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Verneri Rantanen

# Battery swap system for light electric vehicles

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Opinnäytetyö (AMK) | Abstract

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Verneri Rantanen

Our current transportation causes lot of emissions and renewables like solar and wind power aren’t stable enough as energy sources. When we increase wind production how are we going to store excess energy? There are some battery storage projects and prototypes of battery swapping but combining these two systems would be most beneficial.

In this thesis there is research about environmental impacts, grid connection and battery swap system power electronics. Purpose of this thesis is to increase my knowledge of power electronics and to provide material to get funding for my company. This thesis is therefore made for my company Necaemission.

Environmental impact assessment was made with using many sources, electrical grid connection part was made with using my own thinking about problems with current system with sources to check my thinking and power electronics part with my own understanding, using academic papers and trying many things and figuring things as I went on.

Results show that this battery swap system could reduce emissions in transport and energy production sectors. This system can also increase electrical grid resiliency and reduce energy price peaks. Results for power electronics also look good and it show what basic components are needed to have bidirectional and good quality electricity.

Keywords:

Renewable energy, battery storage systems, battery swapping, power electronics, sustainability

# Contents

## Images

# Used abbreviations or glossary

| | |
|---|---|
| $CO_2$ | Carbon dioxide |
| NOx | Nitrous oxides |
| g/kWh | Grams of carbon dioxide for every kilowatt hour |
| $gCO_2$/km | Grams of carbon dioxide for every kilometer |
| NMC | Nickel manganese cobalt |
| Lifepo4 | Lithium iron phosphate |
| PWM | Pulse width modulation |
| PID | Proportional, integral, derivative control |
| LC filter | Inductor and capacitor filter |
| RMS | Root mean square |

# 1 Introduction

Transportation and energy sector are changing fast to more sustainable and efficient systems but higher prices, not constant energy production or harder to use systems make this transition much harder than it needs to be (IEA, 2023).

In this thesis I am doing research on what environmental and sustainability things this idea of battery swap system could solve, how this system can help our electrical grid to grow more sustainable and how actual battery swap power electronics work. Target for this thesis is to increase my understanding of environmental and electronical components. It would be also used as base where I could expand this idea with my company after I graduate and be part of how I get funding for my company.

## 1.1 Research phases and methods

Thesis has three parts where the first one is mostly finding material to figure how much emissions this system would save. Method for this research phase is literature review using many sources to get mainly numerical information that I can use in my research.

Second part is more about thinking possibilities for electric grid using my thinking about what problems current system has that are talked about in news and other media. I used some sources to check my thinking.

Third and maybe biggest part is to first think how power electronics work in this system and then using MATLAB’s Simulink to build models to show high understanding of power electronics theory. For simulations part I mainly use what I already knew and testing many things and reading power electronics forums and academic material. Power electronics model should give good basis for starting to build actual prototype.

# 2 Environmental and Sustainability Assessment of Battery Swap System

## 2.1 Greenhouse gas emissions

Our transportation produces quite much $CO_2$ emissions and other types of greenhouse gases. In Finland average car emissions are 180 $gCO_2$/km and total number of cars are 2,8 million (Autoalan tiedotuskeskus 2023). Total driven kilometers in an example year 2020 with personal cars are 39 092 million kilometers (Tilastokeskus 2021). That makes entire emissions $3,9092 * 10^{10}$ km $* 0,18$ kg/km $= 7,03656 * 10^9$ kg of $CO_2$. That is quite a lot of emissions just from getting around and I think we could do much better. Changing to renewable fuels is good idea but because combustion engines are quite inefficient, we would need much those fuels and I think those fuels are better suited to provide heat in plug in hybrid vehicles in winter or at homes because then you don’t waste energy but use high amount of it as heat.

Next one somewhat better way to travel with lower emissions are electric cars. Average sized electric car would produce about 57 $gCO_2$/km over its lifetime (Suomen ilmastopaneelin autokalkulaattori 2023). That is better than combustion engine cars but still on higher side and that is mainly because batteries produce $CO_2$ when they are made, and electric cars usually need quite big batteries to be usable and have good charging speeds.

Now we start to get to very low emission vehicles and those are trains and electric busses. Especially trains can get very low emissions in Finland like 1,5 $gCO_2$/km (VR group 2022). Trains are good for longer distances, but they lack flexibility that many people want and using trains with other vehicles or if you have much stuff with you is quite hard.

If we want to combine low emissions from trains and flexibility of personal transport, we need many types of light electric vehicles like electric two wheelers (e-bikes, e-mopeds, electric motorcycles) and other light three- or four-wheel vehicles. These vehicles usually need much less materials to build and batteries are much smaller that reduce production emissions and they also use much less electricity than electric car. Electric bikes have 4 to 14 g$CO_2$/km emissions (Pyöräliitto ry 2018). With smart usage and new battery technologies we can reduce emissions close to zero.

One problem with small electric vehicles with small batteries are limited range and slow charging that limits their usage to shorter trips. That’s where battery swap system comes in. Battery swapping isn’t a new idea and in many Asian countries you can see battery swap stations. Advantages of this is that you don’t as much battery because you practically can’t run out of range when 30 seconds battery swap is all you need to get on the road. This reduces need for batteries and reduces emissions for travelled kilometer because batteries have emissions when they are produced. For now you would need more batteries with light electric vehicles because you can’t charge small batteries fast enough or travel effectively between charge stops.

Wind power emissions are 10-11 g$CO_2$/kWh during wind power plant lifetime (Dolan & Heah 2012). When we build much more wind power, we have some problems that we can’t effectively use all produced energy efficiently but must use processes that have low efficiency increasing our effective emissions from wind like converting excess energy to hydrogen, but total efficiency is much lower than any battery system connected to grid. Current battery storage systems try to combat this problem, but batteries still have production emissions that must be included in calculation. For most energy dense li-ion battery chemistry NMC emissions are about 80 kg$CO_2$/kWh and for longer life Lifepo4 chemistry emissions are about 60 kg$CO_2$/kWh (Jorge A. Llamas-Orozco etc. 2023, 4). Let’s take closer look at Lifepo4 chemistry because it’s one of the best choices for battery storage systems. Lifepo4 batteries can last 2000 cycles (Intercel n.d). Emissions for stored kwh is 60000 g$CO_2$/2000 cycles = 30 g$CO_2$/kWh but this current situation because many cells are made in China but there are some European manufacturers increasing production like Northvolt in

Sweden who promises 10 kg$CO_2$/kWh by 2030 and they also develop sodium-ion cells for even lower emissions.

