ANALYSIS OF THE PSC MOTOR

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ABSTRACT

The phase capacitor in a PSC motor circuit has been used as a means for both insuring rotation and also starting torque. PSC circuits are used most commonly (in a residence) for blower / air handler fan circuits, and also AC compressors. The presenter has noticed that there are an increasing number of failures of capacitors utilized in PSC circuits. The failures manifest themselves in several ways, including the destruction of the capacitor itself, as well as a fire developing in the motor.

The capacitors typically make use of a polypropylene dielectric with aluminum deposition, as well as zinc which has been applied with the Schooping process. In use, the capacitors that are subject to catastrophic failure as arcs develop in the capacitor and slowly ablate the total area of the capacitor. As the capacitance lessens, the attached motor will dissipate more power, resulting in thermal stress on insulation and more loading on the bearings. The end result is that the motor is more prone to failure IF the capacitor does not completely fail first.

Capacitors subject to this shifting in value have been analyzed by using stereo microscopy, SEM / EDX, FTIR, and CT scan x-ray. We outline here the nature of the dielectric breakdown, the probable cause, and the manner in which a capacitor can be analyzed to determine why it first undergoes parametric changes, followed by catastrophic failure of the capacitor. We note that there are multiple failure modes that can result in capacitor degradation, but the instances cited here were a result of poor circuit design, and not an inherent defect in the capacitor.

THE PSC MOTOR

The PSC (Permanent-Split Capacitor) motor is one of the main motor circuits used in residences and commercial buildings where 3 phase power is not available. A typical circuit for the PSC motor is shown below in Diagram 1.

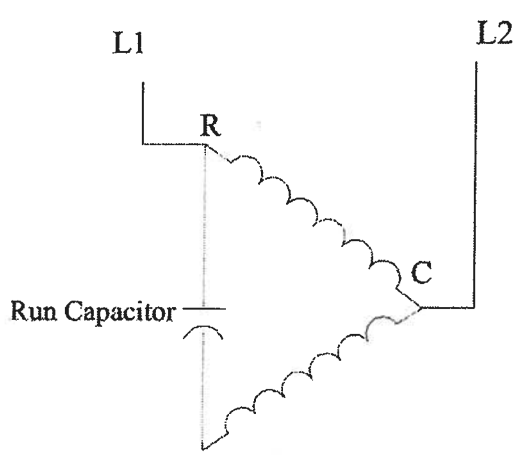
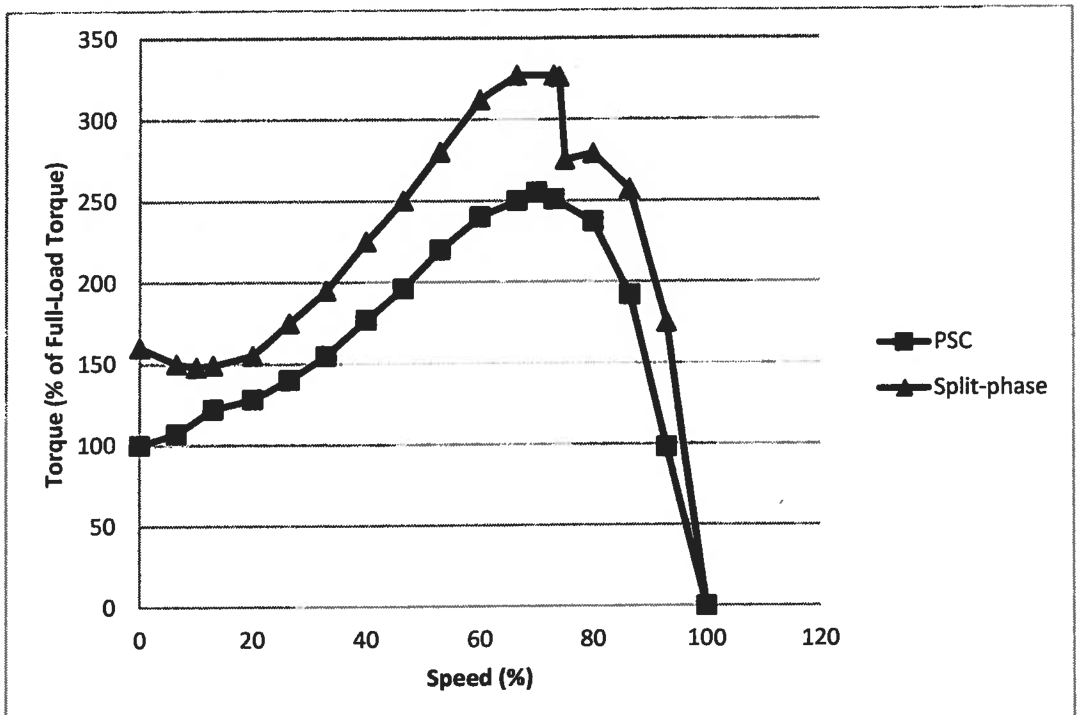


