WEC Back-to-back Topology

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Abstract

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A system proof-of-concept has been made to show that a DC-link connected inverter can send power to the grid based on DC control principles. This system works reliably and uses Clarke and Park transformations as well as DSOGI-filtering to achieve a stable frequency lock in comparison to the grid. An User-Interface has been made to simplify control and give an overview of the system while it is running. The user can then set a current that they want to deliver to the grid, and also a current that they would like to consume, although the latter has not been tested. The system has some possible security flaws that may lead to an explosion of the DC-link electrolytic capacitors. To prevent this from happening, a solution has been presented that includes implementing security features within the software but also some sort of digitally controllable switch that can disconnect the grid at any time. This setup should easily be able to scale into a back-to-back configuration with an actual generator and rectifier instead of laboratory equipment acting as the DC-supply. This means that a control system for the rectifier and generator has to be implemented, but it will be similar to the solution that has been presented.
Preface

Renewable energy sources have risen fast as a cheap and environmentally friendly alternative to the fossil energy sources of the past. The modern day energy sources are all about being easy to install and scalable. This brings new challenges in terms of connectivity and energy storage, which is where the need for research in these areas come into play.

Wave energy is a controversial method for harvesting clean energy, because it comes with a handful of difficult challenges such as salt water, wear on the components and inconsistencies in the behavior of waves. This project is meant to delve into the latter; the inconsistency of the waves and how to solve the problem of efficiently harvesting this energy.
# Contents

**Nomenclature** .......................................................... 4  
Terminology .................................................................. 4  
Abbreviations and acronyms ........................................... 4  
Mathematical notation ....................................................... 4  

1. **Introduction** ........................................................... 5  
1.1 Background .................................................................. 5  
1.2 Purpose ..................................................................... 5  
1.3 Goals ....................................................................... 5  
1.4 Method ..................................................................... 5  

2. **Theoretical reference frame** ........................................ 6  
2.1 Clarke-transformation ................................................. 6  
2.2 Park-transformation ..................................................... 6  
2.3 DSOGI-filter ................................................................ 6  
2.4 SRF-PLL ................................................................... 7  
2.5 Power Regulator .......................................................... 7  
2.6 The complete control system ........................................ 8  
2.7 Carrier based PWM ...................................................... 8  

3. **Technical implementation & Results** .............................. 9  
3.1 Electrical setup .......................................................... 9  
3.2 The program ............................................................. 10  
3.3 Running the system ..................................................... 11  

4. **Analysis and discussion** ............................................... 16  

5. **Conclusions and recommendations** ................................. 17  
Acknowledgements .............................................................. 18  

**Bibliography** .................................................................. 19  

**Appendix** ................................................................... 20
Nomenclature

Terminology

Name                      Explanation
CompactRIO                Industrial computer used to make measurements and operate control systems.

Abbreviations and acronyms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Explanation</th>
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<tbody>
<tr>
<td>PWM</td>
<td>Pulse Width Modulation</td>
</tr>
<tr>
<td>DSOGI</td>
<td>Dual Second Order Generalized Integrator</td>
</tr>
<tr>
<td>SRF-PLL</td>
<td>Synchronized Reference Frame - Phase Locked Loop</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated Gate Bipolar Transistor</td>
</tr>
<tr>
<td>PI</td>
<td>Proportional Integrator</td>
</tr>
<tr>
<td>UI</td>
<td>User Interface</td>
</tr>
<tr>
<td>UX</td>
<td>User Experience</td>
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Mathematical notation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Explanation</th>
<th>SI-unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>Voltage</td>
<td>V</td>
</tr>
<tr>
<td>I</td>
<td>Current</td>
<td>A</td>
</tr>
<tr>
<td>R</td>
<td>Resistance</td>
<td>Ω</td>
</tr>
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1. **Introduction**

1.1 **Background**

Flexible systems for power control and power flow is hugely requested in the modern electric market, with increasing volume of small scale producers, and decreasing amounts of big synchronous generators in the grid. Here is where active rectification and inversion using IGBT’s and/or other active components have become popular in the past decade, with decreasing costs, increased computational power and availability. They have numerous advantages over passive components, including but not limited to: controllable switching frequencies, high efficiency and multipurpose use. This makes for an exceptional component to use when the control of the system needs to vary and a specific type of performance is needed.

1.2 **Purpose**

The system that has been created is designed to be able to convert a DC-bus voltage into AC that can be sent into the grid. While the system is created in a lab environment it is created in such a way that implementation in a system that includes a generator and rectifier should require minimal work. This will be explained further on.

1.3 **Goals**

The system has a couple of goals to achieve to be considered complete. It should be able to:

- Filter out any reactive power such that no reactive power is transferred to the grid.
- Actively invert the DC-bus voltage so that the grid can absorb the produced power.
- Use DSOGI control to be able to keep track of the phase-angle of the grid, and use this to perform required operations.