Now we shall investigate my battery swap idea and how entire system could reduce need to produce emissions. In short, my battery swap system tries to utilize batteries to their fullest to store but also release renewable energy to grid. There are some battery storage systems being built but batteries are so versatile so why not combine their ability reduce our emissions. If we consider that my system could reduce emissions from driving but also from electricity consumption, we utilize batteries to their fullest and combat their production emissions. Storing renewable energy is important because it reduces need to use fossil fuels to produce electricity during when it’s not windy, but when people use electricity. Electricity emissions increase during colder weather anyways and reduction in wind power increases electrical grid emissions even more to close 100 g$CO_2$/kWh or even worse if our nuclear power goes out of order.

Now let’s make approximations of how much this new system could reduce emissions. Let’s say that 25% of all cars’ driven kilometers are driven with vehicles using this battery swap system. Those car kilometers would use 1,75914 * 109 kg of $CO_2$ not considering how much infrastructure for cars has produced emissions. In battery swap system everybody might need about 4 kWh of batteries but even that might be too much, but at least now extra batteries are used for grid balancing and reducing fossil fuel usage in energy production. If we assume that all drivers replace their trips with my system, then we still need 2,8 million * 4 kWh = 11,2 million kWh of batteries and production of them produces 11,2 million kWh * 60 kg$CO_2$/kWh = 672 million kg of $CO_2$. Even that is still about 10% of what all cars produce in year so we can see cars emissions are quite huge. That energy is same what Olkiluoto 3 can produce for seven hours or almost entire Finland electricity consumption for about hour.

If we first take look at potential emissions saving from energy sector if we assume that batteries are used 50% of time, then we have 5,6 million kWh of storage to store renewable energy. If we compare wind power 10-11 g$CO_2$/kWh and 820 $gCO_2$/kWh from coal electricity production (Luukko 2019). If we can replace all coal power with this system and we approximate that we could store this electricity twice a week we get reduction in emissions (0,820 kg/kWh - 0,011 kg/kWh) * 5,6 million * 2 * 52 = 471 million kg $CO_2$. This would only mean that in year we cycle batteries 104 times when then can easily last 2000 cycles so we can say that this system can last 15 years and reduce emissions by (471 million kg $CO_2$ * 15) – 672 million kg CO2 = 6,393 billion kg $CO_2$. I used coal electricity emissions because this battery swap system should be utilized if electricity prices start to go too high meaning that even producing electricity with coal would be financially feasible.

Now we can look how much potential emissions savings from transportation sector. 50% of those batteries can provide 5,6 million kWh * 2000 * 0,9) / 0,05 kWh/km = 201 600 000 000 km and if one kilometer with produces 0,18 kg of $CO_2$ emissions with car then 201 600 000 000 km * 0,18 kg $CO_2$ = 36,3 billion kg $CO_2$ but now we need to reduce how much batteries produce emissions and some approximation for vehicle and battery swap station emissions and wind power emissions. 36,3 billion kg $CO_2$ - 0,672 billion kg $CO_2$ - (500 kg $CO_2$ * 2,8 million) - (0,011 $kgCO_2$/kWh * 5,6 million kWh * 2000 * 0,9) = 36,3 billion kg CO2 - 0,672 billion kg $CO_2$ - 1,4 billion kg $CO_2$ - 0,111 billion kg $CO_2$ = 34,117 billion kg $CO_2$. To get this emission reduction would likely need more European production but as we can see that cars produce so much $CO_2$ emissions that even with production fully on fossil fuels it would still make huge difference.

So even in Finland total reduction for emissions for this system is 40,5 billion kg $CO_2$ and for one person it is 40,5 billion kg $CO_2$ / 2,8 million = 14 468 kg $CO_2$. Total cars in European union is 249,5 million (European Automobile Manufacturers' Association 2023). For entire European union then we get 249,5 million * 14 468 kg = 3,6 * $10^{12}$ kg $CO_2$. This is quite huge compared to entire worlds energy related emissions in year 2022 of $3{,}68 \times 10^{13}$ kg $CO_2$ (International Energy Agency 2022, 3).

This system still has some problems reducing emissions. If people who already use electric vehicles use this system, then emissions reduction is much lower than replacing car driven kilometers. Reducing electrical grid emissions is quite hard especially if you don't have enough battery capacity and its capacity differs all the time. This system can't create energy so if we don't have enough renewable energy production compared to out ability to store it then we have lower ability reduce emissions. I have also calculated cars emissions using fossil fuels but there are many low emissions fuels that can even make combustion engines more sustainable. Like biofuel Gasum produces here in Finland only has 33,3 g$CO_2$/km average emissions for cars (Trafi 2024).

## 2.2 Air quality

Problem with gas and electric cars are also their higher weight that causes many types of problems for air quality. Tires release microplastics and when roads get worn down, they release other types of particulates (European TRWP Platform 2019, 4). Gas car are probably worst for air quality because they burn fuel and that produces many types of particulates and emissions like $CO_2$ and $NO_x$ from tailpipe and from brakes and tires because unlike electric vehicles, they can't regenerate electricity back to battery (Transport & Environment 2016).

This system's way to reduce air pollution from fossil fuels comes also from that we don't need to burn them for electricity as much as before even if filtering and washing of exhaust from power plants have taken steps toward better air quality. Batteries have become safer and Lifepo4 chemistry is inherently safer and less toxic than traditional high energy density batteries. So, any battery fires that might happen won't be as damaging but safe construction and using quality parts does reduce this risk to very low.

If we can reduce usage of cars in cities, we can build more parks and use more nature in cities it could help improve air quality even more. Trees and plants can be used to reduce $CO_2$ emissions and particulate matter from air and because bad air quality is killing millions of people worldwide (The Nature Conservancy 2016, 1).

If battery swap systems become more common, then people might travel more on light electric vehicles that can regenerate electricity so much less brake pad dust and lighter weight reduces need to brake anyway. Same with tires because weight is much smaller than even smallest cars then you get much less particulates from tires. And because they are powered by renewable energy and don’t need to burn anything they don’t have tailpipe emissions and those are especially important for city usage.

Producing these batteries can be done quite environmentally and with low impact on air quality even close to factories. New types of batteries like sodium-ion reduce need produce many types of emissions that might make air very bad quality and unhealthy.

### 2.3 Resource Depletion

For now, making batteries is quite intensive for environmental reasons and usually this causes resource depletion on areas where materials are found. So, my battery swap system aims to reduce battery usage and get as many people travelling with least number of batteries as possible so we can avoid this environmental problem. Also, this system aims to look for sustainable manufacturers. Now we are making too big electric cars, and they use big batteries when actual need for batteries is much lower than what electric cars now have. Those batteries are also very underutilized when entire range is only use quite rarely and they lack vehicle to grid technology and that is one main point how usage of batteries differ in my system. Also even bit older batteries can be used to balance grid even if they have too low energy content for electric vehicles. Also, because batteries are very modular replacing or recycling broken batteries is much easier than for entire electric car battery, so it reduces need for new materials. So, if one battery from thousands decides not to work it won’t increase need to get new battery for customer and this reduces resource usage.

