Implementation battery system in a virtual synchronous generator system

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Implementation battery system in a Virtual Synchronous Generator System

By: Dongjun He

Where innovation starts

Contents

Chapter 1 Introduction

Conventionally, the generation in electrical network consists mostly of large synchronous power plants with synchronous machines directly-coupled to the grid. Nowadays, due to environmental concerns the situation has started to change. More and more Renewable Energy Sources (RES) and Distributed Energy Resources (DER) are being used. As the amount of the share of RES and DER are growing, it will have important influences on the grid. Many RES and DER are connected to the grid by means of inverter-interface, which is opposite to the conventional directly-connected generators. Presence of significant amounts of RES and DER in the grid can lead to frequency variations since they do not have rotating mass, which physically prevents large frequency variations in case of the imbalance between the active power generation and the load. And in emergency condition even instability of the grid is possible. A way to avoid this is adding virtual rotational inertia with a short-term energy storage.

This is also the major goal of Virtual Synchronous Generator (VSG) project: to emulate/mimic the behavior of a synchronous generator using a power electronic converter with control algorithm and the short-term energy storage to contribute the stabilization of the grid frequency in case of disturbance.

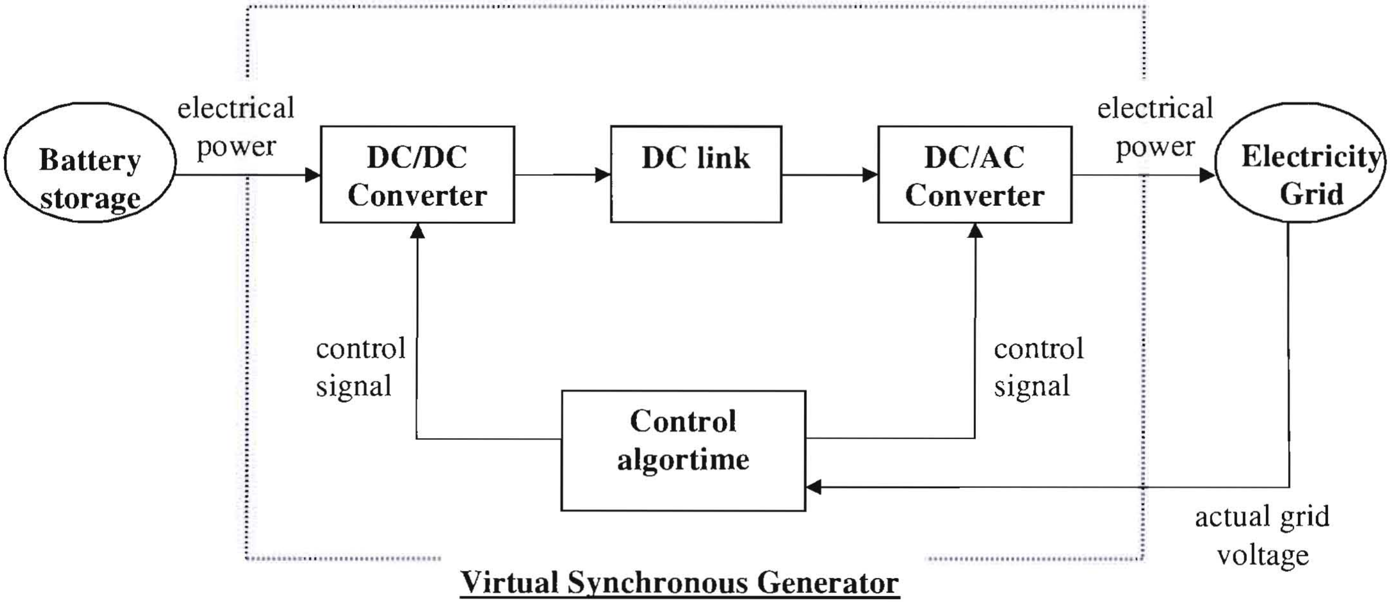


Figure 1.1 VSG diagram

This report contains 2 major parts, the fundamental part and the practical part. The fundamental part explains the general theory of frequency measurement and the methods of frequency estimation. The practical part gives an overview of the use of the Triphase system. For example, how to start up and control the Triphase system using the Matlab program, also how to charge and discharge the different types of batteries will be given in this part.

The report has been written with the use of the Matlab models, the circuit schematics and the pictures. All Matlab files can be found in the enclosed folder or in the system operator's laptop from the Power Quality lab.

Chapter 2 Frequency Measurement

2.1 Introduction

Any deviation from the balance between the power plants supply and the load demand will lead to decrease or increase of the frequency. It is important to measure the actual frequency and counteracts the unbalance in order to maintain the grid's stability.

There are many methods for the frequency measurements. In this chapter the zero crossing detection (ZCD) method and the phase locked loop (PLL) method will be explained.

2.2 Zero Crossing Detection

Zero crossing detection is an open loop method to measure the frequency. A zero crossing point is a point where the signal is equal to zero. In an x-y axis graph representation zero crossing points are the points with zero values on the y-axis. By detecting the time between 2 sequential zero crossing points the sinusoidal signal frequency can be estimated. Namely, $f = 1/T\_period$ or $f = 1/2 * T\_zc$. In practice, the point of zero crossing can be determined as a point on the interval where the signal is changing its sign from positive to negative or vice versa.

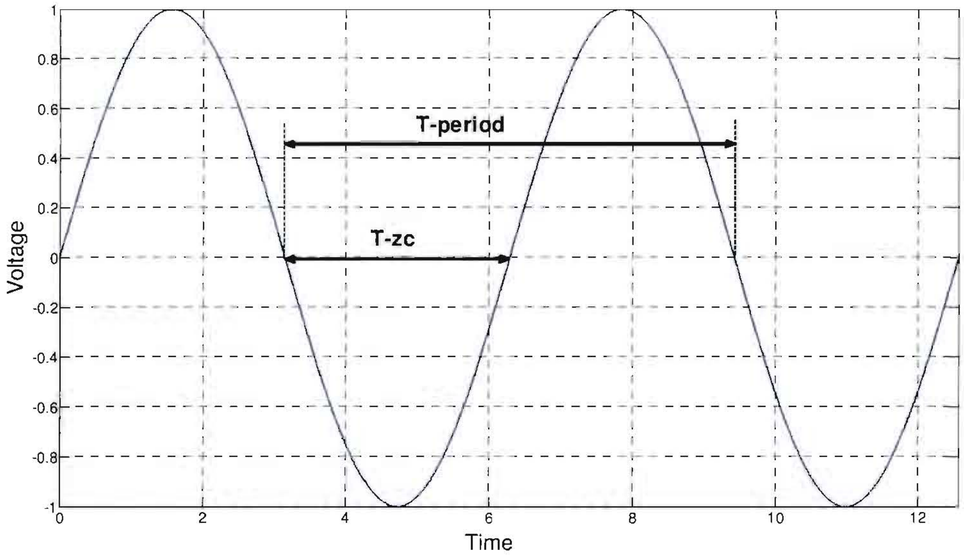


Figure 2.1 Principle of ZCD

The sampling time must be small enough to detect the zero crossing. For example, if a zero crossing occurs within a time step, but the values at the beginning and the end of the step do not indicate a sign change, the zero crossing will be failed in this case. To be sure it will not happen, the sampling time is chosen to be 0.1 ms (corresponding to 10 kHz sampling frequency), which is sufficient for the ZCD of a 50 Hz signal. And it satisfies the Nyquist theorem for sampling which it said the minimum sampling frequency should be equal or higher than the 2 times of the highest frequency of the process.

