Static Var Compensator Protection

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INTRODUCTION

Electrical loads both generate and absorb reactive power. Since the transmitted load varies considerably from one hour to another, the reactive power balance in the grid varies as well. The result can be unacceptable voltage amplitude variations or even a voltage depression, at the extreme a voltage collapse.

A rapidly operating Static VAR Compensator (SVC) can continuously provide the reactive power required to control dynamic voltage swings under various system conditions and thereby improve the power system transmission and distribution performance. Installing an SVC at one or more suitable points in the network can increase transfer capability and reduce losses while maintaining a smooth voltage profile under different network conditions. SVC are installed in transmission systems, sub-transmission and distribution systems, and in large industrial customers as shown in Fig. 1.

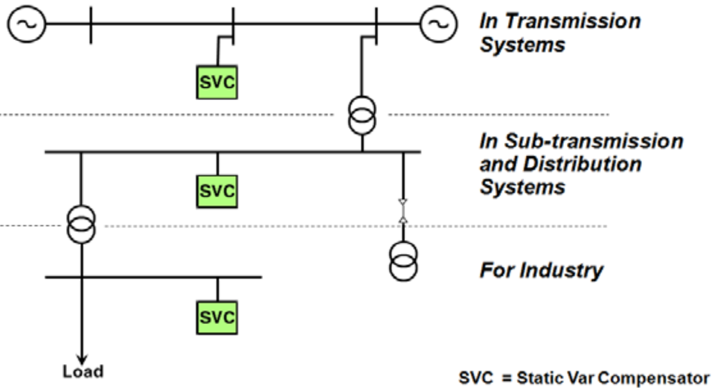


Fig.1: SVC Installation

I. SVC MAJOR COMPONENTS

The SVC consists of reactors, capacitor banks, thyristor valves, cooling system, power transformers, and state of the art control systems. The number of reactor and capacitor bank branches depends on the size of the SVC (Fig.2).

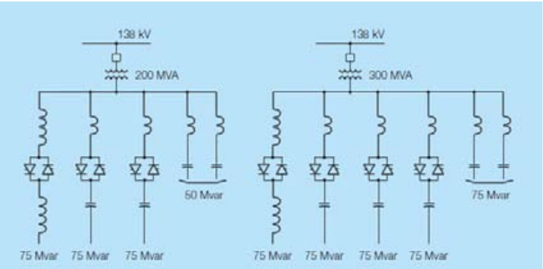


Fig.2: SVC Installation with a number of capacitor banks and one reactor bank

A. Thyristor Valves

The thyristor valves consist of a single phase assemblies (Fig.3) that makes it easy for installation. Each thyristor changes state from the blocking to the conducting state by the electrical firing signal initiated by the control system. The valves conduct only in one direction and turn off at zero current (Fig. 4). The order of firing is communicated via optical light guides from the valve control unit (VCU) to the thyristor control unit (TCU). Each valve comprises of two stacks of antiparallel connected thyristors and each comprises a number of thyristors in series, to obtain the voltage blocking capability needed for the valves.

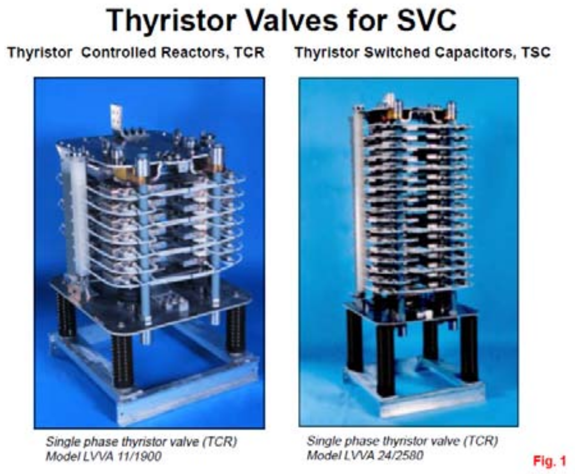


Fig. 3: Thyristor Valves

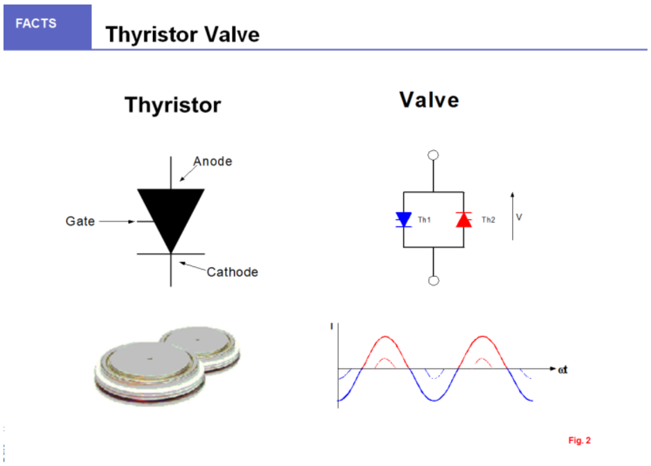


Fig. 4: Bi-directional Conduction Thyristor (BCT) Valve

B. High Voltage Filters and Capacitor Banks

Fixed capacitor banks are installed and sometimes tuned as filters to eliminate harmonics. The Thyristor Switched Capacitor (TSC) is installed in series with damping reactors and switched via thyristor valves. Switching of TSC takes place when the voltage across the thyristor valve is zero, making it virtually transient – free.

