"Reactor Switching and Reactor Switching Devices"

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Abstract

The use of shunt reactors has proven to be an effective method of reducing overvoltages that can occur on lightly loaded transmission and sub-transmission lines thus improving the system power flow and efficiency. Switching reactive loads produces voltage transients and chops currents which can damage the reactor, the switching device, or other adjacent components. This paper presents an overview of application considerations when switching reactors as well as an overview of the various devices commonly used and their advantages and disadvantages.

Introduction

Shunt reactors are utilized as a tool to maintain reactive power balance on systems with medium to long transmission lines, particularly on long, lightly loaded lines. An optimum transmission line would allow all real power generated to be consumed by the line's load (Power Factor of Line = 1). But in reality, when power is transmitted over long lines, that the characteristics of the conductor are a factor in making this difficult to realize.

The major characteristic parameters of a line are impedance (resistance plus inductance) and the shunt capacitance (due to the electrostatic field to earth). An equivalent diagram for a line is show in Figure 1. When the line is energized, but lightly loaded, there is a voltage rise along the line (Ferranti-effect), due to the series impedance of the line and the shunt capacitance to earth. To maintain voltage under this condition, shunt reactors are typically applied at the ends of a line to absorb reactive power and keep the voltage amplitude and phase angle as close as possible to the voltage amplitude and phase angle present at the beginning of the line. When the line inductive load increases, the shunt reactors must be removed from the line. This results in the reactor being switched relatively frequently.

Because of its' specific purpose design, the reactor inductive current is small (generally less than 300 Amps) which makes it very easy for modern SF6 breakers to interrupt. This increases the likelihood of current chopping, which can result in unwanted overvoltages, and reignitions which can damage the insulation of the reactor and cause premature failure of the switching device.

A comparison of switching devices currently applied in this application is the main subject of this paper.

Shunt Reactors – Understanding the Benefits

To understand the effect of adding shunt reactors at the end of a transmission line, it is useful to look at an example of a lightly loaded line with no reactive power compensation and one with shunt reactors added at the ends of the line.

In both cases, the transmission line is a 345 kV line and is 124 miles long. The first example shows an uncompensated line where the second example includes shunt reactors that provide 75% compensation.

V_S = sending end voltage
V_R = receiving end voltage
Z = line impedance
I_S = sending end current
I_R = receiving end current
Y = capacitive coupling to earth

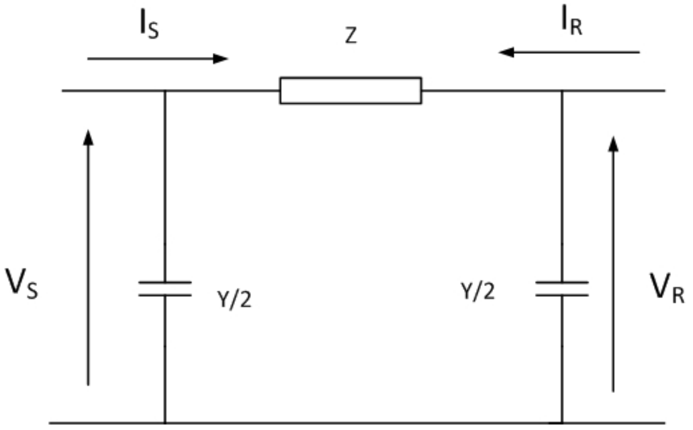


Figure 1: Transmission Line Equivalent Circuit (uncompensated)

Using Kirchhoff's Law the following equation can be created:

$$Vs = Vr + Z\left(Ir + \frac{Vr * Y}{2}\right) \qquad Is = Ir + \frac{Vr * Y}{2} + \frac{Vs * Y}{2}$$

$$Vs = \left(1 + \frac{Y * Z}{2}\right) Vr + Z * Ir \qquad Is = Y\left(1 + \frac{Y * Z}{4}\right) * Vr + \left(1 + \frac{Y * Z}{2}\right) * Ir$$

This allows us to calculate Vr as follows:

$$\begin{bmatrix} Vs \\ Is \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} Vr \\ Ir \end{bmatrix}$$

$$A = D = 1 + \frac{Y * Z}{2} \text{ (per unit)} \qquad B = Z\ (\Omega) \qquad C = Y\left(1 + \frac{Y * Z}{4}\right) \text{ (s)}$$