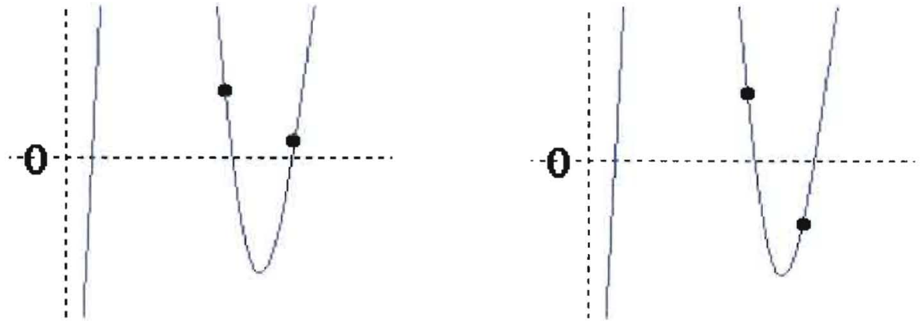


Figure 2.2 The difference of sampling time

Adding the sampling time of 0.1 ms (1/10 kHz) to the fundamental frequency period of 20 ms (50 Hz), gives the total time of 20.1 ms. This corresponds to 49.7512 Hz, which then gives the maximum error of frequency measurement of 0.2488 Hz. This error is quite large. Even with smaller sampling time, there is still some error. This will influence the precision of frequency measurements. To achieve a better result, zero crossing detection is extended with linear interpolation.

Linear interpolation is a method of curve fitting between two points. For example, if two points are known and given by the coordinates (x_0, y_0) and (x_1, y_1), the linear interpolation is a straight line between these two points. The straight line is given by the following equation.

$$y = y_0 + (x - x_0)\frac{y_1 - y_0}{x_1 - x_0}$$

Solving this equation for y=0, the exact time of zero crossing between two sequential points can be estimated. In this case x = t.

$$x = x_0 - y_0 * \frac{x_1 - x_0}{y_1 - y_0}$$

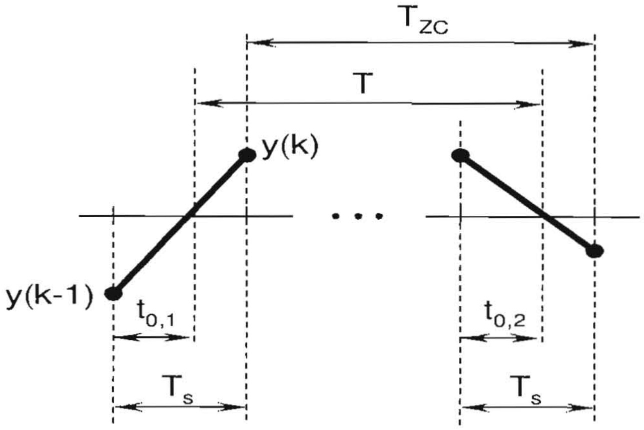


Figure 2.3 Principle of ZCD with interpolation

The principle of ZCD with linear interpolation is illustrated in Figure 2.3. The exact zero crossing time can be calculated as:

$$\mathrm{T} = T_{zc} - T_s + t_{0,2} + T_s - t_{0,1} = T_{zc} + t_{0,2} - t_{0,1}$$

The exact time between two zero crossings can be derived precisely with the corrected zero crossing detection method. This method is implemented in the Matlab model and some simulations have been performed. From the simulation result, it shows this method does not work in the presence of low frequency voltage variations and high order harmonics. As shown in the Figure 2.5. To resolve this problem, a filter is necessary in order to filter out the undesired harmonics before zero crossing detection. The result with filtered zero crossing detection is shown in Figure 2.6.

Various filters with center frequency of 50 Hz are tested with simulation, a proper filter for our application is a 10th order peak filter with center frequency of 50 Hz and bandwidth of 40 Hz. This filter is been chosen in the sense of the best tradeoff between bandwidth size, fastness of response and sensitivity to high/low frequency noise. For more information, please consult the report from my supervisor Anton Ishchenko.

The green blocks of the Matlab model shown in Figure 2.4 are used to create a 50 Hz sinusoidal signal, low frequency signal and 3rd order harmonic signal. These three signals are adding up together to mimic a test signal of the grid and it is delivered to the pink block to filter out the low frequency signal and the high order harmonics. Finally the frequency is estimated with corrected zero crossing detection block.

