Applications

Abstract—**In this paper a circuit topology will be proposed for a solar inverter. This solar inverter should be integrated into the back of the solar panel, together with a battery. The maximum power that it needs to produce is 1 kW, with an acceptable efficiency. One of the main constraints is the physical size, which should not be larger than 38x60x4 cm. Furthermore, it should have the capability to work on and off-grid. In order to achieve a suitable design, different circuit topologies are discussed, among which are a topology based on a 50 Hz transformer, a design with a boost converter using an inductor or flyback converter to step up the voltage and lastly a design making use of a high frequency transformer. Component choices in the circuit design are also discussed in order to achieve the best performance for the lowest possible cost. The design of this solar inverter also includes simulations in Matlab Simulink. In the end a solar inverter design based on a high frequency transformer is proposed with a simulated efficiency of 94.5%.**

I. INTRODUCTION

With the beginning of the industrial revolution, people have started to use more energy every year. In fact, the world wide energy usage is still increasing every year by one to two percent [1]. A lot of the energy is produced from fossil fuels, which is not a clean source. People and companies around the world have been finding new ways to produce clean or renewable forms of energy. One of these sources is solar energy. To harvest energy from the sun, the sunlight can be converted to electric power in a solar panel. This solar panel alone cannot be connected to the grid to deliver power. This is where solar inverters come into play, these convert the electric power that the solar panel outputs to a form which can be applied to the grid. Solar inverters can also be used in an off-grid application to provide energy to a singular home for example.

In this paper the available literature for the design of solar inverters will be used to come to a final topology choice for a micro-inverter. There is a lot of research done in this field already. A good example of a comparison of many inverter topologies can be found in [2]. There are mainly two groups of solar inverters, single stage and double stage topologies [2]. In double stage designs the power supplied by the source and power supplied to the output are controlled by different subcircuits, while in single stage designs they are not. Since single stage inverters mainly rely on a high input voltage to start with, no voltage gain is needed to supply power to the grid. After researching this subject it became clear that a single stage micro-inverter solution would be the most cost effective option, however this solution is not applicable here, since a lower input voltage than the grid voltage is used. Further information about the input of the solar inverter can be found in Section II-C.

This paper will also focus on the choice of components, this is not elaborated on in most research, but the used components are just stated. Another important factor for the topology choice will be the cost. This subject is also mainly not elaborated on in other research, but the design that is proposed is just presented as a low-cost solution, but no indication is present of how cost-effective the design is.

With the demand of energy growing every year, innovations have to be made in order to satisfy the demand. One of these innovations can be made in the field of solar panels and in particular making a standalone solar panel unit, which includes an inverter and battery. If this would come to a finished product, it would make it easy and convenient in certain applications to install an all-in-one solar panel system. To make the system even more versatile, it should include the ability to deliver power to the grid and to function off-grid to power devices in remote areas for example. The design of the inverter needs to be made in order to achieve this goal. In this paper, the design of a micro-inverter integrated into the back of a solar panel is researched. For this specific project a couple of specifications have been determined. The solar inverter should be able to deliver 1 kW of continuous ac power and it should have a maximum physical size of 38x60x4 cm.

The rest of the paper consists of the design requirements that the micro-inverter should meet, which can be found in Section II, along with possible solutions to the problem in Section III. The choice of different component types is discussed in Section IV. Additionally, design choices that were made for the circuit of the chosen design topology are discussed in Section V and the simulation results of this circuit are given in Section VI. Discussion points are brought up in Section VII, together with some recommendations for future improvements in Section VIII. Lastly, the paper is concluded in Section IX.

II. DESIGN REQUIREMENTS

A. The intended market

The complete system consists of a solar panel, battery, micro-inverter and a DC-DC converter to interface the solar panel with the battery. This system is intended for a diverse market. The system could be used for off-grid applications in fields by for example farmers. The system could also provide power to a telephone station, without the need for extending the grid to the (remote) location. Alternatively, this product would come in handy for events like festivals, where electricity is needed, but this is still often achieved with generators running on fossil fuels. A completely different application would be in poorer countries, where no electricity grid is present. The system could then be used to power cell phones or power lights during the nights [3]. There are also countries where the delivery of electricity is not reliable, this system could help in the cases when there is a power outage.

B. Translation to requirements

A main requirement for the solar inverter is that the price needs to be as low as possible, since a substantial amount of people for which this product is intended will not have a lot of money to spend. For the markets where money is not a problem, an alternate version with more features could be developed, but in this paper the focus is on a low budget inverter solution. Because this inverter will work in remote areas or in areas without a lot of technical assistance, the inverter needs to be reliable. The reliability of the inverter is even more important than the price, since it will not be of much help to the people that had little to spend in the first place, that the inverter malfunctions. The cost of the inverter is allowed to increase if that leads to a more efficient inverter, which will mean less energy is wasted and this can also be calculated to a cost that is saved over time.

