Controlled Shunt Reactor – A Member of FACTS Family

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Abstract: The use of shunt reactors in the long extra high voltage transmission lines is widely practiced all over the world to control the dynamic and temporary over voltages. The continuous presence of these shunt reactors in the circuit has a number of disadvantages. In this paper, a thyristorized Controlled Shunt Reactor (CSR) is proposed which offers high flexibility and overcomes all the disadvantages of the fixed shunt reactor. This paper also presents the performance advantages of CSR under various operating conditions over permanently connected shunt reactor.

1.0 INTRODUCTION

Shunt reactors in EHV lines, mainly 400 kV and above are used to compensate the effects of line capacitances to limit the various types of over-voltages. Shunt reactors of suitable size must be permanently connected to the line to limit the fundamental frequency temporary over voltages. Such line reactors also serve to limit switching over voltages to some extent. However, reactive shunt compensation increases the surge impedance of the line and thereby reduces the surge impedance loading (SIL) level that is, the load at which a flat voltage profile along the line can be achieved. These permanently connected shunt reactors also consume active power, which is a continuous loss to the system.

A thyristorized Controlled Shunt Reactor (CSR) suitable for application in EHV line of 400 kV level is proposed which offers all the advantages of the permanently connected shunt reactors and at the same time overcomes all the disadvantages of the later. The basic idea behind the CSR is to control the reactive current of the shunt reactor by using a thyristor valve which can provide the necessary speed of switching and control by means of firing angle control. Thyristor controlled reactors (TCR) are extensively being used as a part of static VAR compensators and in variable series compensation schemes. The CSR thus is a part of the Flexible AC Transmission System (FACTS) family which makes use of power electronic devices and fast digital controls to obtain improved and controlled power transfer over EHV AC lines.

2.0 PHILOSOPHY OF CONTROLLED SHUNT REACTOR

As already mentioned, CSR utilizes control of reactive power through means of controlling current in a shunt reactor. CSR can be controlled to vary reactive power consumption anywhere between zero to full capacity by varying the firing angle of the thyristors between these two limits. A smooth control of reactive power consumption is thus achieved. The CSR can be made ON/OFF type when thyristors operate at only two firing angles corresponding to full and zero conduction.

It is not economical to use a thyristor valve at transmission voltage levels. Hence the concept of a “reactor transformer” with primary winding connected to high voltage side and a secondary (or control) winding suitable for connection to a thyristor valve, forms the basis for CSR. In other words CSR is a high impedance transformer controlled by an anti-parallel connected thyristors (valve) on the secondary side at a suitable voltage level. The impedance of CSR can be controlled by varying the firing angle of the thyristor pair through a controller. The controller is a logical and programmable device, which generates firing pulses, based on the input signals. The bypass circuit comprising a breaker and a choke is provided to bypass the thyristor circuit under various conditions. When this circuit is closed, CSR acts as a fixed reactor irrespective of the thyristor firing status. Fig. 1 shows the general arrangement of the CSR. The function of each of the components is described in further detail in the paper.

3.0 ADVANTAGES OF CSR

The advantages derived from application of CSR are many.

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Some of them are:

a) Fully Controllable Reactive Power: CSR provides the reactive power support to the line only when it is required thus reducing the continuous reactive power draw as in the case of fixed shunt reactors.

b) Reduction in dynamic overvoltage limits: CSR automatically goes out of circuit during increased line loading conditions, thus eliminating the need to limit the reactive compensation to 60% which is the present practice in Indian grids. This feature can be used to provide higher compensation on the lines to limit the power frequency dynamic over voltages. This shall help in reducing the over voltage requirements of all the substation equipments resulting in the overall economy.

c) Increased power carrying capacity of lines: The shunt reactors are manually switching off sometimes to increase the power transfer capacity of the transmission lines during heavy loading conditions. This involves risk of overvoltages during sudden load throw off. As the CSR control system takes it out of circuit under full load conditions of the lines, the increase in power transmission capacity is automatically achieved. In comparison to the lines compensated with fixed shunt reactor, the transmission lines provided with CSR can enhance the power transmission capacity by 25 to 30%.

d) Fast Response: CSR can respond with a short response time of 10 milliseconds for any sudden overvoltage etc. and can come in to the circuit with full reactive power support. This feature eliminates the risk involved in taking out the fixed reactors from the circuit.

e) Full compatibility to single phase auto reclosure: The fast response time of CSR makes it suitable to respond to fault conditions like single line to ground and three phase faults. The control system senses the fault and brings the reactor to full conduction within a short time thus providing full compatibility for single phase auto reclosure. The need for neutral grounding reactor (NGR) is similar to that of a fixed shunt reactor.

f) Ability to directly connect to EHV level: The CSR reactor transformer can be directly connected to the EHV level as against an SVC system which requires an intermediate transformer in addition to controllable reactor.

g) Economy of Size: A single CSR of larger size can be used as bus reactor for controlling bus voltages. In this case CSR can be equipped with continuous control feature.

h) Minimum Harmonics: The continuously controlled CSR is provided with small filters across the delta connected tertiary. This is to limit harmonics generated.
due to variation of firing angle of thyristor valve in accordance with reactive power requirement. The total harmonics generated due to thyristor firing will be less than 2-3% with respect to the nominal capacity of the CSR.