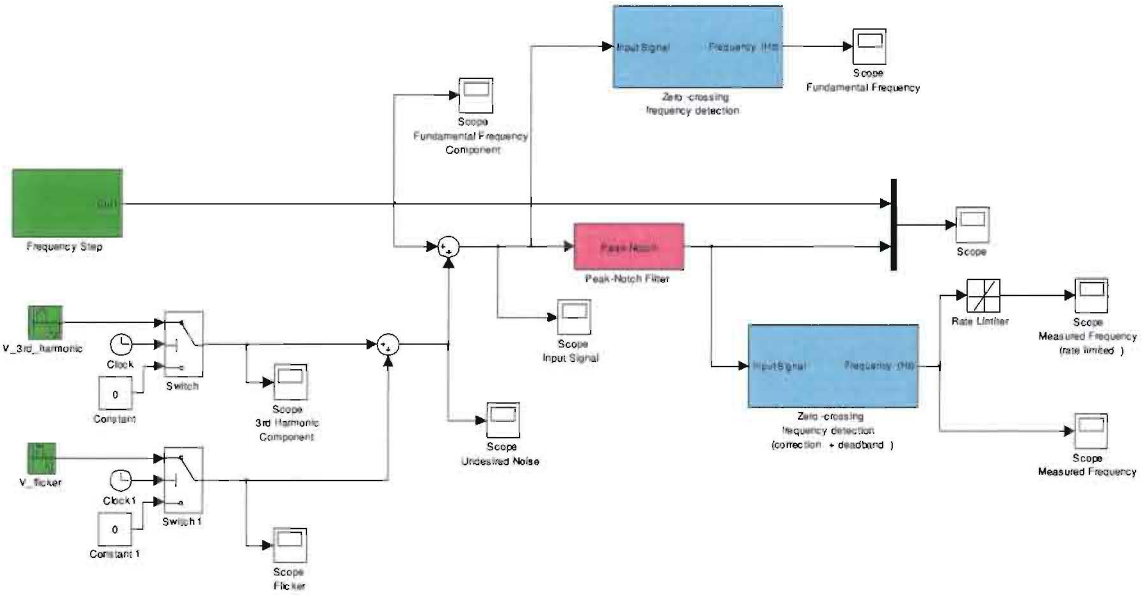


Figure 2.4 ZCD simulation model

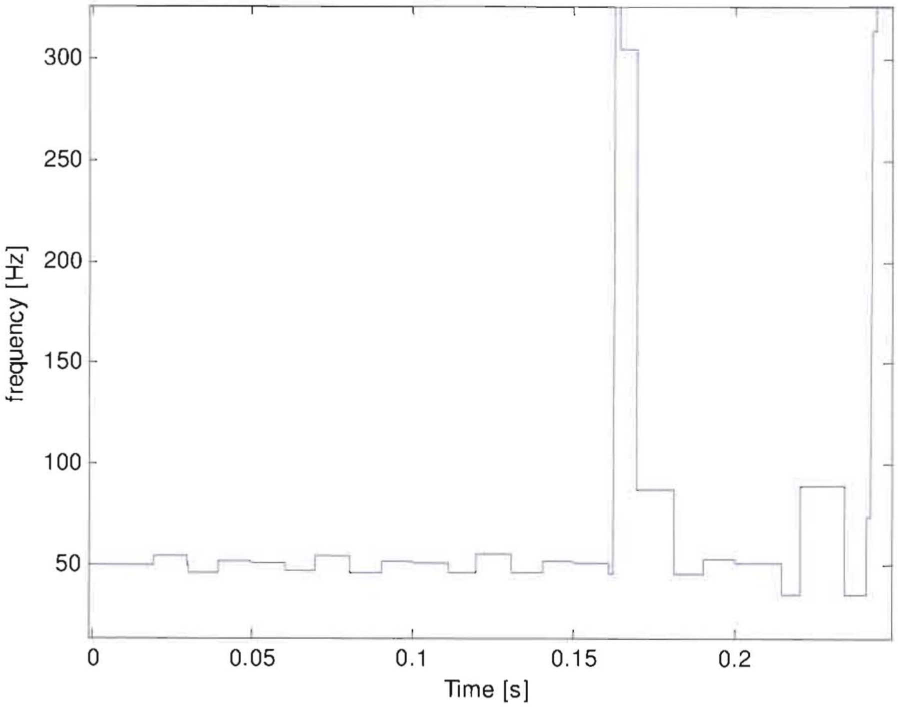


Figure 2.5 Simulation plot ZCD without Correction

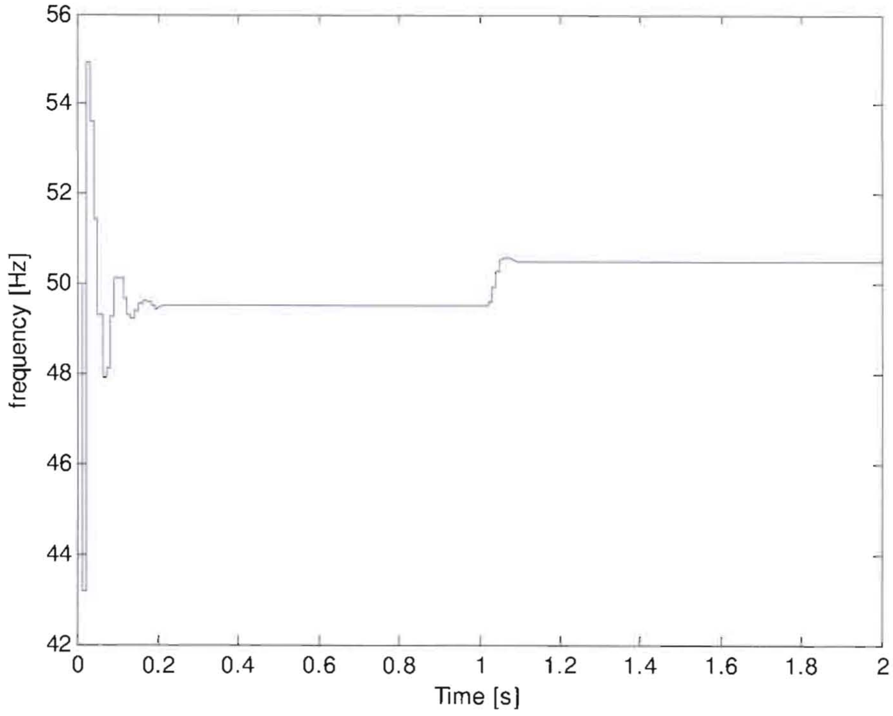


Figure 2.6 Simulation plot ZCD with Correction

2.3 Phase Locked Loop

Phase Locked Loop (PLL) is a closed loop method to measure the frequency. The model consists of three blocks: 1) a phase detector, 2) a low-pass filter, 3) a voltage-controlled oscillator (VCO), as shown in Figure 2.7. The phase detector produces an output signal $V_1(t)$ that is a function of the phase difference between the incoming signal $V_{in}(t)$ and the oscillator signal $V_o(t)$, in most simple practical scheme the phase detector is just mathematical multiplication. The low pass filter is used to filter out the high frequency of $V_1(t)$. The filtered signal $V_2(t)$ is the control signal that is used to change the frequency of the VCO output. The VCO block is an oscillator that produces a periodic waveform. The purpose of a Phase Locked Loop filter is the regeneration of phase information of the incoming signal.

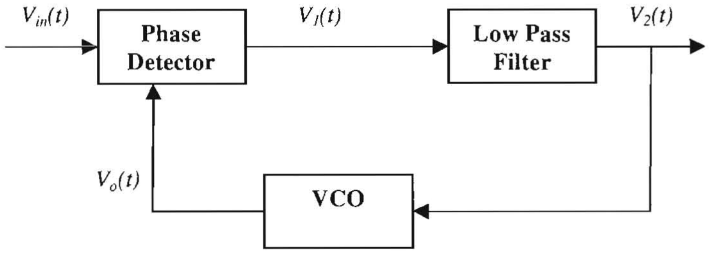


Figure 2.7 Basic principle of PLL

In mathematical form it is assumed that the input signal is:

$$V_{in}(t) = A_i \sin[\omega_0 t + \theta_i(t)]$$

The VCO output signal is:

$$V_o(t) = A_0 \cos[\omega_0 t + \theta_o(t)]$$

where

$$\theta_o(t) = K_v \int_{-\infty}^{t} v_2(t) dt$$

where K_v is the VCO gain constant. Then PD output gives:

$$V_1(t) = K_m A_i A_o * \sin[\omega_o t + \theta_i(t)] * \cos[\omega_o t + \theta_0(t)]$$

$$V_1(t) = \frac{K_m A_i A_o}{2} * \sin[\theta_i(t) - \theta_0(t)] + \frac{K_m A_i A_o}{2} * \sin[2\omega_o t + \theta_i(t) + \theta_0(t)]$$

where K_m is the gain of the multiplier. Only the first term of $V_1(t)$ pass through the LPF.

The LPF output signal is becoming:

$$V_2(t) = K_d \sin[\theta_e(t)] * f(t)$$

$\theta_e(t)$ is the phase error, $\theta_e(t) = \theta_i(t) - \theta_0(t)$;

K_d is the equivalent PD constant; $K_d = \dfrac{K_m A_i A_o}{2}$;

$f(t)$ is the impulse response of the LPF.

The Phase Locked Loop model is implemented into a Matlab model. And some simulations are performed. The result is shown in Figures 2.7 and 2.8. Oscillation at the initial time interval is because of the start-up of the PLL measurement.

