An Investigation and Optimization of DC-Bus Energy Storage Requirements in Single Phase Inverter

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Abstract: *Abstract: Power electronic converters that convert DC to AC, or vice versa, require an energy buffer between the AC and DC ports of the converter to compensate for the instantaneous power mismatch. Electrolytic capacitors are mostly used for these buffering applications because of the high energy density when compared to other capacitors, but unfortunately this type of capacitor also has low reliability. This dissertation proposes a general solution from a fundamental approach to solve the required capacitor power requirements on the DC-bus of an inverter. From the resulting model, an alternative active filter design technique to reduce the required capacitance of the DC-bus capacitor of a single phase inverter is presented. In this model, the minimum and maximum voltages of the capacitor can be chosen and the corresponding waveforms are calculated. An optimum region for the choice of capacitor voltage is shown to visually illustrate the trade-offs between the capacitor voltage, capacitance and converter losses. In this optimum area the reduction in capacitance is enough to allow the elimination of electrolytic capacitors, while maintaining comparable volume.*

Keywords: *Renewable Energy system, PV Array, Electrolytic capacitors, DC-bus, Fuel Cell, DC/DC Converter.*

I. Introduction

Power electronics is a term that describes a very wide range of technology and products that convert and control the flow of electrical energy. This energy processing capability of power electronics have become part of our everyday lives. From cell phones and tablets, to cars and power systems, almost all forms of modern technology use power electronics to function. Renewable energy power sources also require power electronics for the generated energy to be used effectively. The AC port of the converter must usually be able to deliverer power at a very high power factor at twice the line frequency [1]–[3].The result of the applications mentioned above is a converter with a DC port on the input or output side and an AC port on the other side. The converter is then responsible to interface between the constant power DC port and the variable power AC port. An instantaneous power mismatch will occur when the instantaneous power generated by the source and consumed by the load does not match. An example of this can be seen when looking at a single phase inverter or rectifier as seen in Figure 1-1. The DC side supplies or consumes constant power at the average power value, where the AC side supplies or consumes power at twice the line frequency [4]–[7]. An in depth study of the equations and physics that govern the working of a capacitor is required before the design process can start. Comprehensive studies into the basic workings of a capacitor are widely available, and the relevant details will be discussed in this chapter. The literature form this section has mainly been found in [9]–[11].Capacitors and inductors are passive components that are used to temporarily store energy within a power electronic circuit. For a power electronic circuit to be used effectively, these components need to be optimised [10], [11].

II. Related Work

[1] F. Blaabjerg et al. proposed maximum power tracing system using PSO algorithm, which showed enhancement of 65% over conventional source. This avoids pre-convergence of data points using PSO.

[2] K. Ma et al. Renewable energy power sources also require power electronics for the generated energy to be used effectively. Solar panels generate Direct Current (DC) which has to be processed and converted to Alternating Current (AC) in order for it to be used elsewhere or in a normal household.

[3] U. M. Choi et al The result of the applications mentioned above is a converter with a DC port on the input or output side and an AC port on the other side. The converter is then responsible to interface between the constant power DC port and the variable power AC port.

[4] P. T. Krein et al. A promising alternative active filter configuration is discussed in [4]. In this configuration, a third port, in addition to the DC and AC ports, is introduced to manage the ripple power of the inverter. The ripple power is controlled directly to achieve the desired double frequency power value and therefore the voltage variation of the capacitor can be large by design.

[5] M. Mellincovsky et al The fundamentals of the instantaneous power mismatch and required energy buffering capabilities have been well established. The two main categories of the solutions that exist are active filters and passive filters. The fundamentals and working of each of these solutions are discussed below.

METHODOLOGY

With all the building blocks now available, a general solution can be formulated. In this section, a step by step design procedure of how the approach described in this research can be implemented, to achieve the desired outcome, is presented. This section is applicable to any converter or any capacitor and enables designers to implement the converter or technology that they are most comfortable with.

The assumptions for the guide to be applicable are as follows:

The inverter is single phase.

The average power rating and line frequency of the inverter are available. The choice of direct capacitor power control has been made.

The inverter is operating at a maximum point of operation.

Case 2: Choice of maximum Capacitor Voltage.

