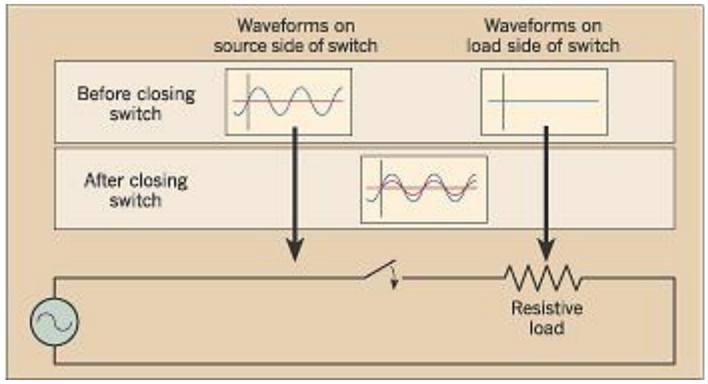
The Trouble With Capacitors Part 1

Dec 1, 2003 12:00 PM, By R. Fehr, P.E., Engineering Consultant

Although shunt capacitors offer several advantages at all voltage levels, those advantages come at a price. Not only must you purchase, install, and maintain capacitor equipment, you must be able to switch it in and out of service to get the most from the system. When load levels are high, a shunt capacitor system is beneficial. When the load drops off, however, the capacitor can do more harm than good. An excess of capacitance in service can lead to higher than desired voltages, excessively leading power factors, and resonance phenomena.

This is why many capacitor banks are designed with switching mechanisms that allow you to connect them to and disconnect them from the system as needed, sometimes even as often as several times a day. While this may seem like a simple proposition, it can lead to problems because switching a capacitor bank is different than switching a normal load. To understand this difference, we first need to understand how an electric circuit is energized and interrupted.



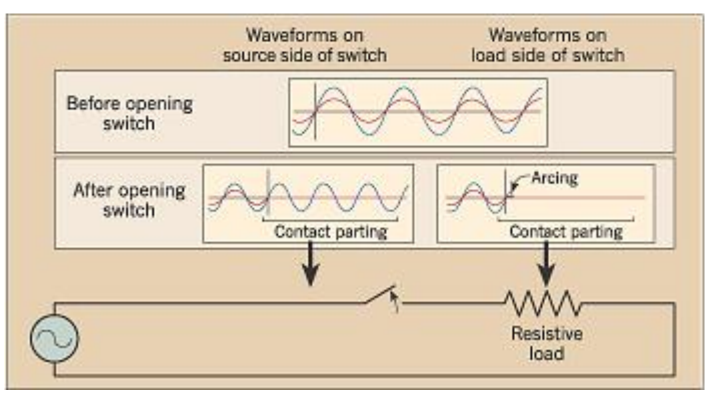
Switching a ‘normal’ load. Energizing a load begins with a switching device in the open position. When the switch is closed, the load is connected to the rest of the energized system and whatever voltage magnitude exists on the switch's source side will be applied across the load at the instant of contact touch. If the load is a pure resistance, this isn't a problem. The voltage across the resistance (shown in blue in **Fig. 1** above) will give rise to a current flow (shown in red) according to Ohm's Law.

Fig. 1 also shows the switch closing just as the voltage waveform crosses zero. This is the preferred time of closing. If the switch closes at any other time, the voltage and current waveforms on the load side of the switch will experience a sudden “jump” or discontinuity. The rapidly rising voltage and current during this transient period adversely affects the system's power quality. (**Part 2** of this article, which will appear in next month's issue, will explore this phenomenon in detail.)

Now let's look at how a resistive load is de-energized. Prior to de-energization, the voltage and current waveforms are in phase. At some point, the switch contacts will begin to separate. It's not physically possible to fully separate the contacts instantaneously because of the inertia associated with the contact masses that must be accelerated. One electrical cycle at 60 Hz has a period of about 16.7 msec. Most mechanical and hydraulic operators will take several electrical cycles to transition the contacts from closed to fully open. This operation, which is slow in electrical terms, will be the root cause of a serious problem.

