Why do Capacitors Overheat?

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Background

All maintenance people, sales people and engineers will tell a story or two about capacitors overheating. Indeed, sales people from competing companies will relate horror stories of capacitor failures, fires, insurance debacles and general mayhem allegedly caused by capacitor and capacitor-based power factor system failures of one kind or another. Mostly, these stories are wrong, incomplete, or just downright malicious. The fact is that all electrical items have losses and produce heat which has to be dealt with, and it is a sad reality that many designers of electrical systems do not understand all of the design parameters and make allowances accordingly. Once the causes of heat generation are understood then it is a relatively simple process for a competent engineer to deal with them. This technical document deals specifically with heat generated in capacitors and the design steps required to mitigate the risks.

How Capacitors get Hot

There are only two ways a capacitor can get hot:

- Heat generated from inside the capacitor
- Heat generated from outside the capacitor

There is the additional problem of failure of cooling systems such as air conditioning, which affects the capacitor externally (this will be discussed as a further section).

Heat Generated Inside the Capacitor

Heat that is generated inside the capacitor is caused by:

- Internal and ongoing losses in the capacitor cell itself

- Internal losses in the cell terminations inside the can
- Extra losses in the cell caused by overloads

Internal and ongoing losses in the capacitor cell are a function of the cell design, the quality of the raw film used, the cell geometry, the design of the film, and the amount of impurities wound into the cell during the manufacturing process. Nowadays, cell winding is done in a controlled atmosphere 'clean' room and so impurities during manufacturing are quite well controlled. Similarly, by buying films from known good suppliers (European as opposed to Asian), film quality is not a major issue. Further, there are a number of different characteristics of film that various capacitor manufacturers favour, but mostly these are for specific cell behaviours and not for thermal considerations. Examples of these parameters of film are wave cut, reinforced edge, segmented, ramped, double sided, etc. For this document, standard plain film is assumed because it is by far the most frequently used.

Whenever there is an electrical path through which a current flows there are losses, and capacitor cells are no different. A measure of these losses is called equivalent series resistance, or ESR. As the name implies, ESR is essentially a resistance, and whenever there is a current flowing through a resistance, there is heat generated following Ohm's law.

$$\text{Heat}_{\text{watts}} = \text{I}_{\text{amps}}^{\ 2} \text{ x Resistance}_{\text{ohms}}$$

This begs the question: *What affects the resistance (ESR) of the cell?* Every time there is a connection or termination, there is the possibility of raising the ESR through a poor joint. However, by far the biggest input to ESR is the geometry of the cell. It is known that a cell is a continuously wound length of MPP (metallised polypropylene). If the cell is made of 1000 turns of film, instead of thinking of it as a continuous length of film, think of it as 1000 cylinders of film that are joined together at their edges. Any one cylinder will have a specific ESR from top to bottom of the cylinder, determined by the specifications of the film. This will be specified in ohms/metre. This means that a tall cylinder will have a higher ESR than a short cylinder. Working through an example, the ESR for this first cell is a parameter 'R_1'; the ESR for the next cylinder is 'R_2', 'R_3', and so on. There are 1000 of these cylinders, and using the laws of resistance the combined ESR can be calculated:

$$\text{ESR}_{\text{Total}} = \frac{1}{\{(1/R_1)+(1/R_2)+(1/R_3)........+(1/R_{1000})\}}$$

This means that as the number of cylinders increases, the ESR drops. This is the single most important factor in capacitor design because it means that short cells with high numbers of cylinders will generate less heat than tall cells with a lower number of cylinders.

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Short Cells = many Cylinders
Generates LESS heat

Tall Cells =
few Cylinders
Generates
MORE heat

Therefore, if a power factor system designer only did **just one thing** to mitigate heat generation when designing a power factor system, the absolute best choice would be to choose a capacitor vendor offering short and fat capacitors as opposed to tall and skinny capacitors. This is very often overlooked.

Termination resistance is essentially a manufacturing quality parameter. There are terminations/connections from the cell to the safety cut-out unit; from the safety cut-out unit to the capacitor terminals; and of course, there is connection of the MPP film to the ends of the cell. This is a process whereby all the cylinders described above are joined together by a process called 'schooping'. Whilst this is not a simple process, it is thoroughly understood and controllable such that most European capacitor manufacturers have it well managed. Generally, this is not a problem.

Heat Generated Outside the Capacitor

Extra losses or contributing heat loads outside of the capacitor can include:

- ambient air temperature
- heat generated by other items in close proximity
- poor or non-existent air flow
- excess currents drawn due to the presence of harmonics on the supply

It is worth nothing that over-voltage can cause early capacitor failure, but it does not actually contribute to heat generation in any significant way. By choosing capacitors with a high enough voltage rating to cope with spikes and transients, voltage or over-voltage is an easily managed parameter. In general, capacitor voltage rating needs to be 480V as a minimum, with 525V being preferred. There are capacitor vendors in New Zealand and Australia offering 440V rated Power Quality Capacitors – these are not really adequate in today's market.

