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# OPTIMIZED POWER FLOW CONTROL THOUGH A GRID TIED INVERTER

By

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# Contents

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*Chapter 1*

# PROBLEM STATEMENT

Grid connection of renewable sources poses certain challenges and is an active research area. In distributed renewable systems, all the available energy is not fully utilized to its installed capacity. Certain users might not be using their installed resources to their optimum. So in such cases, the excess energy can be fed to the grid. Hence each user, after fulfilling the local needs, can be able to supply the excess energy to the grid, thereby allowing utilities to shift the load off from conventional fuels to renewable resources.

For the benefit of the end user, this energy flow can be optimized. Optimization parameters can include the current weather conditions, available energy storage, utility tariffs and many such things. So based on the above mentioned parameters, an optimum amount of power flow can be calculated.

For implementation of the above mentioned strategy, an active control of the power flowing to the grid is required. This control will enable a user optimized, user controlled flow of power from storage or renewable sources to the grid.

*Chapter 2*

# BACK GROUND AND RELATED WORK

## 2.1 BACKGROUND

In recent years, due to soaring prices of fossil fuels, threats caused by the nuclear power, environmental hazards due to conventional fuels, the focus of investment and research in energy sources is now shifting to renewable sources. Of the many available renewable technologies, grid connected PV is among the fastest growing technologies. Grid connected PV showed a 60-percent annual average growth rate for the five-year period[1].

However, grid connection of solar and other renewable sources pose certain challenges. These include fidelity and availability of solar power, impact caused by the grid connection on the quality of the grid electricity such as THD and lives voltages.

## 2.2 INVERTER

Inverters are the basic building block for the conversion of a DC to AC voltage. Various types of inverters use various techniques, devices and topologies.

Efficient inverter design is among current research areas.

Inverters may be characterized as follows

### 2.2.1 Supply

Inverters may be characterized by the source that they utilize. Current source inverters use a current source whereas voltage source inverters use a voltage source as main power supply.

### 2.2.2 Switching techniques

Inverters may also be classified on the basis of the switching techniques that are used.

**i) Square Wave Inverter**

A square wave inverter is switched by a 50Hz (or 60Hz based on the utility standard) switching source. Then harmonic elimination and cancellation techniques are applied prior to filtering to get a 50 Hz sinusoidal output from a 50Hz square wave.

**ii) PWM Inverter**

In another technique, called PWM inverter, the 50Hz signal is modulated with a high frequency carrier to obtain a PWM signal. This PWM signal is then used to drive an H Bridge. The output of the H Bridge is then filtered to obtain a high power 50Hz sinusoidal signal.

**2.3Optimization Function**

With the advancement in the power systems and the integration of various renewable energy sources with the grid requires a challenge in optimizing the grid (smart grid). The Optimal Power Flow method is an intelligent way that employs techniques to automatically control and adjust the power system control settings while simultaneously solving the optimizing operating conditions within specific constraints.

Objectives that may be achieved if optimization is being done:

- Minimize system real & reactive power losses
- Minimize generation fuel costs
- Minimize system energy costs
- Maximize system performance
- Optimize power exchange with other systems (on-site generation, utilities, IPP's, & power grids)

- Minimize load shedding
- Control generator's MW (governor) & MVAR
- Determine control settings

Currently research is being done on the optimization of power flow and various methods have been suggested. We are intended to use the following methods but proper research on an accurate method is in progress and we may either employ one of the following methods to do optimization or may use some other method that may not be mentioned here (depending on what further research suggests).

- Linear programming/Quadratic Programming with Lagrange multipliers
- Newton-Raphson
- Some dynamic programming algorithms with Lagrange multipliers
- Swamp optimization techniques

As a first step, a non-optimal ruled-based algorithm has been developed. It guarantees operation of the system with respect to the constraints. The ruled-based powers schedule will be used as the reference to compare the performances of the optimization algorithms.
The most commonly used techniques for optimization are linear programming (LP), dynamic programming (DP), and quadratic programming by formulating the problem in relaxing form with the Lagrange multipliers

**2.3.1 Linear Programming**

According to its name, LP implies that the problem is linear.

In our case, to formulate the problem on linear form, it is necessary to integrate a binary variable and so discretizing it. Actually, in this case, the problem has to be solved again over the period left at each unpredicted disturbance with the forecast (important computation time).

### 2.3.2 Dynamic Programming

DP is a graph-based technique corresponding to the shorter path algorithms. The advantage is that the performance index and the constraints can hold all the natures (linear or not, differential or not, convex or concave, etc.) and no specific mathematical solver is needed. DP can also be used for reactive optimization by correcting the predictive strategy at each unpredicted disturbance according to the real values. As DP works on discrete or sequential problems, evolution of the system has to be decomposed into several steps. A similar approach has been used for deterioration and maintenance model of wind turbines.

**Implementation difficulties of Dynamic Programming**

The weakness of this technique is its high memory needs when the studied period is long and discretized with a small time step. However, it is not problematic if the computation parameters are well chosen. In addition, the computation time can be reduced by appropriate modifications.

## 2.4 Quadratic Programming

Quadratic programming gives very good results since the problem is formulated in a relaxing form through the Lagrange multiplier. However, this method needs the objective function to be convex (or concave), which generally implies simplifications of the problem. Also, quadratic programming is suitable only for a small problem (less than 50 variables) and works only with continuous variables. This technique is a strong candidate for reactive optimization and is most widely used in HEV application.