Diagram 1 – Wiring of a PSC motor

Note that by winding both of the windings in bifilar (symmetric) fashion, one can reverse the direction of the motor by changing which side of the capacitor in which the 'hot' lead is fed. This attribute is used by manufacturers of garage door openers and gate openers to change the direction of motion with no change in torque characteristics.

The PSC motor can be thought of as a 'two phase' motor, with the START winding increasing starting torque. However, the torque attributes of the PSC motor, when compared to a capacitor start or split phase motor, are medicore at best. See the torque curve below, in Graph 1.



Graph 1 –Torque-speed curves for PSC and split-phase motors. The discontinuity on the split phase motor occurs when the centrifugal switch changes the motor circuitry.

The low starting torque is one reason that some air conditioning systems require a 'hard start' kit to function. The PSC motor, despite the low starting torque, is probably the most-used motor circuit. It is extremely reliable because it does not require a centrifugal (mechanical) switch that can wear out over time.

Inherent in the proper operation of the PSC motor is a functioning capacitor. Historically, this capacitor has been of the Metallized Film (MF) design. The MF capacitor makes use of poly- propylene film as a dielectric, and aluminum as the plate material. Construction calls for the capacitors to be wound in jelly roll fashion. Zinc is applied to the ends of the roll to make for connections that are low inductance; this zinc application makes use of the Schooping process. A CT layer of the capacitor and the jelly roll are shown below in Photo 1 and 2.

