Analysis of Example Capacitor Bank Switching Solution and Recommendations for Revision

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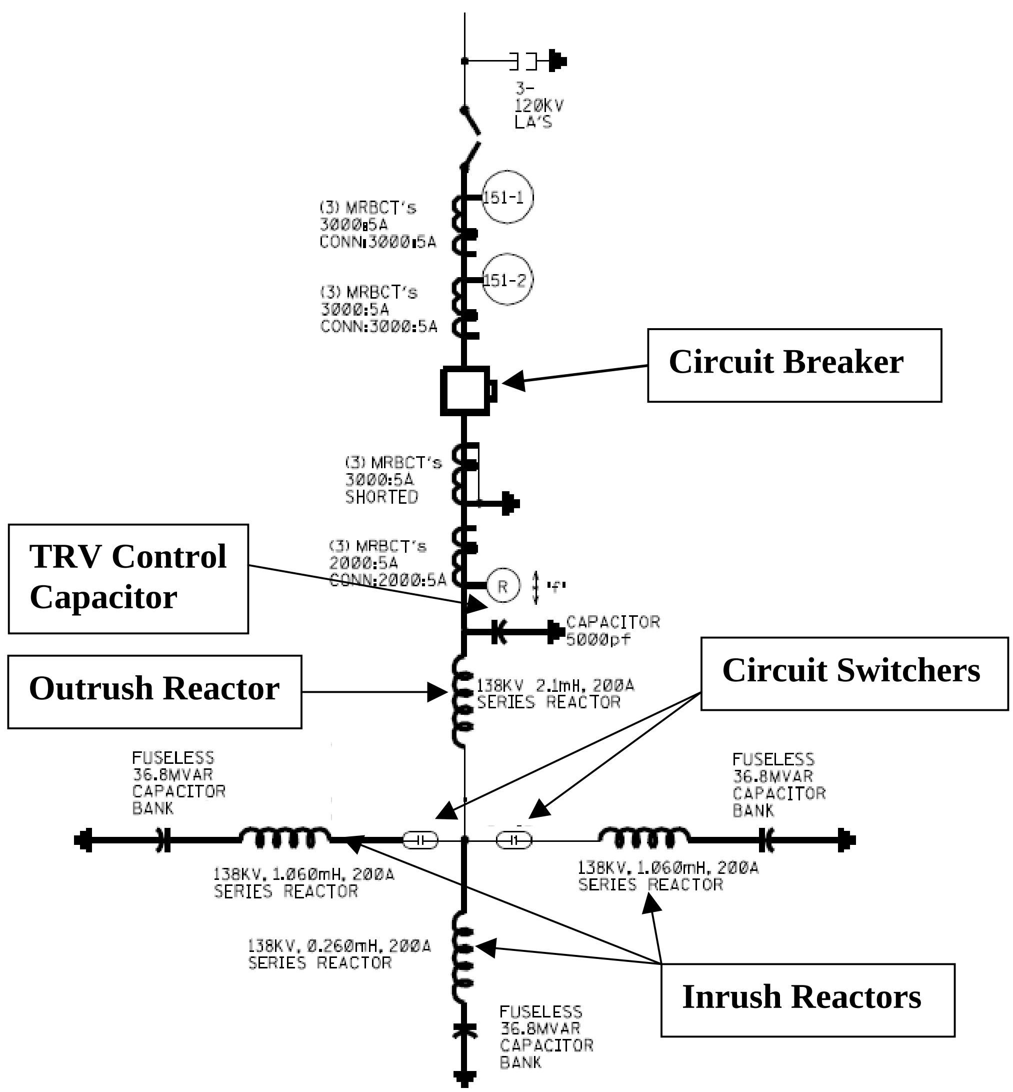
Abstract - The life of SF_6 interrupters is limited in applications where daily switching of capacitor banks causes high cumulative damage to the contacts and to the nozzles. This report analyzes this from a generic point of view and from an application specific point of view. Traditional solution methodologies suggested by standards do not offer the best alternative now available as a result of the development of a new, reliable, application-specific, pre-insertion resistor type capacitor switching device—Southern States ***CapSwitcher***®. This new device allows the elimination of many, if not all, of the reactors previously used to limit the inrush currents. The reactors have been necessary to limit the damage to and premature failures of general-purpose devices such as circuit breakers and circuit switchers. The adoption of the Southern States ***CapSwitcher***® results in a significant cost savings of up to 33%. Additional benefits include space savings, a reduction in voltage transients and current transients, and significant improvements in reliability.