Disconnection is effected by suppressing the firing pulses to the thyristors which will be blocked when the current reaches zero. The TSCs are characterized by stepped control, no transients, no harmonics generated, low losses, and offers redundancy and flexibility.

C. Reactors

The dry-type air core reactors and thyristor valves are incorporated in each single phase branch, similar to the high voltage capacitors. The reactors can be either switched on with or without controlling the current via the thyristor valve. The Thyristor Controlled Reactor (TCR) on-state interval is controlled by delaying triggering of the thyristor valve relative to the natural zero current crossing. The TCR consists of a fixed reactor in series with a bi-directional thyristor valves. Usually the reactors are divided such that one reactor is on each side of the thyristor valve. This approach reduces the stresses on the thyristors under fault conditions. The Thyristor Switched Reactor (TSR) does not regulate the reactor current and is switched on like TSC.

D. High Voltage Power Transformer

A direct connected SVC has no need for a step down power transformer. This brings benefits to the project in a variety of things, such as no transformer maintenance costs, easy expandability since transformer rating and secondary voltage rise is not an issue when adding branches, and shorter lead times not influenced by long transformer delivery times. But for most applications, a step down transformer is needed.

Depending on the application, the power transformer may have to be overloaded for a very short period when the SVC is switched on to compensate for changes in the power system. For example, an SVC installation with a power transformers rated at 125MVA feeding combined loads of 337.5 MVAR, consisting of one TCR and two TSCs, each rated at 112.5 MVAR. When the system voltage dips, the SVC operates with an initial supply to the system of 225 MVAR and reduces its output to 125 MVAR after 2 seconds.

E. Cooling System

The cooling system consists of a closed loop piping circuit where a mixture of de-ionized water and glycol is pumped through the thyristor valves and outdoor water to air heat exchangers. Usually, there are two water-circulating pumps, one is in operation and the other is standby. In case of a pump failure an automatic switch over to the cooling with minimum losses. The cooling system is automatically controlled by the computerized control system and can be manually controlled via the HMI. A small portion of the flow is bypassed through a water circuit where the coolant is continuously de-ionized and filtered.

An outdoor dry air cooler is used, that is connected directly to the main circuit. Low noise fans are utilized for reducing sound levels. All fans are individually controlled to ensure sufficient cooling with minimum losses.

F. Control Systems

SVC controls platform is based on standardized hardware, windows application, a user friendly high level functional programming tools and open interfaces. Since SVC performance requirements are high, sub-cycle action then is often needed. The control system uses an industrial PC equipped with state of the art signal processors, powerful enough to ensure accurate switching of the SVC thyristors, even for the most demanding applications.

The control system applications are supported by a Human Machine Interface (HMI). The HMI uses the hardware platform into which user friendly databases and information applications are programmed. The customer is provided with precise, relevant and accurate information. Since the SVC is normally unmanned the focus of the HMI is to provide simplicity and accuracy when needed. Extensive diagnostic systems and event handling facilities make sure that the operator and/or the engineer will always have the correct and relevant information.

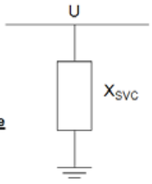
II. SVC THEORY OF OPERATION

The SVC control system determines the susceptance needed in the point of connection to the power system, in order to keep the system voltage close to some desired value. This function is realized by measuring the system voltage and comparing it with the reference value. In case of a discrepancy between two values, the SVC control system order changes in the susceptance until equilibrium is attained. The SVC operation results in a susceptance order which is converted into firing orders for each thyristor. The overall active susceptance is given by the sum of susceptances of the harmonic filters, continuously controlled TCR, and the TSC if switched in operation. Shown below in Fig. 5 is a simplified representation of the susceptance (B).

A. Susceptance

$$\overset{\text{Impedance}}{Z_{SVC}} = \overset{\text{Resistance}}{R_{SVC}} + \overset{\text{Reactance}}{jX_{SVC}}$$

$$\overset{\text{Admittance}}{Y_{SVC}} = \frac{1}{Z_{SVC}} = \overset{\text{Conductance}}{G_{SVC}} + \overset{\text{Susceptance}}{jB_{SVC}}$$



$$\boxed{B_{SVC} \approx -\frac{1}{X_{SVC}}} \qquad \boxed{Q_{SVC} = U^2 \cdot B_{SVC}}$$

Fig. 5: Simplified susceptance representation

B. Valve Control Unit and Thyristor Control Unit

The computer system which stores the firing order algorithm to the thyristor valves sends signal to the valve control unit (VCU). These signals are converted to fiber optic signals where they are sent to the thyristor control unit (TCU) as either a controlled signal or a switched signal to the thyristor valves. The TCU sends back signal to the VCU of the status of the thyristors valves.