When the switch contacts begin to open, the dielectric strength of the gap between the contacts is low, since the separation distance of the contacts is small. As the separation distance grows, so does the dielectric strength of the gap. After the voltage waveform crosses zero, its magnitude begins to grow. This voltage that builds across the separating contacts is called the recovery voltage. It may grow more quickly than the dielectric strength across the parting contacts, so current will re-establish through an arc between the contacts.

As the switch contacts continue to separate, the dielectric strength of the gap will quickly exceed the recovery voltage. When the dielectric recovery of the switching device grows more quickly than the system recovery voltage, the arc will extinguish when the current waveform next crosses zero, the current will stop flowing, and the circuit will be successfully interrupted.

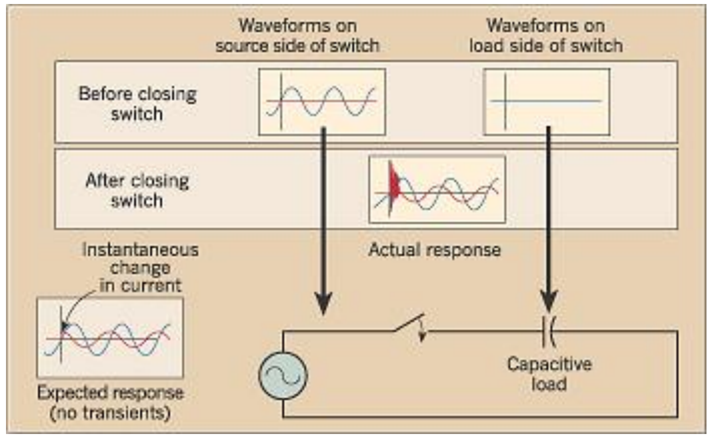


Most switching devices are designed to safely dissipate the energy of the arc. A small transient disturbance will occur to the voltage waveform during the arcing, but this short-lived perturbation is usually insignificant. **Fig. 2** shows the de-energizing process graphically.

Switching a capacitive load.

If the load contains inductance or capacitance, the situation is quite different. The laws of physics state that neither the current flow through an inductor nor the voltage across a capacitor can change instantaneously. In reality, some inductance and some capacitance are present in all circuits, although the values may be very small.

So, what happens when the switch is closed to energize an inductive or capacitive load? In the case of a capacitive load, the current waveform leads the voltage waveform by 90°. If the switch contacts close as the voltage waveform crosses zero, the current would have to instantaneously jump to its maximum value at that time, giving what's referred to as the “expected response” (**Fig. 3**). But an instantaneous change in current isn't physically possible, so instead a very fast — but not instantaneous — change in current that overshoots the maximum value takes place. The peak current inrush magnitude, as defined in the following equation, is a function of the rated capacitor current and the strength of the system to which the capacitor is connected, quantified by the available short-circuit current.



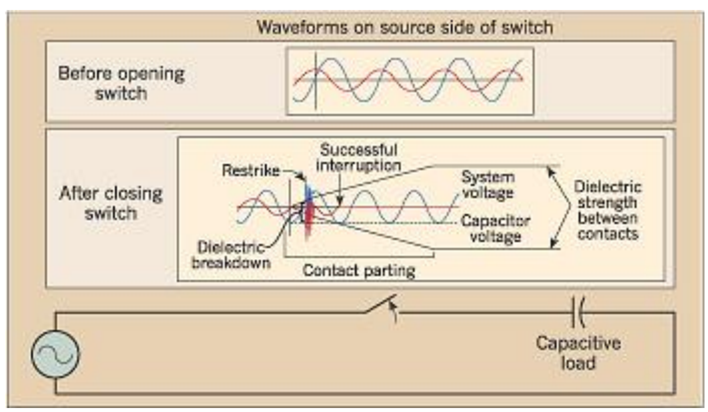
$$I_{inrush\text{-}peak} = \sqrt{2} \times \sqrt{I_{SC} \times I_{CAP}}$$

The differential equation that describes this case has a solution that contains an exponentially damped sinusoid. This transient decay occurs at a frequency much higher than the power system frequency, typically in the kilohertz range. This frequency is determined by the same parameters that defined the peak inrush current and is described by the equation below.

$$I_{inrush\text{-}peak} = f_{system} \times \sqrt{\frac{I_{SC}}{I_{CAP}}}$$

As the current rapidly increases, the voltage rapidly decreases, following Ohm's Law. The voltage and current waveforms oscillate, or ring, at a frequency much higher than the power system frequency. After a short period of time, the waveforms then settle down to their steady-state values, as expected. Graphically, energizing a capacitor looks like the “actual response” labeled in Fig. 3.