C. Overview of the problem

The design of a solar inverter consists of multiple subparts. The sole task of the solar inverter is to convert the DC-battery voltage to the grid level voltage, while synchronising with the grid too if the inverter is functioning on the grid. The battery that is currently present is built up in a 14S7P configuration. This means that the input voltage to the inverter will be in the range of 35-58.8V, if the batteries will be fully charged and fully discharged. Additionally, the current battery includes a passive cooling system. In this case the solar inverter is intended to work on the 220-240V 50 Hz grid, since that grid is mostly used [4]. This grid level is also present the most in the areas of the intended market.

III. A FITTING DESIGN TO THE PROBLEM

Taking everything in mind from Section I, a couple design topologies were considered. An overview of the pros and cons of these topologies can be seen in table I.

1) A design with a 50 Hz transformer, which would reduce parts count, since no components are needed on the secondary of the transformer to connect the inverter to the grid.
2) A design with a boost converter stage, using an inductor to step up the voltage, and an inverter stage, using an H-bridge.
3) A design with a boost converter stage, using an interleaved flyback converter, and an inverter stage, using an H-bridge.
4) A design with a boost converter stage, using a high frequency transformer to step up the voltage, after which the voltage on the secondary of the transformer is rectified. This DC voltage is needed for the inverter stage, which is implemented using an H-bridge.

The design with a 50 Hz transformer is not a suitable solution for this problem. The main issue here is that the price of this topology will be too high, compared to the other topologies, while there is no significant change in efficiency. The price will be higher in this case, because a 1 kVa rated 50 Hz transformer is physically a lot bigger than higher frequency transformers, which leads to a high price. The 50 Hz transformers were estimated to be 6-7x more costly than higher frequency transformers.

Then there is the topology with a general boost converter stage. This topology looked promising at first, because of a relatively simple boost converter stage, with a low parts count. This topology could work, but it is not the best option for the problem laid out here. The main issues for this type of design are that the voltage needs to be stepped up to the 220-240V grid level. Doing that from a minimum battery voltage of about 40V, means that almost 10x gain needs to be achieved. According to Fig. 1 the efficiency of solely the boost converter stage will drop to a best value of 89%. This was deemed to low, since a lot of available battery energy would be converted to heat, which is a waste of energy. Additionally, a more efficient system would save more energy over time, which could be converted to monetary value. An estimate for the cost of the energy that the user of the system would lose during a 10 year span can be made according to the cost of energy, and the average energy a solar panel produces in a year. This means that though this boost converter topology is a cheap solution, the more efficient solution for a lower price will be better, because less energy is wasted over time, and the extra cost will be compensated by a short payback period.

The next design using a flyback (transformer) converter was not chosen, because it is generally used in low power applications, since the transformer design topology does not scale well with power handling. This type of converter will then end up being less efficient or more costly, depending on the size to which the converter is made, since making a big transformer will cost more, since more material is used.

The last option that was looked at uses a high frequency transformer to achieve the gain needed to step up the voltage efficiently. This topology is used a lot in solar inverters and it is sometimes also referred to as a ”transformer-less design”, this is a misleading term, because a high frequency transformer is in fact used.

This topology can achieve high efficiency for a reasonable cost. The main cost of the design would be the high frequency transformer, since this part is not as widely available in a variety of specifications as for example capacitors are. However, if the high frequency transformer can be sourced from a manufacturer for close to the material cost, the cost of the design would be comparable to the inductor based boost converter design, which means that it is relatively low-cost. This is why the high frequency transformer design using a full-bridge inverter will be chosen as it is regarded as the best compromise between cost and efficiency.

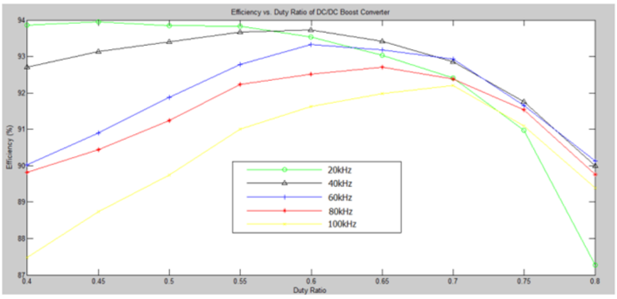

Fig. 1: Efficiency of an inductor based boost converter [5]

Topology	Price	Efficiency	Parts Count
1	High	High	Low
2	Low	Low	Medium
3	Low	Low	Medium
4	Medium	High	High

TABLE I: Table with an overview of the different topologies

IV. PARTS TYPE CHOISES

Since the micro-inverter will be built using electrical components, the most cost effective solution needs to be chosen. This will be further elaborated on in the following subsections.