Chapter 3

# DESIGN METHODOLOGY AND TOOLS

## 3.1: SYSTEM LEVEL DESIGN

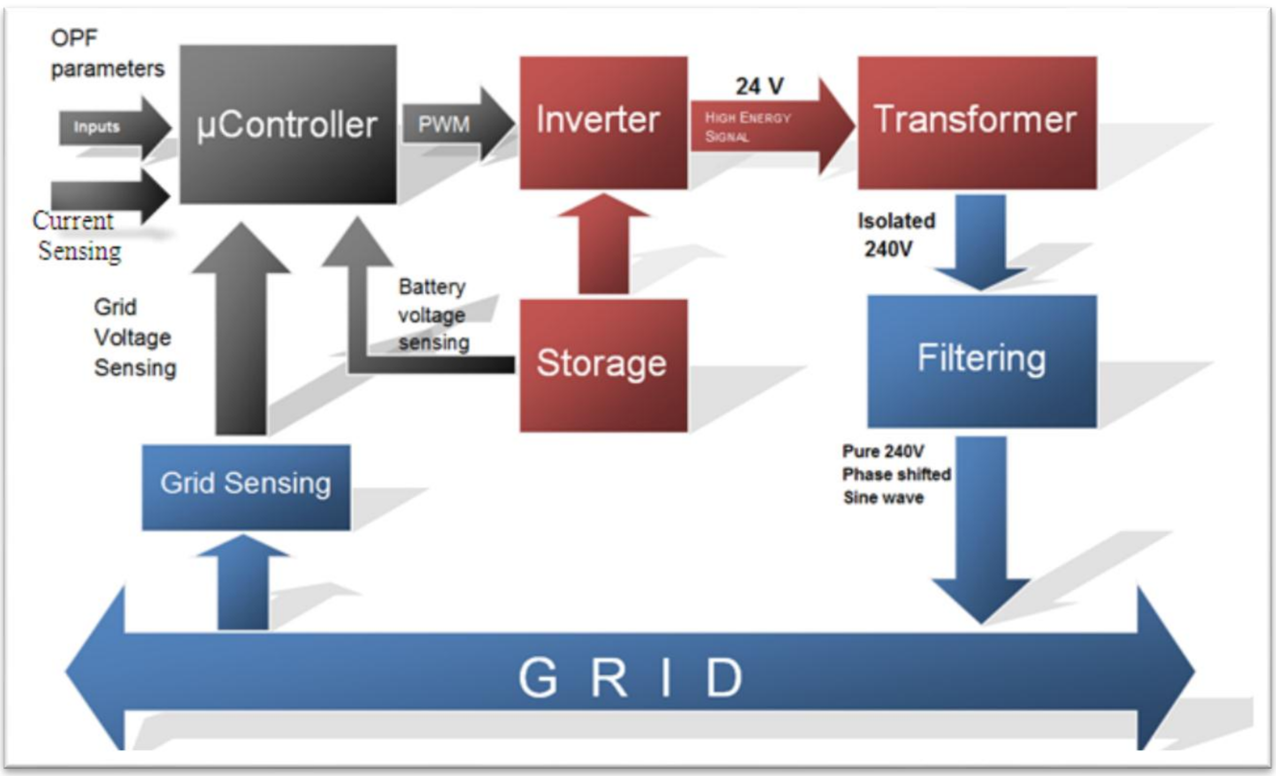



Figure: 3.1

### 3.1.1: Design Choices

The choices that we take in various components of the project are as follow:

*Microcontroller choices:*

We could have chosen between ATMEGA-8, ATMEGA-16, ATMEGA-16L, ATMEGA-32. Our choice was ATMEGA-16L because of the past familiarity with ATMEL features. In ATMEL specifically this particular model was chosen because its maximum operating frequency is 16MHz.

Also its internal memory was enough to fit our requirements. ATMEGA-8 had 1 input and 1 output port which was not enough for our project. This we chose 4 I/O ports ATMEGA-16L.

### *Inverter choices:*

From Square wave, Modified Square wave, Square wave harmonic cancellation and PWM sine wave inverters, we chose the last one because of the following advantages:

- Pure sine wave output with least THD
- Simple current mode operation possible
- Unity gain in using current mode for grid tie operation
- Flexibility in operation by integration with a micro-controller
- Simpler in design

### *MOSFET choices:*

The MOSFETs are being used on primary, low voltage end. For the inverter to be 1KW, voltage across them does not exceed 40V at maximum. Thus the voltage requirement was low. However the current required at this end is large. Thus we chose IRF3710 which has the current and voltage rating of 57A and 100V respectively.

### *Transformer choices:*

We could have chosen from iron core or ferrite core transformer. Our mode of operation requires high frequency switching. In such cases ferrite core transformers are ideal. These transformers have the following advantages over the iron core ones:

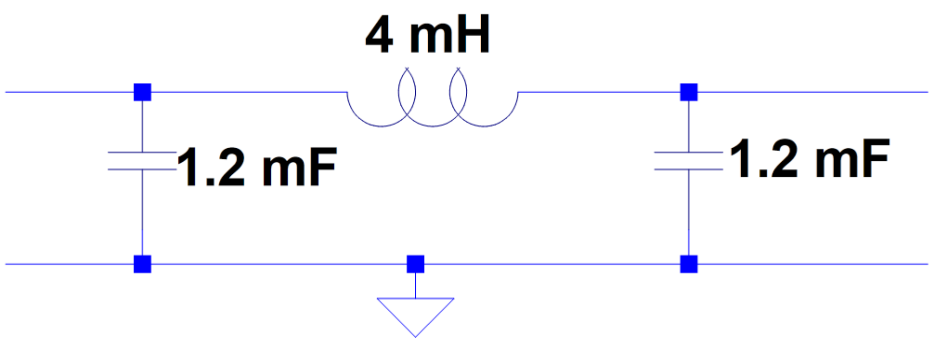
- Small size
- Light weight
- High resistivity
- Negligible eddy current losses
- Small BH curve, low hysteresis losses

The specific core model that we used is EE85, which was locally available. It does meet our flux density requirements.