De-energizing a capacitive load poses even more challenges. Because the current waveform leads the voltage waveform by 90°, the current is interrupted very close to its zero crossing when the voltage is at its maximum absolute value. Looking at **Fig. 4** on page 20, the initial current interruption occurs at the y-axis. At that time, both the system voltage and the voltage on the capacitor are at their maximum negative values. As the contacts open, the charge that maintains the capacitor voltage is trapped in the capacitor, thus keeping the capacitor voltage constant at its maximum negative value. The capacitor voltage is shown as a dashed black line in Fig. 4. According to IEEE Standards 18-2002 and 1036-1992, the trapped charge in a power capacitor must dissipate such that the voltage on the capacitor is no more than 50V 5 min. after de-energization. This voltage decay is very slow compared to the timeframe discussed in this article, so it's necessary to consider capacitor voltage while de-energized to be constant, as shown by the horizontal dashed black line in Fig. 4.



As the contacts in this example continue to separate — a process that will take about three electrical cycles or 50 msec at 60 Hz — the dielectric strength of the gap between them increases in a fairly linear fashion, as shown by the solid black line in Fig. 4. But the voltage difference across the contacts, which is the difference between the sinusoidal system voltage and the constant capacitor voltage, increases more quickly. At the restrike point the voltage across the parting contacts exceeds the dielectric strength of the gap between the contacts. This will cause an insulation breakdown, which will result in an arc that re-establishes current flow. This re-establishment of current flow occurs after a quarter of a cycle of initial interruption in the example. Thus, this re-establishment of current flow is called a “restrike.” Had the restrike occurred in less than a quarter of a cycle after initial interruption, it would have been called a “re-ignition.”

When the current is re-established, it becomes a high-frequency, exponentially decaying sinusoid. The high-frequency current oscillations give rise to high-frequency voltage fluctuations, similar to that of the capacitor energization case. Resistance present in the system quickly damps these oscillations.

At the next current zero, the arc will be interrupted again, but this time the contacts will be farther apart than during the first interruption attempt, thereby providing a greater dielectric strength between the parting contacts. At the second interruption attempt in the example, the dielectric strength between the parting contacts, which are still at less than half of their ultimate separation distance apart, will slightly exceed the voltage difference across the opening contacts. This will allow a successful current interruption. In some cases, a second restrike would occur at this point, and successful interruption would have to wait until the third attempt.

A capacitive switching device must be designed to endure the thermal stresses caused by the re-ignitions and restrikes. Some circuit breakers fail to meet this level of performance. This is why switching devices used for capacitor switching must be designed specifically for that application. In many cases, such devices have a higher transient recovery voltage rating than general-use circuit breakers. This makes the slope of the solid black lines labeled “dielectric strength between contacts” in Fig. 4 steeper, which reduces the probability of re-ignitions and restrikes.

Part 2 of this article will examine the detrimental effects capacitor switching has on the rest of the system and discuss the methods of minimizing them.

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Sidebar: Why We Use Capacitors

Capacitors have many uses in electric power systems. When used as sources of reactive power they're connected line-to-neutral, or in shunt. These shunt capacitors, which are often called “power factor correction capacitors,” are used at all voltage levels.

At the transmission and subtransmission levels (above 34.5kV), shunt capacitors increase the power transfer capability of a transmission system without requiring new lines. Due to the high cost, long lead-time, and problems associated with transmission line construction, utilities use high-voltage capacitors today more frequently than ever.