Introduction – Back-to-back switching of capacitor banks presents a very tough duty on switching devices because of the combination of the high inrush currents and the frequent switching of larger and larger banks. Early switching devices such as oil circuit breakers, vacuum switches, and vacuum circuit breakers have interrupter characteristics that cause significant damage to the interrupters as a result of high inrush currents. While oil was more sensitive to high di/dt and vacuum was more sensitive to high peak currents, both have largely faded from applications at transmission voltages. The advent of SF_6 devices has significantly reduced the severity of the problems of capacitor switching applications; however, problems continue to persist and cause premature failure of some SF_6 capacitor switching devices. Some SF_6 capacitor switching devices also require the use of reactors in the circuit for higher duty capacitor switching applications. The introduction of Southern States ***CapSwitcher***®, an application-specific SF_6 capacitor switching device equipped with pre-insertion resistors, gives utility engineers an economical and compact solution to this very difficult switching application. The use of general-purpose SF_6 devices for capacitor switching duty is no longer the most reliable and economical solution. The application-specific SF_6 capacitor switching device, Southern States ***CapSwitcher***®, is not only more compact and economical but also reduces voltage surges on the power grid better and has a much longer operational life than other SF_6 devices.

Example Standard Capacitor Bank Configuration - A substation arrangement with a single general purpose circuit breaker protecting three capacitor banks (36.8 MVAR each) and using two circuit switchers, one circuit switcher each to energize the second and third banks, is evaluated on a comparative basis and used as a basis for making recommendations for improvements. The capacitor banks are arranged to be switched in three steps with reactors for current inrush and outrush control. All three are protected against a possible fault in any one of them by the single general-purpose circuit breaker which is also required to switch on the first capacitor bank.

The peak inrush current in capacitor switching applications can be quite high, and ANSI standards have recommended limiting this inrush current to 16 kA peak at a frequency of up to 4.2 kHz by applying series reactors in the circuit. This is a quite common solution for back-to-back switching of capacitor banks. Given the available alternatives, this use of reactors was a major improvement over the previous option of switching capacitor banks without them.

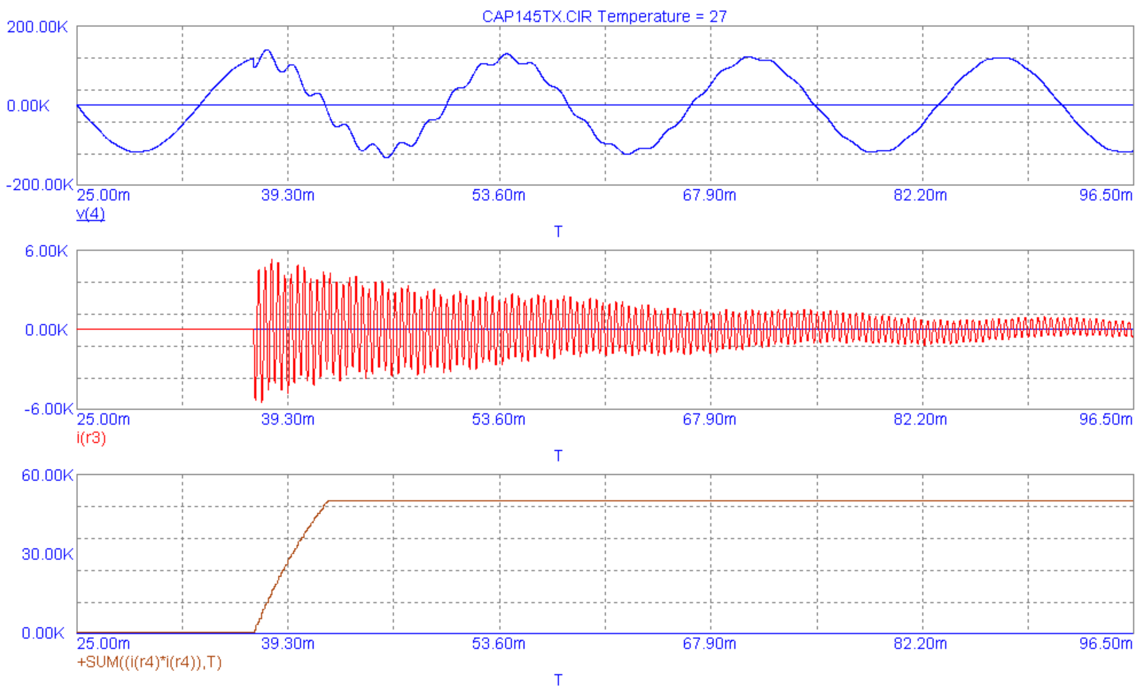
These three capacitor banks are connected to the bus as is shown in the diagram below. The circuit breaker is connected to the substation bus and then connected to an outrush reactor before an interconnection point where three capacitor banks are all connected through inrush reactors. Two circuit switchers are then used to control the second and third banks after the first bank is switched on by the circuit breaker. A TRV (Transient Recovery Voltage) control capacitor is used to control the TRV for a reactor fed fault should a capacitor bank or any other component flash over to ground.