- The first step of this design procedure would be to decide on the maximum capacitor voltage. This value will typically depend on the ratings of components that are already available to the designer. It must be noted that, because the capacitor will be decoupled from the DC-bus, the chosen voltage value is of no relevance to the DC-bus voltage. It is advised to choose this value relatively close to the DC-bus voltage. This will avoid too much strain on the converter and avoid the need to design for high conversion ratios. Theoretically, the voltage can be any value chosen by the designer.system.
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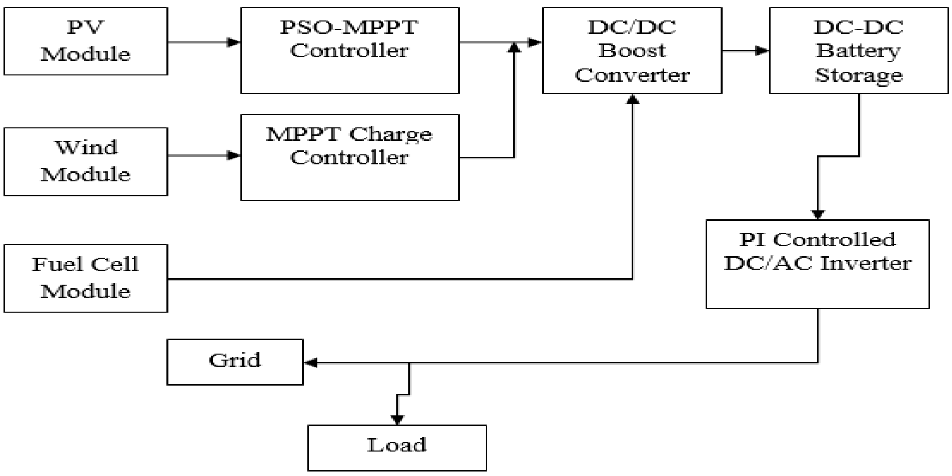

Figure 1: Block diagram of Case 2

Case 3: Approximate trade-off between Voltage Variation, Capacitance and Losses:

One can now move on to the trade-off between the voltage variation, capacitance and losses. This step, as in Block One, must be chosen with the converter design in mind. If the choice of the absolute minimum voltage is made, the converter will be subjected to very high stress and conversion ratios, which usually requires complicated control and unnecessary losses in the converter.

Case 4: Choice of Minimum Capacitor Voltage:

After the approximate voltage variation has been decided on, the specific minimum capacitor voltage must be chosen, keeping in mind the comments of Block Two.

Case 5 Capacitance Calculation:

The capacitance value calculated will likely not be commercially available. It is then the designer's responsibility to compare the calculated result of the capacitance with an available capacitance and then select a new capacitance as close as possible to the calculated value. The designer must then return to the capacitance calculation and calculate a new value for the minimum or maximum voltage. This must be done to ensure that the power processed by the capacitor remains as predicted.:

CONVERTER LOSS MODEL

As stated in the previous Chapter to be able to use the model to its full potential, a loss model of the chosen converter is also required. It is not a necessity to incorporate a loss model into the general solution, but it will add the ability to accurately choose a set point voltage variation. The trade-off between voltage variation, capacitance and losses can be viewed on the same plot simultaneously and an informed decision can then be made.

For the purpose of this study, a simple full bridge converter is chosen as seen in Figure:1 below. As it is not the purpose of this research to optimise the converter design, a simple PWM modulation technique is assumed, along with hard switching of all the transistors across the entire operating range.

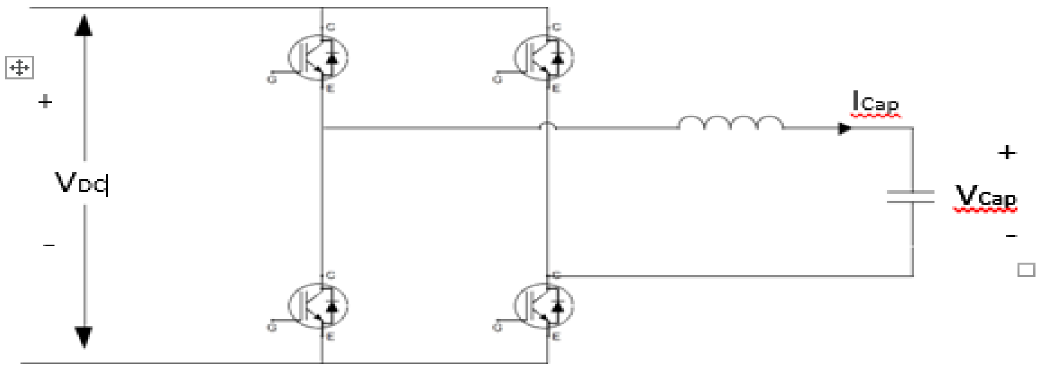

Figure :2 Bi-Directional Full Bridge converter configuration.

CONDUCTION LOSSES:

The conduction losses in a transistor occur when the transistor is in full conduction. These losses are governed by the Collector – Emitter saturation voltage and the current that is flowing through the transistor at that time. The presence of voltage over the transistor and current through the transistor at the same time, equates to power being dissipated by the transistor in the form of heat.