## 2.4 Noise Pollution

Other important aspect why we should adopt these light electric vehicles is much lower noise levels. If we compare cities with high car usage, then we can see that its much louder than city with less cars. Also, this system would be first targeted for electric mopeds that could replace all gas powered loud inefficient mopeds and I think we should ban sales of gas mopeds especially after battery swap system is working because then you won't have any reason to ride that outdated tech that produces more sound than big trucks. If you have many cars driving on roads it causes much noise in cities and requires more careful planning how you block sound from highways. This problem is for electric cars also but for lower speeds, even if it is not as bad as some gas cars. Lightweight vehicles have much lower noise levels because they produce much less rolling noise and especially gas mopeds and motorcycles are very loud at about 100 dBa (Not Just Bikes 2021).

## 2.5 Heating cities

Because combustion engine cars are quite inefficient, and they have much unnecessary space for one person they can generate hotspots and increase cities heating by producing much heat from engine and air conditioning system. This impact is more local but can still affect pedestrians outside cars. Also, more cars we use more space they need, and we also need bigger roads that retain sunlight leading to increased heating. More roads and parking spaces we have, less nature we can incorporate into cities leading to increase in heating. Trees can provide shading and grassy areas keep much less sunlight leading to cooler cities and keeping surface temperatures low (The Nature Conservancy 2016, 28).

## 2.6 Sustainable Urban Development

These light electric vehicles with battery swapping should be quite high on list for cities to implement. With well placed swapping stations you could even increase people who visit your city. Light electric vehicles need much less space and that is in vain in many cities. When cities become more walkable when all space is not needed for cars then you can build more parks and incorporate more nature in cities. Cars also don’t fit that well in cities when there are so many people. Light electric vehicles usually have better view to outside and much lower mass means that collisions with pedestrians are much less dangerous. Battery swapping makes it easy to own electric vehicle in city because you don’t need to think where you charge or how to carry batteries inside because you can just swap them when going shopping. So, battery swap places should be close to places people use often. There is already interest with cities legislators to reduce gas cars, but we should reduce all cars in cities.

## 2.7 Battery Recycling and Waste Management

Because in this system customers don’t own batteries there is no risk that batteries aren’t recycled or that the waste management isn’t done properly. When my company handles batteries, I would follow reduce, reuse, recycle. Reduce is thing why this system could have quite big impact on material usage because I wouldn’t try to sell as many batteries but to as many people and I would create value with good service and prices would reflect that customer shouldn’t use too many batteries. Reuse is that using batteries as long as possible like only as battery storage. Recycling would be done as well as current technology allows even if it would be more expensive to recycle than to just buy new. All these things combined reduce need to recycle batteries and when recycling is topical then waste management is done to standards to best in industry.

## 2.8 Socioeconomical sustainability

Usually, it’s considered that sustainable choices decrease economic growth and prevents opportunities for poorer people (Teachout 2021). Things are changing fast, and this system would be at forefront of this sustainability. It could provide many jobs that help economy grow and provides more money for state that can be used to help many with like supporting poor people with benefits. Transportation also is big cost for state and for many poorer people so light electric vehicles that are sustainable but still available to as many people as possible would-be commendable target. Now countries and manufactures are mostly focused on electric cars and that is better that we had but big vehicles with big batteries are expensive, and we aren’t replacing gas cars at fast enough rate and even electric cars have many problems like they are too expensive, they have noise problems and have still quite big environmental impact (Lakshmi 2023). Many poorer people are also stuck with expensive electricity prices so battery swapping system could store cheap wind power that could be also sold to poorer people with reasonable prices that reflect actual prices on market with reasonable profit margins. But even being part of electrical grid would decrease prices and reduce electric prices for everybody.

There are still some challenges to applying this system to real world. For this system to significantly reduce emissions would require shift in people’s thinking about transportation. If battery swapping is too expensive many probably wouldn’t want to have this extra expense over their car. This system would also need to be quite widespread to have enough battery swap stations and batteries for reliable usage. Having vehicles that support this battery swap system would be quite expensive compared to many cheap Chinese alternatives and many people still see light electric vehicles as only city vehicles where need for battery swapping isn’t as crucial.

# 3 Electric grid connecting and its possibilities.

## 3.1 Introduction to Electrical Grid Connection

This battery swap system would be tightly integrated to provide storage and smooth out consumption and production peaks. Connection is three phase 400V to suitable access point or even with transformer to connect straight to 25 kV grid if power requirements it require. Battery swap point would have main circuit breaker inside swap station, but electrical fuses would still be used for high safety of this system. Main power wires would be mounted underground for good protection against weather and other things that might damage cables. Cables would be connected to fuses and main circuit breaker inside station with suitable electrical installation team that has required knowledge to install high power AC/DC converters and who have necessary certifications. Because this system uses high currents on phase wires, installation needs to be good quality and power cables strapped down well and routed accordingly to guidelines provided by my company. Because this system can provide much power it requires high levels of fault tolerances, and it needs to be able to handle high continuous power without wasting energy or without unnecessary heating of input cables and connectors. Also, because this system is bidirectional, and it’s working almost always at high power to provide virtual inertia it requires careful planning to work at its fullest (Ujjwol Tamrakar etc. 2017, 1).

## 3.2 Renewable Energy Integration

Because renewable energy production isn’t stable, we need to have enough energy available all times this bidirectional battery swap system can provide three things to have well working electrical grid.

First is providing energy when it’s not windy or sun won’t shine. This system reduces need to use fossil fuels to produce electricity and decreases prices because burning fossil fuels to produce electricity is expensive and usually quite inefficient. This battery swap system can provide electricity with when electricity is expensive and that reduces prices on market.

Second thing this system can provide is backup energy during unexpected energy production deficits. Because batteries and power converters in my simulations can react in about 0,2 seconds so that means any problems with power production can be negated and if we use same number of batteries as in environmental impact assessment part, we could even power Finland for quite many hours if we lost even biggest power production facilities. This would increase our resilience to unexpected things. This system could make money on balancing energy and balancing capacity markets (mFRR) but because number of batteries in this system differ, so it has some challenges with regulations because it’s hard to promise that capacity and power is available when situation calls for it.

Third thing this fast-reacting system could do is providing virtual inertia and that means that battery swap stations would keep looking at electricity grid frequency and try to keep it at 50 Hz ±0,036 Hz (Ujjwol Tamrakar etc. 2017, 4). If we have too high frequency, system will automatically reduce input power to grid and if we had too low frequency system would automatically increase power to grid. This is possible because batteries and power converters have high tolerance to provide high currents in each direction for years to come. This system could make money on Frequency containment reserves (FCR products), Automatic frequency restoration reserve (aFRR) and Fast Frequency Reserve (FFR) (Fingrid 2023, 6).

Money that this system produces can be used to build more battery swap stations and batteries and provide electricity as donations to those who have expensive electricity to show high socio-economic sustainability because being environmentally friendly doesn’t have to stress those who are in lower classes but provide for them and increase social inclusivity.