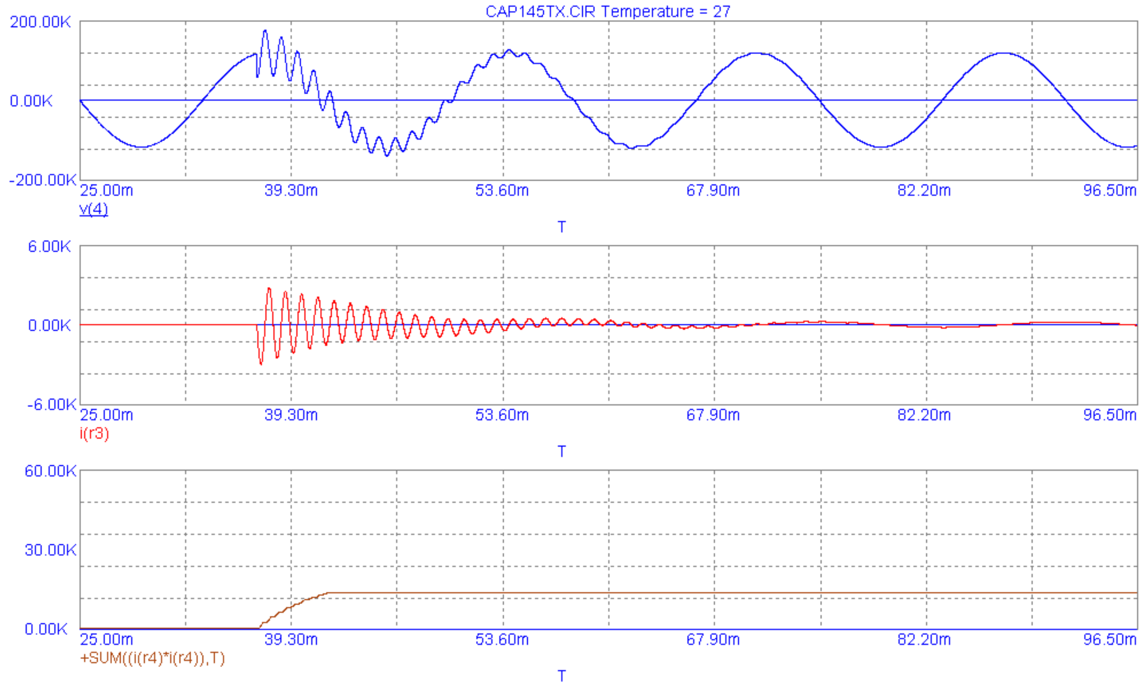
Interrupter Arcing Damage - The damage to contacts and to nozzles is a function of the current magnitude and the duration of the arcing. It is generally accepted that arc damage is related to I^2t. It is on this basis that looking at the next four simulations show this arc damage index in terms of this equation. These simulations also show that back-to-back switching has a significantly higher damage index than single bank switching as the closing currents are much higher. Although this is common knowledge, these simulations show the magnitude of this difference in this specific application.

The first and second simulations are for the example configuration with inrush and outrush reactors, circuit switchers, and a circuit breaker. The third and fourth simulations are for the application of a special purpose capacitor switching device, Southern States ***CapSwitcher***®, without the use of inrush reactors. The presence of the ***CapSwitcher***®'s pre-insertion resistor dramatically limits the currents. The details of the circuit being simulated are shown in the appendix of this report.

