# DESIGN REQUIREMENTS FOR THE VARIOUS TYPES OF CAPACITORS USED IN MODULATORS

*David K Woodburn*
D Woodburn & Co Ltd, Caterham, Surrey, England
*Walter Crewson*
Crewson Engineering, Inc., Ridgefield, CT, USA

**Abstract**

The various types of capacitor used in modulators all have very different design requirements and require differing dielectric characteristics. These capacitors range from the high voltage storage types used in the classical Pulse Forming Network modulator and the newer MOSFET modulators, the types used in the actual PFNs and the newer requirements of relatively low voltage types and IGBT snubbers which are both used in the CLW modulator. These design requirements are discussed in conjunction with the advantages and disadvantages of the different types of modulator.

## INTRODUCTION

The various types of capacitor used in modulators all have very different design requirements and require differing dielectric characteristics. As the capacitors have a critical role to play in the efficient and reliable working of the modulator, attention to their design is of great importance. Often circuit designers regard capacitors as necessary evil devices that take up a large amount of the total volume available in the modulator. They are therefore tempted to use capacitors that were not designed for the job, risking long-term unreliability for the whole modulator. Reliability and long life are paramount and should not be traded for size reduction or cheapness.

Some types of modulator require less sophisticated and others more complex capacitors. The varying design requirements are discussed in conjunction with the advantages and disadvantages of the different types of modulator.

The capacitor parameters that are important are: -

Reliability and life

Capacitance tolerance

Capacitance temperature coefficient

Capacitance voltage coefficient

Inductance of the capacitor

Losses

- Effective Series Resistance
- Dielectric loss and its frequency dependence

Size

- Energy density

Each of these parameters assumes a different degree of importance depending on the circuit requirements and some are mutually exclusive. We therefore need to know in detail the circuit parameters such as: -

Is the application basically DC or are there AC components?

If there are AC components, what is the waveform? In particular, one must consider:

The repetition frequency.

The rate of change of voltage and current

The choice of a suitable dielectric is necessary to fulfil the capacitor parameter requirements listed above. If tolerance is an important parameter we would then not choose a ceramic dielectric as it is very difficult to manufacture such capacitors to close accuracy and they usually have both a high temperature and voltage coefficient. However, ceramic capacitors usually have low dielectric losses (plus the capability of withstanding high temperatures) and are therefore often suitable for RF use. Similarly, polyester film has relatively high temperature capability but its dielectric loss is frequency-dependent. This dielectric is therefore suitable for capacitors that are basically DC. Polypropylene has a lower temperature capability but its loss angle is low and nearly independent of frequency. This dielectric is therefore used in AC and many pulse applications. Mica has great stability, is capable of withstanding very high temperatures and has a very low loss angle over a large frequency range. However, capacitors constructed using mica as a dielectric have an extremely low energy density and, as a result, are large and very expensive.

## 1. CAPACITORS FOR CLASSICAL PULSE FORMING NETWORK MODULATORS

In a classical PFN modulator capacitors can be used as a reservoir in the charging circuit and are used in the PFN for pulse shaping. The design of the two types of capacitor is totally different, as, in the first case, the capacitor is basically a high voltage DC device, whereas in the second they are subjected to pulse operation.

For the reservoir capacitor the dielectric normally used is a mixture of oil-impregnated paper and polyester film. The paper is used between layers of polyester and between the aluminium foil and the polyester to act as a wick allowing oil impregnation of the capacitor element. However, as the insulation resistance of the polyester is several orders higher than that of the oil impregnated paper, nearly all the DC stress falls on the polyester and very little on the paper and the interfaces between the various layers; this means that damaging ionisation is avoided. A typical reservoir capacitor working at, say, 20kV would have four series sections each working at 5kV with the stress on the polyester film approaching 200V per micron. The energy density of such a unit would be around 68 Joules per litre if lifetime is to be several tens of thousand hours. Of course, not all the total volume is taken up by the dielectric, as major insulation to the metal case to be able to hold off 20kV is also required. Furthermore, clearance must be allowed for the HT terminal and this adds to the overall space requirement.

However, the PFN capacitors are totally different as in normal operation; at each pulse discharge, they are subjected to a rapid change of voltage from their working level to around zero or just below zero. The pulse current resulting from these voltage changes is high, as are the component frequencies. It is therefore important to use a dielectric that has a low loss angle over a wide frequency spectrum. Furthermore, the rapid change of voltage means that damaging ionisation within the dielectric layers is a constant problem and it has been found over the years that this can be avoided if the number of capacitor elements in series is high and the energy density low. Typically, a PFN capacitor working at around 20kV would have 20 capacitor elements in series. Each element would use polypropylene and oil impregnated paper as the dielectric; polypropylene is chosen as it has extremely low dielectric losses over a wide frequency range and the losses, in the capacitive part of the PFN, are thus kept to a minimum. However, the trade-off for this is an increase in volume and a very significant reduction in energy density, to a figure as low as 3 Joules per litre for lifetimes of several tens of thousand hours.

This classical PFN modulator, apart from being much larger in volume for a given output power than some of the newer types, has the disadvantage of producing a fixed pulse length that cannot be altered without considerable difficulty. A further complication is the use of a thyratron as the switching device. This component has a relatively short life measured in a few thousands of hours and this can be substantially shortened by damage caused by load arcs.

## 2. CAPACITORS USED IN SERIES SOLID STATE SWITCHED MODULATORS

This title covers several different attempts to bring solid state technology to modulator design with varying degrees of success.