High-voltage shunt capacitors also support the transmission system voltage, which is often necessary when the transmission grid is pushed to and perhaps beyond its design limits as a result of open access to the grid and decreased capital spending on network upgrades. Since the capacitors produce reactive power (VARs), generators no longer need to produce as much, enabling them to operate at higher power factors and produce more real power (watts). Also, fewer VARs transported through the transmission system not only frees additional capacity on the lines for watts, but also reduces system losses by reducing the total current flowing on the lines.

Shunt capacitors also slightly increase transmission bus operating voltages. As the transmission voltage increases, less current is necessary to supply a typical load, so transmission losses decrease again.

Utilities use shunt capacitors at distribution and utilization voltages to provide reactive power near the inductive loads that require it. This reduces the total current flowing on the distribution feeder, which improves the voltage profile along the feeder, frees additional feeder capacity, and reduces losses. In fact, substation transformers experience lower loadings when utilities install sufficient capacitors on the distribution system. The reduced loadings not only improve contingency switching options on the distribution system, but also extend equipment life and defer expensive additions to the system.

The Trouble With Capacitors Part 2

Jan 1, 2004 12:00 PM, By R. Fehr, P.E., Engineering Consultant

Here's how to reduce the effect of capacitor switching on your power system

Last month's article discussed exactly what happens when electric utilities switch shunt capacitors: power system components are exposed to transient voltages and currents produced by energizing and de-energizing these devices. Those transients may be short-lived, but they have high peak values and frequencies much greater than the power system fundamental frequency. Now it's time to investigate the effects these transients have on your power system.

Negative effects aplenty. When an electric utility or end-user energizes a shunt capacitor, the high-frequency switching transients produce overvoltages on the capacitor bus. These overvoltages may be significant enough to cause arrester operation or even equipment failure. However, these overvoltages aren't always localized. Since the transients have a frequency much higher than the power system frequency, the system behaves much differently when subjected to these high frequencies than it does with the normal power system frequency.
Transient high voltages can often show up a considerable distance from the capacitor bus due to resonance-like conditions caused by the switching transients. Fast transient overvoltages, which occur as the transients pass through transformers and are magnified due to capacitive coupling, are symptomatic of this condition. Open-circuited lines also contribute to overvoltage conditions by reflecting the traveling transient voltage waveform back to the source, where it can add to the standing voltage waveforms and produce high-voltage surges.

De-energizing a shunt capacitor can also cause power quality problems due to the transient overvoltages produced by re-ignitions and restrikes during the current interruption process. Because of the increased probability of excessive arcing in the switching device during current interruption, the likelihood of switching device failure increases significantly during the de-energization process.

In both the energizing and de-energizing cases, equipment very near or at significant distances from the capacitor location will be subject to voltage stresses that could result in insulation failure. Surge arrester operation and failure are also more likely to occur during capacitor switching than under steady-state conditions.

High-frequency transients at the capacitor location often introduce electrical noise into control circuits, which can lead to equipment misoperation. Even nuisance tripping or damage to devices is possible. A ground potential rise during the transient period can cause system protection misoperation and even pose a safety hazard to personnel working nearby if grounding is inadequate. These effects are potentially serious and must be counteracted in some way.

Double trouble. To further complicate the situation, two or more capacitor banks located close to one another make the situation worse. These negative effects of the transient become extremely severe in the vicinity of the capacitors for several reasons.
The transients produced when a shunt capacitor is energized in the vicinity of an already-energized shunt capacitor are much more severe than those produced when a single isolated capacitor is switched. It's very important to understand this phenomenon, which is called back-to-back switching, to avoid the negative consequences.