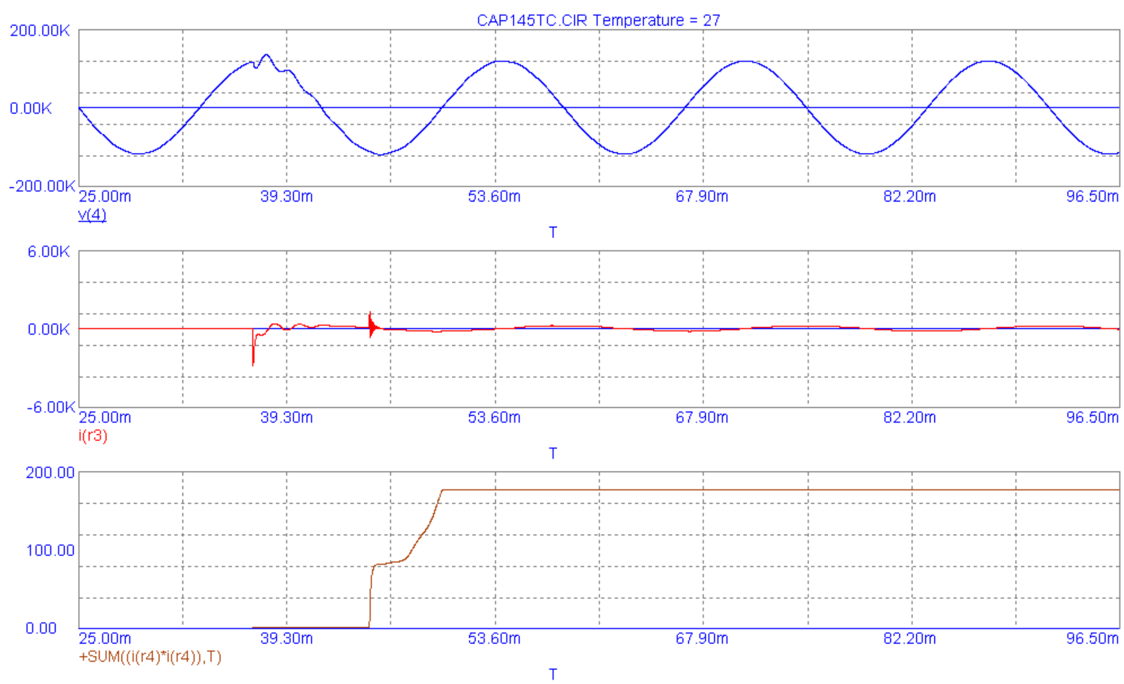
Example Configuration – Back-to-Back Switching with Inductors (Simulation 1) – Last Bank Energized = 49,650 (I^2t) Main Contact Arcing Energy



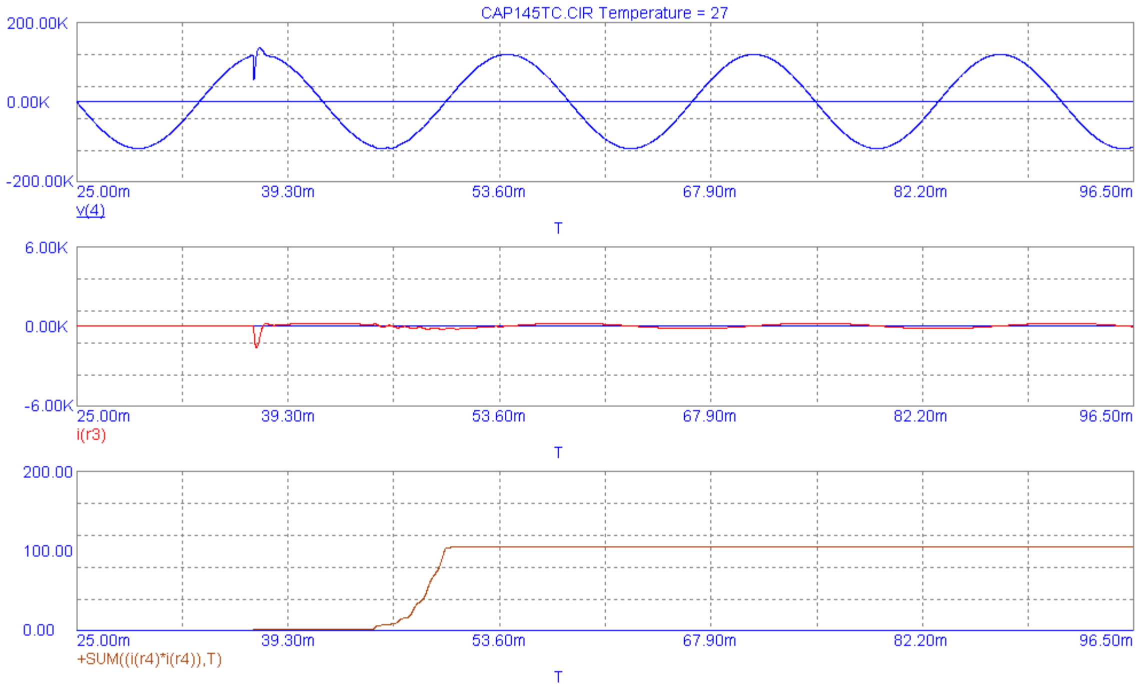
Example Standard Configuration – First Bank Switching with Inductors (Simulation 2) – First Bank Energized = 13,554 (I^2t) Main Contact Arcing Energy