1.4 **Method**

First of all, it was really important to have a main perception of how the system was going to be built and how the theory of it was going to work. Therefore simulations using Simulink was carried out to prove that the separate components of the information-collection actually work, and these components are: Clarke/Park-transformations, DSOGI-filter and the PLL.

When the simulations were proven to work and yielded satisfying results, practical work was done to connect all the needed components in the lab. This was an iterative process with many changes and the final result can be observed in the Appendix of this report. In parallel with this practical work, development of the controller in LabVIEW was made, and this was an iterative process as well.
2. **Theoretical reference frame**

2.1 **Clarke-transformation**

The Clarke transformation[1] simplifies a three-phase signal into a two-phase signal which holds information in amplitude and relative phase angle.

\[ V_\alpha = \frac{1}{3} (2V_a - V_b - V_c) \]  
\[ V_\beta = \frac{1}{\sqrt{3}} (V_a + 2V_b) \]  

2.2 **Park-transformation**

The Park transformation[1] requires information about the phase angle of the grid to work, therefore a PLL that locks on the grid angle is required. When this is provided, the alpha and beta signals can be converted into DC-signals.

\[ V_d = V_\alpha \cos(\theta) + V_\beta \sin(\theta) \]  
\[ V_q = -V_\alpha \sin(\theta) + V_\beta \cos(\theta) \]  

In the equations above, \( \theta \) is the phase angle of the grid.

2.3 **DSOGI-filter**

The DSOGI-filter is applied to the alpha-beta transformed phase signals and produces orthogonal vector components in each case. These components are called alpha-quadrature and beta-quadrature and are marked with a prefix q to distinguish them from the original signal. By subtracting beta-quadrature from alpha, the desired alpha component is achieved, and by adding alpha-quadrature to beta, the desired beta is achieved.

\[ V_{\alpha_{des}} = V'_\alpha - qV'_\beta \]  
\[ V_{\beta_{des}} = qV'_\alpha + V'_\beta \]  

This effectively removes harmonics and other irregularities that is perceived when measuring voltages on the grid and makes the computation of the Park-transform more even and balanced. By setting the DSOGI-dampening factor seen as ‘K’ in figure 2.1 to \( 1/\sqrt{2} \), optimal dynamic response is achieved.[2]
2.4 SRF-PLL

The SRF-PLL depends on some sort of regulation signal which in this case is the quadrature component of the grid voltage. This regulation signal \( R_s \) is then added with the grid frequency, and for better performance also multiplied by two. As with every integration, the mathematical component of \( dt \) must be used in the integral, which in the program corresponds to \( 1/4000 \), i.e. the period of one cycle. This then gives the theta which is required

\[
\theta_{\text{grid}} = \int 2(R_s + 50)\,dt \tag{2.7}
\]

and also note that the output of \( \theta_{\text{grid}} \) is wrapped, and that means that it only gives an output of \( \pm 1 \).

To increase the stability and the performance of the SRF-PLL, a so called DSOGI-filter can be implemented, as described in section 2.3.[3]

2.5 Power Regulator

This part of the system controls the actual power which is sent out to the grid, as well as the power that might be sent into the DC-bus (although this has not been tested). It is done by using one PI-controller for each of the measured DC-currents (i.e. the Park-transformed three-phase currents out of the inverter) and by setting a desired current out, the inverted Park and Clarke transforms will produce a three-phase reference voltage out, which is sent to a Carrier-wave type of PWM.
2.6 The complete control system

The model in figure 2.2 is largely inspired and collected from a previous research project here at Uppsala University at the division of electricity. It remains unchanged in many parts but some, like the harmonic filter, uses different component parameters.[4]

![Complete control system diagram](image)

*Figure 2.2: Complete control system*

2.7 Carrier based PWM

To control the inverter a carrier wave type of PWM was used. This is a common way to implement power regulation and control in many digital systems, and is favorable due to its low losses in terms of switching and the easy digital implementation.[5]
3. Technical implementation & Results

As explained in section 1.4, the system was set up in a lab environment. Measurements were made with one out of two measurement boxes, which are constructed by another student as his bachelor project.[6] These measurement boxes are connected to a CompactRIO (cRIO)[7] which contains the FPGA[8] that runs the main program that is used in this project.

There is also another module connected to the cRIO which is mounted to a proprietary controller card that controls the inverter. These cards were used in the Project in Electrical Engineering (1TE668) to control the inverter, and the principle is exactly the same here.

3.1 Electrical setup

The inverter DC-bus is connected to a laboratory power pack, which is a variable amplitude rectified one phase sinusoidal voltage. The inverter is then connected to a three phase load inductor which is shunt-connected with a three phase load capacitor. This works as a harmonic filter, and removes harmonics and spikes from the inverter which are inevitable due to the switching frequency.