Since the line is lightly loaded the effect of $Z * Ir$ is negligible and can be ignored. This allows us to calculate Vr under a no load condition using the equation:

$$Vr = \frac{Vs}{A}$$

Example 1: Uncompensated Transmission Line – 362 kV, 125 miles long

$z = 0.515 + j0.563$ (Ω/mile)
$y = j6.76 * 10^{-6}$ (S/mile)

	Real	Imag	Units
z	0.0515	0.563	ohm/mile
y	0	6.76E-06	S/mile

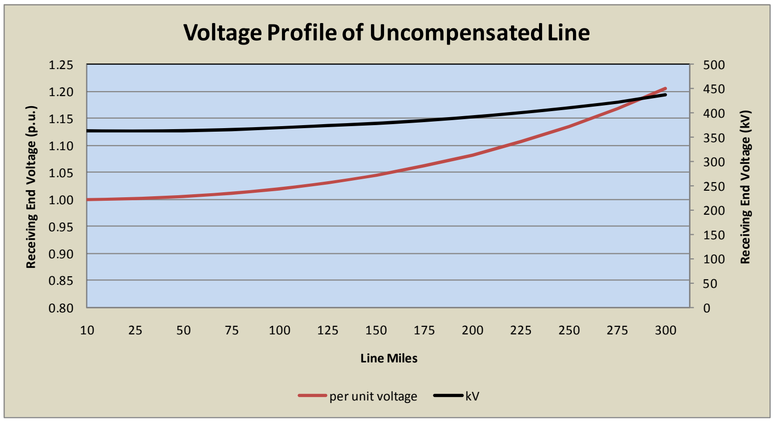
Using the equations above, we can calculate that the no-load receiving end voltage is:

Compensation	0%

$$Vr = \frac{362\ kV}{A} = \frac{362\ kV}{.9703} = \mathbf{373.1\ kV}$$

	Magnitude	Angle (deg)	Real	Imag
Z	70.67	84.77	6.4375	70.375
Y	8.5E-04	90.00	5.17625E-20	0.000845
Y*Z/2	2.99E-02	174.77	-0.02973344	0.00271984
Y*Z/4	1.49E-02	1.91E+03	-0.00446501	0.01424543
1+Y*Z/4	0.996	0.82	0.99553499	0.01424543
A = D =	0.9703	0.161	0.970266563	0.00271984

As the line length increases voltage regulation becomes more important.

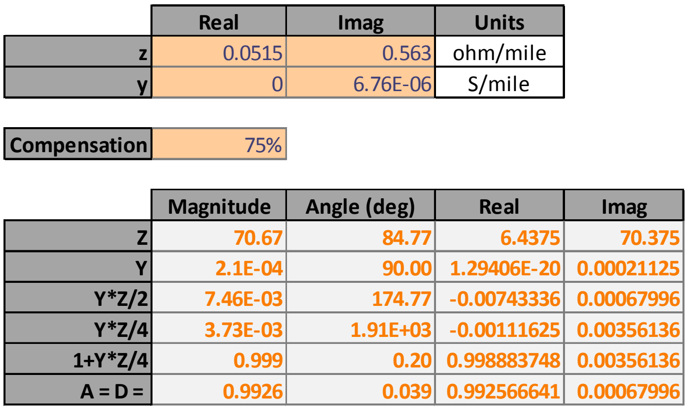


<u>Example 1: Transmission Line with 70% Compensation – 362 kV, 125 miles long</u>

$z = 0.515 + j0.563$ (Ω/mile)
$y = j6.76 * 10^{-6}$ (S/mile)

Using the equations above, we can calculate that the no-load receiving end voltage is:

$$Vr = \frac{362\ kV}{A} = \frac{362\ kV}{.9926} = \mathbf{364.7\ kV}$$



	Real	Imag	Units
z	0.0515	0.563	ohm/mile
y	0	6.76E-06	S/mile

Compensation	75%

	Magnitude	Angle (deg)	Real	Imag
Z	70.67	84.77	6.4375	70.375
Y	2.1E-04	90.00	1.29406E-20	0.00021125
Y*Z/2	7.46E-03	174.77	-0.00743336	0.00067996
Y*Z/4	3.73E-03	1.91E+03	-0.00111625	0.00356136
1+Y*Z/4	0.999	0.20	0.998883748	0.00356136
A = D =	0.9926	0.039	0.992566641	0.00067996

Switching Shunt Reactors

Shunt reactor switching is a difficult duty for the switching device. Shunt reactors carry a small current, typically less than 300A, which is easy for SF_6 interrupters to interrupt. The difficulty that comes with easy interruption is that if the interruption occurs before there is adequate contact gap the interrupter is likely to suffer a **reignition**. Because of the small inductive currents being interrupted, the switching device will interrupt the current at the first current zero after the contacts part. In most cases, the interrupting medium has not recovered sufficiently and the contact separation is still too small to withstand the recovery voltage that appears across the contacts. In this case a reignition of the arc occurs and the voltage across the reactor will rapidly assume the value of instantaneous voltage on the line side. The frequency of this recovery voltage can be several hundred kHz.