Revised Configuration With *CapSwitcher*® Having 40 Ohm Pre-Insertion Resistor – Back-to-Back Switching <u>Without</u> Inductors (Simulation 3) - Last Bank Energized = 176 (I^2t) Main Contact Arcing Energy



Proposed Configuration (With Overvoltage Control) With *CapSwitcher*® Having 40 Ohm Pre-Insertion Resistor Being Used On The First Bank Switched – First Bank Switching <u>Without</u> Inductors (Simulation 4) - First Bank Energized = 104 (I^2t) Main Contact Arcing Energy



The reduction in damage index due to using the pre-insertion resistor equipped *CapSwitcher*® is rather dramatic and hence the expected life of the contacts in the interrupter is also anticipated to be significantly longer as the predominant switching mode is the daily capacitor bank switching rather than the occasional fault clearing. Hopefully there is never a need for clearing faults on a capacitor bank, but one must be prepared for that possibility. This reduction in arcing damage also extends the interrupter life for that potential time when it is required that a fault be interrupted and cleared.

The reason for concern about this arcing damage due to capacitor switching is the fact that interrupter life is significantly reduced and the effects are cumulative over time. Power tests in laboratories generally demonstrate capability of new devices but are rarely done with hundreds of operations in power test labs on 72.5 kV and higher voltage rated equipment. This is principally because the cost of doing these tests is generally quite expensive. As a result of this, reliance on actual field experience is the best method to verify cumulative arcing damage on interrupter nozzles and contacts, but this does take time to expose weaknesses and verify field performance. In the absence of many years of field experience, calculations of damage from arcing are made to compare design differences and application differences.

The results of such calculations are shown in the following Life Calculation Table. This compares the Southern States *CapSwitcher*® with a circuit switcher used in capacitor bank switching applications. The numbers in the chart highlighted in bold are taken from available literature from that circuit switcher. The numbers with a tan background show the closing operations one would expect if the maximum switching current were present for routine capacitor switching. The Southern States *CapSwitcher*® has a design topology that makes it impossible for the inrush current to get to its maximum magnitude. This is so because the pre-insertion resistor in the ***CapSwitcher***® limits the magnitude of the inrush current. The inrush reactors limit the inrush for the circuit switchers. The expected switching life is shown in yellow (back-to-back applications) and green (single bank applications) for both types of devices. Clearly, there is more damage and expected shorter contact & nozzle life for both designs in the back-to-back switching as compared to single bank switching.

Life Calculation Table

Contact & Nozzle Life Calculations

Example Of Switching Configuration For 3 Capacitor Banks

KEY
ANSI Max.
Back-to-Back
1st Bank

***CapSwitcher*®** 145 kV without Reactors

Exp. = 2

Current KA	Erosion Life I^Exp.2 * t * No.	Opening Operations	Closing Operations
40	192	**10**	5
31.5	192	16	10
25.0	192	26	25
20.0	192	40	60
16.0	192	63	188
12.5	192	102	307
10.0	192	160	480
8.0	192	253	759
6.3	192	401	1,202
5.0	192	634	1,901
4.0	192	1003	3,008
3.2	192	1587	4,760
2.5	192	2510	7,531
2.0	192	3972	11,915
1.6	192	6284	18,852
1.3	192	9943	29,829
1.0	192	15732	47,195
0.8	192	24891	74,673
0.6	192	39383	118,149
0.5	192	62312	186,937
0.4	192	98592	295,775