A. *Mosfet Choises*

The end product will eventually use mosfets. These devices come in a variety of chemistries. The main ones that are used widely are: Gallium Nitride (GaN), Silicon Carbide (SiC) and Silicon based. SiC based mosfets were deemed unnecessary for this application, since they are mainly used where higher voltages and currents are present and using these would lead to a higher cost of the system (3x more expensive than Silicon (Si)). Additionally, SiC mosfets require gate voltages of about 18-20V to fully turn on and -3 to -5V to fully turn off, this means that the drive circuitry would also become more complicated and thus more expensive. GaN could be a viable solution depending on the switching frequency of the design. This chemistry is mainly used where high power demands and frequencies are present. The design will thus use Si or GaN devices, because SiC devices do not increase the efficiency of the design as significantly as the topology choice does, using Si or GaN devices are preferred depending on the operating frequency. Looking at Fig. 2 it is clear that there is another option called Super Junction (SJ). This is a special variation of the Si mosfet using the super junction technique, especially made for higher switching frequencies and thus they incorporate low switching losses. The cost of GaN mosfets is about 10x higher than the cost of SJ mosfets, while having about a 8x lower $R_{ds(ON)}$. This difference in resistance leads to a difference in efficiency of 0.5% when the inverter is operating at 1 kW. This difference scales linearly with the output power of the inverter, so it is concluded that the 10x price difference is not worth the relatively small increase in efficiency and the design will make use of SJ mosfets. This choice does affect the operating frequency of the transformer, since the SJ mosfets are better suited for high frequency operation than regular Si mosfets, but GaN devices can operate at even higher frequencies [6].

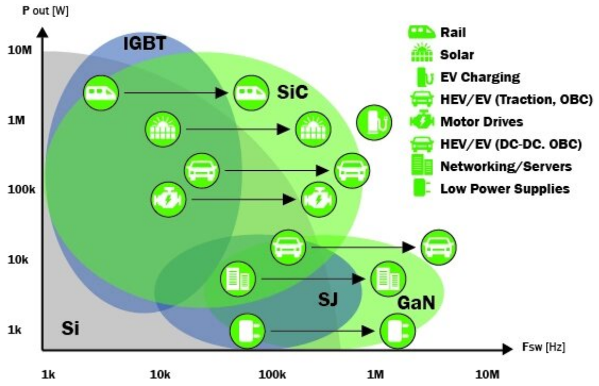

Fig. 2: Application range of several types of switching devices [6]

B. *Diode choice*

The diodes that are the most suitable for this design are schottky diodes for the low voltage side, because the operating frequency and voltage lends itself for the use of this type of diode. Using schottky diodes on the low voltage side results in diodes with typically the lowest forward voltage, thus the least power is lost. Because of the operating frequency this type of diode choice is also best, because fast recovery diodes rated for the same voltage will be roughly as expensive as schottky diodes, while having a higher forward voltage. For the rectification on the high voltage side of the inverter, fast recovery rectifying diodes are a suitable solution, since they are mainly used on higher voltages than schottky diodes. However, there are Silicon Carbide (SiC) schottky diodes as well. These seem like a promising option as well. When looking at datasheets of these two types of diodes from the same manufacturer, it became apparent that the SiC schottky diodes will waste more (max. 0.8 W) or equal amount of power for 2-3x the cost. Important factors in diode losses are the forward voltage of the diode, reverse recovery currents and reverse recovery times. SiC schottky diodes make a trade-off between recovery behaviour and forward voltage. This trade-off is more beneficial for higher voltages, thus SiC schottky diodes are mainly used for voltages higher than 650V [7]. Since the breakdown voltage of the diodes will be in the vicinity of 600V, fast recovery diodes will be the best option.

C. *Capacitor choice*

For implementing capacitors into a design, a couple of types can be considered. The cheapest type of smoothing capacitors are electrolytic capacitors. The main concerns with these capacitors are that the rated capacitance can drop over time and that they do not last as long as other types of capacitors. The lifetime for electrolytic capacitors is mostly given in datasheets at 105 degrees Celsius. For every 10 degrees Celsius less that these capacitors experience, the lifetime doubles [8]. A quick calculation results in a maximum lifetime of 36 years when the capacitors are at 55 degrees Celsius and used all the time. Using these capacitors would thus be a good choice, since the average lifetime of a solar panel is 25 years and the design lifetime of the end product will be in the region of 10 years, since the battery will last about that long. Electrolytic capacitors can be used to frequencies in the Megahertz range. This means that this choice of capacitor is suitable and if it is decided that the operating frequency becomes higher than that, a small ceramic capacitor is usually placed in parallel to negate the inductive effects of the electrolytic capacitor at high frequencies.