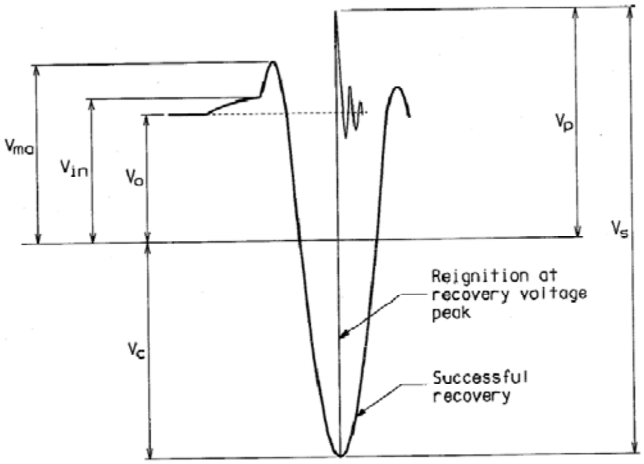


Figure 2: Interrupter Reignition (IEEE Std C37.015-1963)

The reignition creates a complex interaction between the switching device and circuit, releasing energy stored in the reactor inductance, causing electromagnetic transients that lead to switching overvoltages with high rates of rise. In many cases the reignition contains low energy. In these cases the current continues to flow and on the next opportunity to interrupt, current zero, the interrupter successfully interrupts the current. On the other hand if the interrupter suffers a high energy reignition the high rate of rise and overvoltages can damage and fail the interrupter by damaging the nozzle or contacts. This high rate of rise, for the overvoltage also puts the reactor in jeopardy resulting in turn to turn wiring damage in the reactor leading to eventual reactor failure.

Several reignitions may occur before the arc is finally extinguished due to the high frequency of the recovery voltage that results in a very steep slope, narrowing the time between current zeros. Since a shunt reactor is often switched daily, the repeated high magnitude *reignitions* that occur can result in premature interrupter (nozzles and contacts) or reactor failure. Devices used for shunt reactor switching need the ability to mitigate reignitions and current chopping.

The kind of damage that can be expected in SF_6 interrupters includes nozzle punctures, arcing over insulating surfaces and damage to contacts. This kind of damage will eventually render the interrupter ineffective and it will completely fail to interrupt and require that a back up breaker clear the fault. The interrupter switching the reactor will have to be rebuilt or replaced.

The damage that can happen to a reactor is much more costly. The turn to turn overvoltages can cause dielectric failures in the windings shorting out windings. This will generally lead to overheating and the end of the life of the reactor.

Current chopping is another problem that can result from shunt reactor switching. Arc instability may result in a negatively damped current oscillation superimposed on the load current (Fig 3), resulting in the interrupting device trying to clear at a forced current zero *(current chopping).* The instability forces the voltage to change very quickly reaching a current zero and extinguishing the arc at the wrong point on the current wave leaving energy stored in the inductor. This energy creates a very high transient recovery voltage following current interruption equivalent to the sum of the peak voltages of the source and overvoltage initiated by the current chopping. Recovery Voltages with frequencies up to 5 kHz are commonly experienced during current chopping events. This condition causes overvoltage conditions in the reactor that can cause turn to turn damage in the reactor. When the voltage flips, the interrupter is likely to be in a condition that will cause a reignition to occur, causing the damage described previously.