C. TCR and TSC Operating Principles

The switching of the TCR and the TSC changes the reactive power (Q) of the SVC which results in the changes of the bus voltages. The TCR produces a current profile I_R (I_{TCR}) shown on Fig. 6 that looks different from the current profile I_C (I_{TSC}) of switched TSC. The firing control angle of TCR (Fig. 7) is between 90^o to 180^o where the maximum peak I_R (I_{TCR}) current occurs at 90^o. Control switching of TCR produces harmonics but if the voltage-time areas of the positive and negative cycles are of equal size and shape, then the wave forms include only odd harmonics. In some application, the resulting harmonics may not be a concern so harmonic filters may not be necessary.

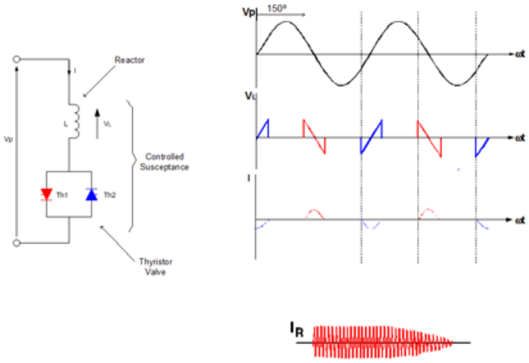


Fig. 6: TCR current profile

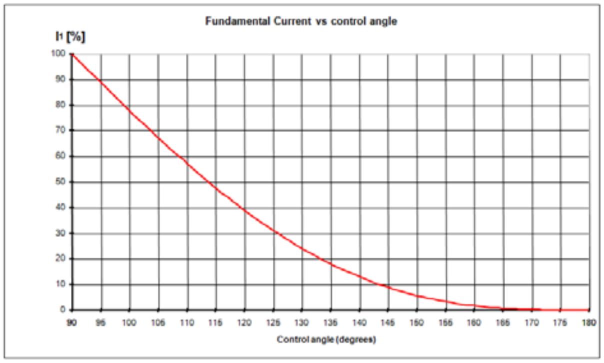


Fig. 7: TCR fundamental current vs. the firing control angle.

The TCR and TSC single phase branches are connected in delta configuration. With a symmetrical net, the multiples of three harmonic currents are zero sequence currents, which are circulating or trapped inside the delta bank, these leave harmonics order of 5, 7, 11, 13, 17, and 19 ….outside the TCR delta. Fig. 8 below shows the voltage and current profiles of the combination of TCR andTSC operation. The total SVC current I_p is the sum of I_R (I_{TCR}) and I_C (I_{TSC}) .

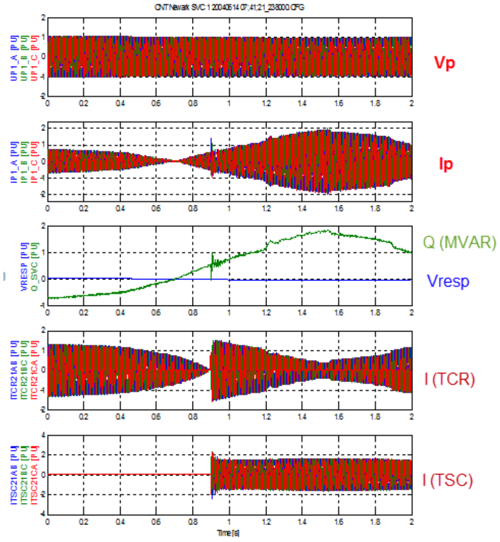


Fig. 8: TCR and TSC Combination

D. Voltage Control

The gain of the voltage regulator component in the control system determines the response and stability of the control system. The control system determines the gating pulses of the thyristors and responds to a signal representing the susceptance reference (B_{ref}) which represents the output voltage. The closed loop control (Fig. 9) takes the controlled output voltage (V_{act}) and feed it back to the summing point with the reference voltage (V_{ref}).

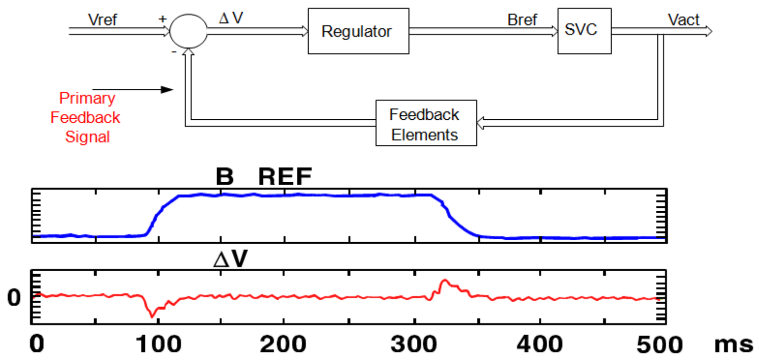


Fig. 9: Susceptance reference and voltage change

E. Slope – SVC Characteristics

In most applications, SVC is not used as a perfect terminal voltage regulator, but rather the terminal voltage V_{act} is allowed to differ from V_{ref} in proportion with the compensating current represented in the control loop as full output ofB_{ref}. One way to achieve this is to feed back a proportional amount of B_{ref} as a regulating slope (Fig. 10). This regulating slope allows the linear operating range of the SVC to be extended, improve stability of the voltage control loop regulation, and enforce automatic load sharing between SVC as well as the regulating device.