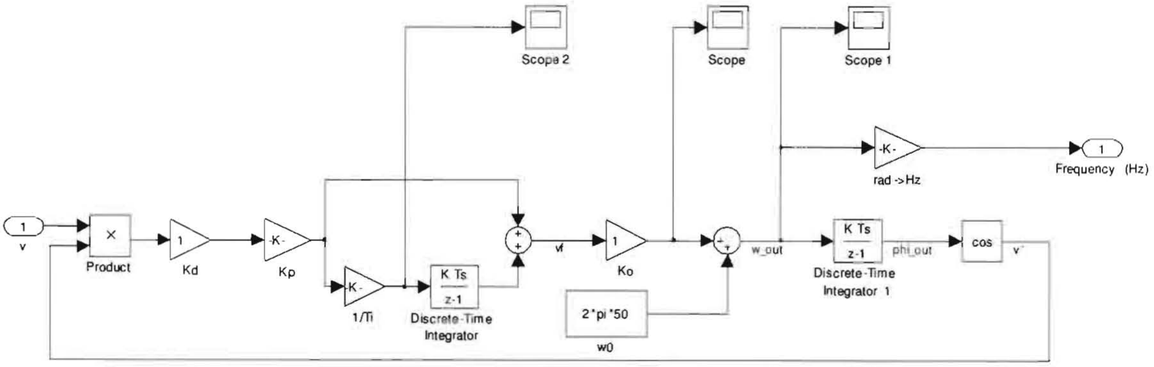


Figure 2.7 Simulation model PLL

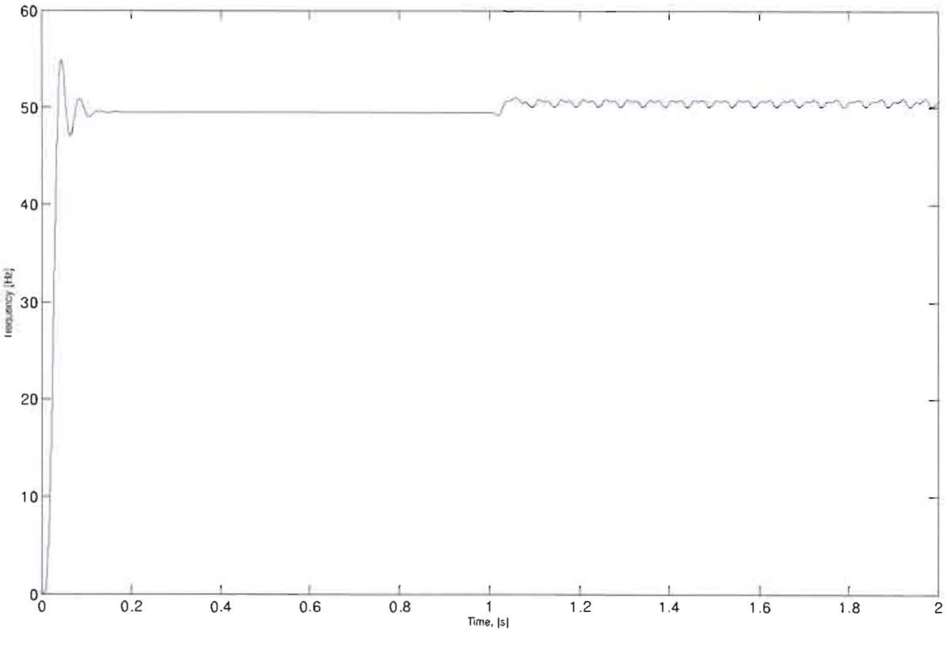


Figure 2.8 Simulation plot PLL

2.4 Frequency measurement test using Triphase converter

From above chapters it is verified that both methods are working in the simulation. Now it is the time to test how the both methods will perform in reality. The models are now connected with the Triphase system (see chapter 3.2). The system is programmed to give three-phase sinusoidal voltages with a step of frequency from 49.5 Hz to 50.5 Hz at 1 second after begin of experiment. Then the actual voltage of phase A of Triphase system AC output is measured and processed using different methods of frequency measurements. The results of both methods are plotted and shown in Figure 2.9 and Figure 2.10. As can be seen, ZCD has a longer delay about approximately 200 ms, compared with PLL 100 ms. And ZCD has less smooth signal compared with the PLL. But in the sense of precision ZCD is better, PLL is fluctuating continuously.

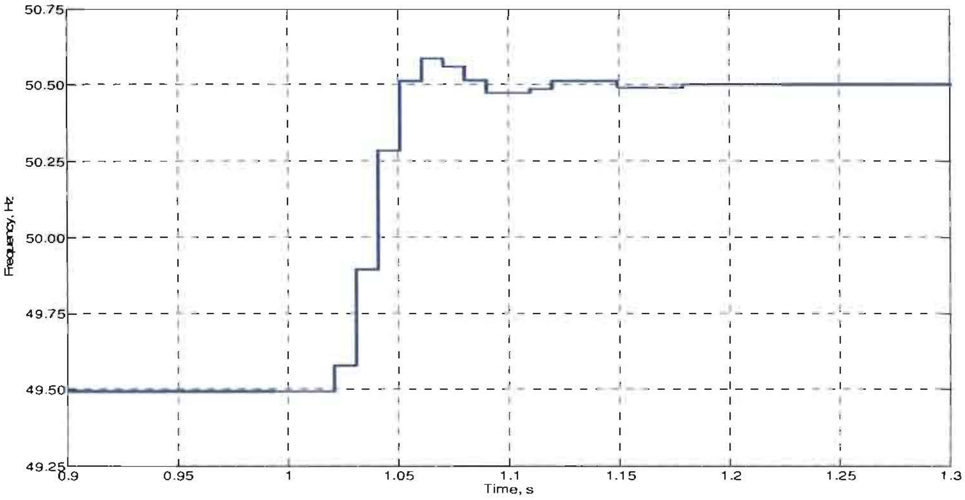


Figure 2.9 Measured plot ZCD with Triphase system

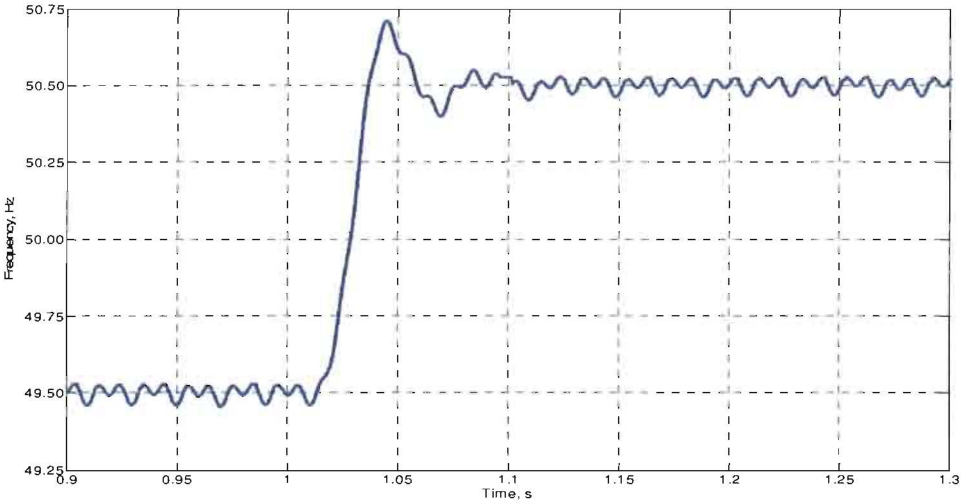


Figure 2.10 Measured plot PLL with Triphase system

Chapter 3 VSG Hardware Setup

3.1 Introduction

In this part of the report the hardware and principles of its control will be presented. First it starts with the explanation of the electrical scheme of the Triphase system and description of how to start up and use it. Then, the main characteristic of the Lead Acid batteries, the Super Capacitors and the Brusa charger are given. And last but not least, the controlling of the converter for the basic operation with the Triphase system will be explained.

3.2 Triphase system

Triphase system is a fully programmable hardware platform for rapid prototyping of power electronic converters control. It allows to analyze, test and validate the ideas related to Visual Synchronous Generator.

Figure 3.1 Triphase system

The Triphase system consists of different parts, each part with its own, individual functionality. Starting from right to left of Figure 3.2. The Triphase system includes 1) an auxiliary connection to ac 230 V 50 Hz, 2) a converter with DC-link bus, 3) a low pass filter, 4) a 3 phase output connection, and 5) three external DC connections.

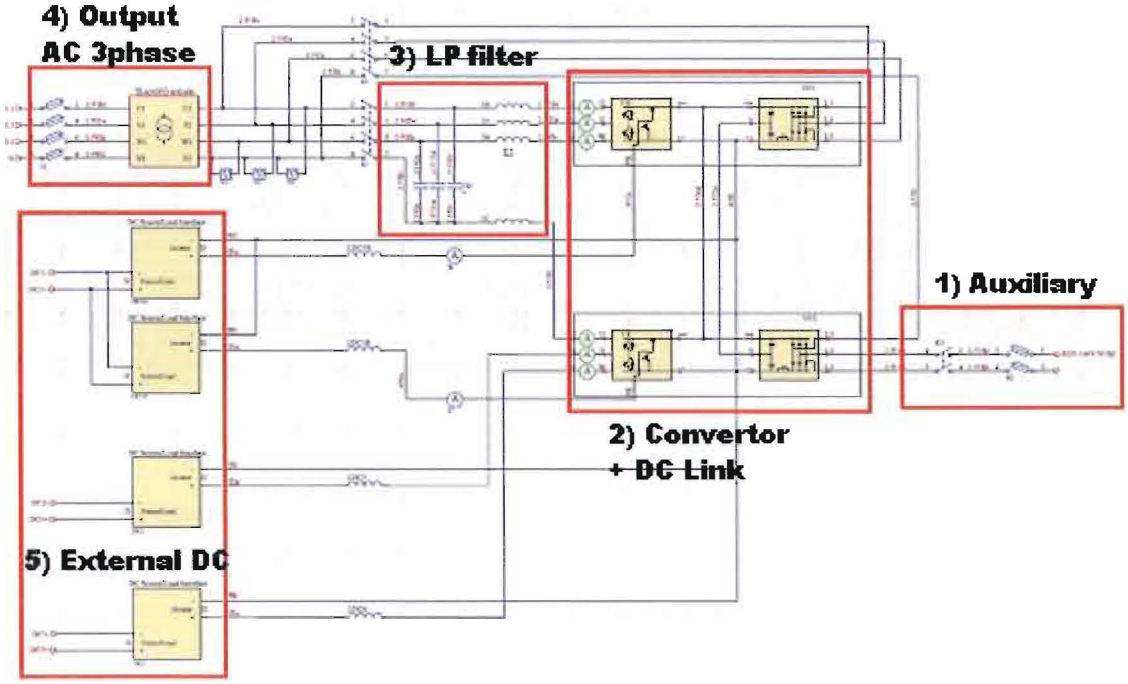


Figure 3.2Tthe electrical scheme of Triphase system

Depending on the control of the converter, the DC voltage that comes from external batteries is either converted to higher DC voltage on the DC-link bus (boost of DC-link voltage) or fed directly to the DC-link using anti-parallel diodes. From the DC-link bus the DC voltage is inverted into AC voltage and delivered to the output AC three phase. In between, a low pass filter is applied to depress the high frequencies. And finally a 400/400 transformer is used to isolate the output AC 3phase grid side.