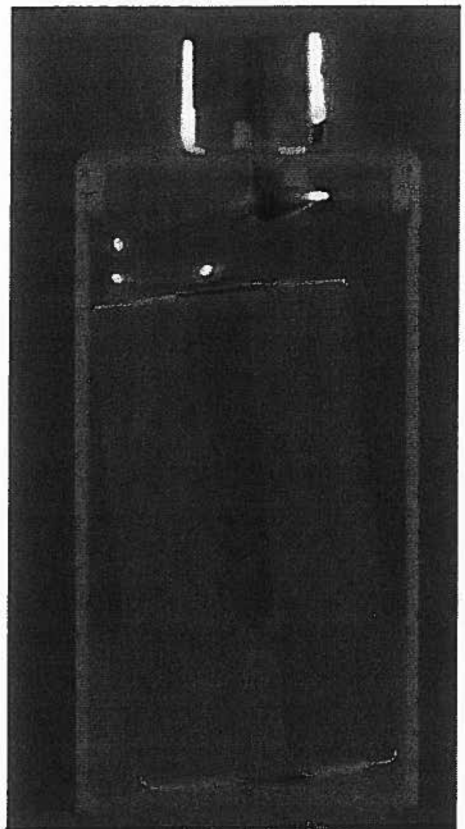


Photo 1 –CT layer of capacitor, frontal plane

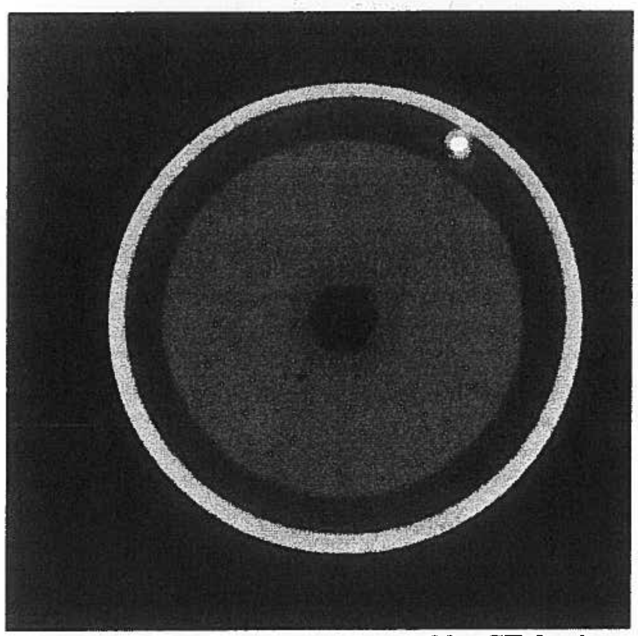


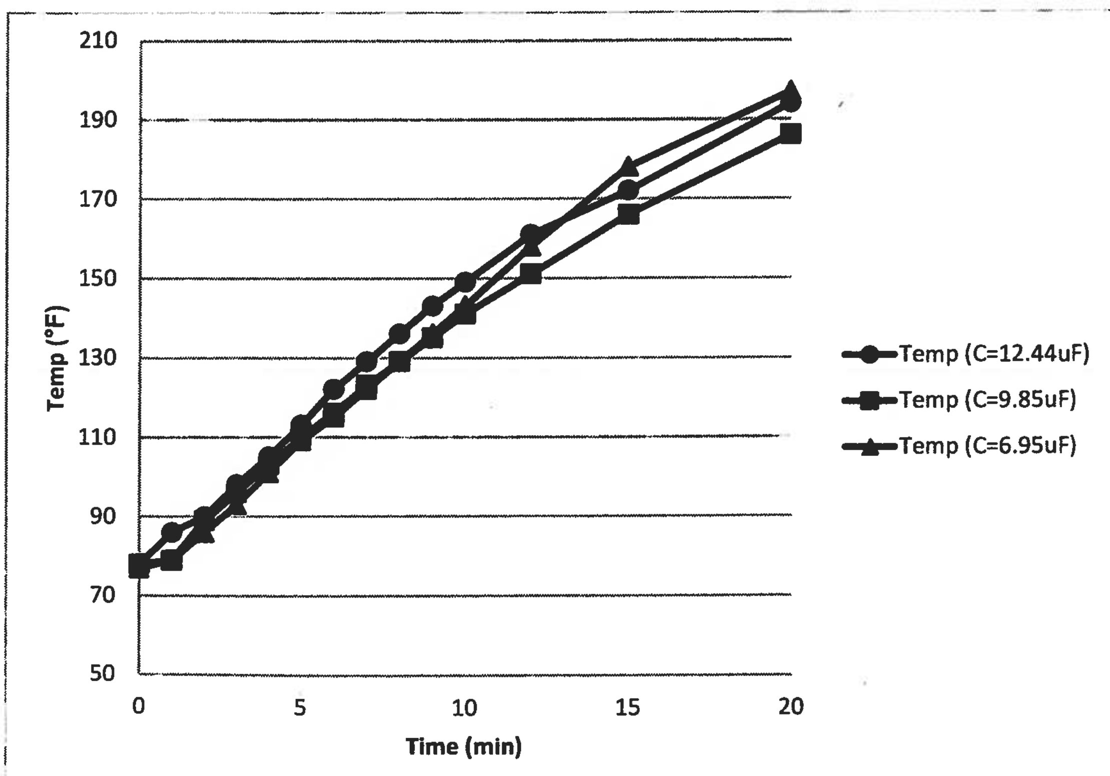
Photo 2 – Layer of jellyroll as reconstructed by CT, horizontal plane