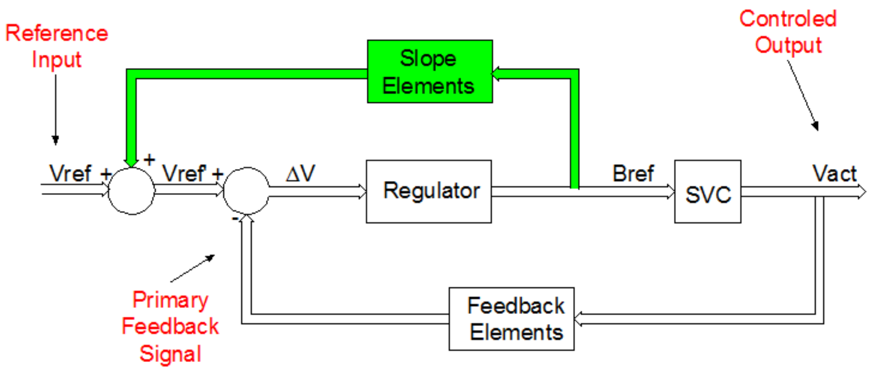


Fig. 10: SVC Regulating Slope

The slope is defined as the ratio between the change of voltage and the change of the SVC current over the control range. It determines the steady state operating point and is normally set between 2-5%. The voltage at which SVC neither generates nor absorbs reactive power is the reference voltage V_{ref}. This reference voltage can be adjusted within some certain range. The slope of the SVC characteristic represents a change in voltage with SVC reactive current and can therefore is seen as slope reactance X_{SL}. The SVC response to a voltage variation will then be given by $V_T = V_{ref} + X_{SL} I_{SVC}$.

F. Operating Modes

The two fundamental operating modes of the SVC are manual mode or manual control and automatic mode or voltage control. In manual mode, the SVC works on constant susceptance entered by an operator. The control system fires the thyristors in such a way that the SVC maintains the susceptance according to theB_{ref}. Manual mode has an open loop control.

The automatic mode is a constant voltage mode where the susceptance is regulated. The control system fires the thyristors in such a way that the SVC maintains the voltage according to the V_{ref}. Automatic mode has a closed loop control and utilize regulating slope based on the SVC static characteristic or the V/I characteristic models.

Leading SVC manufacturer incorporates several control system design functions of SVC which allows bump-less transfer between the two operating modes, standby mode, and exercise modes. In automatic mode, the B_{ref} follows the actual susceptance while in manual mode the V_{ref} follows the actual voltage V_{act}. For normal system voltage the SVC will be in stand-by mode where the thyristor valves are blocked form operating. The SVC leaves the standby-by mode when the system voltage goes below the SVC operating set point voltage.

Since the SVC will be most of the time in standby mode, an exercise mode is included to make sure that the SVC is ready for operation when needed. Exercise mode will be interrupted if SVC is needed for operation due to a system fault.

III. SVC APPLICATIONS

To understand how the SVC compensates, a review of the equations used in a simplified model of a power transmission system with two end buses. The two power sources connected by a transmission line which is assumed lossless and represented by $X_{L.}$ The voltages are $V_1\angle\delta_1$ and $V_2\angle\delta_2$ which represent the voltage phasors of the two buses with angle$\delta = \delta_{1-}\delta_2$.

The magnitude of the current in the transmission line is give by: $I = \frac{V_L}{X_L} = \frac{V_1\angle\delta_1 - V_2\angle\delta_2}{X_L}$

The active power and reactive power at Bus 1 are given by: P_1=$\frac{V_1 V_2 \sin\delta}{X_L}$, Q_1=$\frac{V_1(V_1 - V_2\cos\delta)}{X_L}$

The active power and reactive power at Bus 2 are given by: P_2=$\frac{V_1 V_2 \sin\delta}{X_L}$, Q_2=$\frac{V_2(V_2 - V_1\cos\delta)}{X_L}$

The equations above indicate that the active power, reactive power, and current flow can be regulated by controlling the voltages, phase angles, and line impedance of the transmission system. The voltage magnitudes of the two buses are assumed equal as V and the phase angle between them is δ. At the midpoint of the transmission line, if a switched capacitor is connected, the injected reactive power at the midpoint is calculated as $Q_C = 4\frac{V^2}{X_L}(1 - cos\frac{\delta}{2})$. The power angle curve (Fig. 11) shows that the transmitted power can be significantly increased.

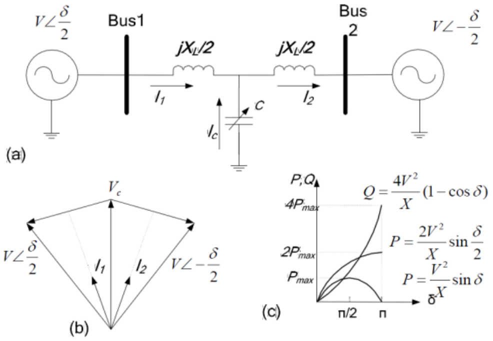


Fig. 11: Power Angle Curve

Using this basic principle to an SVC compensated line demonstrates various applications described below.