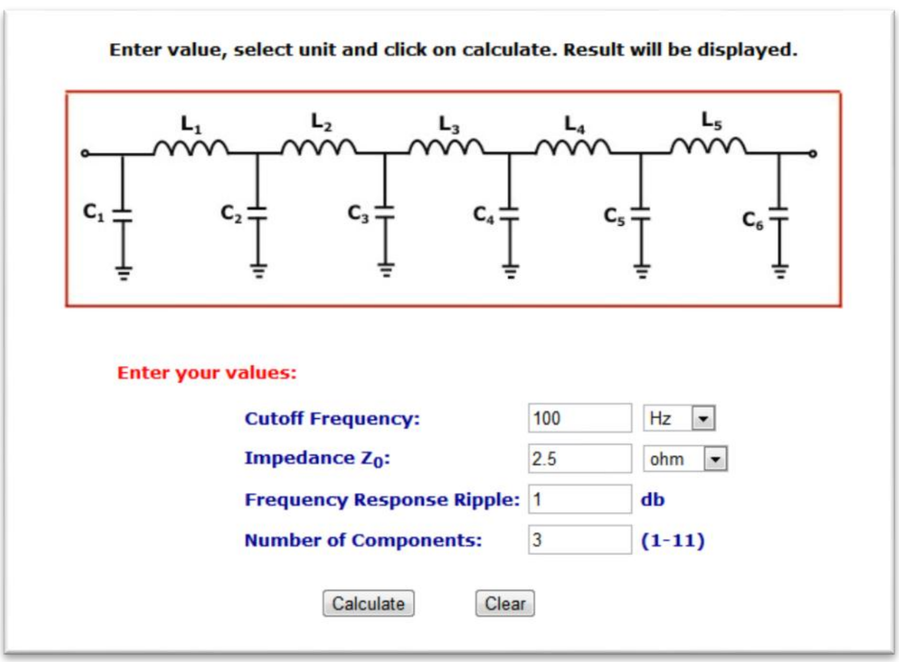
## Filter choices:

We chose 3rd order pi configuration of Chebyshev LP filter. This was our choice because of the factors:

- Steep roll-off factor
- 3rd order to reduce component cost
- Ripple in pass band not an issue because of single pass frequency component




Filter design




Filter value design

## 3.2: DESIGN METHODOLOGY

### 3.2.1 Transformer design

We used the following procedure for designing the transformer.

$K_{gfe} \rightarrow$ $Geometric\ Core\ Constant$

$\lambda \rightarrow$ $Primary\ peak\ volt - \sec = 1.44\ mVs$

$\rho \rightarrow$ $Resistivity\ of\ wire = 1.68 \times 10^{-6} \Omega cm$

$I_{TOT} \rightarrow$ Total rms winding current, reffered to primary = 60A

$\frac{n_2}{n_1} \rightarrow$ Required turns ratio = 10.28

$P_{TOT} \rightarrow$ Allowed total power dissipation = 2W

$K_u \rightarrow$ Winding fill factor = 0.75

$\beta \rightarrow$ Core loss exponent = 2.6

$K_{fe} \rightarrow$ Core loss coefficient = 25

$A_c \rightarrow$ Core cross − sectional area

$W_A \rightarrow$ Core window area

$MLT \rightarrow$ Mean length per turn

$l_e \rightarrow$ Magnetic path length

$\Delta B \rightarrow$ Peak ac flux density

<u>*Step 1:*</u>

- $Kgfe \geq \frac{1}{4Ku(P)^{(\beta+2)/\beta}} \rho \lambda^2 I^2 10^8 (Kfe)^{2/\beta}$

Putting values we require the $K_{gfe}$ of our core to be greater than 0.364. We have selected a core that has a $K_{gfe}\ of\ 0.4$. So after selecting the core, we know the following values

$A_c = 3.59 cm^2$

$W_A = 9.84 cm^2$

$MLT = 15.6 cm$

$l_e = 22.9 cm$

***Step 2:***

- $\Delta B = 10^8 \rho \lambda^2 I^2 (MLT) \frac{1}{2KuWA^3 l\beta K_{fe}}$

Putting values in above equation, $\Delta B = 0.1T$ which is bellow the saturation flux density. So we are in the safe limits.

***Step 3:***

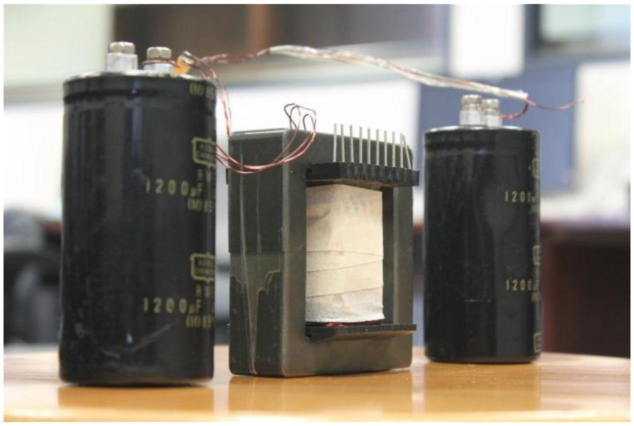
- $n_1 = \frac{\lambda}{2\Delta BA} 10^8$

$n_1 = 20\text{turns}$ from the equation but we used the value of 24, to give a cushion of 20%

***Step 4:***

- $n_2 = n_1 (n_2/n_1)_{effect}$

$n_2 = 247\text{turns}$ putting values in the above equation.