Circuit Switcher with Reactors

Exp. = 1.75

Current KA	Erosion Life I^Exp.2 * t * No.	Opening Operations	Closing Operations
40	NA	NA	NA
31.5	NA	NA	NA
25.0	??	??	??
20.0	22.7	10	30
16.0	22.7	15	44
12.5	22.7	23	68
10.0	22.7	34	101
8.0	22.7	50	151
6.3	22.7	75	225
5.0	22.7	112	337
4.0	22.7	168	503
3.2	22.7	250	751
2.5	22.7	374	1,122
2.0	22.7	559	1,677
1.6	22.7	835	2,505
1.3	22.7	1247	3,742
1.0	22.7	1864	5,591
0.8	22.7	2784	8,353
0.6	22.7	4160	12,480
0.5	22.7	6215	18,645
0.4	22.7	9286	27,857

Assumption **"t"** = 12 ms Opening & 4 ms Closing

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The results of the analysis clearly show an increase of more than 200 to 1 in the expected life of the interrupter contacts and nozzle for the Southern States ***CapSwitcher***® with its pre-insertion resistor versus the circuit switcher. It also follows that there is no additional advantage to using inrush reactors with the ***CapSwitcher***® as they provide no additional reduction in the inrush current. The intrinsic interrupter design capability (Erosion Life – 192 vs. 22.7) shows an 8 to 1 improvement when using the ***CapSwitcher***® in lieu of the circuit switcher in this comparison simply based upon the intrinsic interrupter design. The rest of the improvement in interrupter contact life and interrupter nozzle life comes from the fact that the pre-insertion resistor is much better at limiting the inrush currents than is reasonably possible with the use of reactors.

Voltage Transients - These are significantly reduced by the use of the ***CapSwitcher***® and are most dramatic when comparing the second simulation to the fourth. These are simulations of switching on the first capacitor bank with the general purpose SF_6 circuit breaker and with a ***CapSwitcher***®, respectively. The reduction of the current transients is equally impressive.

Cost Savings From Changing Away From The Example Solution - It is clear that the previously mentioned improvements have a substantial impact from a reliability and life cycle point of view. Additionally, not having to replace equipment that is subject to failures from high operational life in-service is a further advantage. Changing to the use of the *CapSwitcher®* with its pre-insertion resistor and eliminating inrush reactors results in significant savings as well. In that the inrush reactors are a necessary solution for capacitor switching devices without surge control, their need is eliminated by the newer technological approach of using the *CapSwitcher®* with its pre-insertion resistors, and the *CapSwitcher®* is now available and in service at many utilities. The elimination of these otherwise-needed components saves considerably on the installed cost of a substation capacitor bank switching solution.

The use of the *CapSwitcher®* results in a space savings as well; however, this was not included as a financial benefit. This advantage can be significant in applications where there is a need to retrofit or upgrade existing capacitor banks in older substations if there is no space to install reactors.

The table below also shows there are possible cost savings of up to 24% for substations that have a 63 kA fault level and up to 33% for substations that have a 40 kA fault level. The savings are based on the substation being reconfigured to use *CapSwitcher®*s instead of a circuit breaker, two circuit switchers, and reactors. The tables below outline the configuration options evaluated and their respective savings.

Cost Comparison Tables

Substation Cost Configuration Comparison

145 kV- 63 kA - Three Capacitor Banks (36.8 MVAR each) in Parallel

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	Unit per Price (k$)	Example Standard Configuration Quantity	Extended	SSLLC Suggested Quantity	Extended	SSLLC - Proposed (With Voltage Control) Quantity	Extended
Standard Circuit Breaker (63 kA)	69	1	69 K$	1	69 K$	1	69 K$
Standard Circuit Breaker (40 kA)	53	0		0		0	
Inrush Reactor (200 A - 33 kA)	5.5	9	49.5 K$	0	0 K$	0	0 K$
Outrush Reactor (450 A - 40 kA)	13	3	39 K$	3	39 K$	0	0 K$
L-G Capacitor for TRV Control	3	3	9 K$	3	9 K$	0	0 K$
Support Structure for X_L or X_C	1.5	15	22.5 K$	6	9 K$	0	0 K$
Foundation for X_L or X_C	3	15	45 K$	6	18 K$	0	0 K$
Circuit Switcher - 40 kA Close	34	2	68 K$	0	0 K$	0	0 K$
CapSwitcher® - 63 kA Close	59	0	0 K$	2	118 K$	3	177 K$
Equipment Total			302 K$		262 K$		246 K$
Equipment Savings			0 K$		40 K$		56 K$
Installed Estimate	1.5 Factor		453 K$		393 K$		369 K$
Life Cycle Costs for 20 Years							
Replace Interrupters							
@ 8 Yrs. Circuit Switcher	5	3	15 K$	0	0 K$	0	0 K$
Circuit Breaker	Not Required						
@ 16 Yrs. Circuit Switcher	5	9	45 K$	0	0 K$	0	0 K$
CapSwitcher®	Not Required						
Total Costs			513 K$		393 K$		369 K$
Net Savings		**0%**	**0 K$**	**23%**	**120 K$**	**28%**	**144 K$**