Ambient air temperature is easily measured and in most applications, easily controlled. Although capacitors are often specified to handle up to 55^{o}C, and sometimes higher, the simple fact is that the lower the operating temperatures are kept, the longer the life of the capacitor. A high ambient temperature can be mitigated to some extent by a high air flow. Rule of thumb would be if the ambient air is going to be above 40^{o}C, further parameters should be considered.

Options include installing air conditioners, designing a very high air flow system, or simply an acceptance of a shorter life of operating components. This is no different to any electrical device and if comparing with an Electronic Power Factor System or SVG, capacitors are rated at a higher operating temperature and certainly produce less internal heat in the first place.

Additional heat generated within the cell caused by things happening outside the cell are almost always initiated by harmonic producing loads that are present on the supply. These harmonic currents are attenuated by using harmonic blocking reactors to reduce the harmonic currents being presented to the capacitor, but nevertheless, a harmonic rich supply will increase the current going into the capacitors and due to ESR, more heat will be produced.

Cooling System Failure

Cooling systems such as air conditioners, inlet and exhaust fans, convection and radiation cooling are all very easily managed and maintained. Further, their imminent failures are able to be predicted by monitoring and measurement. For example, as an inlet filter becomes blocked and the pressure across it consequently changes, it can be measured as well as alarmed. Similarly, air flow can be measured and a protection system designed. Generally, external cooling systems can be designed as to shut the system down in the event of failure. Cooling systems inside the capacitor itself are part of the design of the capacitor and hence are in the hands of the capacitor designer.

Considering where the heat is actually generated, the path that heat travels, and the transfer of that heat to some mechanism that will cool it – the heat is generated inside the cell and somehow has to get to the exterior surface of the can so that cooling air or other heatsink can remove the heat. The heat is generated in the cell, specifically all the way along the current path where the ESR is. It follows that metallisation on the MPP gets hot, as it is the electrical conductor. This heat is linearly generated everywhere the metallisation is present. Considering a wound cell and how heat is generated in the centre of the cell, in order for it to be cooled, the heat has to travel either from the centre out through the radius of the cell to its exterior surface before it can be taken away, or it has to travel along the metallisation to either end of the cell before it can be dissipated. For heat to travel radially, it needs to pass through all the windings of polypropylene which are a thermal insulant. In practical terms, no heat escapes radially. This leaves the heat having to travel along the metallisation (usually aluminium) to the ends of the cell. This is in fact, what occurs in capacitors, as it is far easier for heat to travel along aluminium than through polypropylene. This is supporting evidence as to why a tall skinny cell cannot run as cool as a short fat cell – the heat simply has further to travel (i.e.: the height of the cell). Further, once the heat is at the ends of the cell, it needs to be transferred to something that can take it to the walls of the can (usually made of aluminium), where it will quickly pass through the can wall and be taken away by the atmosphere. In order to transfer from the ends of the capacitor to whatever is the transporter, surface area of the end is a critical dimension, with the greater surface area of the end being much more efficient at dissipating heat. This is yet another reason why short and fat capacitors beat tall and skinny capacitors, always.

Up until about 2000, the majority of capacitors were filled with a vegetable based oil, usually Canola or Castor oil. These oils transfer heat very well and also have a high dielectric breakdown, meaning a long, reliable life. Unfortunately, oil burns, and if there is a leak in the sealing of the capacitor, using oil can be very messy. Various epoxy and polyurethane resins have been tried over the ages but it is only in the last few years that polyurethane resins have been developed to the point that they are now considered as good as oils for thermal transfer, without the issues surrounding burning and leaking. There are some manufacturers that use inert gases to fill capacitors, and on the surface these seem ideal. Nitrogen in particular transmits heat quite well but there are drawbacks. Gases expand when heated and this expanding can falsely trigger the safety over pressure disconnect unit inside the capacitor. The biggest issue is the fact that if there is a leak in the seal, the user does not know because there is no mess (as opposed to oil filled). Furthermore, when there is a leak, the gas leaves and when the capacitor cools down it will draw in surrounding air, laden with moisture and thereby reduce the life of the capacitor. Therefore, good system designers will specify polyurethane resin filled capacitors.

Once the polyurethane resin has taken the heat from the cell to the wall of the aluminium, it is simply aluminium conduction that passes the heat through to the exterior surface. Various techniques can enhance the hand off of heat from the aluminium to the air, such as:

- painting the capacitor black
- ripple effect aluminium (to increase surface area)
- addition of fins (to increase surface area)
- water cooling jackets

All are available for certain applications but mostly not required for normal power factor systems.

<u>Summary</u>

With modern harmonic blocking reactors, high quality capacitors, and careful air flow design, power factor systems can enjoy a long and reliable service life. If a system is not delivering acceptable outcomes, it is probably not well made. This may be by not using quality components but more likely it is underperforming due to poor design. kVArCorrect can most often solve these problems, even on older systems.

<u>About the Author</u>

The opinions expressed here are the researched views of Allan Ramson, General Manager, kVArCorrect Ltd. All claims have been substantiated by testing and observations from the Australasian market between 2007 and 2018. Having been associated with the design, manufacture and supply of many thousands of power factor capacitors and over 500 power factor systems, kVArCorrect are confident that the KBR capacitors are the best capacitors tested and used.