Filter

**3.2.2 Inductor design**

We used an EE core for inductor design.

The design is given below:

$$L = \frac{n^2\ \mu\ A_C}{l_e}$$

Using the values of constants, and L = 4mH;

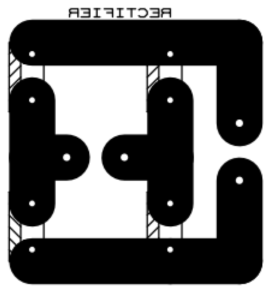
n = 20

**3.3: TOOLS**

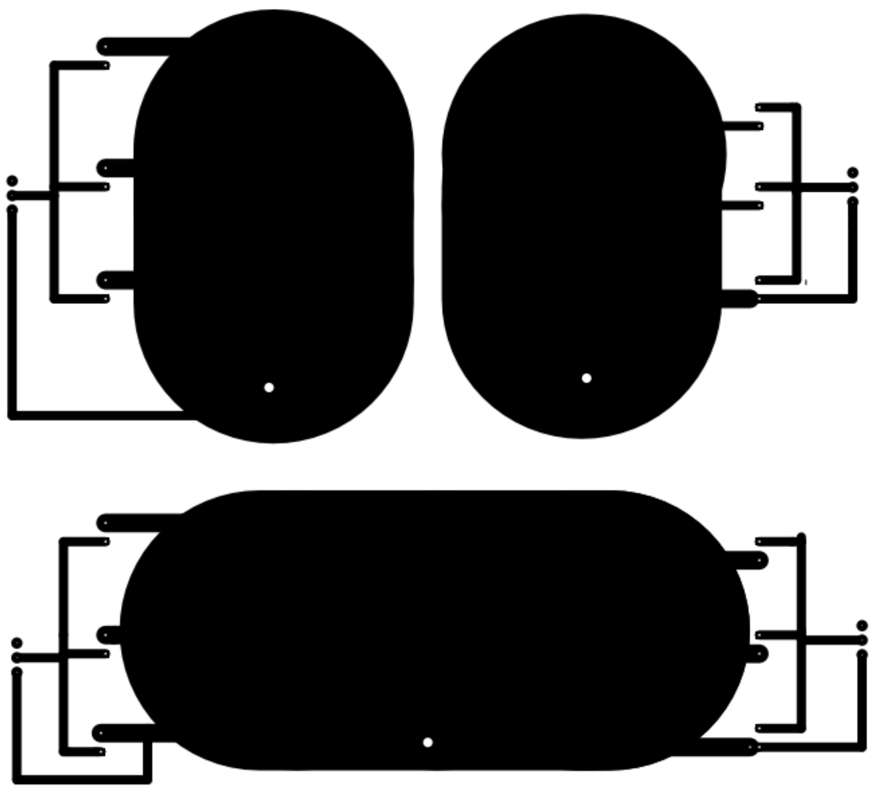
Proteus was used for PCB designing. For simulation results, the two softwares used were SIMULINK and LT-SPICE.

### 3.3.1: Proteus:

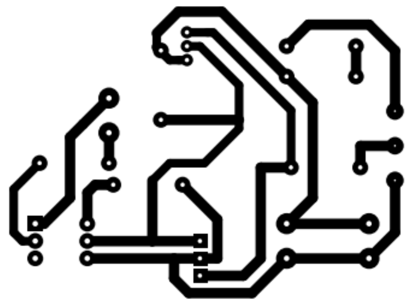
Following are the layouts of the PCB:



Rectifier



Power H-Bridge



Gate Drive

### 3.3.2: LT-SPICE:

Initially LTSPICE was used for gate drive and filter simulation. However due to lack of accurate models and slow simulation results, it was not very helpful. Cascading output of inverter with filter gave extremely slow processing and error.

### 3.3.3: SIMULINK:

Following is the simulation circuit in Simulink:

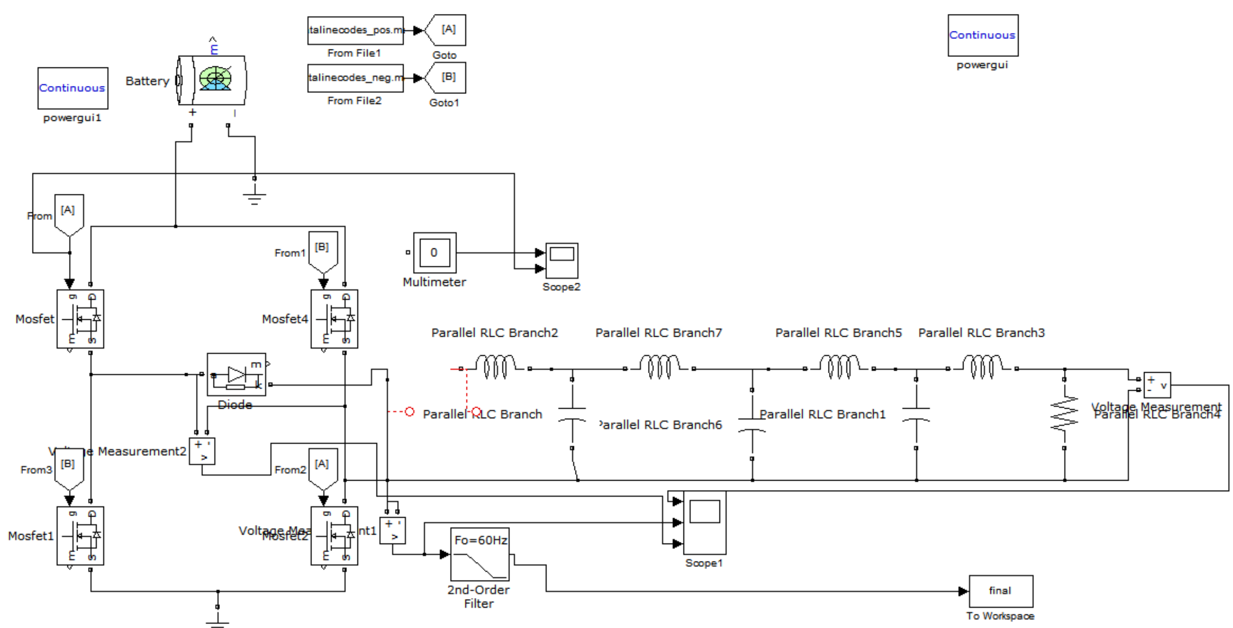


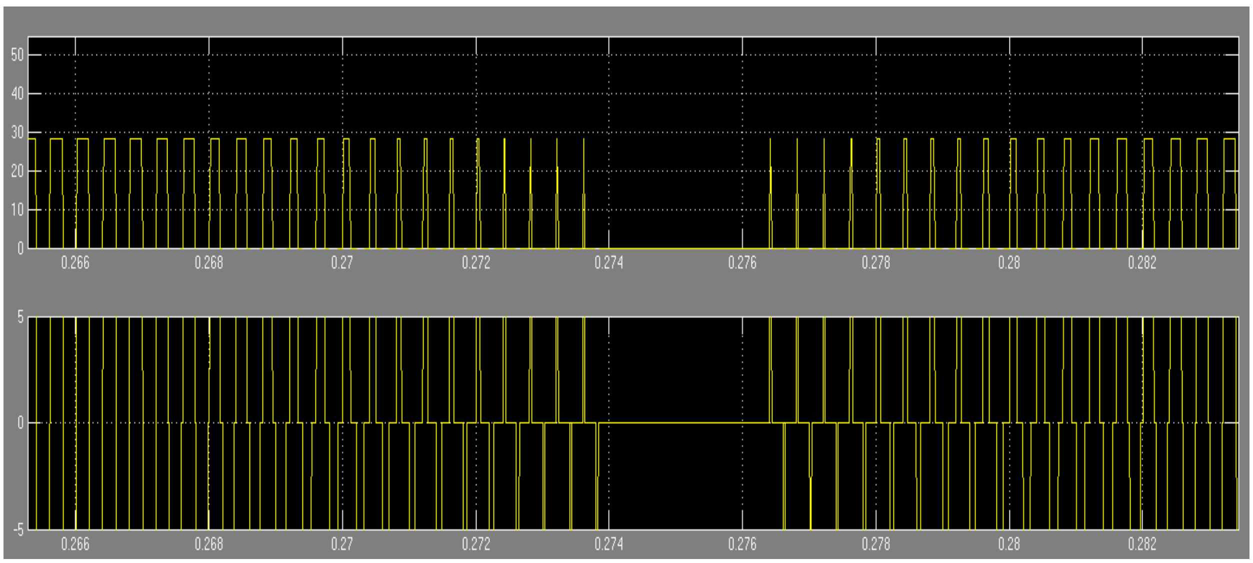

Figure 3.3.2

*Chapter 4*

# SIMULATION AND IMPLEMENTATION RESULTS

## 4.1: SIMULATION RESULTS:

Simulation results from Simulink are shown below:




The waveform on the bottom is the input signal provide to the gates of the MOSFET, i.e. the input PEM waveform. The waveform on the top is the amplified and rectified version of this PWM.

## 4.2 PWM DESIGN:

If we use the usual PWM it will not be helpful in reducing the size of transformer as it has a lot of energy in 50 Hz component. So we applied various schemes. Fourier transform of each scheme was found and the energy from 50Hz signal was almost reduced to zero. By using this enhanced scheme, a high frequency (small sized) transformer design would be possible now. The various schemes developed and their Fourier transforms are given bellow:

### 4.2.1 Basic PWM:

In 50 Hz frequency component, 79.5% energy was found. Thus clearly high frequency transformer cannot be used in this case as high energy 50Hz signal will saturate the transformer core.