### 3.3 Smart Charging and Grid Communication

It would be good idea to work with electricity providers so system can be used effectively, and it would reduce electricity provider's need to buy electricity that they might not sell at all (Moreno Escobar JJ 2021, 1). My system could provide stability and predictability and they could provide good control strategies that suit their needs. If we want to use batteries to their fullest potential, we will need many types of prediction models and how they would work together.

First thing we would need to predict is how much renewable energy production we will have in the future, so we won't charge batteries on higher price and on higher emissions electricity that we need (Moreno Escobar JJ 2021, 8). Wind power is somewhat predictable but there are always errors that need to be considered. Solar power prediction isn't that important because its potential for now is quite low, but swap stations could be fitted with solar panels for extra production or for thermal management inside swap station.

Second thing we should predict is how many batteries are needed and where they are needed. Amount of people travelling isn't constant and because this system is first mainly for electric mopeds and motorcycles, so summer usage is probably much higher than winter usage, but this isn't problem because need for battery storage systems is much higher in winter because electricity consumption differs even at daily basis. Some days people travel more and even weather can affect how many batteries are needed. Target for these predictions is to have as many batteries always connected to grid but still providing enough batteries for people's transportation and fast swap times.

Third thing we should predict is when to sell and buy electricity for this system to best provide stabilizing effect on electrical grid. Daily main electricity peaks are at mornings and evenings and this system could provide extra electricity possible even stopping any blackouts even if we lose some production at critical times (Cygnel 2022). To maximize this system effectiveness, we should charge from grid at highest power when electricity is cheapest and discharge to grid when electricity is most expensive. This would make most financial and environmental sense because prices reflect on how much emissions are produced. Wind and nuclear power have lowest prices, but they also produce least emissions (Vakkilainen etc. 2017). Next is solar with more emissions but it has higher price. Anytime we need to burn anything it has emissions and particulates even with good filtering and washing in power stations.

If this system gets enough information, it means reduction of needed batteries and it increases their potential and reduces entire system emissions. If communications with electricity providers is made well it would mean less need to predict things and increasing positive impact of this system on entire electric grid and for people who use this system. Batteries would mainly be charged during night but if there is extra energy available in daytime batteries could still be charged.

### 3.4 Possibilities of microgrids

One interesting possibility with battery swap stations is to provide energy during local grid blackouts. Many small battery swap stations make system quite distributed and makes it possible to setup microgrids. Microgrids means that some geolocation has circuit breakers around it so in possible blackouts in this smaller part of grid can anti-island itself and continue function like normal (Moslem Uddin etc. 2023). This system would be hard to implement with current battery storage systems because they are quite huge and usually quite far where battery capacity is needed. So, during blackout this microgrid is detached from electrical grid but because battery swap stations have still nice amounts of power and energy available it could be used for homes and businesses around battery swap station and prevent loss of capital like food in restaurants or supermarkets. This also means that grid connected solar panels from individuals and from customers could continue to function because my battery swap station works as small energy production facility. Usually in situation like this all the solar panels connected to grid would be deactivated and then they can’t produce energy. But if battery swap station can keep powering this small microgrid then those solar panels never lose grid connection. This system would be suited for bit smaller blackouts but depending on the communication between devices and users in this microgrid that could be expanded to even days if needed. Even if needed power peak is huge and system needs to react very quickly this isn’t problem to this battery swap station because it has modern power converters and powerful batteries. To effectively make this system needs cooperation between energy production companies, grid controlling agencies, local companies and local people. If grid blackout includes more than one battery swap station, they could work together so smaller blackouts could never happen.

# 4 Battery swap power electronics

## 4.1 Basic working principles

Battery swap system for light electric vehicles requires well working power electronics that can communicate in real time with node server in battery swap station. Node servers also communicate with main server for entire system control. In this battery swap system power electronics convert electricity bidirectionally to provide necessary functions to charge and discharge batteries. This system will have bidirectional inverter with grid synchronization and power factor correction. Inverter will also have good control loops and safety measures that are required by grid connected converters. Also, in one battery swap system there will be many bidirectional buck boost converters that will reduce inverter dc bus voltage to batteries level but also boost battery voltage to dc bus voltage. This bidirectional buck boost converter would also communicate with node server and have own control loops. These converters combined and with well optimized control should provide reliable conversion with good efficiency.

## 4.2 Bidirectional inverter/rectifier

Bidirectional inverter/rectifier would use six-switch boost-type active three-phase rectifier for its high performance, high controllability and smaller size of inductors and capacitators because it can use high switching frequencies. It has some drawbacks like high voltage stress in semiconductors, need of high input inductances and shoot-through of bridge leg. This high-power inverter needs EMI filter that filters harmonics from switching, reduces electromagnetic interference and reduces susceptibility to electromagnetic fields itself. (Vieira etc. 2014, 3.)

Working principle when pulling electricity from grid: When pulling electricity from grid it’s important to measure all phase voltages and currents to have power factor as close to 1 as possible. Because this converter has high dc link capacitance it would cause phase shift and non-sinusoidal current to be pulled from the grid and that would cause unnecessary current to bounce back and forth in the electrical grid and that isn't good idea because electrical grid is already quite at its limit. This is where this boost type design comes into play and using phase oriented PWM control to make sure that pulled current is in phase with voltages in all three phases and its shape is as sinusoidal as possible. Because this system is high power, we would use continuous conduction mode where inductor currents never goes to zero.

Working principle when pushing electricity into grid: When pushing electricity to grid it's important to measure zero crossing points and phase voltages accurately. Because grid impedance is small, difference in inverter phase voltages compared to grid phase voltages causes big currents so good PI loop is necessary. Also, good current measuring across all the phases is important to push sinusoidal current into electrical grid and provide means to have good safety measures. Delays in system can cause phase lag that we want to avoid.

Both systems working together: By adjusting PWM duty cycle for all switches we can adjust inverter/rectifier phase voltage and if its lower that grid voltage then we are pulling power from grid and if its higher, then we are pushing power into the electrical grid. Anti-islanding is important for safety of this system because if we lose grid connection inverter/rectifier should disconnect itself from grid to prevent breakdowns or unsafe conditions. By telling PI control loop if we want to push or pull power from grid it adjusts PWM duty cycle according to set values. If we measure phase and dc bus voltages and dc bus and phase currents, we should be able to use them well in PI control loop. Inductors on phases are usually controlled by having higher PWM duty cycle during after our zero-crossing point to pull more current than otherwise would happen. Inverse of this happens at highest point of phase voltage because we need to limit current flow because high phase voltage wants to charge our dc link capacitor too fast. When pulling electricity from grid if we did not have this power factor correction then we would charge our capacitator too fast and when pushing electricity to grid we would discharge our capacitator too fast. When we pull electricity from grid, we run in boost mode and when pushing electricity to grid we operate in buck mode. Doing things this way will enable good control and reduce harmonics.