D. *Transformer choice*

A transformer with an operating frequency of 250 kHz was chosen, because this leads to a cheaper transformer. Compared to a 100 kHz transformer, the 250 kHz has 4x less volume and costs 2x less. This choice of frequency results in a switching frequency of 500 kHz, which is in the working region of what the chosen mosfets can work with [6]. The transformer has a turns ratio of 1:10, because the transformer will still produce enough voltage on the secondary when the battery is almost empty.

V. CIRCUIT CHOICES

Keeping in mind everything stated in Section IV, a simulation can be made according to the choices that were made, but first the circuit needs to be defined, along with the operating conditions. In the end a full-bridge inverter was chosen as mentioned in Section IV, because of mainly its simplicity and reliability. On the low voltage side the full bridge converter to drive the primary of the transformer was chosen, because a half bridge usually requires two split voltage sources. This is not available in this case, since the design is operating from a battery, this split voltage could be made of course, but this would add unnecessary cost, since a full bridge converter is a more economical solution. Another design that could be considered is the one given in [9], this uses a half bridge style of driver for the primary side of the transformer, however since this design requires two coupling capacitors from the primary of the transformer to the switching devices, it was not chosen, since the cost of the extra mosfets can be offset by not needing the relatively big capacitors. Furthermore, if a full bridge design is chosen instead of the design in [9], the diode on the low voltage side can be removed, which improves the efficiency of the design by an estimated 1% when the inverter is running at its maximum power of 1 kW.

The output of the full bridge inverter needs to be filtered to the transformer, this is done to reduce Electromagnetic Interference (EMI) and to make sure that the transformer does not saturate, since it is up to the end designer to choose a suitable transformer. The filter can be seen in Fig. 3 as well.

On the output a full bridge rectifier is used to convert the AC voltage to DC voltage again. This rectified voltage is then smoothed by a capacitor, to get a steady DC link voltage, which is used in the next inverter stage. In order to determine the voltage level of the DC link, the worst case scenario can be taken into account. In Australia the regulations for a safe grid voltage are among the least stringent. According to those regulations, the voltage on the grid is allowed to rise with a maximum of 10%, thus the DC link voltage should be higher than 360V to give some headroom for voltage loss in the output circuit. Most designs use a voltage between 380-400V. In this case 380V was chosen, because this gives enough headroom to supply power to the grid.

The inverter stage has an output LCL filter to smooth the Sine wave Pulse-width Modulation (SPWM) waveform generated by the inverter stage into a sine wave. This filter was decided to be the most cost effective option, since using an LCL filter results in lower component values, compared to a L or LC filter [10]. However, resonance issues in the output voltage could arise, but this can be fixed by adding a damping resistance.

A version of the inverter could also be made without the LCL output filter, which would reduce the cost, since a lot of modern devices can function with a square wave voltage. This would also reduce the cost of the control circuitry, since no SPWM signal needs to be generated in that case.

By taking all that is said into account a circuit diagram can be made to give the reader an overview of the design, which can be viewed in Fig. 3.

An additional feature of this topology is that the battery can be charged from the grid as well, this could open up a few possibilities to end users that want to have that capability.

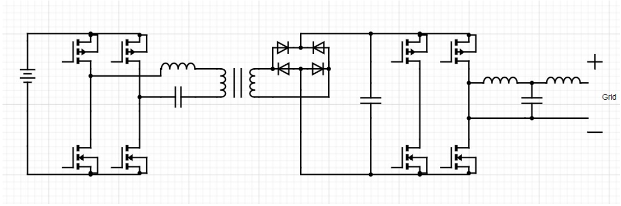

Fig. 3: Design overview

VI. SIMULATION RESULTS

The circuit given in Fig. 3 was simulated using MatLab Simulink. This program was chosen after working with LTSpice, because it could handle signal processing with idealized components, so no real circuit implementation was needed, which cuts down a lot on simulation time. The design was simulated in three parts to cut down on simulation time as well and to avoid complexity. These parts are numbered and they consist of:

1) The full bridge inverter connected to the transformer with an LCL filter
2) The full bridge rectifier circuit with the smoothing capacitor
3) The full bridge inverter with the output filter connected to the grid. This full bridge inverter is controlled by SPWM signals.