The polypropylene design allows the capacitor to be thought of as 'self healing.' That is to say that a focal failure in the dielectric strength will cause ablation of the 'offending' portion of the metallized plate and dielectric. Per one manufacturer, the capacitor loses about 100 pF of its value after the arc and its subsequent healing have taken place. [1]

THE PROBLEM

The problem, as experienced by this writer, is that some PSC motors are making use of less than quality components. The capacitor can change value over time, resulting in less than optimum running results. Regrettably, this process feeds on itself. As the capacitance shifts, so does the power factor and efficiency. Motor temperatures rise, as does the work the motor must do. This decreases bearing life and also causes higher motor and capacitor temperatures. The higher temperatures then cause a decrease in life in the windings, bearings, and capacitor. The capacitor continues to fail and heal, allowing the motor to continue to run but at further reduced efficiencies. In the end, the shifting capacitance value will bring about a motor that could potentially fail to operate; the worst outcome will be a motor that fails by way of the windings breaking down and the motor catching fire.

Motor lifetime is affected chiefly by two parameters, bearing lifetime and motor winding lifetime. Both are believed to have Arrhenius characteristics. For this reason, we also measured motor temperature as a function of time. A plot of the same motor, using the three different capacitance values, is shown below in Graph 2.



GRAPH 2 – Temperature rise as a function of capacitor value

Motor temperature was measured using a type K thermocouple, placed on the case. Winding temperatures would be higher.

As bearing temperatures increase, the amount of work that the motor must do to overcome these parasitic losses increase. This increased work results in both higher bearing and higher winding temperatures.

It is very common to design PSC motors with some form of thermal overload. Historically, the TI / Sensata 7 AM "Klixon" has fit this application well. The Klixon comes in two separate series, and the difference lies in internal metal resistance. With the 0xx series, the base metal has a low resistance. With the 2xx series, the base metal has a higher resistance. The effect of base metal resistance is that the 0xx series is more sensitive to sensing external heat, while the 2xx series develops some of the heat internally, particularly in a LRA (Locked Rotor Amperage) situation. Despite the presence of properly situated thermal protectors, the protectors cannot protect against 'random' dielectric failures in the windings of the coils. If focal heating develops on a motor, the thermal protector has no practical way of sensing such an event.

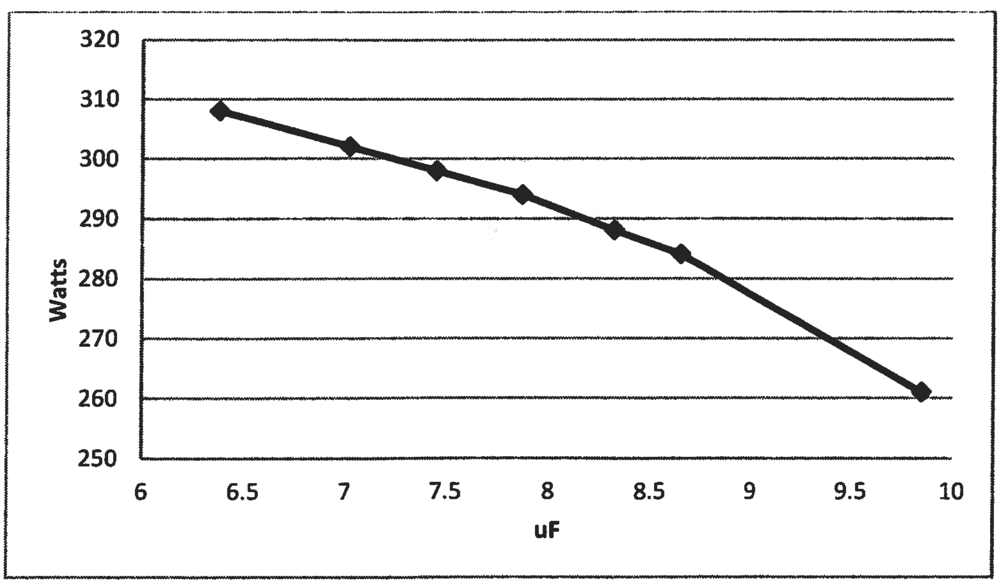
FAILURE ANALYSIS

A number of motors and capacitors were presented for failure analysis. These motors had been used in motion applications, and many had capacitors that were bulged or otherwise damaged. The nominal capacitor rating was 10 uF, while the measured values for six of the units randomly pulled (in descending order) were as follows:

9.97 8.65 8.32 7.87 7.45 7.02 6.38

Capacitance values throughout the paper were taken using a Philips PM 6304 RCL meter.