## 4.3 Bidirectional buck boost for battery charging

Another important power electronics part is bidirectional buck boost converter after bidirectional inverter/rectifier. Its job is to reduce about 1000V dc link voltage to 72V nominal voltage for batteries but also to boost that battery voltage to 1000V dc link voltage. This converter will have two switches top and bottom one, one inductor and one capacitator at battery's side. We want to measure the input and output currents and input and output voltages that we feed to node computer so we can control them externally. In buck mode or when charging battery, we drive top switch with duty cycle D and bottom switch with duty cycle with D-1. When top switch is on inductor current begins to rise and when set value in our PI control loop is achieved then we switch top switch off and turn bottom switch on and we will include some deadtime to prevent short circuit between out high voltage dc link bus. Deadtime depends on many factors, but it should be measured with oscilloscope to have best performance. When bottom switch is on inductor's magnetic field collapses and provides high current for battery. In boost mode or when discharging battery, we drive top switch with duty cycle D-1 and bottom switch with duty cycle with D. When bottom switch is on the inductor current begins to rise and when set value in our PI control loop is achieved then we switch bottom switch off and turn top switch on. When bottom switch is on inductor's magnetic field collapses and provides high voltage for dc link.

## 4.4 Entire power electronics system working together.

When we want to charge batteries, we will first set values for all bidirectional buck boost converters and calculate total needed power. Then bidirectional inverter starts to increase power we pull by running phase PWM at bit lower voltage than grid phase voltage, so we start pulling current. Also, converter needs to have phase locked loop running so we are in phase with electrical grid. Converters measure power and adjust PI loop values to have same power values. Also control loop adjusts PWM signals to pull sinusoidal current from electricity grid phases. So, if we have 10 batteries and each of them charges at 1 kW then we want to pull about 10 kW from grid using this bidirectional inverter/rectifier. When pushing energy to grid we just calculate total power batteries are pushing to grid and adjust values based on that. When pushing energy to grid our inverter phase voltages is bit higher than grid phase voltages, but PI control loop keeps that in check by measuring phase currents and dc link current at many kHz.

4.5 Why we need power factor correction when pulling electricity from grid.

I started my simulations with modelling basic three phase rectifier that converts three phase ac to dc voltage. This is most basic ad/dc converter, but it also has worst performance, power factor and harmonics.

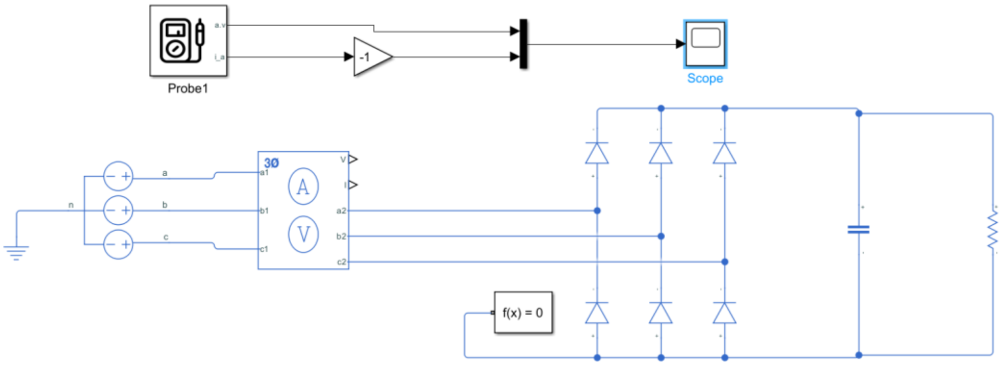


Figure 1: Schematic of basic three phase diode rectifier

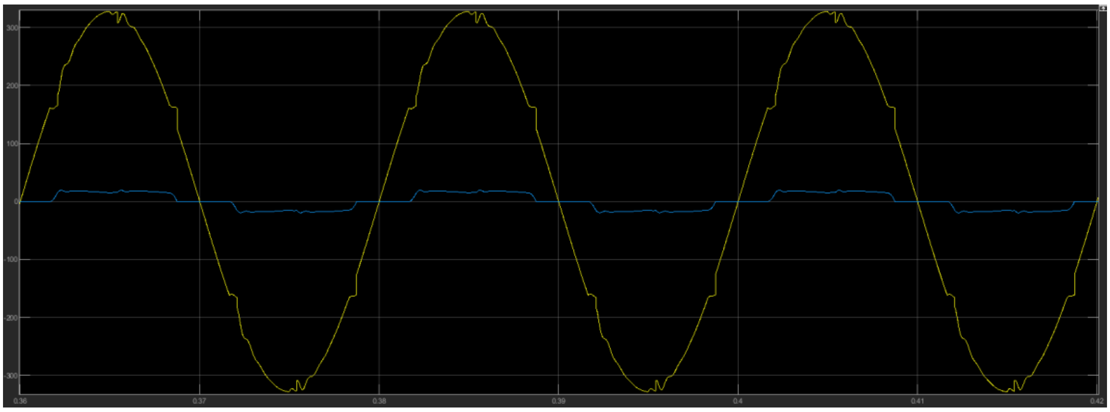

Figure 2: Scope of basic three phase diode rectifier

As we can see from figure 2 scoping phase a with voltage as yellow and current as blue that current isn’t sinusoidal but quite rectangular and this increases our reactive power that we want to avoid. This is caused by dc link capacitator.

4.6 Simulating high voltage bidirectional dc converter and testing running it with three phase diode rectifier.

Second simulation I made was bidirectional dc converter. With this simulation I started building my simulation knowledge and seeing how PID loop affects system’s response.