To calculate the conduction losses of the above mentioned converter, a discrete Microsoft Excel model has been created. In this model, one full current cycle is evaluated with discrete time steps. In each of these time steps, the transistor state (on or off), voltage and current is evaluated, to determine the instantaneous power dissipated in that specific time period. a generic equation of the calculation of power, is adapted to fit the discrete model.

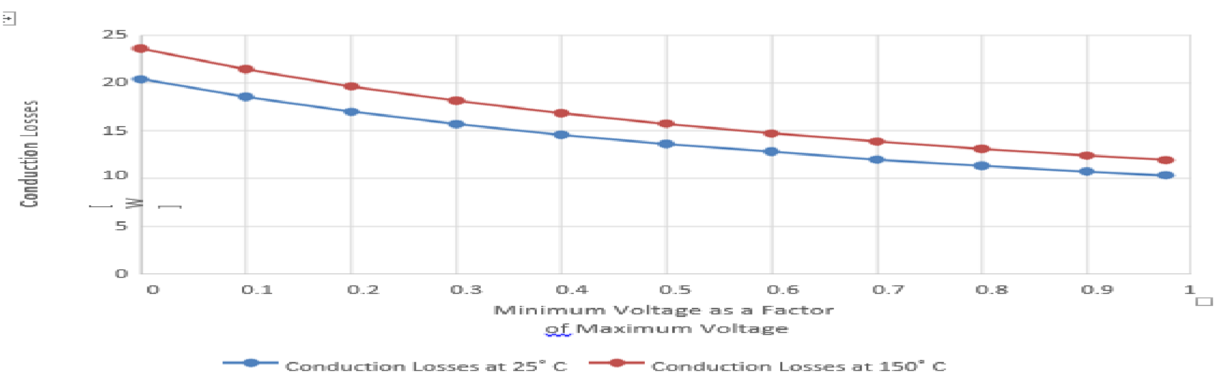

Figure 3: Calculated conduction losses of Full Bridge converter as a function of the selected minimum capacitor voltage

SWITCHING LOSSES

Switching losses occur in a transistor in the transition period when the device is either turning on or off. In this period, for a very short time, there will be significant current through and voltage over the transistor, which will result in power being dissipated in the transistor.

As stated previously in the chapter, for an accurate model, researchers usually measure these transitions to be able to predict the switching losses. For the purpose of this study, the datasheet of the specific transistor will be utilised.

In this datasheet, the energy dissipation values of the turn-on, turn-off and total energy dissipated per transition had been supplied. These values at different temperatures can be seen in Table 1 below:

Table 1 Switching Energy Losses of Chosen IGBT

IGBT Junction Temperature (˚ C)	Total Energy Dissipated (mJ)	
	IC=2A	Ic =7.5A
At 25	**0.06**	**0.17**
At 150	**0.08**	**0.24**

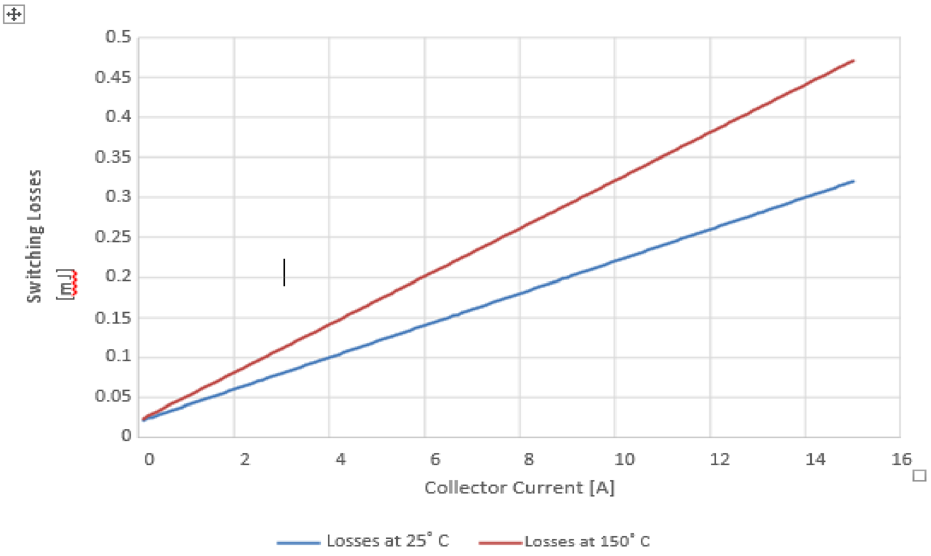

Figure 4: Total IGBT switching losses function per transition at 25 ˚C and 150 ˚C respectively.