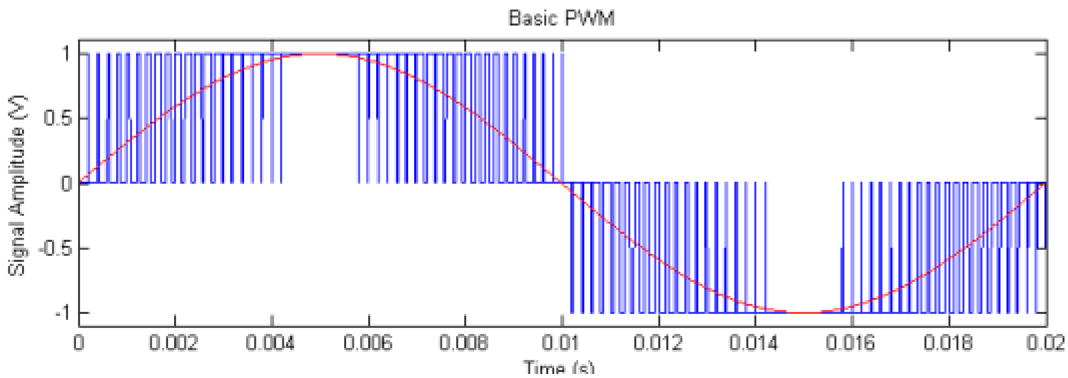



Figure: 4.2.1.1

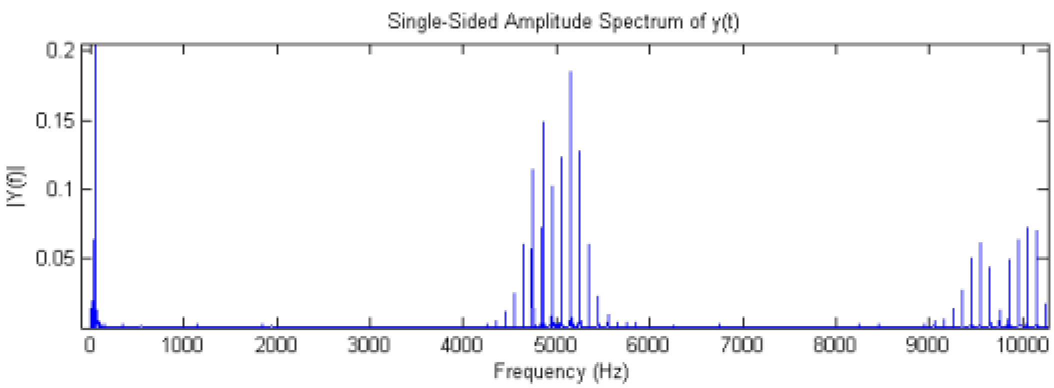



Figure: 4.2.1.2

### 4.2.2Unipolar PWM

In 50Hz frequency component, 49.5% energy is found. It is better than the Basic PWM but still a lot of energy lies in the low frequency thus making the scheme unusable.

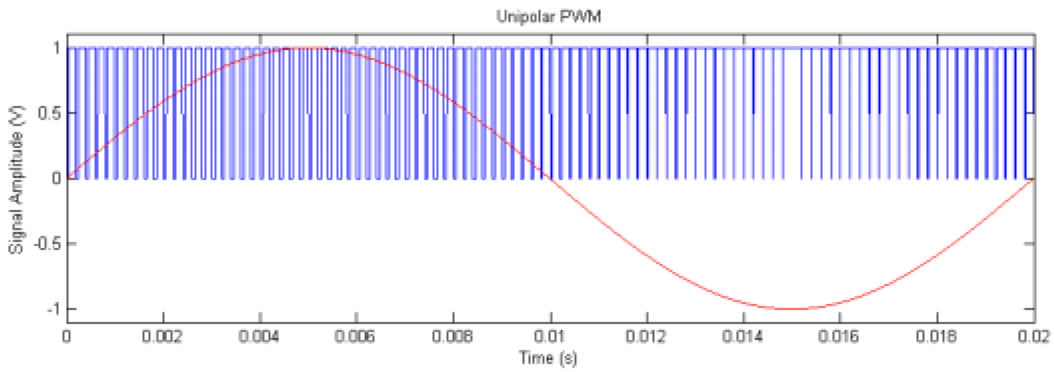



Figure: 4.2.2.1

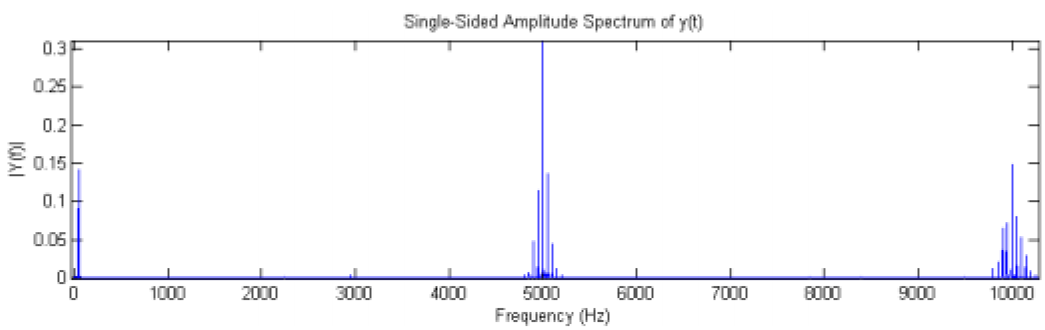



Figure: 4.2.2.2

### 4.2.3 Line Coded PWM (Before Rectification)

Energy in 50Hz signal is 0.024%. Thus the Line Coded scheme will work well with high frequency, small transformer. The scheme has been inspired by Communication systems Line Codes.