A. Damping of Power Oscillation

Large power systems like the North American power grid have many interconnections and bulk power transmissions over long distances. Sometimes large active power oscillations can appear in the power transmission system or low frequency inter-area oscillations which make system vulnerable to cascading failures. The SVC is equipped to counteract such oscillations by means of Power Oscillation Damping (POD) regulators which automatically go into action if the oscillations exceed certain preset level.

B. Power Quality Mitigation on Wind Farms

The wind power generations using doubly fed induction generator (DFIG) do not contribute to regulation of grid voltage since they are substantially absorbers of reactive power. Wind power is usually connected far out in the grid, on sub transmission or distribution levels, where the grid was not originally designed to transfer power from the system extremities back to the grid. The system in most cases is very weak and a change in power flow direction will strongly affect the voltage level.

The power production, and thus reactive power consumption, in wind farms also vary with wind speed. There are several phenomena associated with power produced from the wind introduce voltage flicker on the connecting node. This voltage flicker has a deteriorating effect on other electrical loads connected to the system, causing complaints from power consumers. By connecting an SVC on the grid connection points, the voltage flicker can be mitigated.

C. Maximum Power Transfer Improvement

The power angle curve shows how SVC installation in the mid section of the transmission line increases the maximum power transfer capacity of the line. The maximum power, as shown on the power angle curve equation, that can be transmitted in the steady state with the give reactance and given the voltages occurs at a displacement angle $\delta = 90^0$. The value of maximum power may be increased by increasing either of the internal voltages or by decreasing the circuit reactance.

D. Transient Stability Margin Enhancement

Any disturbance in the system will cause the imbalance between the mechanical power input and electrical power output of the generators connected in the system to be affected. Generator by itself has its own control systems to respond to these imbalances when generators' speed tends to ramp up or ramp down during the disturbances. If a particular generator tendency speed swing is too great, it will no longer remain in synchronism with the rest of the system. This phenomenon is referred to as generator out of step.

Referring to transient stability equal area criterion of the power angle curve, the application of the SVC enhances the transient stability margin by increasing the deceleration area margin to attain stability during generation swing caused by system disturbances.

E. Voltage Stability Enhancement

SVC will prevent system over voltage during load rejection events and enables the management of power system stability in case of system disturbances without resorting to under voltage load shedding.

Another example is an installation with transmission network that is 100% cable based, that is heavy reactive power generation as a consequence. Before the SVC, the need for reactive power absorption was solved by extensive use of shunt reactors at vital points in the network, fixed as well as mechanically switched. This operation had not been fully satisfactory in certain respects due to the following reasons:

a. A need for frequent switching of reactors, with associated switching transients, circuit breaker wear, and requirements for maintenance of the breakers.
b. Limited dynamic capability in situation where fast operation of reactors would be advantageous from a system point of view.
c. Only stepwise switching of reactive power was possible, which did not admit optimum utilization of the power system with respect to losses as well as active power carrying capability.

IV. SVC Protection

A. Protection handled by Controller

There are certain protective functions that the computer control system of the SVC handles: undervoltage protection, overvoltage protection, synchronizing voltage supervision, thyristor fault monitoring, thyristor firing supervision, TCR thyristor direct current control, TSC capacitor overvoltage protection, TSC valve overvoltage protection, and TSC overcurrent protection.

1. Undervoltage Protection

Typical setting for this element is 0.4 per unit of primary system voltage. When the voltage becomes less than 0.4 pu, the automatic voltage control is blocked, and the output of the SVC is driven to 0 Mvars. When the voltage recovers to 0.43 per unit, the automatic voltage control is restored and the SVC resumes normal operation.

2. Overvoltage protection

At voltages below 1.05 per unit of primary system voltage, the SVC is in normal operation. The SVC can be controllable from 1.15 to 1.3 pu maximum primary system voltage. If the voltage exceeds 1.15 pu, the thyristor switched capacitor is blocked, and the SVC operates in the inductive mode by just controlling the reactor. If the voltage exceeds 1.15 per unit for more that 3 seconds, the SVC is tripped.

3. Synchronizing voltage supervision

If the voltage drops below 0.3 per unit for 100msec, the control pulses are blocked. Should the voltage return within 1 second, the SVC resumes normal operation.

4. Thyristor triggering system supervision

This system compares the simulated amount of current that should be generated for a thyristor pulse with the actual amount of current generated. TCR greater than twenty five per cent of nominal generates a trip after 100msec. TSC current greater than fifty per cent of nominal generates a trip after 1000 msec.

5. TCR direct current control

This control minimizes the effect of even harmonics during normal operation. If a DC offset is detected in the TCR current , the TDCC will add a contribution to the control pulses on the positive and negative half cycles to counteract the DC currents.