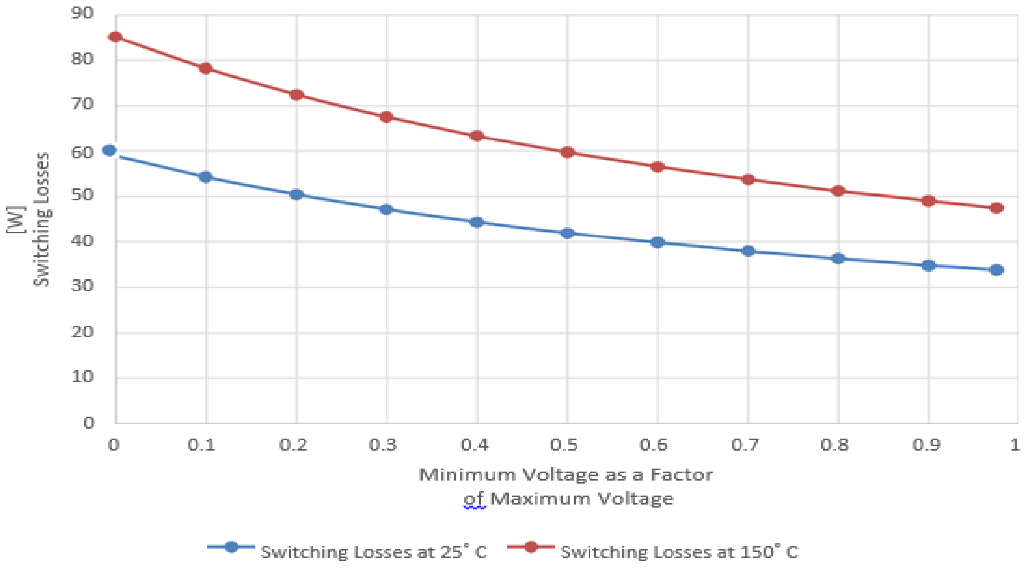

Figure 5: Predicted switching losses of converter.

Total Converter Losses

The total converter losses, including conduction and switching losses of the entire converter, can be seen in Figure 5 below:

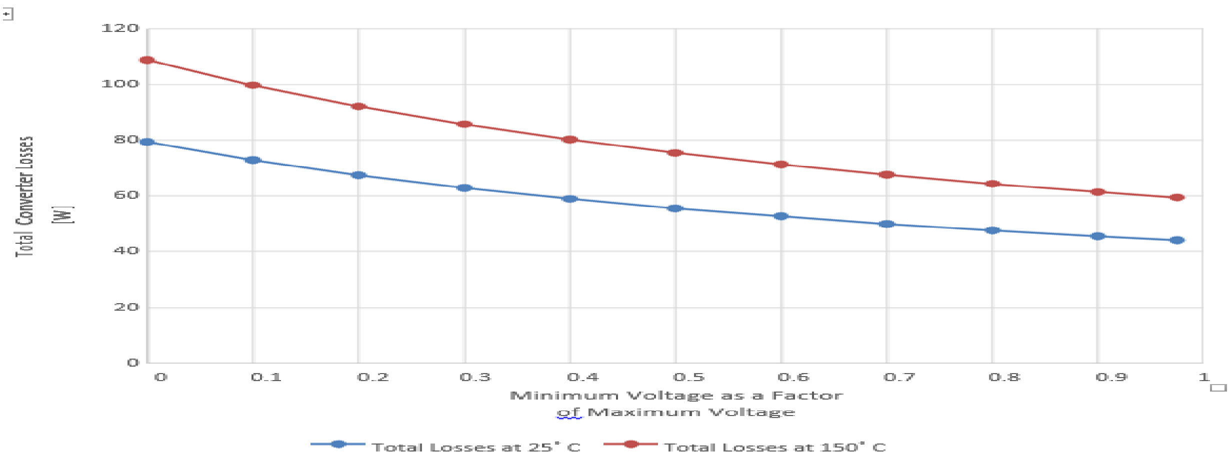

Figure 6: Total calculated losses of Full Bridge converter as a function of the selected minimum capacitor voltage

Optimum Choice of Minimum Voltage

In this Chapter the trade-off between capacitance and choice of minimum voltage could be seen, and in the chapter before, the trade-off between the converter losses and minimum choice of voltage could be seen. In the figure below both of these trade-offs can be seen on the same axis:

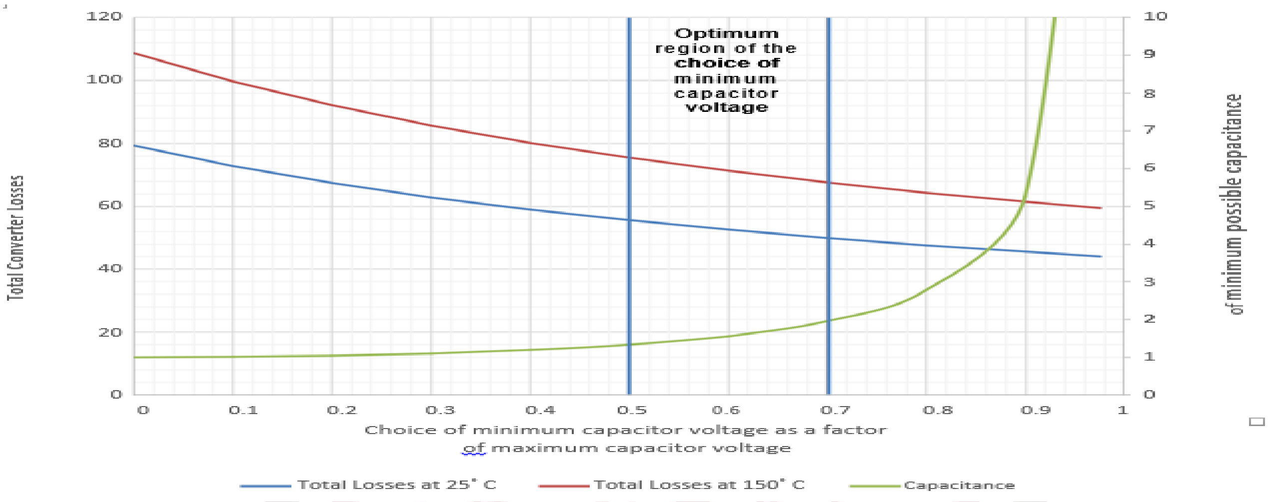

Figure 7: Trade-offs illustration between converter losses, capacitance and capacitor voltage, also indicating the suggested region of the optimum choice of minimum capacitor voltage.

PROTOTYPE DESIGN

Passive Filtering

Table 2: Passive Filter Capacitor

Parameter:	Value:
Capacitance	1.5 mF
Manufacturer	Kemet
Rated Voltage	550 VDC
Volume	393.4 cm^3

According to the Equation this capacitor will be able to keep the required voltage under the allowable 3%.

Active Filtering

a.Topology Selection

For the topology selection any arbitrary bi-directional converter can be chosen that is able to processes the required power. For the argument presented, a Full Bridge converter has been chosen as seen in this chapter.

b. Component Selection

The most important component to select in terms of this research is the capacitor, as the converter and other components would be subject to the decision of the designer.

Research had been done to compile datasheets of film capacitors from Kemet, Illinois Capacitor and TDK and the appropriate film capacitors have been selected as seen in the table below:

Table 3: Active Filtering Component Selection

	Solution Two	Solution Three
Capacitance	80 µF	120 µF (80 µF + 40 µF)
Manufacturer	Illinois Capacitor	Illinois Capacitor
Rated Voltage	700 VDC	700 VDC
Volume	125.6 cm^3	203.3 cm^3

When the volume of the capacitors are compared, it is seen that for Solution Two the total capacitance is 33% less than the capacitance of Solution Three. It can also be seen that the volume of the capacitor of Solution Two is 38% less than the volume of Solution Three

c. Calculated Losses

As all the needed information to calculate the associated losses is now available, the predicted losses for Solution Two and Solution Three can now be calculated.

SIMULATION RESULTS

This chapter describes the simulation results of the above mentioned case study, but does not include the passive filtering case study. Both of the active filter solutions are presented, discussed and verified on a simulation level.

This case study is not presented on an experimental level, as the goal of this research is to present a general solution of capacitor power management and not a specific application solution.

The configuration of the active filter in conjunction with the full bridge single phase inverter can be seen below. Both of the active filter scenarios in the case study make use of exactly the same circuit, only with different capacitances. A triangular waveform of 100 000 kHz was used as the carrier waveform and the fundamental voltage waveform calculated in this Chapter was implemented using C code. All of the simulations were conducted in PSIM.