The auxiliary connection is used to test the control of the converter. With the source of 230 V it will charge the DC-link bus to a level of 340 V dc during the operation.

There are different operating modes that can be applied with the Triphase system depending on the control of the converter:

- Power flow from Auxiliary source to DC output, to charge the external batteries.
- Power flow from DC supply to a DC load, to discharge the batteries and deliver power to the DC load.
- Power flow from DC supply to AC 3phase load, to feed the AC load

More detail of the different operation modes will be explained in the chapter 3.6 “Controlling of the convertor”.

The following procedures describe how to start up the Triphase setup and run on a Matlab model.

1) Switch on the main switch on the front panel
2) Switch on twice the F2 switch inside the Triphase system
3) Switch on the internal PC at the top of the Triphase system

4) Wait until the fan is on (User **must** wait until the fan is on, before start the following steps in the Matlab.)
5) Type the following commands in the Matlab:
    - shellOntarget('192.168.0.60')
    - tg=xeno('192.168.0.60')
    - tg.eclist
    - open an exist model or make a new model
    - build the model (click on): Triphase → Build
    - activate the model (click on): Triphase →Activate This model
    - Connect and start the model (click on):
        a. Tools→external mode control panel
        b. connect→start real time code

3.3 Lead Acid Batteries

The Lead acid batteries which have been used are Enersys Odyssey PC625 batteries. These batteries use absorbed glass mat (AGM) technology which is more expensive than the conventional lead acid batteries and can provide high ampere current for both a short duration (2250 A for 5 seconds) or low rate long duration drains. The Odyssey batteries are specially designed for long storage times and deep discharge recovery. They are capable to provide 400 charge/discharge cycles in case of 80% of depth of discharge.

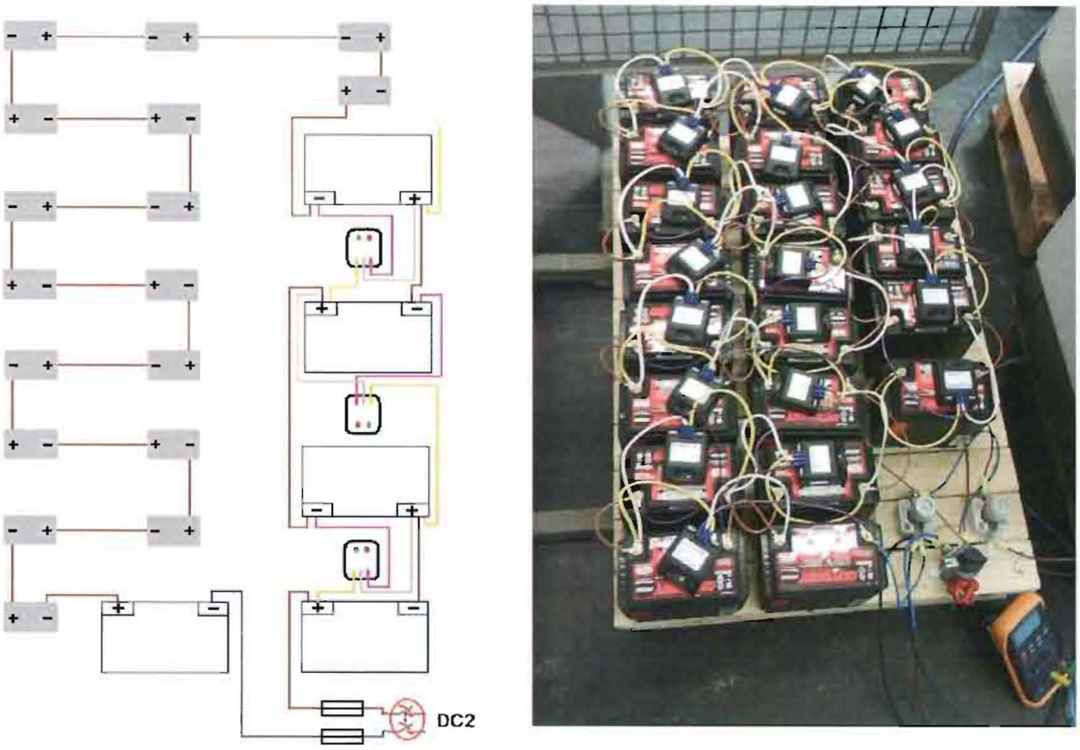


Figure 3.3 The setup of Lead Acid batteries

22 lead acid batteries are connected in series, when in fully charged having 12.84 V each, which gives in total 282.48 V. Between every two subsequent batteries there is one equalizer, in total there are 21 equalizers. These equalizers are being used to equalize the voltage level between the batteries and to maintain the same level of voltage over all batteries. Equalizer starts to equalize when the voltage difference is larger than 150 mV between two subsequent batteries. Led lights indicate the operating mode during operation:

Green led:

- Solid Led indicates that equalizer is in full equalization mode.
- Frequent blinking led indicates that equalizer is in the equalization process.
- Infrequent blinking led indicates that equalizer equalization is just beginning or it is tapering off.
- No led indicates idle and means all batteries are at an equal charge.

Red Led:

- Solid led indicates that a battery is exceeding or falling below normal operating voltage (10.5 V – 16.5 V) or that there is a problem with the wiring connection.

For the safety of Triphase system, the battery setup is connected through 20 A fuses, and the cables are able to withstand the current around 20 A. In this case, the maximum power that can be delivered from this setup is around 5.5 kW. (280 V * 20 A = 5600 W)

Table 3.1 and Figure 3.4 show the relationship between open circuit voltage and state of charge for the Odyssey Lead acid batteries.

Voltmeter Reading [V]	State of Charge
282.48	100%
275	75%
267.96	50%
261.36	25%

Table 3.1 State of charge as a function of open-circuit voltage

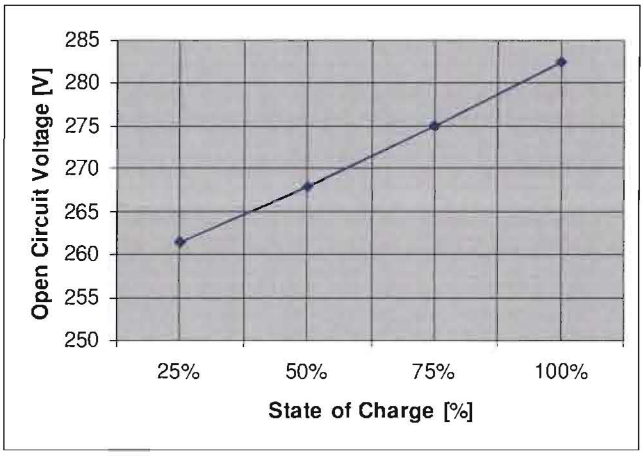


Figure 3.4 State of charge as a function of open-circuit voltage

3.4 Super Capacitor

The main difference between the Lead acid batteries and the Super capacitor is the amount of current that Super Capacitor can deliver in a short time interval. It is significantly larger. The amount of charge/discharge cycles is not an important issue for the Super Capacitor. But the disadvantage is that the Super capacitor has much shorter storage time capability due to relatively high self-discharge rate.