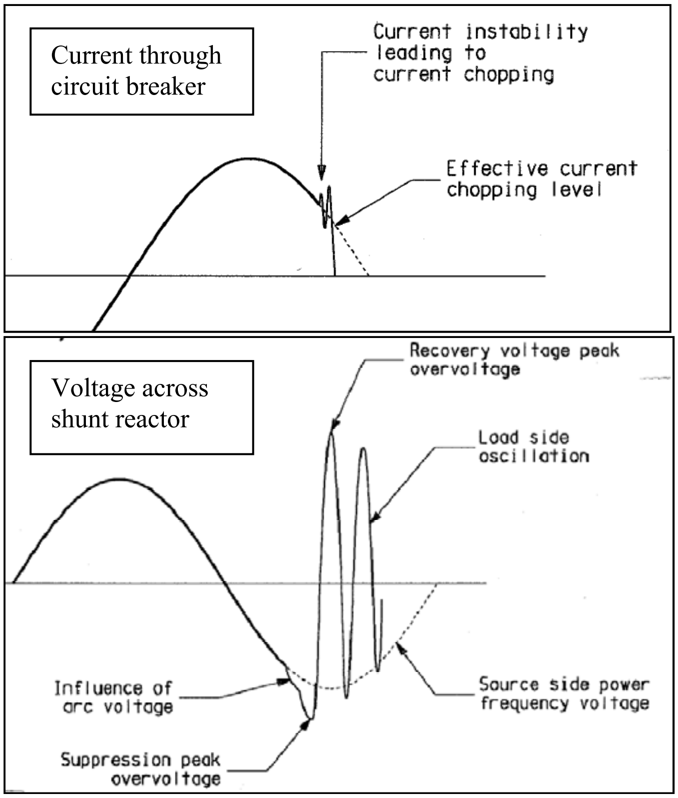


Figure 3: Current Chopping Phenomena (IEEE Std C37.015-1963)

When surge arrestors are used to protect the reactor, the switching overvoltages to ground, caused by current chopping, can be effectively limited to a safe level. The application of an arrestor though has little influence on the steepness of the voltage. For reactor insulation, the extremely high rate of rise of the voltage transients caused by reignitions that is the most damaging. The transient, lasting from 1 to a couple of microseconds, distributes the overvoltages unevenly across the reactor windings causing insulation damage and eventual breakdown.

Common Devices Used To Switch Reactors

A. Power Circuit Breaker

Power circuit breakers are general purpose devices designed for line/bus switching and protection. They have been used for shunt reactor switching for many years. Circuit breakers will almost always interrupt the current at a forced current zero or the first current zero following contact separation. At this point, the contact separation is usually not sufficient to withstand the *recovery voltage* imposed upon it, resulting in multiple reignitions that will result in contact wear and nozzle punctures resulting in breaker failure if corrective maintenance is not performed in time.

Recognizing the difficulty circuit breakers have interrupting the small reactor load currents, manufacturers now recommend that either opening resistors or opening controls be added to the circuit breaker to help minimize the likelihood of reignitions occurring. Opening resistors are connected in parallel with the main contacts of the breaker and are effective in reducing overvoltages seen by the breaker as well as modify the TRV. When using opening resistors, it is important that the closing resistor value is very close to the ohmic reactance of the reactor.

Another approach is to add opening controls to the circuit breaker (synchronous or zero voltage control). When an open command is given to the breaker, the controls delay the opening until the first voltage zero crossing. The controls tell the breaker when to open based on mechanical opening time and expected contact separation so that arc extinction occurs at a time when the probability of reignition and voltage escalation are at a minimum. To open at targeted time, the controls must take into consideration the effects of control voltage fluctuations, ambient temperature, tolerances of the mechanism's stored energy and operating wear.

Fig. 4. Shunt reactor switched with a SF_6 breaker

If circuit breakers are used for reactor switching, it is recommended that metal oxide surge arresters be located close to the breaker to help mitigate the associated transient voltages across the reactor during current chopping.

The circuit breaker used as a reactor switching device has the following advantages:

- Full interrupter ratings
- Bushing mounted current transformers
- Local visual gas system indicator
- Remote gas monitoring
- Making and breaking the circuit in SF_6
- Potential us of opening resistors for transient mitigation
- Potential use of Synchronous controls for transient mitigation and reduction of reignitions

They also have the following disadvantages:

- Short Interrupter life and high maintenance costs
- High initial cost (e.g., synchronous close and opening resistor designs)
- Synchronous closing is inherently difficult to achieve repeatability over a large number of operations
- Multiple mechanisms (one per phase) to achieve synchronous closing and opening
- Failure of one mechanism to operate can result in single phasing of the reactor

B. Vacuum Breaker

Due to their ability to withstand higher rates of recovery voltage than standard circuit breakers, vacuum breakers are often applied to switch medium voltage shunt reactors. It is recommended that metal oxide surge arresters be located close to the vacuum breaker to mitigate the transient voltages across the reactor.

