A Review on Enhancement of DC-Bus Energy Storage Supplies in Single Phase Inverters

Daharwal Anilkumar Bhagchand [1] and Vinod Meena[2]

[1]Electrical & Electronics Engineering Department, RKDF University, Bhopal, M.P, India
[2] Electrical & Electronics Engineering Department, RKDF University, Bhopal, M.P, India
[1]anil.daharwal98@gmail.com , [2]vinod.meena0@gmail.com

Abstract: *The DC-bus capacitor is decoupled from the DC-bus to allow wide voltage variation and the power processed by the capacitor is directly controlled, instead of the bus voltage. The allowable voltage variation of the capacitor can also be selected to fit the application or traded off in favour of capacitance as chosen by the designer. This general solution is applicable to any bi-directional converter used to decouple the capacitor from the DC-Bus.*

Keywords: *DC link energy storage; energy efficiency; fluctuations; supercapacitors; grid-connected inverter; power quality.*

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.

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].

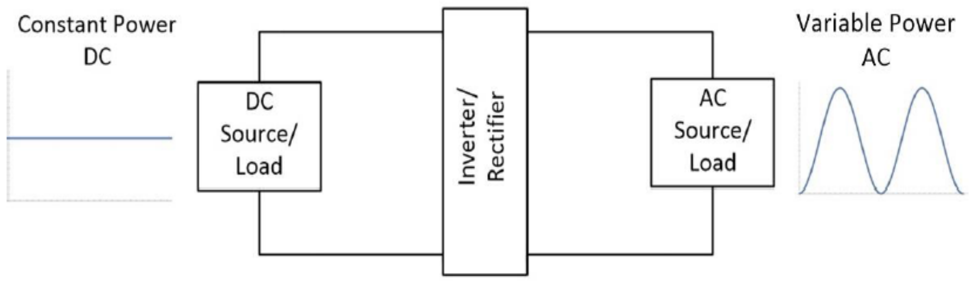

Figure 1. General arrangement of an AC to DC or DC to AC converter indicating power waveforms of the source and load.

The design challenge in the figure above is that the inverter or rectifier must provide internal energy storage to support the conservation of energy between the two ports.

The DC power in Figure 1 will take the form:

$$P_{DC} = P_{avg} \quad \dots (1)$$

and the AC power will take the form of:

$$P_{AC}(t) = P_{avg} + P_{avg}\sin(2\omega t) \quad \dots (2)$$

The instantaneous power mismatch problem has been solved by introducing a large capacitor over the DC-bus to buffer the energy mismatch as seen in Figure 1-2 and Figure 1-3. This method is called passive filtering. The energy storage device will store energy in the part of the cycle where the instantaneous AC power is less than the average DC power, and then supply that stored energy in the part of the cycle where the AC power is more than the DC power. In steady state conditions the amount of energy supplied and stored by the energy storage device will be equal [4].

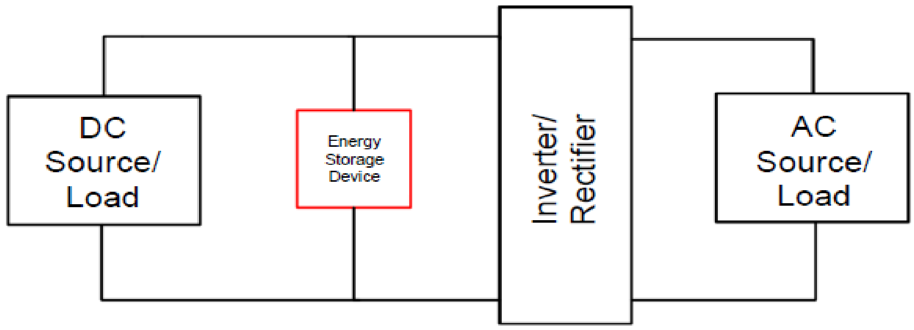

Figure 2. General Arrangement of an AC to DC or DC to AC converter with an energy storage device included.

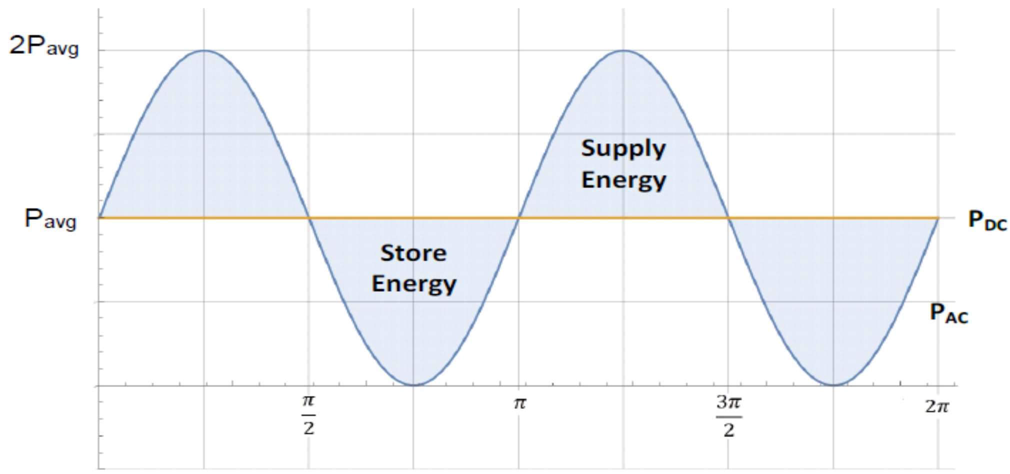

Figure 3. Instantaneous power mismatch between the DC and AC ports of a Single Phase Inverter and indication of where the energy storage device will store and supply energy.