6. TSC Capacitor overvoltage protection

The capacitor is protected from overvoltage by blocking the firing of the control during overvoltage condition.

7. TSC valve overvoltage protection

Prevents the TSC valve from firing if the valve voltage becomes too high.. Also prevents firing when the capacitor voltage and synch voltage have opposite polarity.

In addition to these protective functions, the controller also monitors the cooling system and takes preventative action should the cooling system fail.

There are several parts of the static var compensator that need additional protection. They are: SVC bus , TCR, and harmonic filter.

B. SVC bus protection

1. SVC Bus Ground fault protection

The SVC bus ground fault protection consists of a residual overvoltage relay with a definite time characteristic. Potential transformers with a grounded Y primary are connected to the SVC bus. The residual voltage is calculated from the sum of the three phase line to ground voltages. Simulations should be run to determine the residual voltage for a fault inside the TCR delta during the minimum bus voltage conditions. For a 69kV system, this voltage will be about 18V. This will be a typical setting for the residual overvoltage relay.

2. SVC Bus Overvoltage protection

This protection is coordinated with the controller overvoltage protection as discussed earlier. The controller maximum voltage can be set from 1.15 to 1.30 p.u. voltage. For a setting of 1.25 per unit, and a 115v secondary potential transformer. The relay voltage would be 144v.

$V_{Relay} = 1.25 \cdot 115V = 144V$

Set the relay 5% above this or 150 v.

3. SVC Bus Undervoltage protection

This setting also must coordinate with the SVC control strategy. The SVC can operate down to 60% of nominal voltage. For a 115v potential transformer, the undervoltage relay setting is

$V_{relay} = 0.6 \cdot 115v = 69$ v.

4. SVC Bus Differential Protection

The protective zone for the bus differential relay includes the main circuit breaker and SVC bus as shown below. A differentia relay is chosen so the relay will operate for faults inside the protection zone, but be unaffected by external faults.

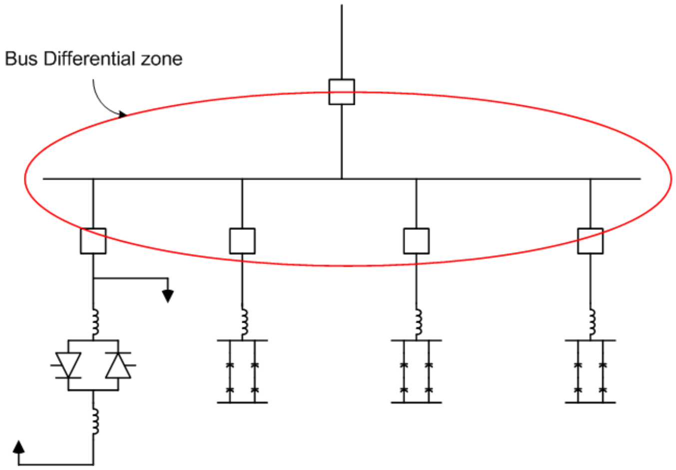


Fig.12 SVC Bus Differential Zone

5. SVC Bus overcurrent protection

This function should be coordinated with the downstream protection.In this case the TCR and harmonic filter overcurrent protection. Typical setting would be 130% of the maximum continuous current of the SVC.

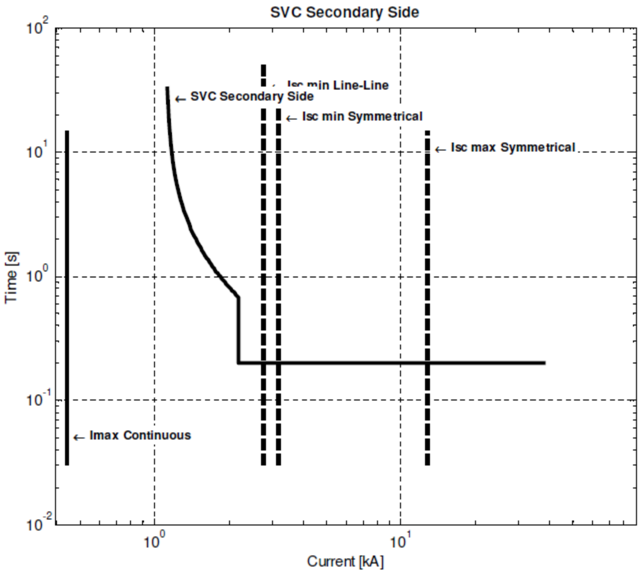


Fig.13. Overcurrent protection for SVC Bus

C. TCR Protection

1. TCR Differential protection

A transformer differential relay is used. The differential relay will operate for faults inside the protection zone, and restrain for faults outside the zone and for inrush currents with high second harmonic content. In some instances a long DC time constants during energization causes the 2nd harmonic blocking to drop out, which can operate the differential element. To prevent this, a time delay is introduced between the differential pick up and trip. The time delay is bypassed if the current is greater than 120% of rated current.