It is also possible to eliminate the circuit breaker outright where substation faults are at or below 40 kA by using the 40 kA interrupting capability of the *CapSwitcher*® and enabling the *CapSwitcher*®'s inherent fault interrupting capability by providing the *CapSwitcher*® with current sensing via the SSIPower LLC *CMD*™ three phase non-contact current transformer. This solution amounts to a possible savings of up to 33% ($154,000) in total life cycle cost.

Substation Cost Configuration Comparison

145 kV- 40 kA - Three Capacitor Banks (36.8 MVAR each) in Parallel

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	Unit per Price (k$)	Example Standard Configuration Quantity	Extended	SSLLC Suggested Quantity	Extended	SSLLC - Proposed (With Voltage Control) Quantity	Extended
Standard Circuit Breaker (63 kA)	69	0	0 K$	0	0 K$	0	0 K$
Standard Circuit Breaker (40 kA)	53	1	53 K$	1	53 K$	0	0 K$
CMD™ on Disconnect Switch	15	0	0 K$	0	0 K$	2	30 K$
Inrush Reactor (200 A - 33 kA)	4	9	36 K$	0	0 K$	0	0 K$
Outrush Reactor (450 A - 40 kA)	13	3	39 K$	3	39 K$	0	0 K$
L-G Capacitor for TRV Control	2	3	6 K$	3	6 K$	0	0 K$
Support Structure for X_L or X_C	1.5	15	22.5 K$	6	9 K$	0	0 K$
Foundation for X_L or X_C	3	15	45 K$	6	18 K$	0	0 K$
Circuit Switcher - 40 kA Close	34	2	68 K$	0	0 K$	0	0 K$
CapSwitcher® - 63 kA Close	59	0	0 K$	2	118 K$	3	177 K$
Equipment Total			269.5 K$		243 K$		207 K$
Equipment Savings			0 K$		27 K$		63 K$
Installed Estimate	1.5 Factor		404 K$		365 K$		311 K$
Life Cycle Costs for 20 Years							
Replace Interrupters							
@ 8 Yrs. Circuit Switcher	5	3	15 K$	0	0 K$	0	0 K$
Circuit Breaker	Not Required						
@ 16 Yrs. Circuit Switcher	5	9	45 K$	0	0 K$	0	0 K$
CapSwitcher®	Not Required						
Total Costs			464 K$		365 K$		311 K$
Net Savings		0%	0 K$	21%	100 K$	33%	154 K$

Summary - The reliability of example capacitor bank switching arrangement can be significantly improved and cost reduced by the adoption of the *CapSwitcher*®, Southern States definite purpose capacitor switching device. The cost savings can be as high as 24% for substations that have 63 kA fault levels and up to 33% for substations with 40 kA fault levels. In addition, voltage transients and inrush currents will also be reduced compared to the current example capacitor bank switching configuration. Several alternatives and configurations are presented here, allowing the customer to choose the desired configuration based on specific installation needs for new and existing substations.

Conclusion - The application of Southern States *CapSwitcher*®, a pre-insertion resistor device, in capacitor bank switching substation applications will increase the reliability and equipment life while also reducing costs as compared to the example capacitor switching configuration. This is because the *CapSwitcher*® is designed for twice the number of mechanical operations of most other available equipment and because the *CapSwitcher*® eliminates the need for inrush reactors. Additionally, the life of the interrupter is 10 to 200 times that of other devices used in this capacitor switching application because of the Southern States *CapSwitcher*®'s pre-insertion resistor. The recommendation of eliminating the inrush reactors allows a smaller substation footprint and saves $100,000 per installation (20 %). The opportunity exists to increase this savings to 24% for substations having 63 kA available fault current.