The whole process of absorbing and supplying power by the DC-bus capacitor creates a ripple on the DC-bus. This ripple is inversely proportional to the capacitance of the DC-bus capacitor, and directly proportional to the system power. The DC-bus ripple must also remain within strict limits in order to avoid damage to converter itself, the DC-bus capacitor and even the load or source it is connected to.

II. Capacitor Study

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].

The main focus of this paper is to optimise the energy flow to and from the capacitor. This can be done in one of two ways. Either by advancing the capacitor technology itself by improving properties of the materials and dielectric material it is made of, or by advancing the control techniques of the energy flow of the capacitor. This research will only consider existing capacitor technologies and will expand on the energy flow control techniques to solve the given problem.

II-A Basic Capacitor Energy and Power

Capacitors and inductors can be used for many applications in a power electronic circuits. These applications include filtering, regulation and buffering applications, but for this research, only capacitors used as an energy buffer will be discussed.

A capacitor can be used as an energy buffer interface between the DC and AC port of a single phase inverter, to accommodate the instantaneous power mismatch between the two ports.

In a buffering application, energy is periodically injected and extracted from the capacitor, usually at a far lower speed than the switching frequency of the circuit. The maximum energy that can be stored in a capacitor is given as:

$$E_{store,max} = \frac{1}{2} CV_{max}^2 \qquad \dots (3)$$

II-B Capacitor Technology Comparison

Electrolytic capacitors are the most common capacitors used in energy buffering applications. This is mainly because of their large energy storage density when compared to film capacitors of the same volume. Unfortunately, the trade-off for higher energy storage density is also much higher equivalent series resistance, which limits the current due to overheating.

The rated RMS current of an electrolytic capacitor must be considered when designing with these type of capacitors, because they are generally lower than other types of capacitors. The thermal effect caused by the current is the main reason electrolytic capacitors are generally unreliable and prone to failure.

Electrolytic capacitors are also usually polarised, making them an attractive solution to DC-bus buffering applications, where a large capacitor is required, with no possibility of negative voltages.

II-C Energy densities of Electrolytic Capacitors vs. Film Capacitors

A very comprehensive study of the commercially available capacitors has been done in dissertation which led to [7]. In this resource, the most applicable conclusions to this study are found in the section on highest energy storage density regions of the different capacitors.

The findings conclude that for electrolytic capacitors, the region up to 2 µF and 400 V to 500 V yields the highest energy density. This shows that electrolytic capacitors are best fitted for medium voltage applications that require high capacitance. This region for film capacitors can be found in the 400 V to 800 V and 600 µF to 1200 µF range, but still with approximately an order of magnitude lower peak energy density than electrolytic capacitors.

III. Previous Work

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 [4], [5]. The fundamentals and working of each of these solutions are discussed.

The problem that this research addresses has also been cited by Google and the Institute of Electrical and Electronics Engineers (IEEE) as one of the main challenges when designing an inverter in their competition. In this competition a very high energy density, 2 kW inverter had to be designed and built. Some of the methods and results from teams that entered this competition are also discussed, to account for current global research and assist in formulating a solution.

III-A. Passive Filtering

Passive filtering is the simplest method of solving the given problem. It entails a large capacitor that is connected over the DC-bus of the inverter. With an arbitrary large capacitance connected, the DC voltage and DC side current will become approximately constant. The challenge with passive filtering is that it requires a time varying voltage over the capacitor to allow energy flow, where the DC bus has to remain within certain predetermined limits [12], [13].

The exact amount of energy that will have to be stored and supplied by the energy storage device can be calculated by integrating the power function for one half cycle as seen in Figure 3 by using Equation (4) below.

$$E_{Buff} = \int_0^{\pi} P_{AC}(t)\, dt \qquad \dots(4)$$

This equation can then be further reduced by performing the integration of the specified area in Figure 3 to yield:

$$E_{Buff} = \frac{P_{avg}}{\omega} \qquad \text{----}(5)$$

This calculated value of E_{Buff} is the energy that is injected and extracted by the passive components according to the laws of conservation of energy.

III-B. Active Filtering

As an alternative to passive filtering, researchers have turned to several different methods of active filtering to manage the double line frequency energy flow. In most of the active filter applications, the buffering capacitor is decoupled from the DC bus with a power electronic converter circuit.

The capacitor is now decoupled from the DC bus, and therefore wide voltage variation of the capacitor can be achieved, while still maintaining very narrow voltage ripple on the DC bus. The figure displays an example of a shunt connected capacitor reduction circuit, although several techniques exist where the circuit is series connected [6], [14].

In this configuration, a much larger part of the energy stored by the capacitor can be utilised by the circuit. This will in turn lead to a much smaller required capacitor for the same amount of energy transferred in a given cycle, and also to smaller volume of the storage capacitor.

III-C. IEEE Inverter Competition

The Little Box Challenge was a competition hosted by Google and the IEEE Power Electronic Society in 2014, and the winners were announced in 2016. The goal of this competition was to build a 2 kW inverter, but about ten times smaller than the current leading technologies.

In this challenge, four main reasons why this goal was not currently possible is presented in the problem statement of the competition. One of the problems was the DC-bus filter as presented in the introduction. All of the teams that made it to the final had to present a short document of how they solved the problem. Even though they are not academic journals, it has been decided it would be very advantageous to see how the current world leading technology solved the problem, and to be able to compare the results of this research and the results of some of the top qualifying teams.

All of the teams used some form of active filter to solve this problem. It seems that most of the solutions incorporate very complicated control to manage the energy flow and the transition conditions.

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