The circuits of the three parts of the system can be found in Fig. 7, Fig. 8 and Fig. 10 in the appendix. The component values are listed in Fig. 6. They were calculated according to the formulas given in [11] and [12]. For the internal resistances of the capacitors and inductors a value of $0.01\,\Omega$ was used. For the diodes a forward voltage of 0.6V and R_{ON} of $0.2\,\Omega$ was taken and for the mosfets M1-M4 an $R_{ds}ON$ of $0.01\,\Omega$ was used. Finally, for the mosfets M5-M8 an $R_{ds}ON$ of $0.45\,\Omega$ was determined. All of these specifications of the diodes and mosfets were determined from commercially available datasheets. The value for the smoothing capacitor in Fig. 8 was calculated using the formulas in equations 1 and 2.

$$E = \frac{1}{2}CV^2 \tag{1}$$

$$E = Pt \tag{2}$$

The simulation was done for three power levels: 100 W, 500 W and 1000 W, to give a good impression of the efficiency over the whole operating range. The efficiencies of the different subsystems can be found in table II. These efficiencies were determined using integrator blocks, which can be seen in Fig. 7, Fig. 8 and Fig. 10. Because the power draw in the system is not constant or equal to a sine wave, integrator blocks needed to be used, so the average power draw that Simulink gives cannot be used.

The output voltage of the inverter is made using an SPWM signal, this signal is a square wave which changes in dutycycle and this signal is then used to drive the full-bridge inverter. The output waveform is then filtered by the LCL filter to approach a sine wave. The output voltages under 1 kW and 100 W power draw can be seen in Fig. 4 and Fig. 5 respectively. The output voltage of the inverter under 1 kW power draw is distorted, but this is regarded as acceptable and it is expected as a trade-off was made in the design to decrease the size and thus the cost of the filter components.

The SPWM signals are generated by comparison of a saw-tooth and sine waveform. The Simulink circuit to generate the SPWM signals can be seen in Fig. 9 in the appendix. The comparison is made using a subtraction and a comparison to zero block. This makes sure that the signals created are sine waves. The mosfets of the full-bridge inverter need to be switched on in pairs and one pair can be active at a time. This functionality is implemented by another comparison to the phase of the sine waveform.

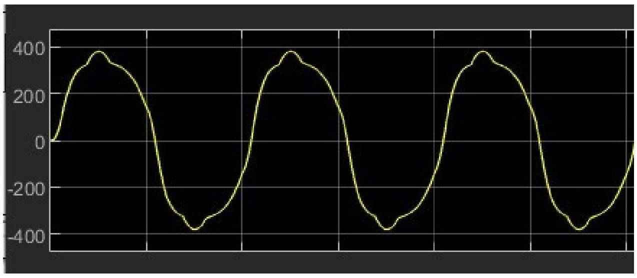

Fig. 4: Output voltage with a power draw of 100 W

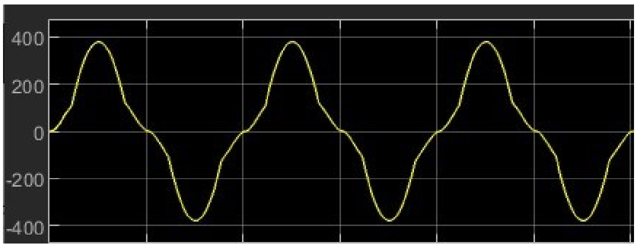

Fig. 5: Output voltage with a power draw of 1000 W

Power Level	**Part 1**	**Part 2**	**Part 3**	**Total**
100 W	98.5%	98.6%	97.3%	94.5%
500 W	97.2%	98.2%	98.7%	94.3%
1000 W	95.3%	98%	98.1%	91.6%

TABLE II: Efficiencies of the different parts of the inverter

VII. DISCUSSION

Something that should not be forgotten in the implementation of a real world design based on the topology given in Fig. 3, is the safety of the system. An overvoltage protection system should be present that monitors the voltage that is applied to the grid, because of the regulations mentioned in Section V. Over-current protection should be implemented as well, by using fuses or monitoring the current draw in the system, preferably on the battery side of the system, so that all short circuit faults can be detected. In a final circuit implementation when the inverter is intended to deliver power to the grid, the output waveform should be synchronised with the grid, this is often achieved by using an opto-coupler to sense the phase of the grid.

Additionally, a point of concern is the Electromagnetic Compatibility of the system. This means that the system should not be influenced by or influence other electronic devices, in a harmful way. Since relatively low switching (500 kHz) frequencies are used, this should not be of great concern, however this is something that the device should be tested for and this will also have an influence on the cost of the end product of course.

Lastly, a control system should be added to control the dutycycles of the mosfets, according to the battery state-of-charge and the power that needs to be applied to the grid or device connected to the inverter. This can be done by the combination of an analog circuit and micro-controller, since a cost effective micro-controller cannot generate the 500 kHz signals needed for the mosfets.