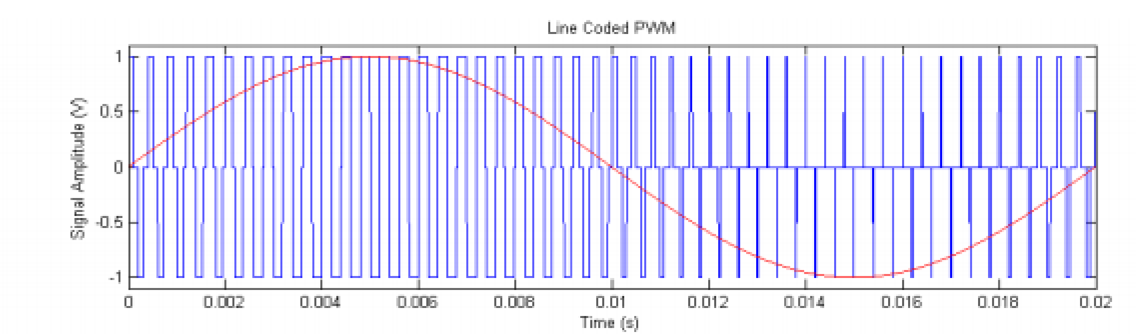



Figure: 4.2.3.1

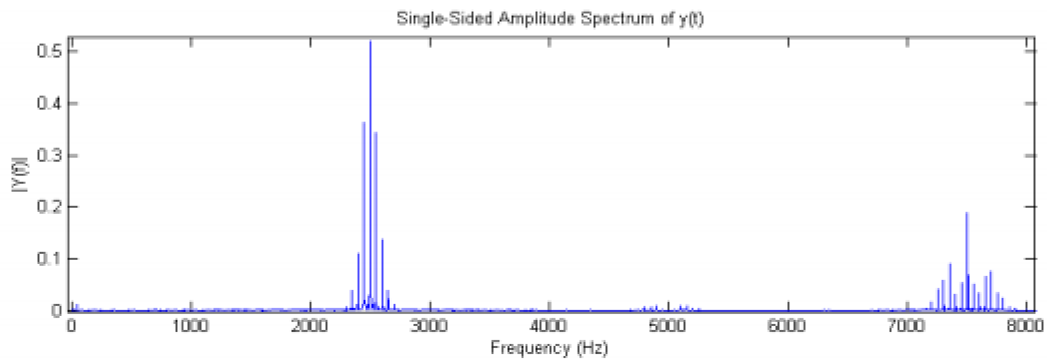



Figure: 4.2.3.2

### 4.2.4 Line Coded PWM (After Rectification)

After passing from transformer the signal is rectified and we see 15.87% energy comes back in 50Hz signal. Thus LPF would recover the original signal

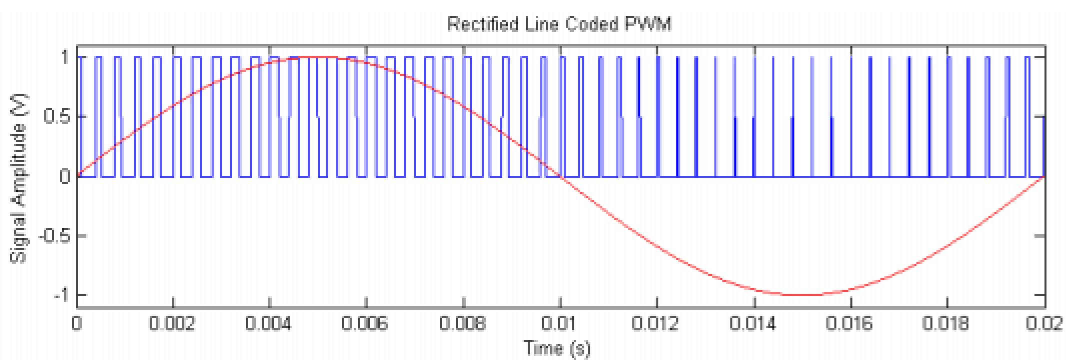



Figure: 4.2.4.1

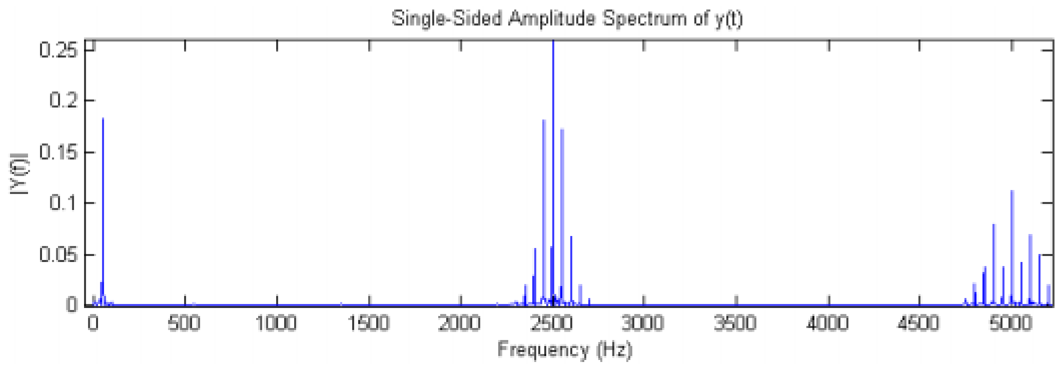



Figure: 4.2.4.2

**4.3 Implementation results:**

The above proposed system was implemented:

Following are the results observed:

- The PWM scheme was tested and proved experimentally. The results were in accordance with the results predicted by the simulations.
- The power efficiency in open loop runs was 65%.

**4.4 Optimization function**

Optimization problem is solved by designing an optimization function that can optimize power flow from the PV source via batteries and inverter to the main grid. The method that is being used is implemented by Yann Riffoneau, Seddik Bacha in their research paper of "Optimal Power Flow Management for Grid connected PV systems with batteries".

The optimization is being done under certain constraints which will be discussed later in the section. The cost function as designed to be our optimization function is minimized by using dynamic programming techniques. Dynamic Programming calculates all the possible states and then gives the solution with the best choice under the constraints. The main components of the hybrid system are the PV generation sources, the batteries that store energy, the load to be served and the distributed grid.

$$Power(t) = Power_{Pv}(t) + Power_{main}(t)$$

There are certain physical constraints of battery which are needed to be taken care of:

$$SOC^{min}(t) \leq SOC(t) \leq SOC^{max}(t)$$

"SOC" stands for state of charge. Its value varies depending on the amount of charge and how the power is being delivered to a specific load.

$$P_{bat}^{min}(t) \leq P_{bat}(t) \leq \; P_{bat}^{max}(t)$$

There is also an upper bound and lower bound on the amount of power that a battery can deliver at a particular time.

$$SOH(t) \geq SOH^{min}$$

"SOH" stands for state of health of the battery. There is also a threshold above which the battery life gradually falls and it starts taking too much time in charging and very small time in discharging. This factor depends on the health of the battery. SOH should be at least above a threshold value for battery to operate efficiently.