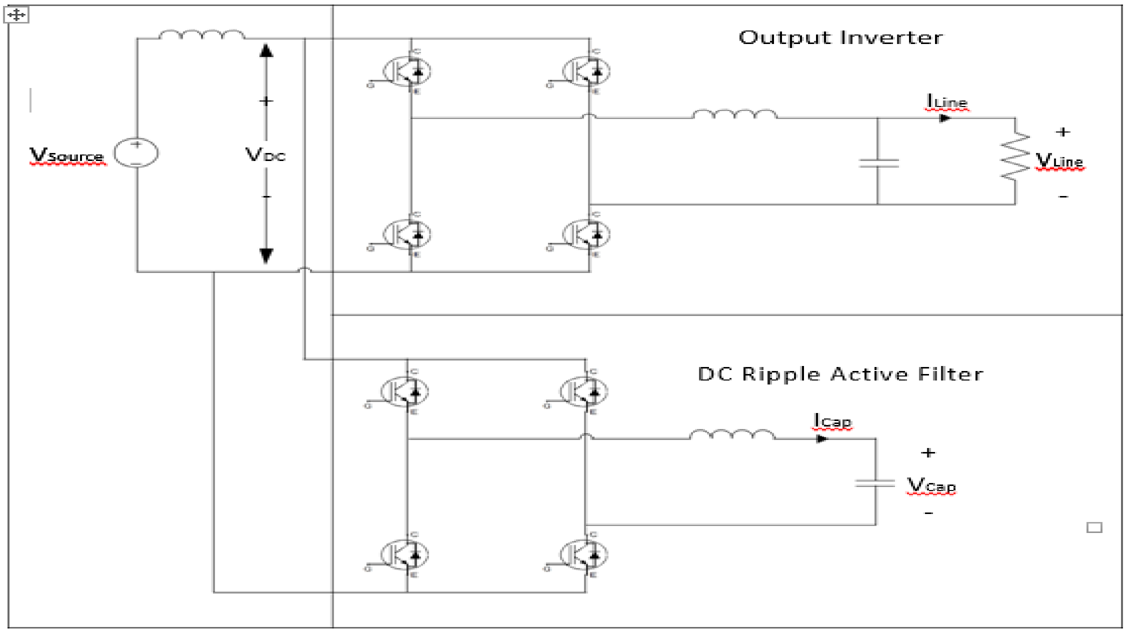

Figure 8: Topology and configuration of simulation setup.

As seen in the figure above, a small inductance has been placed in series with the voltage source. This has been done to weaken the ideal source so that the simulation results are closer to real-world application. An inductance value of 1 mH has been chosen as it is a real-world possible value that that can be found in DC sources.In the plots below, the resulting power is calculated by adding the instantaneous values of the inverter power with the instantaneous value of the capacitor power.

Simulation Results of Solution Two (80 µF Capacitor)

In the simulation, the results and conclusions are based on the converter as a whole, including the inverter and the active filter. For this reason, the plots will illustrate both of the inverter and filter variables on the same axis, and then the net effect of those variables in the system thereafter.

The first simulation is done on the case study where the capacitance was calculated to be 80 µF and a minimum required voltage of 29.07 V. The relevant plots can be seen below.

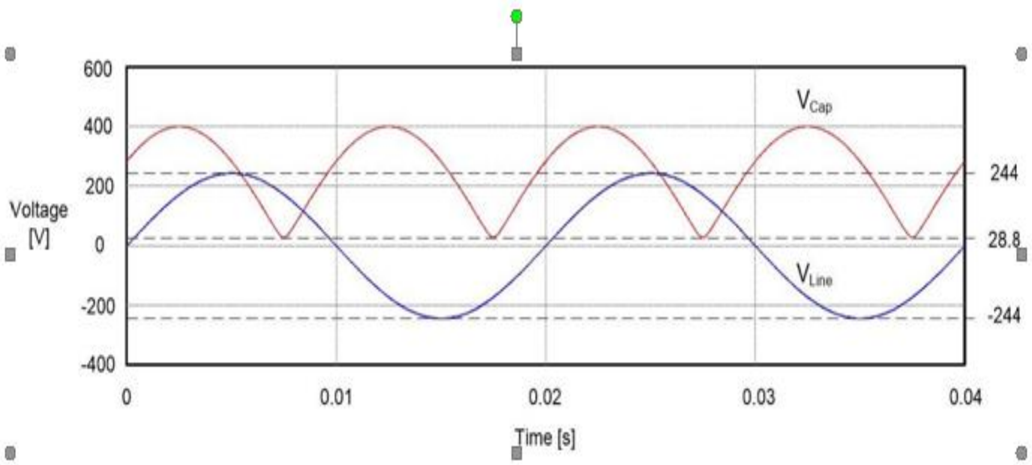

Figure 9 : Solution Two comparison between the inverter output line voltage and the active filter capacitor voltage.

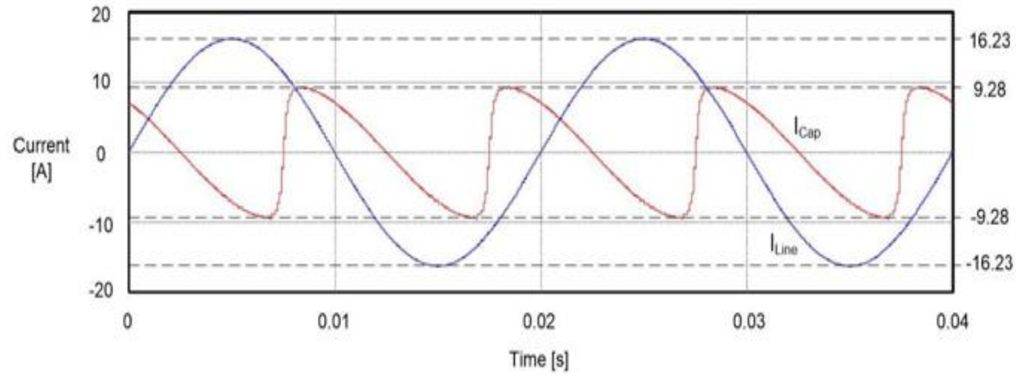

Figure 10: Solution Two current comparison between the inverter output line current and the active filter capacitor current.