The zero voltage that occurs at the moment of contact closure when the second capacitor is energized makes it appear to the system as a short circuit. This apparent momentary short circuit will cause any energized capacitor nearby to discharge into the second capacitor. In addition, the two capacitors in parallel appear as a larger equivalent capacitance rather than one capacitor alone, making the inrush current magnitude much larger than for a single capacitor. The inductance of the system between the two capacitors, L_{eq}, is the quantity that limits the inrush current. Back-to-back induction can be found with the following equation:

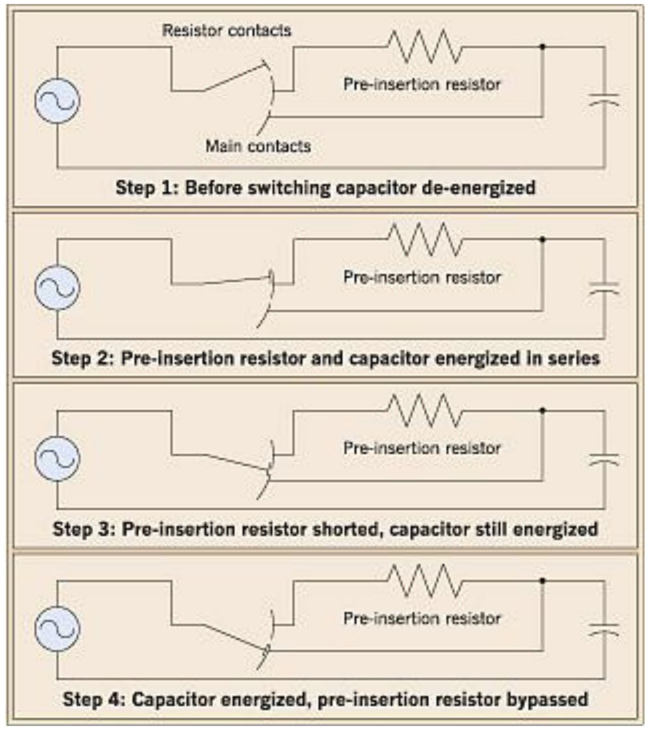
$$I_{Peak\ (Back\ to\ back)} = 1.75\sqrt{\frac{kV_{L\text{-}L} \times I_{cap1} \times I_{cap2}}{L_{eq}\ (I_{cap} + I_{cap2})}}$$

This higher inrush current has a frequency much higher than the inrush current for a single capacitor. Both the magnitude and the frequency of the inrush current during back-to-back switching are typically an order of magnitude larger than those seen when energizing a single capacitor. The frequency of the inrush current can be hundreds of times greater than the power system frequency, f_s, as shown in the equation below:

$$f_{Back\ to\ back} = 9.5\sqrt{\frac{f_s \times kV_{L\text{-}L} \times (I_{cap} + I_{cap2})}{L_{eq} \times I_{cap1} \times I_{cap2}}}$$

Reducing the effects of capacitor switching. You can use one of several methods to reduce the problems associated with capacitor switching, including equipping circuit breakers with pre-insertion resistors, outfitting circuit switchers with pre-insertion reactors, or tightly controlling the point on the waveform when the capacitors are actually switched.

Pre-insertion resistors. One technique involves breaking the switching operation into a multi-step process and inserting a temporary impedance into the circuit during one of the steps. This approach breaks one large transient into two or more smaller ones. Circuit breakers can be built with internal pre-insertion resistors to reduce the magnitude of switching transients. These resistors, typically in the 100-ohm to 400-ohm range for single, extra-high voltage (EHV) capacitors, are in series with the interrupter when the contacts close, but remain in the circuit just long enough to damp the transients, usually for ½ to 1 cycle. After that time, they're shorted out with a make-before-break connection between the resistor contacts and the main contacts, and remain out of the circuit until the next time the breaker is closed. This process is shown schematically in **Fig. 1**.