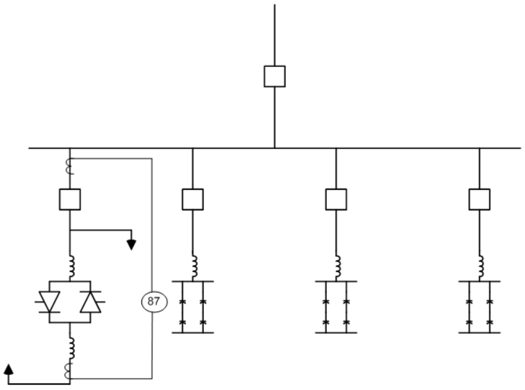


Fig.14 TCR Differential protection

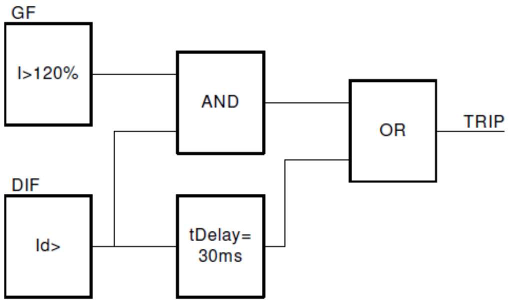


Fig. 15 Addition of delay timer in the operation of Differential Protection

2. TCR Overcurrent protection

The maximum continuous current outside the TCR is used as the reference current. The alarm stage is usually set to 115% of maximum continuous current. The trip stage is set to 200% of the maximum continuous current.

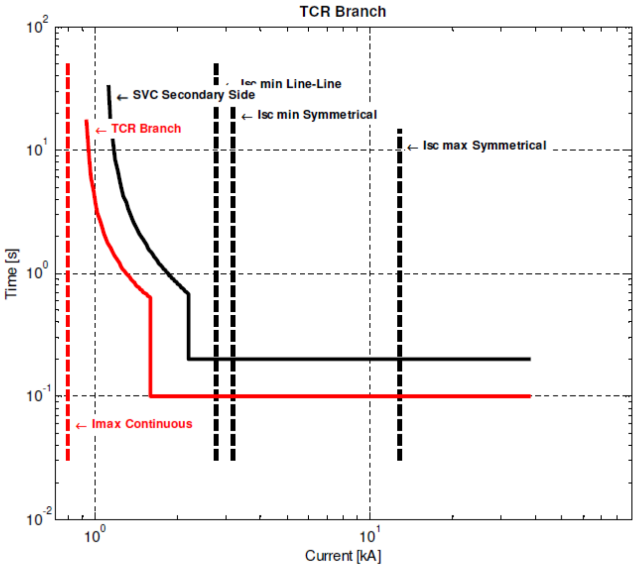


Fig 16 Overcurrent Protection SVC Bus and TCR

Thermal overload relay can also be use to protection the reactors.

D. Harmonic Filter Protection

Typically, each capacitor bank consists of two parallel banks Y – Y connected with ungrounded neutrals tied together. A current transformer in the neutral connection between the two parallel banks detects any unbalance between the two banks. Line currents are measured by current transformers located in each phase. The phase overcurrent protection is primarily intended for short circuit protection, but does supply some backup overload protection. The setting for the low set overcurrent element is typically around 130% of the maximum fundamental current in the filter bank. It has a normal inverse curve. A high set element is set for typically 500% of the maximum current using a definite time characteristic with 100msec delay.

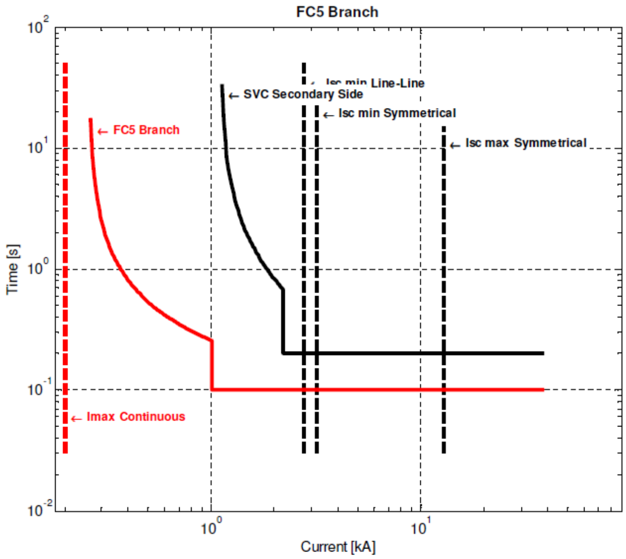


Fig.17 Typical Overcurrent protection coordination for filter bank

1. Current Unbalance protection

The capacitor bank is protected against internal overvoltages by a relay supervising the unbalance current in the neutral tying the two Y connected capacitor branches together. Two different overvoltage criteria are applicable to the capacitor banks, one external criteria allowing an overvoltage per capacitor unit, and one internal criteria allowing for an overvoltage per capacitor element. The limits are :

Externally : 1.1 p.u.

Internally: 1.5 – 1.7 p.u.