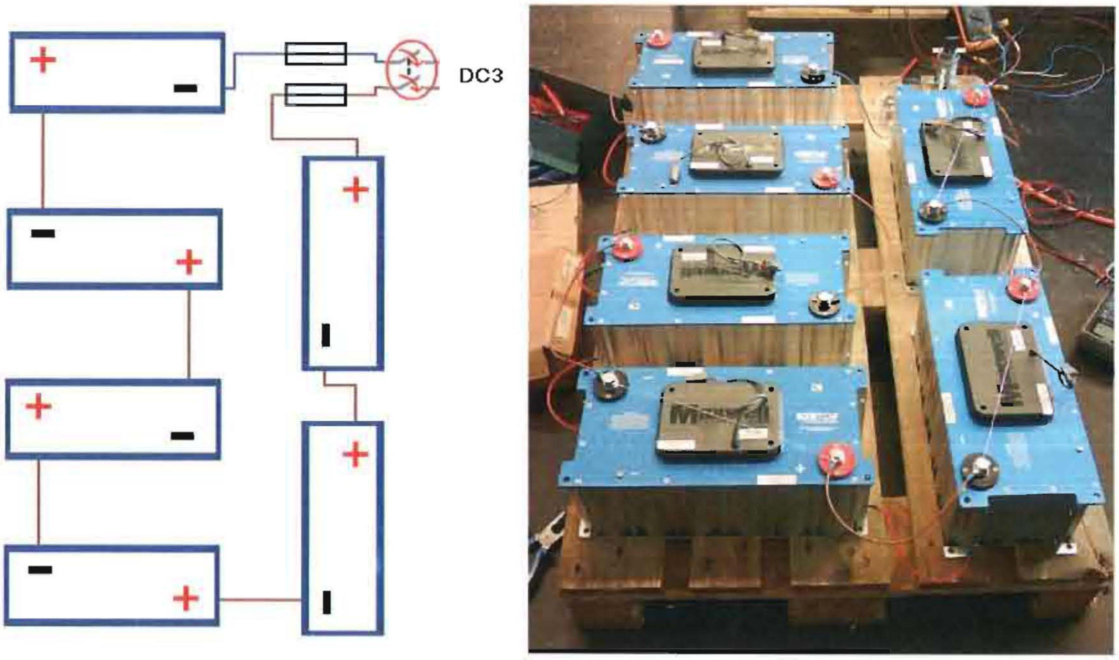


Figure 3.5 The setup of Super Capacitors

As shown in Figure 3.5, six Super capacitors modules of 165 F, 48 V are connected in series with the total amount nominal voltage of 288 V. The capacitance of each capacitor is around 180 F which is higher than 165 F as given. This was reported in the test certificate given by the manufacturer. In this case the equivalent capacitance is 30 F.

$$\frac{1}{C\_equivalent} = \frac{1}{C1} + \frac{1}{C2} + \frac{1}{C3} + \frac{1}{C4} + \frac{1}{C5} + \frac{1}{C6}$$

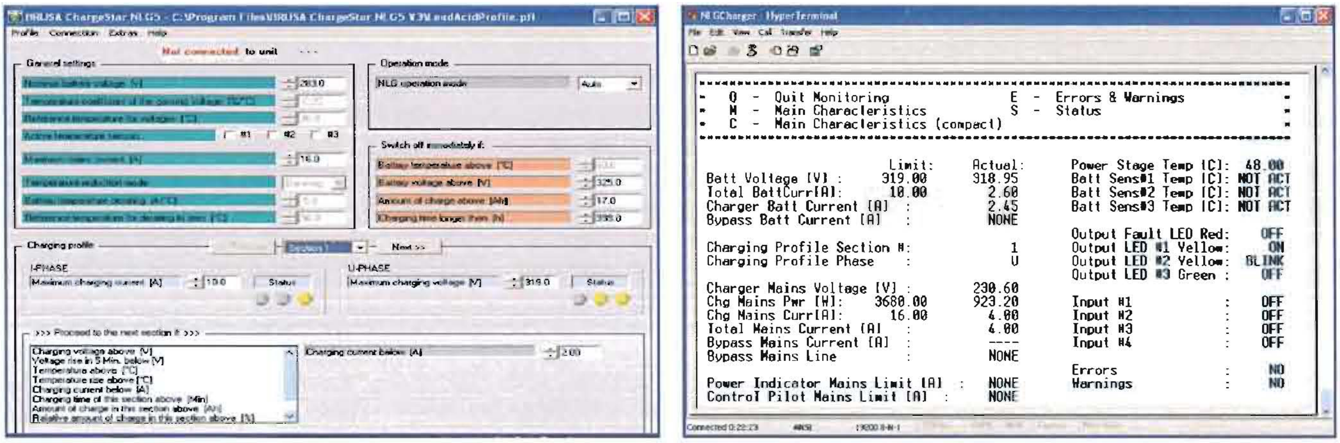
$$\frac{1}{C\_equivalent} = \frac{6}{C}$$

$$C\_equivalent = \frac{C}{6} = 30F$$

The chassis of the module is connected to the Triphase system ground through one of the mounting holes with **red wire**. For the same reason as for Lead acid batteries, the setup is connected with 20 A fuses and the cables are able to withstand current around 20 A. In this case, the maximum power that can be delivered from this setup is 5.7 kW. (288 V * 20 A = 5760 W). Super Capacitor is more suitable to contribute to the grid during imbalance when a high power for a very short time interval in the order of seconds is needed.

3.5 Brusa Charger

The Brusa Charger is a programmable charger for various types of batteries. In our case the Brusa Charger is used to charge the Lead Acid Batteries and the Lithium Ion batteries. The charging profile can be modified with the program "Brusa Chargestar" provided by the manufacturer.



I-PHASE
Maximum charging current [A] 10.0

U-PHASE
Maximum charging voltage [V] 319.0

>>> Proceed to the next section if >>>
Charging voltage above [V]
Voltage rise in 5 Min. below [V]
Temperature above [°C]
Temperature rise above [°C]
Charging current below [A]
Charging time of this section above [Min]
Amount of charge in this section above [Ah]
Relative amount of charge in this section above [%]

Charging current below [A] 2.00

```
*****************************************************************************
*   Q  -  Quit Monitoring                     E  -  Errors & Warnings      *
*   M  -  Main Characteristics                S  -  Status                 *
*   C  -  Main Characteristics (compact)                                   *
*****************************************************************************

                         Limit:      Actual:     Power Stage Temp [C]:  48.00
Batt Voltage [V] :      319.00      318.95      Batt Sens#1 Temp [C]: NOT ACT
Total BattCurr[A]:       10.00        2.60      Batt Sens#2 Temp [C]: NOT ACT
Charger Batt Current [A]   :          2.45      Batt Sens#3 Temp [C]: NOT ACT
Bypass Batt Current [A]    :          NONE
                                                Output Fault LED Red:     OFF
Charging Profile Section #:              1      Output LED #1 Yellow:      ON
Charging Profile Phase     :             U      Output LED #2 Yellow:   BLINK
                                                Output LED #3 Green :     OFF
Charger Mains Voltage [V] :         230.60
Chg Mains Pwr [W]:     3680.00      923.20      Input #1            :     OFF
Chg Mains Curr[A]:       16.00        4.00      Input #2            :     OFF
Total Mains Current [A]    :          4.00      Input #3            :     OFF
Bypass Mains Current [A]   :          ----      Input #4            :     OFF
Bypass Mains Line          :          NONE
                                                Errors              :      NO
Power Indicator Mains Limit [A]  :    NONE      Warnings            :      NO
Control Pilot Mains Limit [A]  :      NONE
```

Figure 3.6 Display of Brusa ChargeStar and NLGCharger monitor

Each section of the charging profile for the Lead Acid batteries typically contains two phases. In the first phase the charger is acting as a constant current source with maximum charging current of 10 A. In the second phase it is acting as a constant voltage source with maximum charging voltage of 319 V, while the charging current drops slowly to 2 A. After that, the charger stops charging since the settings for charging current and charging voltage in the second section of charging profile are zero.