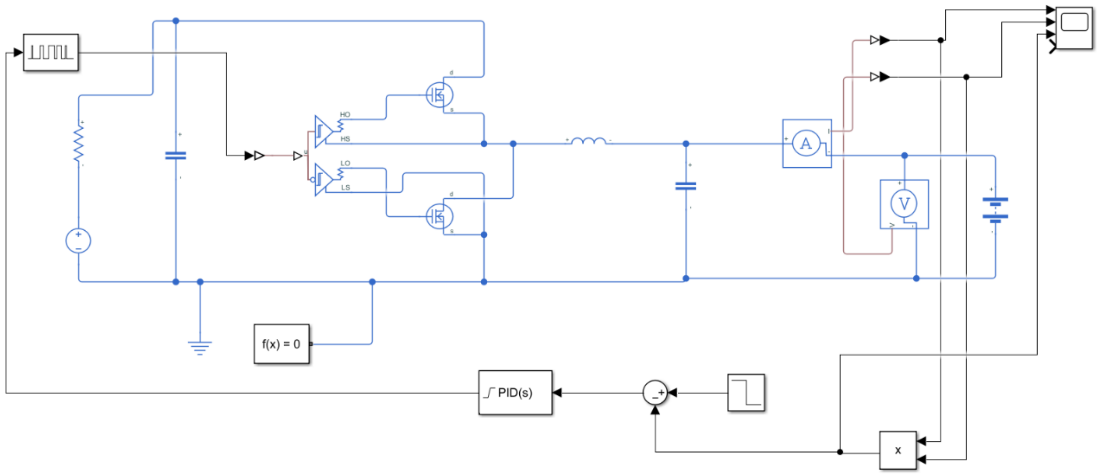


Figure 3: Schematic of high voltage bidirectional buck boost converter

In figure 3 we can see mosfet half bridge that is driven by half-bridge driver with deadtime value of 300 ns. Control is feedback loop using PID controller with P = 3, I = 0, D = 0. We feed our wanted power to sum block where we reduce out measured power using multiplication block from current and voltage sensors. This signal is called error and PID loop tried to reduce it to zero by adjusting PWM duty cycle between 0-1 and we limit values to these by using saturation inside. I used Simulink-ps converter when converting PWM signal for half bridge driver and ps-Simulink converter when converting my measured current and voltage so I can use them in scope and in my PID loop. Used values are: 100 kHz switching frequency, 700 V input voltage with 1 milliohm resistance and output voltage battery's nominal voltage of with 66 milliohm of resistance and this is about 2 kWh battery with 5000 mAh 21700 li-ion cells, Input capacitor is 10 uF and output capacitor is 100 uF. I also gave capacitors start voltage values close to they are connected to, so I don't need to worry simulation transients.

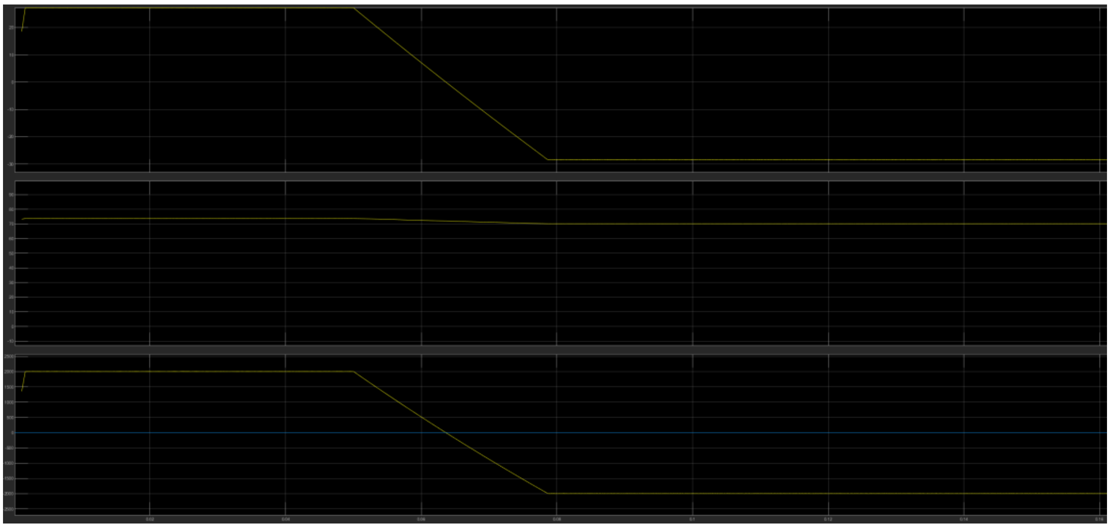

Figure 4: Scope of high voltage bidirectional buck boost converter

In figure 4 we can see battery current at top, battery voltage at middle and battery power at bottom. I used step block to change power from 2000 W to -2000 W and that takes about 30 ms. So first we can see that current rise to about 27A quite fast and after that it stays flat until 0,05s when it starts to drop and goes negative to about -27A and that means that battery is discharging when at start it was charging.

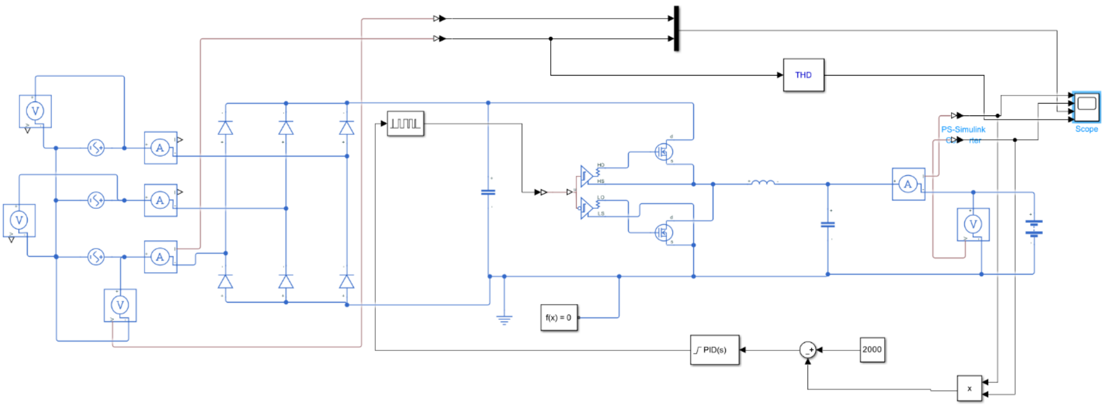


Figure 5: Schematic of three phase diode rectifier connected to high voltage bidirectional buck boost converter

In this simulation I evaluated how three phase currents look and does output stay stable when used with rectifier. I also used total harmonic distortion block and I got 190% of distortion and percentage under 5% is acceptable so this converter works but shouldn't be used on grid.

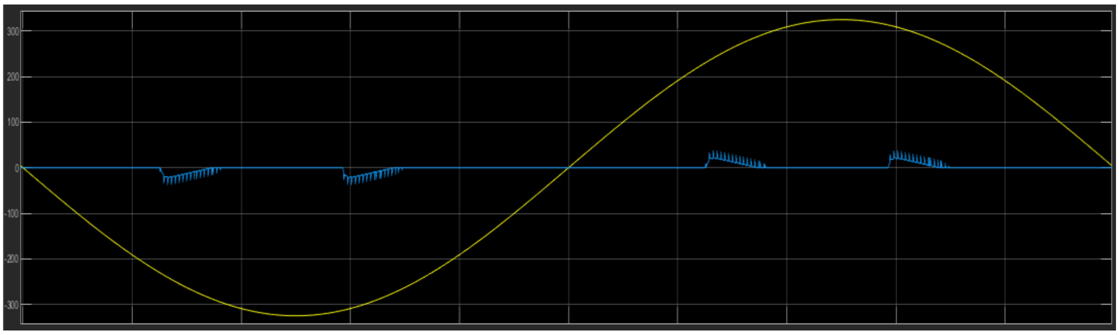


Figure 6: Scope of three phase diode rectifier connected to high voltage bidirectional buck boost converter

If we look one phase cycle in figure 6, we can see that current is far from sinusoidal and it has two peaks with about 20A of amplitude when RMS current should be about 3A. Using power converter like this would cause many problems for grid and wouldn't pass any types of tests.