This harmonic filter is then connected to a Y-Δ-transformer which prevents the third harmonic to be sent to the grid. This transformer is then connected to a grid connection switch where the phase voltages are measured and compared to the grid, before a connection is established. The currents are also measured at this stage, but before a connection is made, there will be no currents flowing. Lastly, the grid connection switch is connected to another laboratory power pack, with a variable voltage level (which means it acts as a transformer) that essentially is the grid.

Due to some error in the program- or the second measurement box which was not found, the grid synchronization were made with a PC-oscilloscope instead of the FPGA program, and while this worked just fine, it meant additional connections of cables.
3.2 The program

The graphical part of the program is executed on the Real-Time (RT) processor of the cRIO. An overview of the graphical program is presented in fig. 3.1. This shows the system running but with no voltage or measurement connected.

![Figure 3.1: The front panel of the RT program.](image)

The main part of the control is done on the FPGA program, and these programs need to be executed in parallel to be able to control all of the functions. The FPGA front panel is shown in fig. 3.2.

![Figure 3.2: The front panel of the FPGA program.](image)
While it may look confusing at first, there is simplicity in this chaos. 'Mult', 'Add' & 'DC-Bus volt mult' only linearly corrects for the error in the measurement sensors, and these controls will remain the same forever unless the measurement box is changed.

All of the 'Ki' & 'Kp', as well as the DSOGI-dampening controls, can be experimented with to achieve different characteristics of the PI-controllers and the DSOGI. The values shown in fig. 3.2 worked well in practice but could have been optimized if that would have been needed.

The controls 'Triangle amp' and 'Triangle(tics)' are the controls for the carrier triangular wave. Note that 'Triangle(tics)' is actually not determined in tics, but a naming error of some sort, and does not have the same name on the block diagram. It is defined in micro-seconds and should have 10 as value for a switching frequency of 10 kHz.

The controls 'qmanual FF', 'dmanualFF' & 'ThetaFF' are used to phase-in the system. Generally 'ThetaFF' does not need to be changed, the phase-in process can be completed with only 'qmanualFF' and 'dmanualFF'. If this seems confusing, that’s because it is, and testifies that this process should be automated for the sake of simplicity.

When starting the system, all of the FF-controls as well as the desired currents out should be set to zero. It is okay if they have values not equal to zero if the IGBT’s are off. When set to zero, the IGBT’s are turned on and the phase-in process is proceeded by altering 'qmanualFF' and 'dmanualFF'. When phased-in correctly, the grid may be connected and the system should behave at intended. Then set the 'current limiter' control to a maximum top value of around 4A. If this value is exceeded, the IGBT’s will turn off.

Turning off the system is done much in the same way that the system is started, but more or less in reverse. Set the 'desired current'-controls to zero, such that no power is delivered to the grid. Then disconnect the grid manually by the switch. If this is done correctly the harmonic sounds will again be heard, that were there when the phase-in process was under way. Proceed to turn off the IGBT’s, and the DC-Bus should begin to bleed off its voltage when the supply for the DC-Bus is turned off.

### 3.3 Running the system

Optimal values for the equipment while starting it up is around 200 VDC for the DC-Bus, and around 40 VAC for the grid. Also the highest current that has been tested out of the inverter is 2A, but this does not mean that it can not handle more. As mentioned in section 3.1, grid synchronization were made with a PC-oscilloscope comparing one phase of the inverter with the corresponding grid phase. Before synchronization was attempted, the voltages may look as in fig. 3.3.
Figure 3.3: The black signal is the inverter voltage and the blue is the grid voltage. They have different amplitude and are out of sync with each other.

The voltage is completely out of phase, but can easily be adjusted in the program by changing the Feed-Forward control. By adjusting the feed-forward control for q, the phase will adjust to what is needed and look as in fig. 3.4.

Figure 3.4: The grid voltage and inverter voltage are in sync, but the latter lacks in amplitude.

There is visibly a phase match, but it lacks some amplitude. This can be corrected by adjusting the feed-forward control for d. Adjusting this will lead to a phase match and voltage match as shown in fig. 3.5.
Figure 3.5: The grid voltage and inverter voltage are completely in sync and have the same amplitude

With these requirements met, the grid connection can be established by switching the grid connection switch. See fig. 3.6.

Figure 3.6: The inverter signal connected to the grid.

The system is now ready to output power to the grid and is currently in sync with it at standby. The overview of the measurements in the program is shown in fig. 3.7.
Figure 3.7: The DC-bus voltage is the top line of the plot. The three phase inverter voltage, when connected to the grid, is shown in red, green and blue. $\theta_{\text{grid}}$ is visible as the striped saw-tooth and the current lies at zero. Y-axis units are not of importance, it is mainly a graph to put the system values in to perspective with each other.