Fig. 5. Air-core dry type shunt reactors switched with a vacuum device

The vacuum breaker is a switching device that has the following advantages:

- Lower initial cost than a circuit breaker with this ability
- Compact design
- No SF_6 gas used - *GREENER*

The disadvantages are:

- Not readily available for HV and EHV applications
- Multiple gaps per phase interrupters increase potential of reignitions if voltage is not shared evenly as one interrupter reignition causes cascading failures for bottles
- Voltage distribution on bottles subject to application restrictions
- Magnetic fields from reactor can trigger difficulties by concentrating the arc in one location causing reignitions and failures
- Limited interrupting capability
- If individual mechanisms are used per phase, then failure of one mechanisms to operate can result in single phasing of the reactor

C. Circuit Switchers

Circuit switchers were originally designed for primary protection of substation transformers. Similar to circuit breakers, they have been used for shunt reactor switching for many years. Being primarily designed for transformer applications, the circuit switcher is typically not designed for the frequent operation required by reactor switching. Experience has shown that circuit switchers, similar to that shown in Figure 6, start approaching end of life at around 500 operations. In addition, circuit switchers are not designed in a way that users can inspect and maintain the contacts. This could result in frequent replacement of the interrupter.

Fig. 6. Oil-immersed shunt reactors switched with a circuit switcher (horizontal interrupter)

Circuit switchers have the following advantages:

- Compact design (vertical interrupter design)
- Significantly less mass of SF_6 - *GREENER*
- If provided with an integral disconnect, it provides a visual isolation point for the reactor

The circuit switcher has the following disadvantage:

- External arcing in air during closing (i.e., older installations)
- No fault closing rating
- Limited or no fault interrupting capability
- Contacts cannot be inspected or maintained
- No transient mitigation
- Low to moderate life expectancy

D. Special Purpose Shunt Reactor Switch

Fig: 6. 230 kV Special purpose shunt reactor switcher

Disconnecting a shunt reactor is extremely difficult due to the very steep recovery voltage that is present when the switching device contacts part and interrupt at the first current zero. Since the recovery voltage decays very rapidly (Fig 2), if we can intentionally delay the extinguishing of the arc until a subsequent current zero, then that it should be possible to either eliminate the possibility of a reignition or minimize the number and magnitude of any reignitions that occur.

That is the theory behind the Southern States *RLSwitcher®* reactor switching device. The special purpose reactor switch has a uniquely designed interrupter (Fig. 7). The geometry of the arcing contacts and gas nozzle are specifically designed to better control the interaction between the gas, contacts, and nozzle material during switching a small inductive load out of the circuit. The interrupter is unique in that it is designed to delay the first interruption to where the gap is large enough to avoid high energy reignitions.

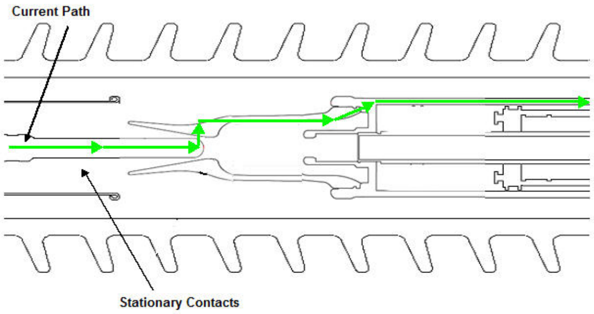


Fig. 7. Special purpose reactor switch interrupter diagram

The delay is accomplished with a special interrupter design that will not allow the interrupter to sustain an interruption until the contacts have developed sufficient gap. For the first couple of current zeros the interrupter deliberately will not interrupt, then there is a transition region where it will try to interrupt and may experience low energy reignitions. Finally the interrupter opens up for a clean interruption. Figure 8 shows an oscillogram of a test run on a 245 kV RLSwitcher.
You can see the extended arcing time as the interrupter opens, a low energy reignition that occurring, and the clean interruption of current disconnecting the reactor.