## 4.7 Building basic sinewave three-phase inverter and testing synchronization with grid at stable setting

First, I design three-phase unipolar dc-link inverter and test what values I need to achieve synchronization with grid. I have 1000V as input voltage for inverter. I use PWM Generator (Three-phase, Two-level) to generate gate PWM signals to drive three half-bridge modules. I have evaluated that in this stable condition Vd = 130,34763V and Vq = 40,4V that I combine with mux to have dq0 for inverse park transform. This inverse park transform takes dq0 and wt. Dq0 is part that has required information to reconstruct our sinewave and wt is our wanted angle in radians. In degrees we can think that every 360 degrees sinewave has completed one period. We have block for our electric grid with arbitrary phase angle of 19,28 degrees. We use phase locked loop that takes ABC voltages in and gives out our phase an angle in radians and it is changing according to how our electric grid voltages change. Then we can use this angle information and give it to inverse park transformation that generates ABC voltages for PWM generator. Then we connect PWM generator gate output to demux that breaks our vector input to each mosfets in our three-phase inverter half-bridges. Each phase from mosfets have LC filter to work as low pass filter to provide excellent quality sinewave at the output. We also have small load connected to our three-phase inverter to evaluate how inverter reacts to load being applied.

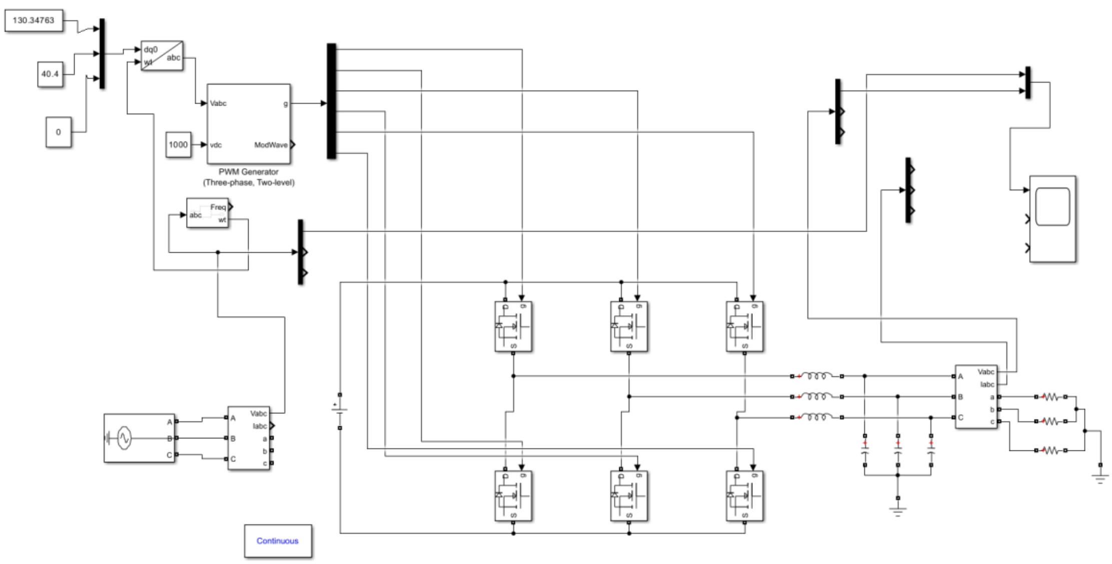


Figure 7: Schematic of three-phase inverter

Figure 8: Scope of three-phase inverter that shows phase A

As we can see from figure 8 output voltage A waveform, we have achieved quite good synchronization with our electric grid. Yellow is out electric grid and blue is our output voltage from inverter. There is little phase shift and voltage amplitudes are very close to each other. If we had difference in voltage magnitudes, we would produce or use reactive power and if we had phase shift between voltages then we would produce or use active power.

## 4.8 Simulating entire batter swap system power electronics and component's working principle

Simulating entire system required many iterations and required information about phase locked loops, Park transformation, inverse Park transformation, active power and reactive power.

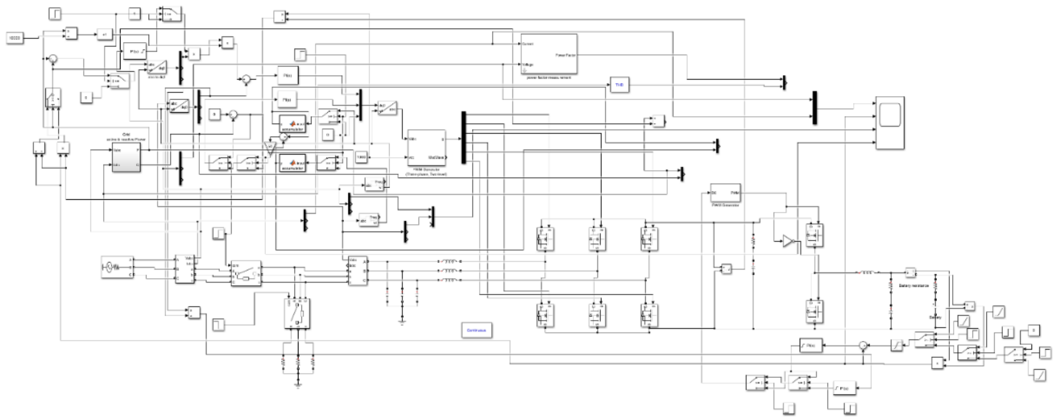

Figure 9: Schematic of entire battery swap system

In figure 9 we can see schematic of entire battery swap system. There are quite many parts but most complicated one is that gives out sinusoidal voltage signals to our six-switch inverter. Parts include electric grid with voltage and current measurement, circuit breaker between inverter and grid, small load for inverter that is disconnected after synchronization, three phase six switch bidirectional inverter/rectifier with LC filter, bidirectional dc-dc buck boost converter for battery and battery modelled as voltage source with resistance, grid active and reactive power measurement, phase locked loops for grid and inverter, park transforms for inverter and grid, inverse park transform for generating reference signals for PWM generator, all the control between Park transform and inverse Park transform and actual PWM generator with continuous conduction mode with sinusoidal PWM and with input for output voltage magnitude.