We were fortunate in this instance that many of the motors were still operational. We found one motor that was like new. We used it and a new 10 uF cap (nominal) as a baseline. We ran the motors at 120V AC (supplied by an Agilent 6813A, programmed for 60 hz). We then measured the power consumption (watts dissipated) of the motor as a function of varying capacitor values. The graph of the capacitor rating vs wattage is shown below in Graph 3:



Graph 3 – Wattage as a function of capacitance

We also took a new motor, and a new capacitor (same lot as other failing capacitors). These values are before and after a 168 hour test, are shown below:

	Before	After
Voltage, volts	120	120
Current, amps	7.28	7.10
VA, volt-amperes	871	850
Watts	252	267
VARs, volt-amperes	834	807
Capacitance	10.03	7.04
Power factor	.29	.32

Table 1 – Motor characteristics at 0 and 168 hours

Clearly the capacitor has changed in value, and this change in value has brought about other parameter changes. The power was a constant 120 VAC, and supplied by the 6813A.

FTIR analysis was conducted on a new capacitor from the same lot. The FTIR showed that the dielectric was polypropylene.

A section of a failed capacitor was examined microscopically with a Meiji stereoscope operating under Nikon software. The photo below shows the amalgam of what is polypropylene and aluminum.

Photo 3: Depicts failed metallization with polypropylene

SEM / EDX (Scanning Electron Microscope / Energy Dispersive X-ray) work made use of a S-3000 Hitachi SEM and an EDAX brand EDX. Metallization was found to be proper.

In that capactor lifetime is thought to have an Arrhenuis function, we measured capacitor temperature. The temperature stayed almost even with room temperature, when operated at both 24 and 40 deg C temperatures; this was no surprise. The temperature rating of the capacitor is 85 deg C. ESR (Equivalent Series Resistance) was measured on both new and degraded capacitors. We determined that the ESR was less than .1 ohm on both 'new' and degraded capacitors. Ergo, the capacitor was not overheating because of an adverse internal resistance issue. Temperature measurements were made on the capacitor's case.

One of the factors we considered in evaluating the capacitor shift is the effect, if any, of Q multiplication. For those unfamilair with classical circuit theory, the 'Q', or Quality Factor of a circuit, is defined as the center frequency (fo) of an LC circuit or banspass circuit, divided by its bandwidth (BW). Or,

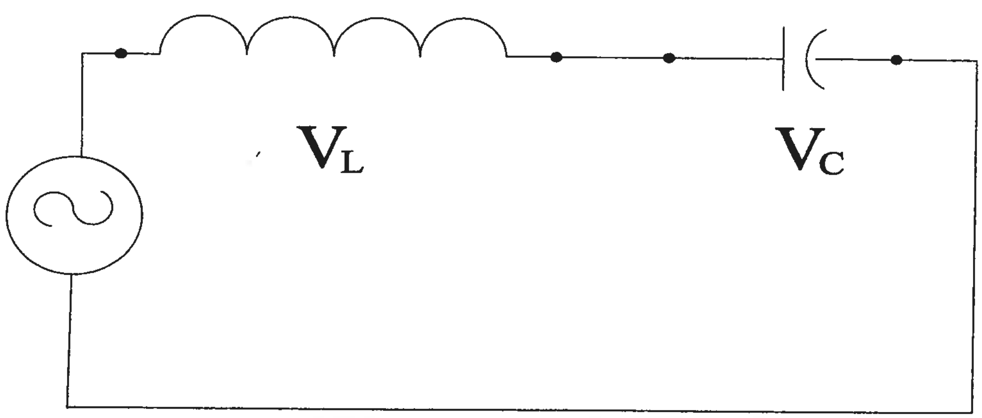
$$Q = f(o) / BW$$

The bandwdth BW of a circuit is the difference (in hertz) of the upper and lower -3 dB points, or where the amplitude of the transfer function has dropped to .707 of its original voltage.