Now the above mentioned factors are described further as:

$$SOC(t) = C(t)/C_{ref}(t)$$

Where C (t) is the capacity of the battery at any instant and Cref (t) is the reference capacity at full charging.

$$C(t) = Q(t0) + Q_c(t) + Q_d(t)$$

Q(t0) is the initial starting charge and Qc(t) is the charge transferred to the battery due to the charging and Qd (t) is the charged transferred from the battery to the grid at any time.

We also mentioned above about the health of the battery which is explained by SOH term. SOH is given by:

$$SOH(t) = (C_{ref}(t - \Delta t)/C_{nomref}) - Z * (SOC(t - \Delta t) - SOC(t))$$

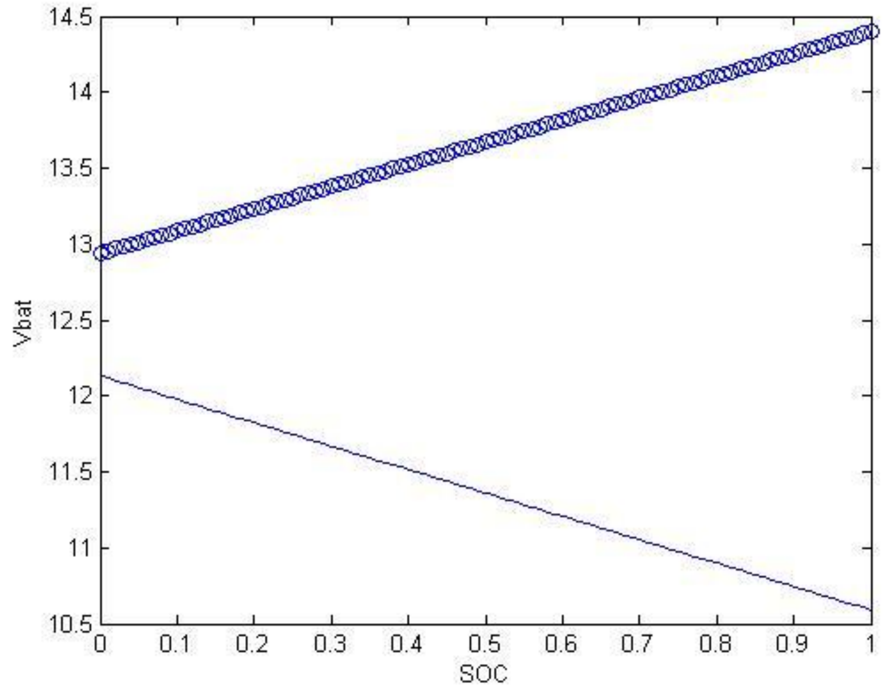
Cnomref is the nominal capacity of the storage and Z is the ageing coefficient whose value is around 0.3 mili.

Voltage of the battery also varies during charging and discharging process and the battery voltage is modeled linearly. The equations for charging and discharging are:

$$V_{bat} = [12.94 + 1.46 * SOC(t)] * N_{bat}$$

Here we have equation for charging with Nbat representing number of batteries. For discharging the equation is:

$$V_{bat} = [12.13 - 1.54 * (1 - SOC(t))] * N_{bat}$$




(o) Charging; (-) Discharging

Finally the cost function is calculated to be of the form of

$$Cost = Cash\ recieved + Cash\ Paid$$

$$Cost = [P_{grid}(t) * FIT(t) * \Delta t] + [P_{maingrid}(t) * Egp * \Delta t + BrC(t)]$$

Here Pgrid is the power generated by PV source, FIT is the feed in tariff at which we like to sell our generated power, Pmaingrid is the power that main grid is providing, Egp is the electrical grid unit price and BrC is the battery replacement cost. The first bracket terms give cash received and the second one show the cash paid.

$$BrC(t) = BiC * (-\Delta SOH(t))/(1 - SOH_{min})$$

BiC is the battery installment cost. Dynamic Programming algorithm to calculate the states of SOC is being used and it optimizes the cost thus giving us the effective power to be fed.

# *Chapter 5*

## COST ANALYSIS

Following table gives the costs of various components used in the project:

| ITEM | QUANTITY | COST (PKR) |
|---|---|---|
| Filter capacitor (1200 uF) | 2 | 5000 |
| Transformer core | 2 | 2200 |
| MOSFET | 8 | 600 |
| Input capacitor | 1 | 400 |
| Heat sinks | 2 | 300 |
| Microcontroller | 1 | 500 |
| PCB | 1 ft | 600 |
| Winding wire (24 AWG) | 0.5 kg | 450 |
| Gate drive | 4 | 600 |
| Ultra-fast/+9- diodes | 4 | 360 |
| Miscellaneous costs | | 500 |
| **Total** | | 11,500 |

*Chapter 6*

# CONCLUSION AND FUTURE RECOMMENDATIONS

The proposed design was implemented. The efficiency was not very high. Following are a few factors accounting for the low efficiency:

- Power losses in the filter due to large ESR of capacitances and inductor
- In our case, the transformer was hand wound. Hence, the efficiency was not ideal for the transformer.

Following factors should be kept in mind for an efficient design:

Considerable attention should be given to the design of gate drives. Gate drives should be designed to keep the delay minimum and to apply sufficiently high voltage on the gates. If a high voltage is applied, the losses in the MOSFET can be reduces, even at very high frequency.

Transformer design should be done with great care. Attention should be given

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