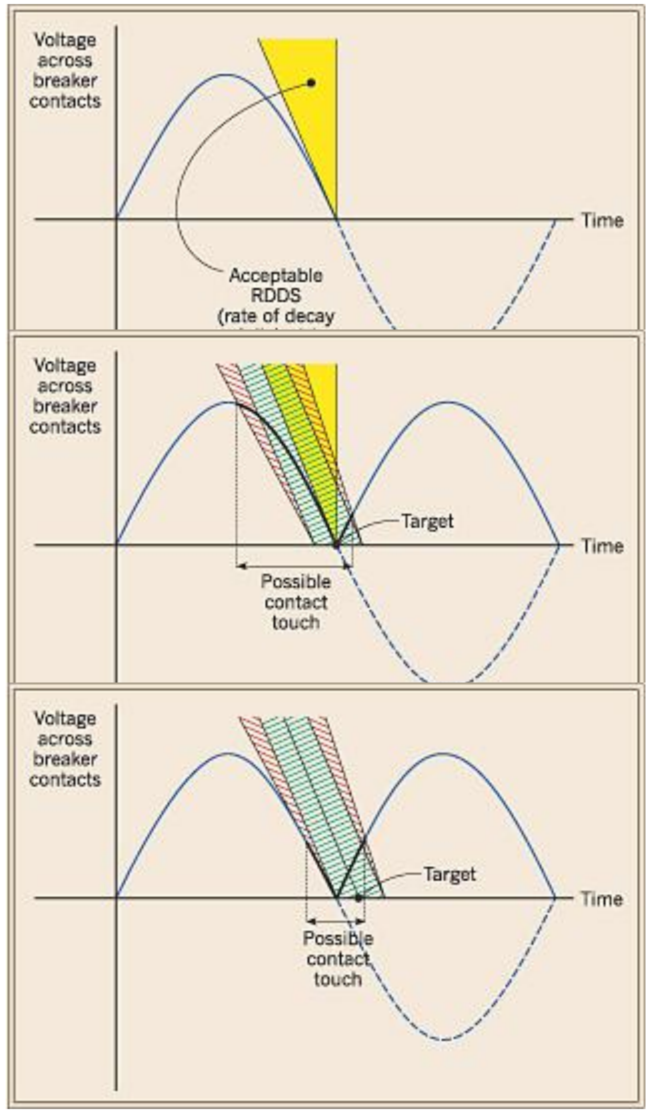
Pre-insertion resistors add both complexity and cost to a breaker. They're also another item that requires scheduled maintenance. While pre-insertion resistors reduce transients during capacitor energization, they're not used when the capacitor is de-energized, so those transients go unabated during that form of switching.

Pre-insertion reactors. Circuit switchers can be outfitted with pre-insertion reactors to reduce transients when closing into capacitive loads. These reactors, which are small air-core inductors typically in the 10-millihenry to 40-millihenry range, are mounted externally on the switcher. When the switcher closes, a spring-loaded contact blade swipes over a reactor contact, energizing the reactor in series with the capacitor when it touches the reactor contact. The reactor remains in the circuit while the blade swipes across the reactor contact, usually for about seven to 12 cycles, depending on the system voltage. The blade keeps moving past the end of the reactor contact, at which point a make-before-break connection is made with the main contact. The blade comes to rest on the main contacts, which keeps the capacitor in the circuit, but bypasses the reactor. The brief period while the reactor is in series with the capacitor is sufficient to dampen the energization transients.

Schematically, this process is identical to the pre-insertion resistor switching process shown in Fig. 1. While less expensive and probably more reliable than pre-insertion resistors, pre-insertion reactors are complicated, require careful alignment and adjustments, and are rather exciting to watch as they arc and spark when operated.

Point-on-wave switching. In the '80s, a different approach to managing capacitor switching transients began to emerge. Instead of electrically modifying the system with resistors or reactors to reduce the effect of the switching transients, engineers left the system as is but addressed the transients themselves. By precisely controlling where on the voltage waveform the contacts touch, it's possible to greatly reduce the magnitudes of the switching transients. This approach, called controlled switching or point-on-wave switching, is used extensively throughout the world not only for switching capacitors, but also for switching shunt reactors, energizing transformers, and even switching transmission lines.

Here's how it works. As the voltage difference across an open circuit breaker increases during closing, the dielectric strength of the gap between the open contacts decays. It's possible to measure a breaker's pre-strike voltage in relation to the time of contact touch. Graphing these measurements approximates a line whose slope represents the rate of decay of dielectric strength (RDDS). For a breaker to be a suitable capacitor-switching device, its RDDS must exceed the rate of the system voltage change. **Fig. 2** shows the acceptable RDDS region.