There are much terminology that I explain before we go into how this system works. Phase locked loops are especially important for grid tied inverters but what it does is to take our phase voltages ABC and it generates out current phase angle in radians for phase A. Because our system is balanced, we can assume that other angles are 120 degrees and 240 degrees apart from this phase A measurement. Park transform and inverse ark transform are particularly important to provide way to use PI loops to control output voltage waveforms. Park transform takes our phases ABC and our grid’s phase angle in radians and generates rotating coordinate frame dq (Yoash Levron etc.). Vd is our direct axis and is in phase with our grid voltage waveform and Vq is our quadrature axis. Vd controls amount of active power and Vq controls amount of reactive power, but both have effect on phase angle and amplitude. Because these components are basically quite simple dc voltages, we can use PI loops to control them. Inverse Park transformation takes our Vd coordinate frame and converts it to voltage waveforms that we can use with PWM generator. PWM generators generate PWM signals that are 1 or 0 and 1 means that connected switch is closed and current starts to flow and 0 means that switch is open and current wont flow. Having right amount of on and off time can make good control possible. PI controllers are means to control this system but adjusting system enough but not too much. PI controllers have input for error and output controls our values. PI controller parameters are important to get right that we have fast response, but we don’t overshoot or have error in our output.

Let’s go over how this converter connects to grid and how it adjusts its values to have good input and output current waveforms. From 0s to 0,2s we have our circuit breaker open, and our dummy load connected to inverter. During this time, we control with PI loop that our Vq is close to 0 and with another PI loop we control that our Vd is close to grid’s Vd. After 0,2s we use phase locked loops to generate inverter and grid phase angles and using accumulator code and switches. Then we start calculating phase angle difference between grid and inverter and we aim for as low phase angle difference as possible before we connect inverter to grid. We also control our input power from bidirectional dc-dc converter to have as small phase magnitude difference as possible. At 1s mark we have achieved good synchronization with grid, and we can close our circuit breaker and with 80 milliohm grid resistance we get only 15-30A peak current between grid and inverter. We also change our control algorithm to keep our Vd as close to grid as possible and our Vq as close to 0 because we don’t want any reactive power to have good power factor. We also start to reduce bidirectional dc-dc converter power because we don’t power dummy load for now anymore. At 1,02s we disconnect our dummy load because we don’t need it after we have made connection with grid. After 1,22s we also include active power control strategies. We use our grid active power measurement to adjust Vd but also using our bidirectional dc-dc power measurements and our dc link voltage measurements and adjust Vd so that our dc link voltage stays close to 1000V. If grid active power is positive, we (1000 Vset / Actual DC-link V) * bidirectional dc-dc converter power and if grid active power is negative, we (1000 Vset / Actual DC-link V) / bidirectional dc-dc converter power. I am doing things like this because during positive active power at grid increasing power from grid would result in increase in our dc-link voltage and decrease power from grid would result on decrease on dc-link voltage. We divide if power is negative because then dc-link voltage reacts inversely. This system uses feedforward control with PI loops so it can react to nonlinear changes better. At 1,8s we start to increase power from grid and stop at 3000W power from grid. Then we keep pulling power until 2,5s and then start to reduce power and keep going until we input 3000W to grid or when battery power is -3000W.

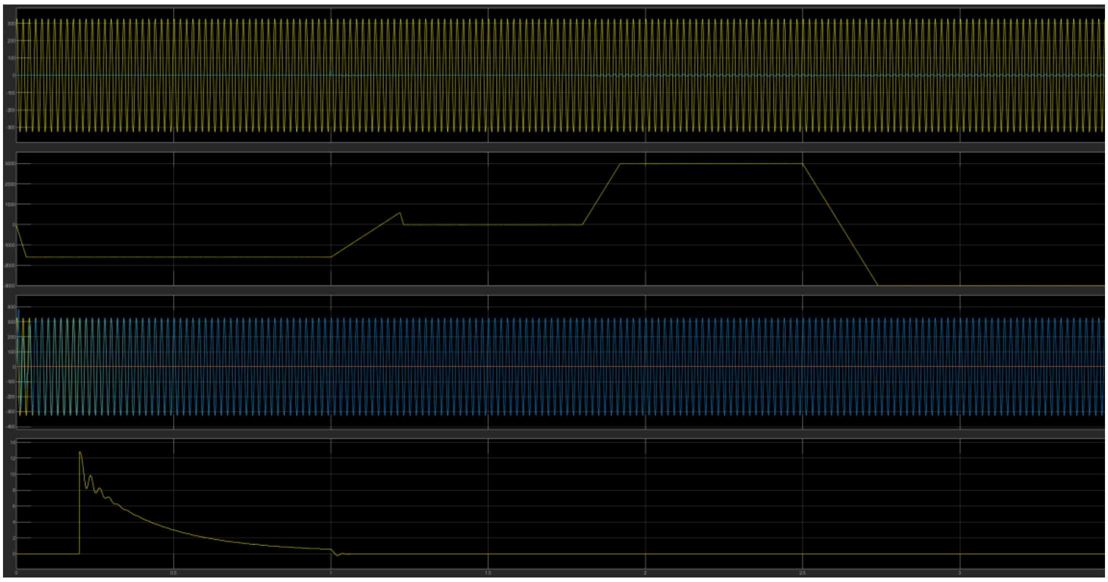

Figure 10: Scope of entire battery swap system

In figure 10 topmost graph is our grid voltage and current waveforms, and important thing is that it is very sinusoidal and that means high power factor and low total harmonic distortion. Second from top is our actual battery power and when pulling or pushing current to grid we can see that grid current waveform is positive when pulling and negative when pushing electricity to grid. Third from up is our grid voltage in yellow and inverter voltage in blue. We are only looking phase A with this scope, but other phases should look same but with phase difference. We can see that it takes about 0,1s to PI loop to get inverter and grid to about same frequency and voltage waveform. After 0,2s we can see that control loop start to decrease phase difference between inverter and grid and at 0,6s we adjust out input power a bit to get amplitudes as close as possible. At bottom we can see phase difference between grid an inverter in radians, but actual radians are 50 times smaller than what is seen on scope.

## 5 Conclusion

Main points of this thesis was to find out what are potentials this system would have and how battery swap power electronics would work. It was interesting to see how much we could save on emissions if we reduced our car usage and what other good things it would bring to cities. I also found many ways how this system could help develop our electrical grid and how to make it more sustainable and resilient. After many tries, I also got power electronics simulations working and that is important part for when I start to look for funding because I can show that I have good understanding of system that I am developing. Simulations are showing reliable results and basic idea of how system would work is working as intended.

Next part how I would continue this project is to start making actual prototype and start looking for certifications. I would also do even wider environmental impact assessment that could also be used for funding. I would also need to figure what market potential and possible partners I could sell these battery swap stations and how actual battery swapping could work. I would also need to figure possible prediction systems for battery usage and when I need to charge and discharge batteries from and to grid.

Thesis has valuable information but doesn’t have information about actual standards or what kind of markets system like this system could have. Power electronics simulations also need more fine tuning to work with higher power and follow grid codes. Also, emission reduction potential might be lower than calculated but it depends how much renewable fuels we can produce and what is actual system’s emissions.

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