For monitoring, HyperTerminal program is used. It is available at Start->Programs->Accessories->Communications folder. First start the program, then open the saved file "NLGCharger.ht", which contains the data for hardware communication between the charger and computer, and type on the keyboard "monitor". The window "Main characteristics" will be displayed. In this display user will find the major characteristic of batteries charging process, such as, the actual battery voltage, actual battery current, and also the status of charging process (the charging profile section and the charging profile phase) are being shown.

Brusa charger uses led light to indicate the status of charging process, and it is freely programmable by the user. In our case, during charging of the Lead Acid batteries, the blinking yellow third led corresponds to the first phase of charging process (constant current source mode), which is followed by the second phase (constant voltage source mode) with the third led being solid yellow and the fourth led – blinking yellow. The third led will become solid green when the charger is in section 2 and stops with charging. In case of fault, the NLGCharger monitor gives an "Error or Warning" signal in the display and also the second led will turn to red color on the charger itself. First led is used to indicate that the charger is connected to the AC supply.

Important! The Brusa charger does not charge the batteries automatically as the battery voltage drops to any level if the charger is permanently connected to the batteries. The user has to re-plug the charger into the power manually in order to charge the batteries. There are many solutions to solve this problem, one option is to use a relay which checks the batteries voltage all the time, and it switches the charger on when the batteries level is under a certain level. For instance, 265 V level, which corresponds to 40% state of charge of the batteries.

File name:	LeadAcidProfile.pfl (charging profile)
	NLGCharger.ht (monitoring)

3.6 Controlling Converter

As mentioned before, there are different operating modes that can be applied with the Triphase system depending on the control of the convertor. Controlling of the converter depends on the switching duty cycle of the halfbridges.

1) Power flow from Auxiliary to DC

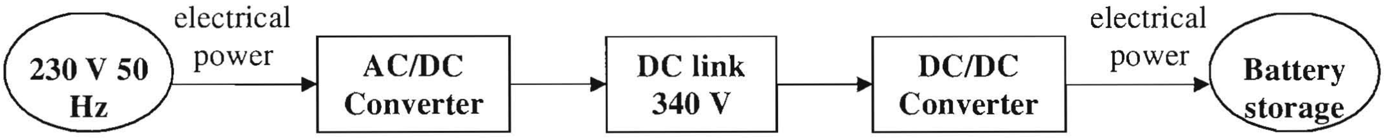


Figure 3.7 The principle of Auxiliary to DC

The electrical power that comes from the auxiliary source is converted to DC 340 V at the DC-link. By controlling the duty cycle of the DC/DC converter the desired power is delivered to the battery storage. In this case the batteries can be charged. And depending on the type of batteries, different controlling mode for the converter is applied. The relation between Duty ratio and the output V_{dc} is given in Table 3.2. As shown in Table 3.2 the Duty ratio is in a range of -1 – 1 which is differently compared with normal Duty ratio of halfbridge which is in a range of 0 – 1. This was chosen by the manufacturer of the Triphase system.

Duty	-1	-0.9	-0.8	-0.7	-0.6	-0.5	-0.4	-0.3	-0.2	-0.1
V_{dc}	0.5604	16.0	32.1	48.2	64.3	80.4	96.2	113.0	128.4	144.9
0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
161.6	177.9	194.0	210.3	226.6	242.8	259.1	275.2	291.0	305.2	325.8

Table 3.2 Relation between Duty ratio and output V_{dc}

Charging of Lead Acid batteries:
The switching duty cycle of the halfbridge 2 of inverter 1 for the Lead Acid batteries is selected to be an exponential function.

$$D(t) = (D_{final} - D_{init}) * (1 - e^{-kt}) + D_{init}$$

With $D_{init} = -1$, $D_{final} = 0.8$ and $k = 0.076753$

The value k defines the fastness of charging. To get this value of k, it is assumed that D(t) for a long time period closely approaches D_{final} value. Suppose, at that time moment it is already 99 % of the D_{final}. It means that $1 - e^{-kt} = 99\%$ and $e^{-kt} = 0.01$. If the time interval about 60 seconds is taken, the value of k will be 0.076753.
Model: test_Aux_to_DC2.mdl

Charging of Super Capacitors:
The switching duty cycle of the halfbridge 3 of inverter 1 for the Super Capacitor is selected to be a ramp function.

$$DutyRatio = k * Vdc\_3 + B$$

With k = 0.0063, B = -1.0015

The value k defines the slope ratio and the value B defines the initial condition. To get these two values of k and B, it is known from Table 3.2 that for duty ratio -1 the output V_{dc} is 0.5604 V, and for duty ratio 0 the output V_{dc} is 161.6 V. Taking these values into the Duty Ratio equation. There will be 2 equations with k and B are the unknown parameters. By solving these 2 equations, the values of k and B can be calculated.
Model: test_Aux_to_DC3_supercaps.mdl

2) Power flow from DC supply to DC load

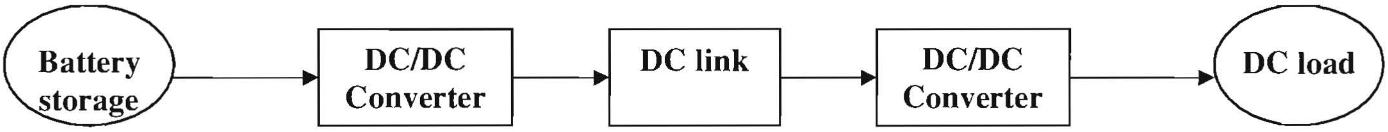


Figure 3.8 The principle of DC supply to DC load

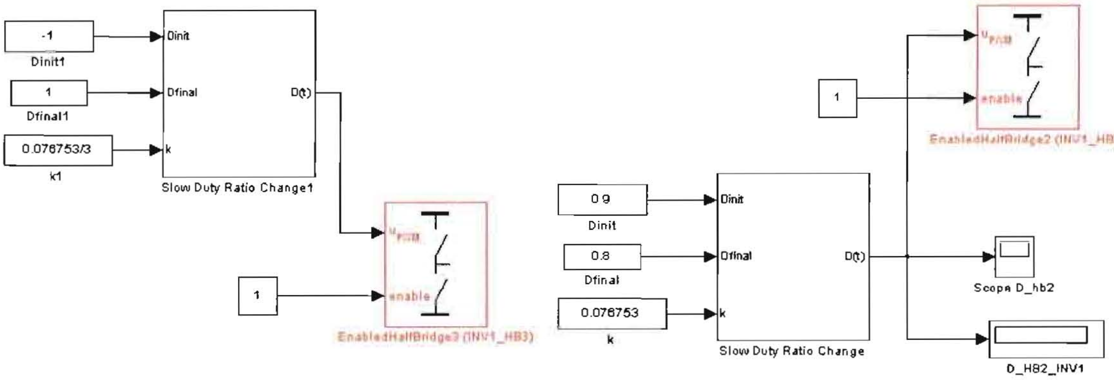


Figure 3.9 Model of controlling DC supply to DC load

In order to discharge the batteries and deliver power to the DC load, there are two halfbridges which have to be controlled. One is for connecting the battery storage to the DC-link; another is for the DC-link to the DC load connection. The first halfbridge is used to adjust the desired voltage level on the DC-link, with duty ratio starting from 1 and going to a lower duty cycle value, which corresponds to boost of the DC-link voltage in Triphase system. The duty cycle of the second halfbridge, starting from -1 and going to a higher duty cycle value, will bring the voltage from 0 V to the desired voltage level for the DC load.