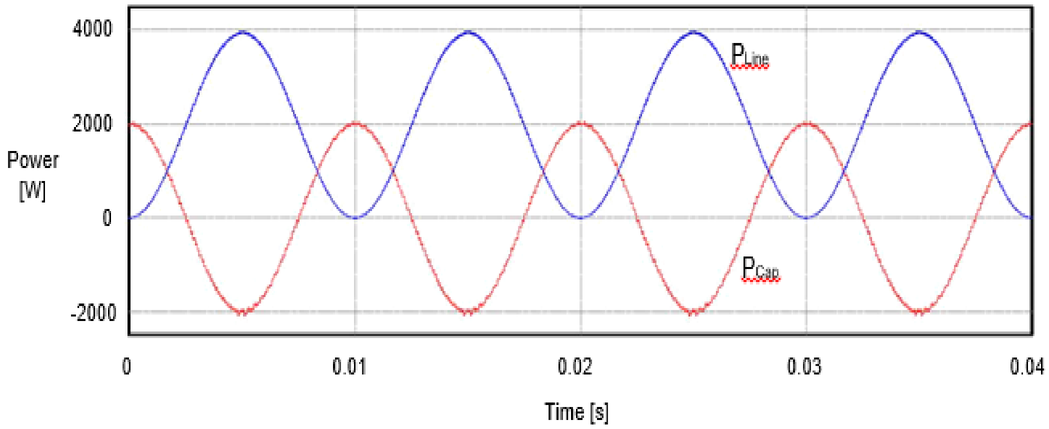

Figure 11: Solution Two power comparison between the inverter output line power and the active filter capacitor power.

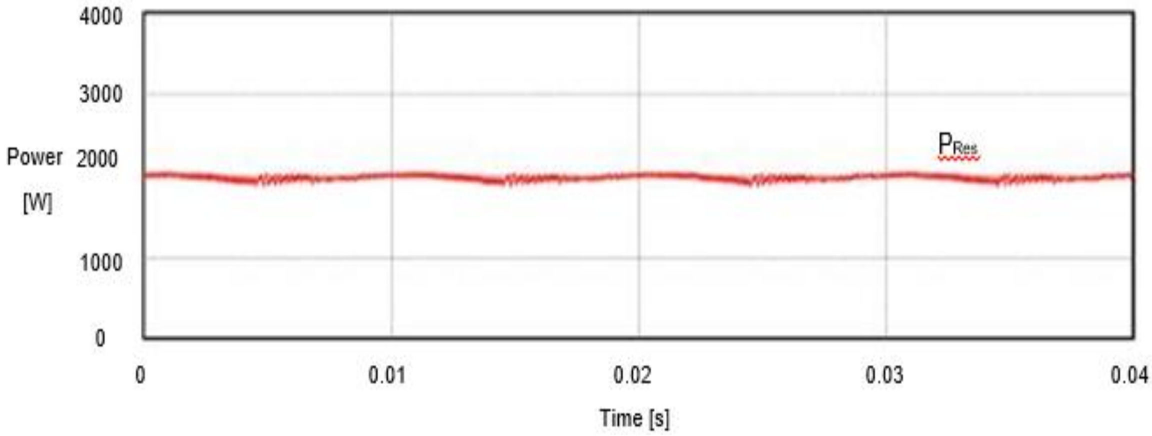

Figure 12: Solution Two resulting power.

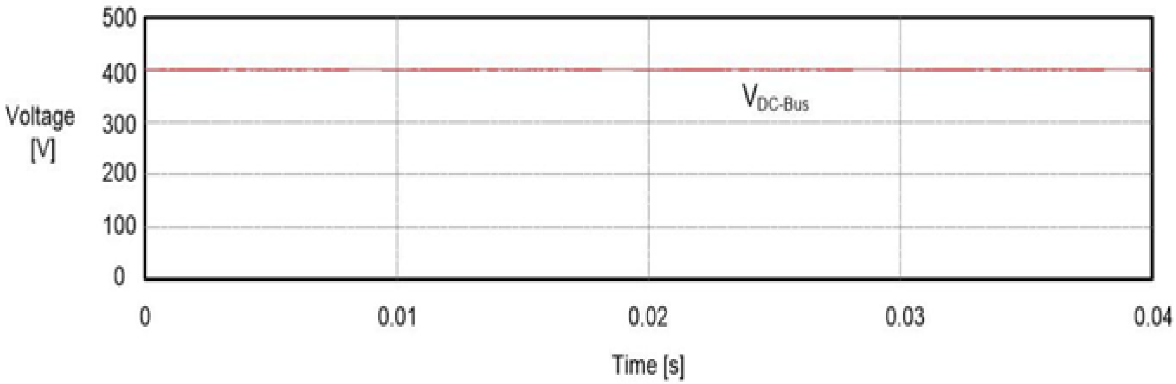

Figure 13: Solution Two resulting DC-Bus voltage.