VIII. RECOMMENDATIONS

The battery pack currently present in the system comprises of Panasonic NCR18650B cells. These cells are of the NCA chemistry type, which means that they contain lithium nickel-cobalt-aluminium oxides. Lithium and cobalt production is centralised. An alternate battery chemistry that could be used is the lithium iron phosphate chemistry. This would result in a battery pack better suited for the outdoor environment, while getting rid of the cobalt element, this means that the battery pack production is less dependent on single countries. The LFP batteries can last for more cycles (3-5x), which leads to a more durable product, but they have about half the energy density of the current battery choice [13][14]. They can also function in wider temperature ranges than the current battery choice, which means less cooling is needed. The prices of the two battery options can vary, but they are roughly the same, but because of the fact that LFP batteries can last longer, they will be more economical over time.

IX. CONCLUSION

According to the simulation results given in Section VI, the device functions properly. An efficiency of 94.5% was achieved, by choosing proper components. In the end a low cost micro-inverter is realised by using a high frequency transformer, which operates on a frequency of 250 kHz, to reduce the size of the filter components in order to save cost. The design for the end product can be adapted to the intended user market, to achieve the best value for money to the end user.

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X. APPENDIX

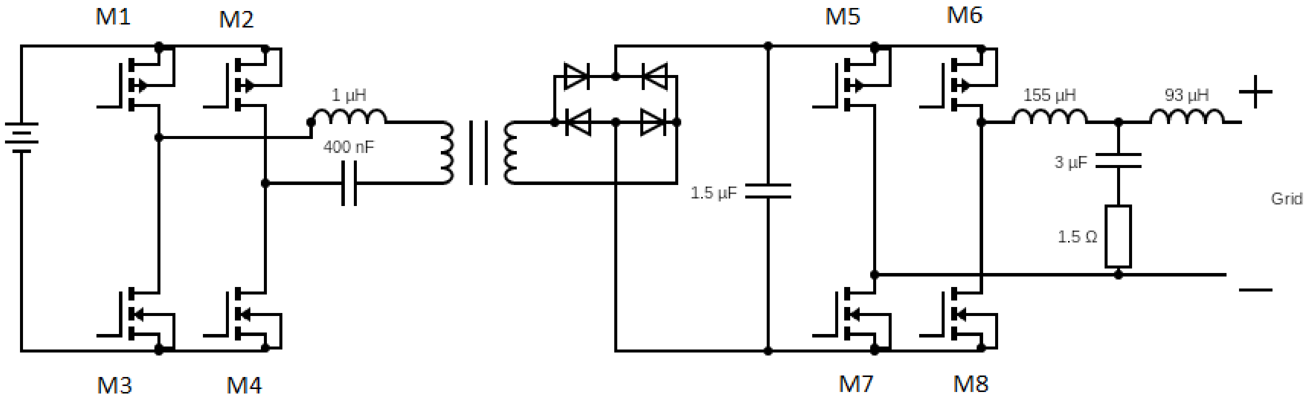

Fig. 6: Circuit with component values

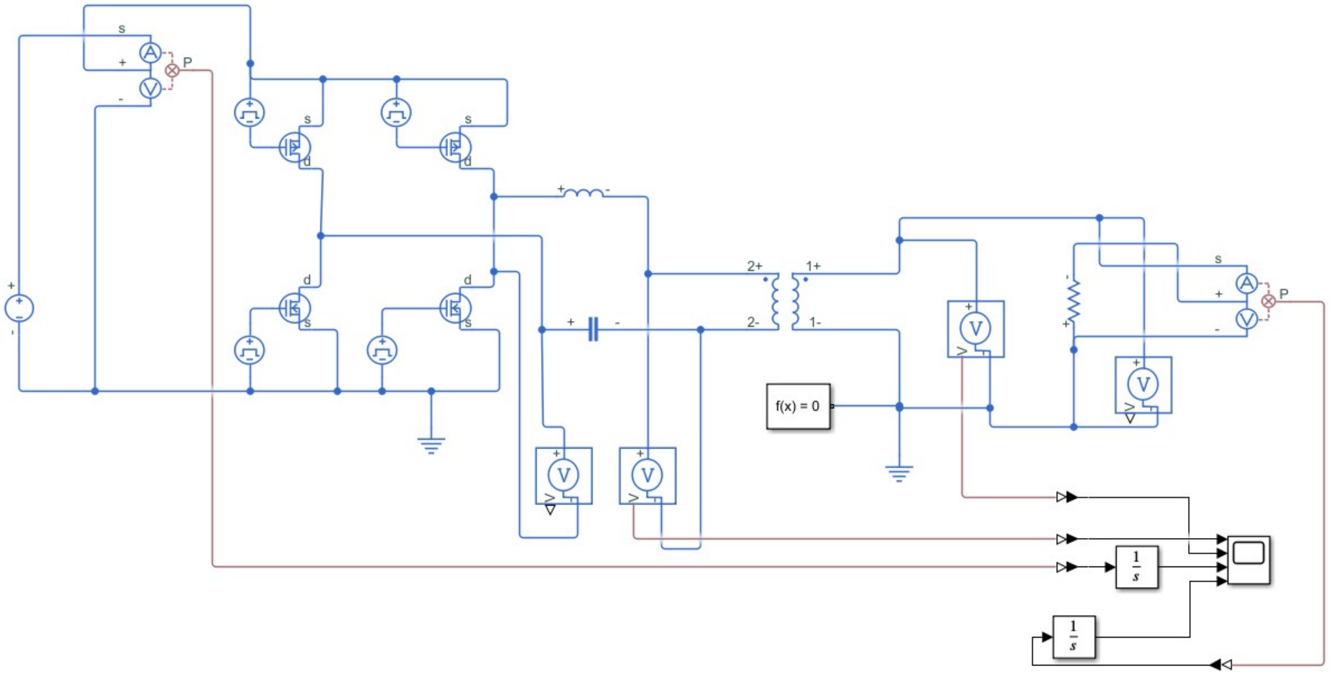

Fig. 7: Part one of the circuit, consisting of the full bridge inverter connected to the transformer with an LCL filter

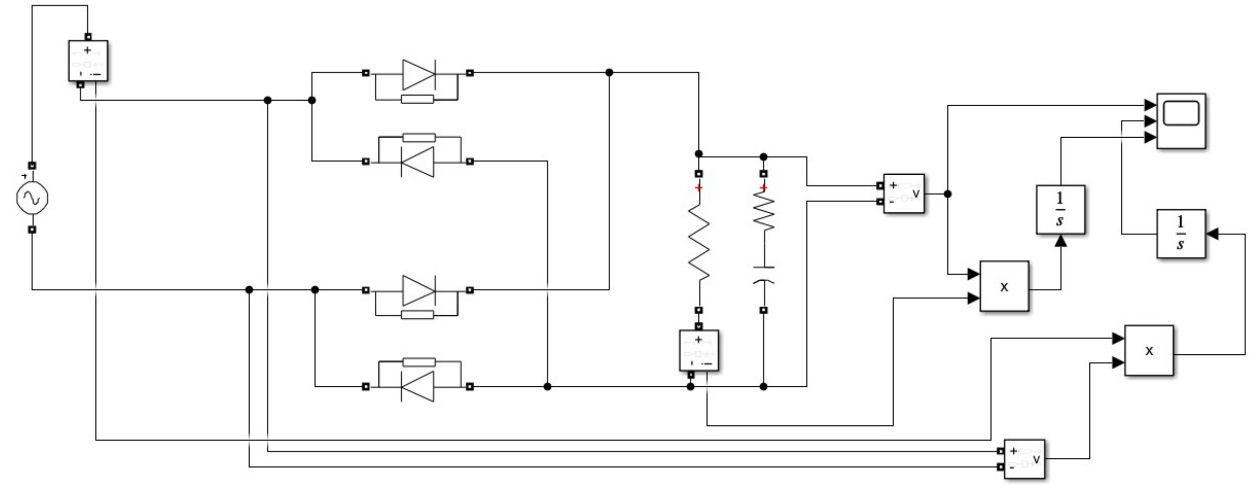

Fig. 8: Part two of the circuit, consisting of the full bridge rectifier circuit with the smoothing capacitor