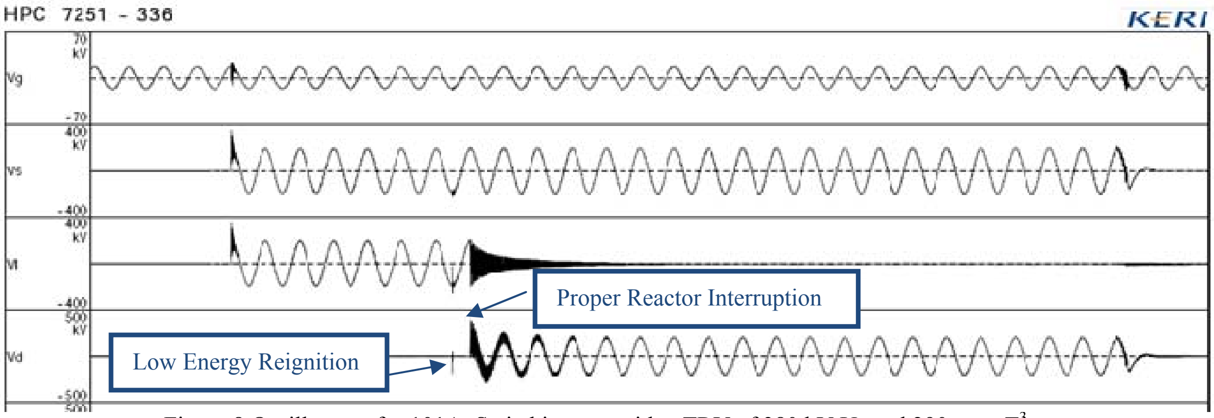


Figure 8 Oscillogram for 101A, Switching test with a TRV of 380 kV Ur and 290 µsec T^3

The design of the interrupter is counter intuitive to breaker designers. Breakers are designed to interrupt at the first possible point in time. Interrupting in the first cycle is very important to a protection scheme, but makes the breaker more likely to experience reignitions. A switch, designed specifically for interrupting inductive loads, on the other hand can take advantage of extending this minimum arcing time. Figure 9 shows a comparison of expected performance between a circuit breaker and specifically design reactor switcher.

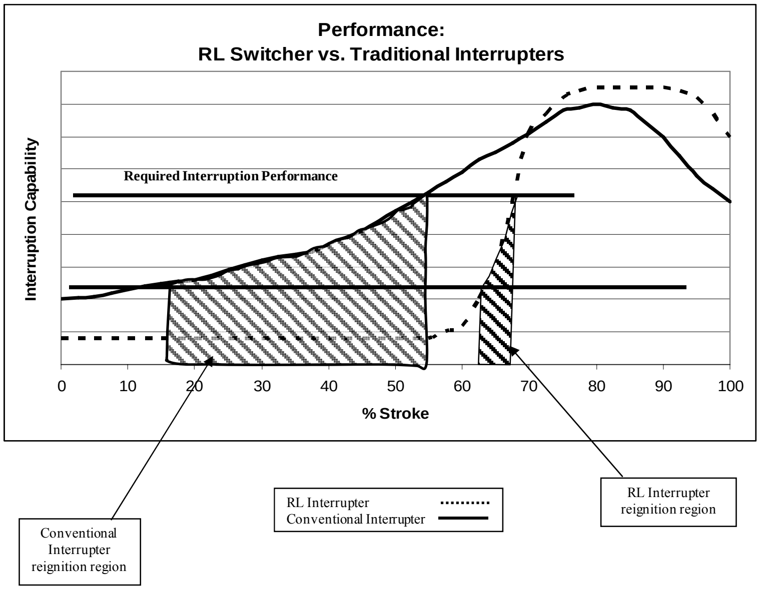


Figure 9: Anticipated reignition regions during interruption

Special purpose reactor switchers have the following advantages:

- Compact design
- Significantly reduced frequency and magnitude of reignitions
- Interrupter designed to withstand reignition without damage or life reduction
- Eliminates need for synchronous opening controller or opening resistors
- Mitigates turn to turn voltage transients on reactor
- Reduces current chopping
- Significantly less mass of SF_6 - *GREENER*
- Local visual gas system indicator
- Remote gas monitoring

The disadvantages are:

- Switching only, no fault interrupting capability
- Not suitable for general application as a breaker

Conclusions

Shunt reactors are an effective tool for maintaining reactive power balance on utility systems and due to the nature of the system loads, they are switched relatively frequently. The small inductive load current for a reactor is easy for modern circuit breakers and circuit switchers to interrupt but due to the fast recovery voltage, there is a high likelihood that the interrupting device will experience overvoltages and reignitions which could result in damage or premature aging of the switching device and reactor insulation. Significant improvements in product life and system stability can be gained using purpose built devices for switching shunt reactors

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