Model: test_DC2_to_DC3.mdl

3) Power flow from DC supply to AC 3phase load

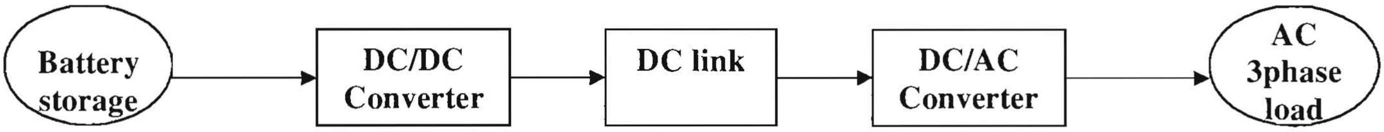


Figure 3.10 The principle of DC supply to AC 3 phase load

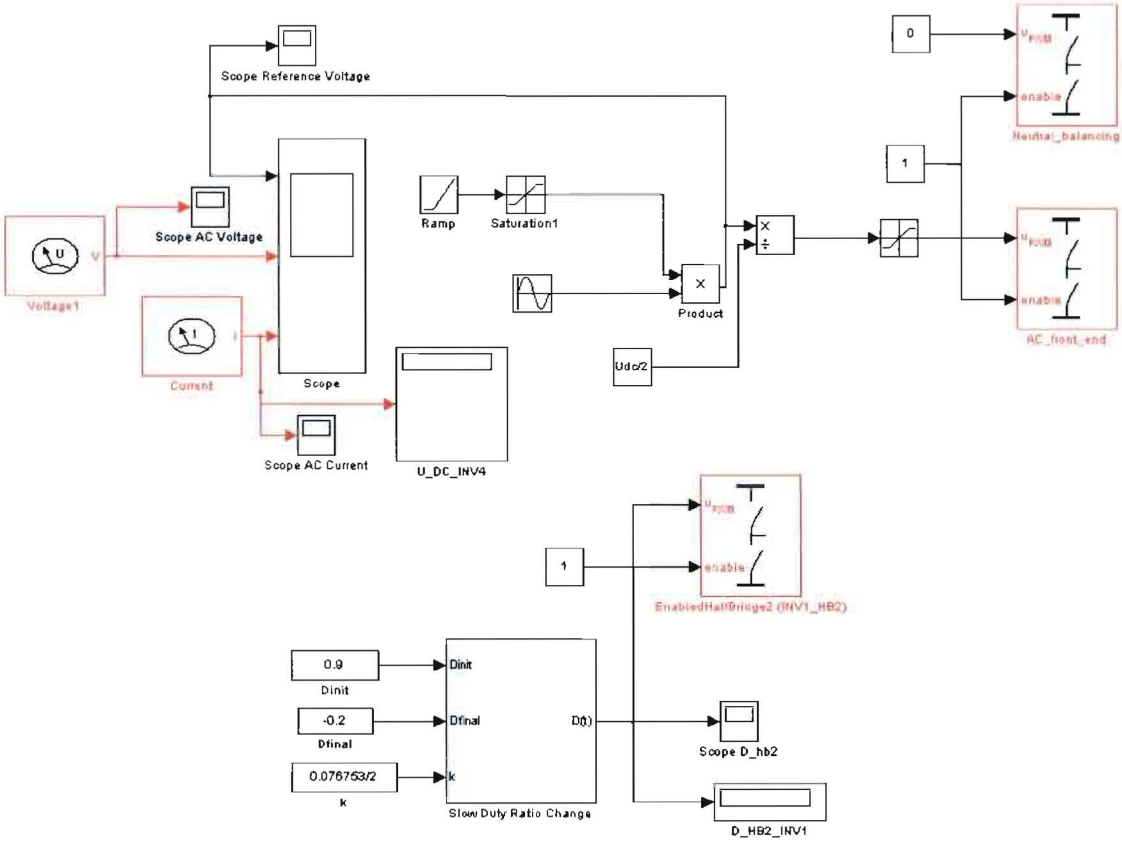


Figure 3.11 Model of controlling DC supply to AC 3 phase load

In order to feed the AC load from the DC batteries, there are two halfbridges which have to be controlled. One is for connecting the battery storage to the DC-link; another is for the DC-link to the AC three phase load connection. The first halfbridge is used to adjust the desired voltage level at the DC-link. The duty ratio is initially 1 and goes to a lower duty cycle values. The voltage level at the DC-link will be boosted. The second halfbridge is used to make an AC three phase signal with desired voltage level and frequency.

Model: test_DC2_to_AC.mdl

Chapter 4 Conclusions

From the theory part it was verified that both methods ZCD with linear interpolation and PLL for the frequency calculation are working in the simulation. And later on both models were tested with Triphase system using a frequency step at the time interval of 1 second with a frequency of 49.5 Hz to 50.5 Hz. In the sense of the stability and the time of delay it is concluded that ZCD method works better than PLL.

There are different operating modes that can be applied with the Triphase system depending on the control of the converter:

- Power flow from Auxiliary source to DC output, to charge the external batteries.
- Power flow from DC supply to a DC load, to discharge the batteries and deliver power to the DC load.
- Power flow from DC supply to AC 3phase load, to feed the AC load

Controlling of the converter depends on the switching duty cycle of the halfbridges. For instance in case of power flow from DC supply to a DC load. There are two halfbridges which have to be controlled. One is for connecting the battery storage to the DC-link; another is for the DC-link to the DC load connection. The first halfbridge is used to adjust the desired voltage level on the DC-link, with duty ratio starting from 1 and going to a lower duty cycle value, which corresponds to boost of the DC-link voltage in Triphase system. The duty cycle of the second halfbridge, starting from -1 and going to a higher duty cycle value, will bring the voltage from 0 V to the desired voltage level for the DC load.

The control of the whole system that automatically compensates the power imbalance of the grid has not been solved. However, the basic idea of how to control the individual part is known – for example, controlling the Lead Acid batteries to the output AC 3 phase load. But still the model that being used now is not optimal yet. For instance, it was chosen to charge the Lead Acid batteries with an exponential function, and it was chosen to charge the Super capacitors with a ramp function. The design parameters for these 2 functions were calculated without considering the optimal solution. In order to find the optimal solution, much more research must be done in the future. But it is also important to take into account the limitations of the components.

From the practical experiments it can be seen that the components on the PCB board of the converter can be easily damaged due to the high peak current or melting of the component material due to the heat problem. It is always desired to use precharge switch first and then the connect switch, to avoid high peak currents. In case when ouput_ac has to be switched on, it is also desired to switch on the input_ac to prevent damaging the halfbridges if a voltage surge will occur. And some technical problem like switching the Brusa charger manually can also be improved with the aid of a relay. It checks the voltage over the Lead Acid batteries, and switches on if the voltage is under a certain level.

Various energy storage systems were tested. The main difference between the Lead acid batteries and the Super capacitor is the amount of current that Super Capacitor can deliver in a short time interval. It is significantly larger. The Lead acid batteries are capable to provide 400 charge/discharge cycles in case of 80% of depth of discharge. The amount of charge/discharge cycles is not an important issue for the Super Capacitor. But the disadvantage is that the Super capacitor has much shorter storage time capability due to relatively high self-discharge rate then Lead acid batteries. Super Capacitor is more suitable to contribute to the grid during imbalance when a high power for a very short time interval in the order of seconds is needed. In case of minutes the Lead acid batteries and the Lithium Ion batteries are more suitable.

Research has shown that Lithium Ion batteries have much better energy storage capability with respect to the self-discharge compared to Lead acid batteries and the Super Capacitors. Based on this point of view it is concluded that Super Capacitors need daily recharging to retain the desired state of charge, for the Lead Acid batteries – weekly, and for the Lithium Ion batteries – once in several weeks.

This internship report mainly based on the practical experiments from the test setups of the Triphase system. Clearly, the basic principles of its control are working. And undoubtedly in the future, it is crucial to make a proper controller for the whole system which automatically compensates the imbalance of the grid by control algorithms.

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