4.0 DEVELOPMENT OF THE MODEL

BHEL in technical consultation with Prof. G.N. Alexandrov of St. Petersburg Technical University, Russia, developed a 11kV, 2 MVAR CSR model which has undergone extensive testing in the shop floor. The tests have demonstrated the validity of the concept and have proved that all the design and performance parameters can be met. The tests carried out on the reactor transformer and the overall scheme are given below.

- Measurement of primary to control winding impedance
- Measurement of no load loss
- Measurement of load loss
- Measurement of ratio, polarity, phase relationship
- Separate source test
- Induced overvoltage test
- Response Time Measurement of CSR scheme
- Continuous control capability and response time to order
- Harmonic measurement during continuous control

5.0 420 kV, 50 MVAR PROTOTYPE CSR

Based on the success of the model, BHEL has gone ahead with design and manufacturing of a 420 kV, 50 MVAR prototype CSR which shall soon be installed at one of the 400 kV sub-stations in India. POWERGRID has been involved during all the stages of this development and has provided useful guidance in deciding upon the design and performance parameters of the model as well as the 420 kV prototype. A detailed simulation study has also been carried out using EMTDC package where all the aspects of CSR have been studied. The study has helped in deciding upon the rating of various CSR components and has also demonstrated the capability of CSR to effectively perform under conditions where a fixed shunt reactor is most needed.

5.1 SYSTEM MODEL

The studies were carried out using PSCAD/EMTDC software. The system modelled is given in Fig. 2. The main circuit components are detailed below.

The source is represented by an infinite source behind an equivalent impedance. The source end breaker is provided with a pre-insertion resistor of 400 Ω and a pre-insertion time of 8 ms. A 50 MVAR fixed shunt reactor, with an NGR of 900 Ω has been connected at the line after the sending end breaker. A transmission line of 300 km length has been simulated by means of distributed line parameters. The load is connected through a breaker at the line end. The sending end and load side breakers are controlled by a timed breaker logic to simulate single phase auto reclosing sequence. Load is represented in some cases by a passive R-L load, and in some cases, it is represented by another infinite bus behind an impedance, drawing the necessary load. The load is taken as 400 MVA @ 0.9 pf.

The voltage magnitude at the load bus has been kept at 400 kV.

The CSR is represented by a 3 phase, 3 winding, 50 MVAR transformer at the load end of the line. Mutual impedance between primary and secondary windings has been taken to be 100%. Secondary side voltage is kept at about 20 kV.

CSR primary neutral is grounded through a NGR whose value has been varied form 0 to 2000 Ω. CSR secondary neutral is solidly grounded without any impedance. Delta is kept unloaded.

Back to back thyristors are connected from phase to ground in the secondary winding.

A bypass circuit has also been included in parallel to the thyristor circuit. This includes a choke of small inductance in series with a bypass breaker.

5.2 THYRISTOR CONTROL AND FIRING CIRCUT

The thyristors are fired with reference to the primary voltage of CSR.

The CSR is in circuit (or is “ON”) when firing angle is 90 degrees. The CSR is not in circuit (or is “OFF”) when firing angle is 180 degrees or if thyristors are blocked. The CSR is normally OFF and is put ON under following conditions –

"When three phase rms CSR primary bus voltage is > 1.05 pu" AND / OR "When bus voltage at CSR primary goes below 0.6 pu in any phase (Fault condition)"

5.2 CASES STUDIED

The study covered the following areas in comparison to the performance of a 50 MVAR fixed shunt reactor,

- Performance in comparison to fixed shunt reactor under line energization condition.
• Changeover between bypass circuit and thyristor circuit.
• Performance in comparison to fixed shunt reactor under load throw off condition.
• Requirement of Neutral Grounding Reactor wrt single line to ground fault and auto reclosure.
• Performance and rating under three phase fault condition.

5.4 STUDY RESULTS

The results of the study for each case as above are as follows.

a) Line Energization: Two cases have been run. One with a CSR at line end and other with a 50 MVAR fixed shunt reactor at the line end. In case with CSR, bypass breaker is kept closed initially and thyristors are kept blocked.