The cost savings opportunity increases up to 33% ($154,000) for a 40 kA available fault current substation should there be a desire to have a different capacitor switching solution for 40 kA available fault current substations versus 63 kA available fault current substations. The most cost effective proposed solutions also provide voltage surge control when switching the capacitor banks. The adoption of these recommended solutions will provide significant cost savings, increased reliability, and reduced life cycle costs.

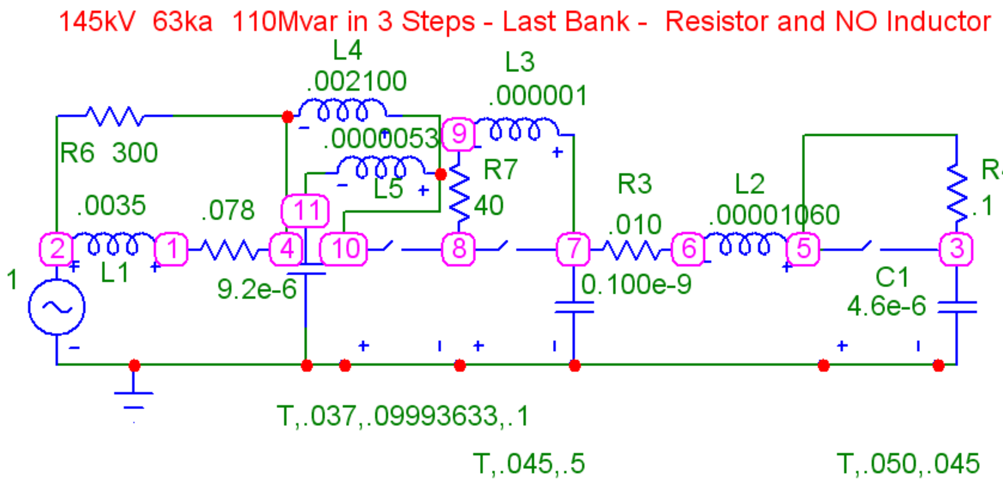
Author Biography – Joe Rostron received his Bachelor of Science degree in Mechanical Engineering from Washington State University in 1970 and his Masters Degree in Business Administration from the University of Pittsburgh in 1984. He has been employed since 1970 by Westinghouse, ABB Power T&D, Siemens Power Transmission and Distribution, and Southern States LLC with titles of Development Engineer, Engineering Manager, Product Manager, Sr. Vice President-Engineering, and is now President of SSIPower LLC (a Southern States company). He has 31 U.S. patents focusing on high voltage circuit breakers and other innovative power system technologies. He is a professional engineer in Pennsylvania and is also a member of IEEE and ASME. His experience covers a wide range of responsibilities for energy product design, development, and testing of new concepts/products; constantly seeking innovation to resolve high voltage power concerns to improve operational efficiencies and to reduce costs. His focus has been on national energy problems and development of new modern products for customer needs.

Editor Biography – David Childress received his Bachelor of Science degree in Engineering from Mississippi State University in 1991. He joined Siemens Energy & Automation in 1991 as an Application Engineer responsible for circuit switchers and disconnect switches and later joined Southern States in 1997 holding positions of Regional Manager, International Sales Manager, Product Manager, and Marketing Manager of Southern States Power Switching Division. He is presently Marketing Manager of SSIPower LLC (a Southern States company) responsible for the marketing, promotion, and sale of three-phase non-contact current transformers. He is a member of IEEE; a multi-published technical paper author; an author of over 100 catalog flyers, catalog bulletins, and other technical/product related documents; and has recently co-authored a chapter for the Electric Power Substations Engineering Book-Second Edition entitled "High Voltage Switching Equipment" (ISBN: 978-0-8493-7383-1)

Editor Note – The economics shown in this paper are specific to the project, configuration, and ratings being analyzed but are representative of the achievable savings for a variety of capacitor switching applications. The performance and installed life enhancement of converting to the Southern States *CapSwitcher*® high voltage capacitor switching device with current sensing via the SSIPower LLC *CMD*™ three phase non-contact current transformer are not specific to just this project, configuration, and ratings; being instead highly representative of many capacitor switching applications.

Appendix

Fixed Inductor Capacitor Switching



CapSwitcher® Capacitor Switching