The end result of Q multiplication is that some LC circuits have voltages developed across them that are far in excess of the driving voltage. As an example, consider the parameters of the following series LC curcuit, which is at resonance:

Sine wave frequency, hertz	400
LC center frequency, hertz	400
Sine wave voltage, volts	64
Bandwidth (BW), hertz	30
Q	13.33

Table 2 – Characterisics of a series bandpass filter / LC tank circuit



LC Circuit at resonance with offsetting voltages VL and VC; VL is equal to VC in ampliude, but 180 deg out of phase

The capacitor and inductor will each have a voltage across them of (64 x 13.33), or 853 volts, albeit the voltages add vectorally and substantively cancel each other because they are 180 degrees out of phase. This 853 volts is far in exccess of the 64 volt power supply that is available.

We determined that Q multiplication was the predominant issue in the capacitor degradation. In this case, the driving voltage (power supply) is 120 volts, and the capactor is rated at 370 volts. Measurement of the voltage across the 10 uF (nominal) capacitor yielded a voltage of 430 volts when using a Hewlett-Packard 34401A DMM. An HP 54600 oscilloscope was placed in a 'triggered' mode across the capacitor and the motor was run for four hours, in an attempt to determine if voltage 'spikes' were somehow appearing across the capacitor – none were.

We performed our testing at 120 VAC. For installations where there was a line voltages of 115 volts or so, as well as a small shift off of the nominal 10 uF value, capacitor life would increase dramatically. However, the circuit was operating adjacent to a steep cliff under these 'tolerable' conditions. An increase in line voltage, temperature, or bearing loading would be capable of immediately pushing the motor into a degradation situation.

The end result of this analysis is that poor component selection allowed the capacitor to see adverse conditions. Bearing lifetime decreased, dielectric strength of the motor windings decreased, thermal protectors were found to be cycling in some cases, and windings were experiencing turn to turn arcing; all of these conditions are conducive to creation of a fire.

SUMMATION

We started this failure analysis process by suspecting bad capacitors – and we were partially correct. The self-healing capacitors were gradually degrading, but through no apparent fault of their own. Rather, the design has assumed that a 120 volt circuit would not have node voltages that were in excess of the power supply. The end result was that a capacitor was being weakened and changed in value while it was operating. This in turn caused the motor to work harder, the dielectric strength of the motor windings to decrease, the bearing life time was shortened, and thermal cycling occurred. Each of these was a precursor to a motor catching fire.

ABOUT THE AUTHORS

Mark Goodson holds a BSEE (Texas A&M (1979). He is licensed in both EE and ME, and holds licensure in 13 states. He studied forensic medicine at UTSW- Dallas. He is a consultant to many Medical Examiner offices, as well as public sector agencies. He served as a Court Master for two years. He holds 3 patents on fire safety and has 4 more pending. He was the first PE board member for the State of Texas Eléctrical Board. He has published in excess of 30 refereed articles. His work is centered around electrical shock issues, as well as inadvertent combustion brought on by electrical and mechanical systems. Mr. Goodson is the principal of Goodson Engineering of Denton, Texas.

Lee Green holds a BSME (Oklahoma State, 2003) and two MS degrees in engineering from SMU. He is licsened as a Mechanical Engineer and has licenses in 7 states. He worked as a design engineer at Peterbilt / Paccar for 5 years, prior to joining Goodson Engineering in 2010. He is the author of 3 refereed papers.

ENDNOTES

[1] Vishay Intertechnology, Inc., Doc 13001, 8 March 2010