In its simplest form the thyratron in the classical PFN modulator, discussed earlier, is replaced by number of solid state switches connected in series. These switches could be either thyristors or IGBTs. Most attempts have proved that this technique is unreliable and this is mainly because of the problems associated with ensuring that all the switches fire at the same moment and the limitations of dI/dt associated with thyristor turn-on physics. If one switch is slower than all the others, for whatever reason, (or is not triggered at all due to trigger system failure) all the stress will be developed across that one switch which will then, inevitably fail. The problems worsen as the voltage of the required from the modulator is increased and the number of series semiconductor elements increases in proportion.

A technique that may prove to be successful for low power modulators is one that uses MOSFETS in series. These MOSFETS are run well below their rated voltage and are laddered with a network of resistors and capacitors to ensure voltage sharing even if there is some jitter in the switching. The pulse is supplied by a high voltage capacitor, charged to the pulse voltage, and which is then discharged into the load - often a magnetron – with a pulse shaping network on the output. The capacitor used in this type of circuit will typically be required to store between ten and twenty times the energy required in each pulse so that it will only "droop" a relatively small amount from its working voltage during the discharge pulse. It will have to be a relatively low inductance capacitor or, rather the capacitor with its discharge switch bank will have to have relatively low inductance, in order to achieve a fast rising pulse. The design of the storage capacitor for this type of modulator is somewhat problematical as it has to have the high voltage major insulation required to protect the capacitor from flashing over to its case or some other nearby low potential point. The problem arises because space is usually at a premium. This may be overcome by submerging the whole modulator in an oil tank thus allowing clearances to be reduced. But this in itself produces a further problem as having the whole modulator under oil normally means that on-site servicing is not possible. As the whole unit is composed of many hundreds of discrete components failure of some component will be likely to occur and, if the failed part is in a critical position, this will necessitate the whole modulator being removed from service and returned to the manufacturer for rectification.

The capacitor used for this duty would normally be very similar to one used for DC duty but with high pulse current capability and low Equivalent Series Resistance (ESR). The low ESR is needed to keep the losses in the capacitor low when it is being discharged. The high current capability is normally obtained by using multi-tabs or extended foil. Care has to be taken when the modulator is working at high repetition rates to ensure that the capacitor losses (normally series resistance losses) do not cause the whole modulator assembly to overheat. The dielectric would normally be mixed polyester and paper as discussed earlier for the Classical PFN modulators. The stress in the polyester film could be around 200V per micron but the energy density would fall to around 50 joules per litre due to the extra requirement for major insulation. Of course, this would be effectively reduced much further as the capacitor is discharged only by between 5 and 10% of its working voltage at each pulse.

## 3 CAPACITORS USED IN THE NLC AND CLW MODULATORS.

Although these modulators are rather different they both use very similar capacitors. We have therefore combined the discussion of the capacitors required for both these modulators but in order to clarify the requirements, we will first discuss the basics of these two new-concept circuits.

In the NLC modulator the secondary of the pulse transformer is composed of a single tube and is, in effect, a single turn. A very suitable voltage for the current range of IGBT switches is around 1kV. If we assume the output voltage is 200kV we would need a voltage magnification of 200:1 so that the primary will have to be 1/200 turns. One two hundredth of a turn is obviously impractical but this can effectively be achieved by having two hundred individual primary coils each with its own magnetic core. These primaries are all discharged at the same time and the resulting high voltage and high power pulse is used to drive the load tube or indeed tubes. This type of modulator is extremely good for very high power pulses provided they are of short duration. The problem arises when relatively long duration pulses are needed, as the amount of magnetic material required becomes extremely high.

In the CLW modulator the fractional primary-turn concept is achieved by winding many individual primaries on several sections of one core whilst the multi-turn secondary is wound around the whole core. Full details of this modulator will be discussed in the paper to be presented here tomorrow by my colleague Walter Crewson. This modulator can be designed to give long pulses and average power up to around 1MW.

In both these modulators capacitors rated at between 1 and 2kV are charged and then discharged using IGBTs to switch the capacitor current both on and off. These capacitors are discharged into the multi-primaries of the pulse transformer with the load tube connected to the single secondary. As in the previous modulator the capacitors are only discharged by around 5% to 10% of their total voltage but because the total voltage is only up to 2kV, metallised polypropylene is found to be a suitable dielectric. This system has the great advantage that it is self-healing and can therefore be used at very high stress and energy density. Work has been started in the use of these capacitors for producing the fast front edge of the pulse and then switching to a large reservoir bank of electrolytic capacitors for sustaining the pulse when long pulses are required. This technique could substantially reduce the overall cost and size of a long pulse modulator but further research needs to be done. Of course, in both the NLC and the CLW modulator the magnetic core volume to sustain long pulses is increased substantially if saturation is to be avoided.

IGBTs used for this type of duty are working at a fraction of their average power rating but are considered safe to be used at twice their maximum current rating when used for pulse duty provided that their voltage rating is not exceeded. Problems arise when a fault in the load such as arcing occurs. IGBTs have a turn-off delay and during this delay time the large current rise through the IGBT can be damaging and in order to reduce the turn-off (LdI/dt) voltage spike it is essential to fit a snubber capacitor between the emitter and the collector of the IGBT. These capacitors must have very low inductance if they are to work effectively and the diode connected in series with the snubber has to have a very fast turn-on if it is start conducting before damage occurs. Effective snubbers have been designed using metallised polypropylene as the dielectric with strip copper lead-outs to reduce the inductance.

This paper has discussed in general terms the capacitor design requirements for a number of different types of modulator and illustrates the reasons why different dielectrics and techniques are used.