IEEE Standard C37.99 -2000 (A revision is in balloting at this writing) Guide for the Protection of Shunt Capacitor Banks gives a lot of information on unbalance protection and how to calculate the unbalance on the remaining capacitors in the stack after one or more has failed. The amount of overvoltage on the remaining capacitors is determined by the construction of the capacitor bank. That is, how many series groups, and capacitors in parallel. For example, for a bank constructed of 4 series groups per phase, and two groups in parallel, the table below can be constructed.

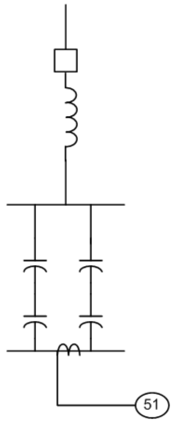
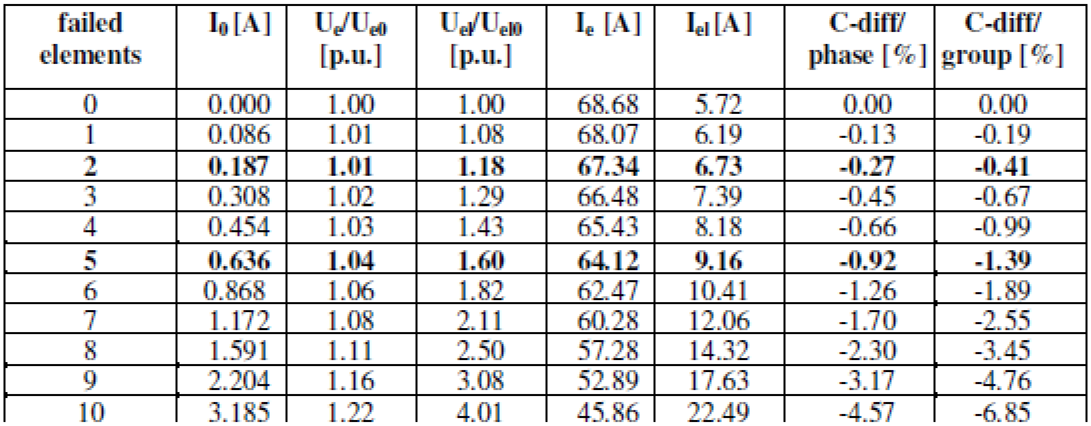


Fig.18 Filter Bank Unbalance Protection



failed elements	I_0 [A]	U_c/U_{c0} [p.u.]	U_{el}/U_{el0} [p.u.]	I_e [A]	I_{el} [A]	C-diff/ phase [%]	C-diff/ group [%]
0	0.000	1.00	1.00	68.68	5.72	0.00	0.00
1	0.086	1.01	1.08	68.07	6.19	-0.13	-0.19
2	**0.187**	**1.01**	**1.18**	**67.34**	**6.73**	**-0.27**	**-0.41**
3	0.308	1.02	1.29	66.48	7.39	-0.45	-0.67
4	0.454	1.03	1.43	65.43	8.18	-0.66	-0.99
5	**0.636**	**1.04**	**1.60**	**64.12**	**9.16**	**-0.92**	**-1.39**
6	0.868	1.06	1.82	62.47	10.41	-1.26	-1.89
7	1.172	1.08	2.11	60.28	12.06	-1.70	-2.55
8	1.591	1.11	2.50	57.28	14.32	-2.30	-3.45
9	2.204	1.16	3.08	52.89	17.63	-3.17	-4.76
10	3.185	1.22	4.01	45.86	22.49	-4.57	-6.85

Table 1 Capacitor bank unbalance calculation

Where:

Failed elements:	number of failed elements in a capacitor unit
I_0	Detectable unbalance current
U_c/U_{c0}	Capacitor unit voltage increase in p.u. of rated capacitor unit voltage
U_{el}/U_{el0}	Capacitor element voltage increase in p.u. of rated capacitor element voltage
I_e	Current through the faulty capacitor unit
I_{el}	Current through the faulty capacitor element in the faulty unit
C-diff/phase	Change of capacitance in the faulty phase in per cent of rated phase capacitance
C-diff/group	Change of capacitance in the faulty half in per cent of rated capacitance

In this example, the alarm setting is chosen at 2 failed elements, corresponding to 18% element overvoltage (1% unit overvoltage)
The trip setting is chosen at 5 failed elements, corresponding to a 60% element overvoltage (4 % unit overvoltage).

As the number of capacitor elements is reduced, the tuning for the filter changes. This example was for a 5th harmonic filter. It was tuned to 4.95 times the fundamental frequency. With the loss of 5 elements the tuning was lowered to 4.9 times the fundamental frequency. As more elements fail, the bank will drift further away from the desired frequency.

Conclusion

SVC’s are becoming a major player in the smart grid for var control. This paper was intended to educate the reader about SVC construction, application, operation, and protection. While the SVC provides a great deal of self protection, there are several parts such as the Thyristor controlled reactor, SVC bus, and filter banks that require additional protection.

IEEE PES Substation Committee has formed a working group to address static var compensators. Working group I9 has submitted a Project authorization Request to develop a new standard titled “IEEE Recommended Practice of a Modern Protection System for Static Var Compensators. Those interested in SVC protection should follow this working group closely.

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