COMPARISON AND RESULTS DISCUSSION

Trade-off Comparison

Chapter 3 and Chapter 4 describes and discusses the trade-offs between minimum capacitor voltage, capacitance and losses that a designer can choose when utilising the general solution presented. In Figure 12 below, these trade-offs of Solution two and Solution Three are illustrated and compared.

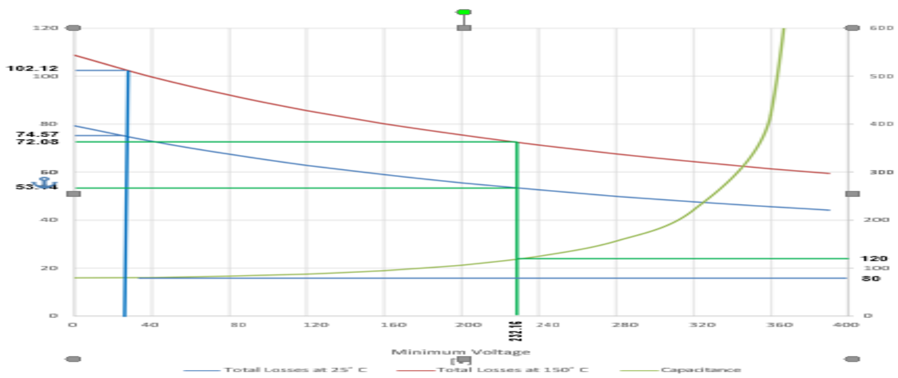

Figure 14: Trade-offs illustration between converter losses, capacitance and capacitor voltage of Solution Two and Solution Three

Capacitor Comparison

From the results above, it can be seen that it is possible to replace the electrolytic capacitor with a film capacitor using the general solution while still achieving the desired goals.
In Table 4 below is a full comparison of all of the chosen capacitors for the different solutions.

	Solution One	Solution Two	Solution Three
Filter Type	Passive	Active	Active
Capacitor Type	Electrolytic	Film	Film
Manufacturer	Kemet	Illinois Capacitor	Illinois Capacitor
Capacitance	1,5 mF	80 µF	120 µF
Rated Voltage	550 V	700 V	700 V
Voltage Variation	394.7 V to 405.3 V	29.07 V to 400 V	232.16 V to 400 V
Series Resistance	204 mΩ @ 100 Hz	2.6 mΩ @ 100 kHz	1.3 mΩ @ 100 kHz
Dimensions	66mm (D) × 115mm (H)	57.5mm (L) × 57.5mm (B) × 38mm (H)	57.5mm (L) × 57.5mm (B) × 38mm (H) + 57.5mm (L) × 45mm (B) × 30mm (H)
Volume	393.4 cm^3	125.6 cm^3	203.2 cm^3

Several interesting conclusions can be made from the capacitor comparison. The first is the large difference in the equivalent series resistance between the electrolytic capacitor and the film capacitors. The series resistance of the electrolytic capacitor is roughly 150 times larger than the film capacitors, as predicted from the capacitor study. It is mainly this resistance value that greatly reduces the reliability of the electrolytic capacitor. The value of this resistance is also given at the correct approximate frequency at which the different capacitors are made to operate**.**

CONCLUSION

To solve the problem of instantaneous power mismatch, a very large electrolytic capacitor is usually implemented because of its large energy density compared to other capacitors. It is known that these electrolytic capacitors traditionally have a short lifetime and are prone to failure. Film capacitors would be a good replacement, but unfortunately have low energy densities.This research proposes a general solution from a fundamental approach of how the power processed by a capacitor can be better defined and then also better addressed, to solve the problem of instantaneous power mismatch in single phase inverters.The mathematics and simulations prove that the presented model is viable as an alternative approach to solve the problem of instantaneous power mismatch in single phase inverters. It is seen that the electrolytic capacitor can be eliminated using this method, whilst still maintaining comparable volume, even when the converter is included**.**

FUTURE WORK

A valuable contribution can be made to see where else the model can be put to effective use, as in the case of the decoupling of the capacitor in single phase inverters. This whole model would apply to inductors as well, but instead of controlling the voltage to force a power waveform, one would control the current.
Future work on the fundamental model can also be done by adding experimental results, and the required control aspects under step changes.

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