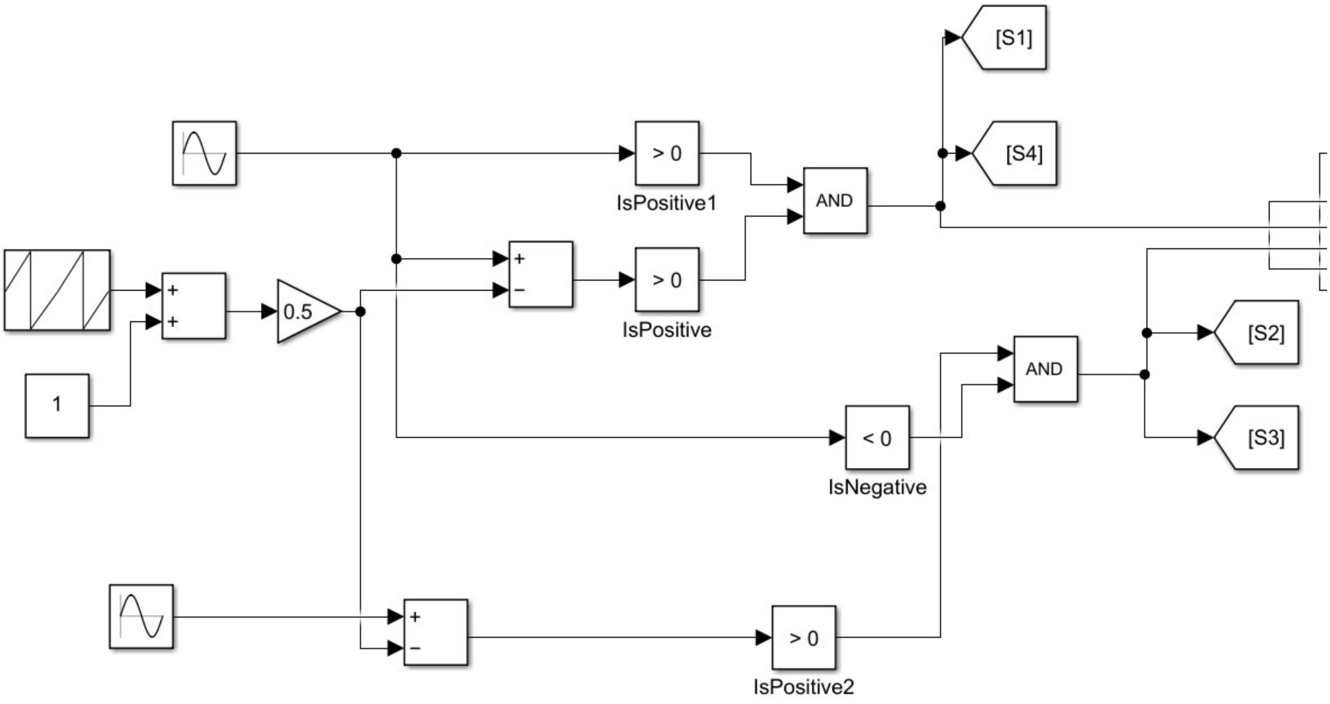

Fig. 9: Simulink circuit that generates the SPWM signals

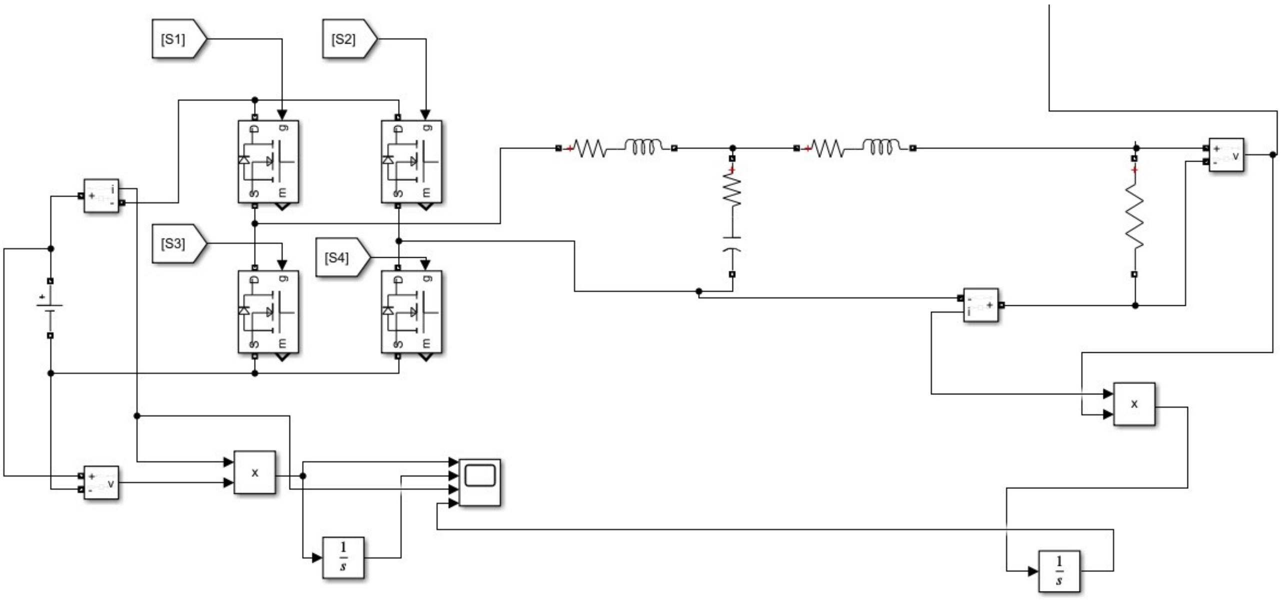

Fig. 10: Part three of the circuit, consisting of the full bridge inverter with the output filter connected to the grid