Ideally, the capacitor should be energized when the voltage across the breaker contacts is zero to minimize switching transients. Consider the zero crossing on the voltage waveform, which is our point-on-wave "target" for contact touch. **Fig. 3** on page 22 shows a green shaded region that depicts the range of mechanical scatter for a particular circuit breaker. The purple shaded region shows the range of dielectric scatter for the same circuit breaker (**Sidebar** below). Since the scatters are additive, contact touch can occur anywhere along the black portion of the voltage waveform.

This possible contact touch time window is skewed considerably to the left of the target, indicating a high probability of circuit completion prior to the zero voltage crossing. Early completion of the circuit will result in pre-striking, which will produce severe transients. This situation can be avoided by slightly retarding the point-on-wave target to just after the zero crossing, as shown in **Fig. 4**. This delay increases the probability of contact touch at the zero crossing.

Another benefit of controlled switching is, unlike the transient mitigation methods discussed earlier, you can use it for capacitor de-energization. The precise timing of each pole is controlled by a microprocessor. The software controlling the timing can be adaptive to adjust for physical and environmental variables, thereby reducing some of the uncertainties represented by scatter. Over the years that controlled switching has been used, the control methods have become much more sophisticated than those used by the first controllers.

Controlled switching is complicated greatly by the mechanical limitations of the circuit breaker. Even with contact speeds in excess of 10 m/sec, transient recovery voltage characteristics of some circuit breakers aren't adequate for some capacitor switching applications. Mechanical and dielectric scatter can lead to a switching performance that's considerably less than optimum performance. One way to avoid these problems is to replace the mechanical circuit breaker with a solid-state switching device.

Solid-state electronics don't solve all the challenges involved with controlled switching. In fact, they tend to exchange one set of problems for another. They do, however, appear to be a viable technology for capacitor switching, particularly at low and medium voltages. Solid-state switching eliminates mechanical scatter, reduces dielectric scatter, and can almost do away with inrush and the associated harmonics during capacitor switching.

Because the current leads the voltage by 90°, the anode-to-cathode voltage of the switching device is reverse-biased for ¼ of the cycle while the current direction is from anode to cathode. This means that self-commutating devices like thyristors must be provided with a gating signal through the full 360° to ensure full conduction. Semiconductor switches used in capacitive switching applications must also endure high peak inverse voltages (PIVs) in excess of 3.5 times the line-to-line voltage. This is because the charge trapped in the capacitor when the switch commutates off holds the absolute value of the capacitor voltage at peak while the system voltage continues to oscillate. This condition exposes the switch to full peak-to-peak voltage, which is 2.83 times the rms voltage. When you allow for tolerances in system voltage and a reasonable safety factor, this PIV requirement can exceed 3.5 times the line-to-line voltage. These requirements lead to high cost components and implementation challenges at the higher voltages. However, as power electronics continue to evolve, these challenges are sure to be conquered.

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Sidebar: Circuit Breaker Mechanics

The stored energy system that moves the movable contact when the breaker's trip or close coil is energized is made up of springs or hydraulic components. The spring has a spring "constant" that determines the contact velocity that will be attained upon opening. However, this spring constant tends to vary slightly with the spring's temperature, age, and the amount of time it was in its compressed state. The performance of the hydraulic system also varies somewhat with temperature, pressure, and the condition of the hydraulic fluid. These variables lead to slightly different operating characteristics each time the breaker operates. Upon statistical analysis of these variables, it's possible to determine a probabilistic distribution of operating speed. This range of mechanical performance is called mechanical scatter.

Likewise, the insulating medium that surrounds the contacts, usually sulfur hexafluoride gas (SF_6) or a vacuum chamber for modern medium- and high-voltage breakers, tends to have slightly different electrical properties under different operating conditions. The number of operations performed by the interrupter, the purity of the dielectric medium, the pressure in the interrupter, and temperature of the dielectric medium are the major variables that affect the electrical properties of the dielectric. More importantly, the condition, namely the surface roughness, of the interrupter contacts and the surrounding dielectric materials, such as gas porting nozzles, influence the electric field distribution within the interrupter. It's also possible to statistically analyze these variables and develop a dielectric scatter. Smooth contact surfaces and clean porting nozzles are vital for successful capacitor switching.