If an output current is set to 1 A, which is done in the program, the currents will rise and give the readout shown in fig. 3.8. Note that the currents are manually amplified in the graph for easier visualization.

Figure 3.8: The same signals as shown in fig. 3.7. Y-axis units are yet again not of importance. The 1 A current applied, shown in yellow, orange and light blue, are significantly scaled for visibility, and thus do not correspond to the scale of the y-axis.

The currents are completely in phase with the voltages, ensuring that only active power is supplied to the grid. The control system relies on these currents to work optimally, but they operate on the dq-values of the currents which are also visible in the program. With 1 A of current out, the dq-graph is shown in fig. 3.9.
While it might look jagged and distorted, this dq-frame does build the reference voltages that controls the PWM. These voltages are shown in fig. 3.10.

These reference voltages are then compared to a carrier triangular wave that runs at a frequency of 10 kHz, therefore the switching frequency of the IGBT’s in the inverter is also 10 kHz.
4. Analysis and discussion

The developed system managed to track the grid and its frequency well, this made it possible for the power regulator to generate a fine three phase reference signal for the PWM to handle. The Clarke and Park transformations worked nicely and gave a satisfying conversion from abc to dq. Considering that the system relies heavily on these features, this was a very important accomplishment.

Considering the small amount of errors, the system performed remarkably well. It responded quickly to desired changes in current. There might be a risk that the system is so quickly adapting to change that if one of the PI-controllers for example decides to diverge, the over-current limiter would turn off the IGBT’s. That would mean that the grid, by passive rectification, will charge the DC-bus as a load. This in turn might mean that the DC-bus and its electrolytic capacitors might explode.

The fact that the phase-in process has to rely on a separate software is a hurdle, because it means that it can not be automated; something that probably wouldn’t be too hard to do otherwise. Either this problem is because of a faulty measurement box, or there was some error within the program that could not be found.

When setting the current out to 1 A, it should be the d-component that corresponds to a current that produces active power. This was not the case in the final testing phase, and this might be due to some irregular connection in the laboratory, although unlikely. It might also be because of some error or phase shift in the program that shouldn’t be where it currently is. If a thorough check is done, the error should be found. Currently, it is the q-component that determines the active power.

There is another similar risk in which way the system is turned on and off that probably would end up in the same scenario described above. Preferably, when starting the system, the grid should not be connected and the IGBT’s should be turned on but with zero current out. This will make sure that no current flows in the system while the phase-in process is being made. After the phase-in process is completed, the grid can be connected. When stopping the system, it has to be made sure that the current out is set to zero before the grid is disconnected. If the IGBT’s are turned off before the grid is disconnected, it will probably end up with the same kind of explosion as aforementioned.
5. Conclusions and recommendations

The system accomplished all goals set out in section 1.3 and presented a comprehensible UI for controlling the system. A small amount of time could be taken to improve the UX quite a lot. For example, it should be constructed such that only the RT-program has to run, and it should contain all the controls that is necessary to use while the system is running. Also power calculations could easily be implemented, both power consumptions and power production, since no matter the amount of transformers, the power on either side of a transformer will be the same (not including transformer losses). While the system is running and is grid connected, it is rather safe in operation and could be experimented with to see maximum performance.

To create a complete back-to-back system with a real DC-Bus, that is connected to a generator, the control system for the generator has to be made. When this is done, only a small correction has to be made to this program which is to implement the DC-Bus control. Currently it works fine because the DC-Bus could be considered strong, since it is powered by the grid, but when it is driven by a real generator, some things could change. For example, since a generator might not power the DC-Bus continuously (i.e. linear wave generator) the program will, when the DC-Bus control is implemented, try to compensate for the loss in voltage on the DC-Bus by powering it up with the grid. This will mean unwanted losses and pointless power consumption. This is therefore something that will have to be considered when building the complete system.

To increase the safety of the system, some sort of contactor or software controllable switch should replace the manual grid connection switch that was used. This will be an effective way of protecting the system against overloading of the capacitors in case of a software error. It will also mean that the system could grid connect by itself when or if an automatic grid synchronization algorithm is implemented. This could then be paired with some sort of sensor setup for a large scale wave energy park, such that the park could turn off when no waves is present, and turn on when there is energy to be harvested.

If speed of the system was of interest, a step-response of increased current could be interesting. This would show how quickly the system would respond to an increased setting of current out.
Acknowledgements

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Bibliography


Appendix

Figure 5.1: The FPGA program block diagram.

Figure 5.2: The RT program block diagram.
Figure 5.3: The Park-transformation block diagram.

Figure 5.4: The Clarke-transformation block diagram

Figure 5.5: The DSOGI block diagram.
Figure 5.6: The laboratory setup.

Figure 5.7: One of the measurement boxes connected.