Maximum overvoltage with fixed shunt reactor at its bus = 1.265 pu
Maximum overvoltage with CSR at its bus = 1.31 pu

It is noted that with CSR, the line energization overvoltage is little higher than the case with a fixed shunt reactor, which is expected due to the presence of choke inductance in CSR secondary. However, the difference is very small.

b) Changeover between bypass circuit and thyristor circuit:

This case was run to check the operation of CSR under changeover from bypass to thyristor circuit and vice versa. Blocking and deblocking of thyristors with bypass circuit with open and opening and closing of bypass circuit with thyristors blocked, was also studied. The CSR primary and secondary thyristor currents are shown in Fig. 3 and secondary thyristor firing angle is 180 deg. The sequence of events in this case is as follows.

0.7s  Thyristor firing angle changed from 180 to 90 deg.
0.9s  Bypass breaker is opened.
1.1s  Bypass breaker is closed.
1.3s  Thyristor firing angle changed from 90 to 180 deg.
1.5s  Thyristor firing angle changed from 180 to 90 deg.
1.7s  Bypass breaker is opened.
1.9s  Thyristor firing angle changed from 90 to 180 deg.
2.1s  Thyristor firing angle changed from 180 to 90 deg.
2.3s  Bypass breaker is closed.
2.5s  Thyristor firing angle changed from 90 to 180 deg.
2.7s  Bypass breaker is opened.
2.9s  Bypass breaker is closed.

The small change in currents is observed when thyristors are conducting and bypass breaker opens or closes. It can be seen that all the operations above are smooth and within capabilities of chosen equipment ratings. The
offset in primary currents at 2.9s, when CSR in put ON through bypass circuit is a phenomenon similar to the line energization case and is similar to the effect on a conventional shunt reactor.

c) Load Throw Off : Two cases were studied - with a fixed shunt reactor and the other one with CSR. In the later case CSR thyristors are firing at 180 degrees initially and after load throw off, the controller senses the overvoltage and changes the firing angle to 90 degrees (when voltage > 1.05 pu). The load has been represented as a passive load. Initially it was 400 MVA out of which approx. 380 MVA is thrown off. The results are given in Table-1.

In the case with CSR, which was OFF initially and becomes ON after sometime, hence, the peaks are little higher than the case with fixed shunt reactor. The response time observed is less than 10 ms. Fig. 4 shows the current into CSR primary after load is switched off at 0.6s.

d) Requirement of Neutral Grounding Reactor wrt single line to ground fault and auto reclosure : The objective of this case was to find out the conduction mode of CSR along with selection of NGR value, if required. A case with CSR with no NGR was run with single line to ground fault at midpoint of the line and with breaker poles in faulted phase open at both ends. Three conditions were simulated. With CSR fully blocked during fault, with only the faulty phase blocked and with CSR fully conducting during the fault. The arcing current into the fault in each of the three cases is given in Fig. 5. It was observed that the case when CSR is fully conducting, gives the least current. Thereafter, different values of NGR were tried to obtain optimum value and which was found to be of 2000 Ω for the study system. This result proves that CSR is fully compatible with single phase auto reclosure and an appropriate value of NGR can be chosen as in the case of fixed shunt reactors.

d) Performance and rating under three phase fault condition : A three phase fault was simulated at the CSR primary bus and cleared after 5 cycles. The recovery overvoltages on the secondary side were observed. The results revealed that it is the best to allow CSR to conduct fully as soon as bus fault is detected.

Once secondary side is short circuited, it does not see any overvoltages. A lightning arrester may be provided on the secondary side for extra protection.

The major conclusions drawn from the study are given below.

- The line energization and load throw off overvoltages are only marginally higher (which is expected also) in case of CSR as compared to a fixed shunt reactor of same rating. This proves the effectiveness of CSR under above conditions.
- The changeover between bypass circuit and thyristor circuit is smooth and bumpless transfer of current between the two is possible without affecting the reactive consumption from the primary.
- The response time of CSR is less than 10 ms as desired. This has been proved during testing of the model also.
- The CSR along with a suitable NGR at the neutral of primary side is fully compatible with single phase auto reclosure operation.

The results of the study were used in dimensioning of the thyristor valves for transient conditions and to finalize the control strategy under different operating conditions.

6.0 CONCLUSION

The paper covers principles and advantages of application of CSR in long EHV transmission lines, various aspects of the model and prototype being developed by BHEL. The results of digital simulation are also presented. The work thus demonstrates that CSR can be utilized as an effective tool to help improve the condition of the power system. Authors are hopeful that the proposed prototype CSR shall soon be in service in a 400 kV Substation of PowerGrid and with which the advantages mentioned in this paper would get field tested and will be proven.

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8.0 REFERENCES

Fig. 3  Changeover between bypass circuit and thyristor

Fig. 4  Load throw off at 0.6s. CSR responds within 10 ms

Fig. 5  Comparison of CSR conduction mode during single phase auto reclose condition
0.8-0.9s - all 3 phases conducting
0.9-1.08s - faulty phase blocked, 1.08-1.2s - all 3 phases blocked