Performance study of a Continuously Controlled Shunt Reactor for Bus voltage Management in EHV systems

S.V.N.Jithin Sundar, G.Vaishnavi

Abstract—In EHV substations, it is a common practice to use breaker switched bus reactors to maintain the bus voltage within permissible limits under varying load conditions. With the development of Controlled Shunt Reactor (CSR) which is a thyristor controlled high impedance transformer, a stable bus voltage can be maintained by providing variable reactive power based on the bus voltage deviations due to the load variations. The high impedance transformer which is also known as reactor transformer (RT) can be made to any size without any limitation unlike gapped core shunt reactors. As a single CSR of large capacity can be realized with suitable control mechanism, this approach proves to be technically superior and economical compared to the existing practice of breaker switched bus reactors.

A CSR with a detailed control system is modeled along with a typical EHV system in PSCAD/EMTDC environment. The study includes the effectiveness of filters introduced in the tertiary of the reactor transformer in controlling the harmonics generated during partial conduction of thyristors. The transient and steady state performance of the CSR system for varying system conditions is studied and the same is compared with the conventional practice. The paper presents and discusses the results of the study.

Keywords: High impedance transformer, shunt reactor, reactive power, compensation, EHV systems, voltage control, thyristors.

I. INTRODUCTION

The application of shunt reactors for controlling the over voltages in power systems is a well known practice. In the context of EHV systems, this has special significance due to the large amount of reactive power generation. The effect of the same, results in dynamic power frequency over voltages during line charging and sudden load throw off conditions. During light load conditions also, the capacitive reactive power generated in the line results in steady state over voltages. For the above reasons, the presence of shunt reactors is a mandatory requirement for the operation of EHV lines. But the permanent connection of the shunt reactors leads to reduced voltage levels and decreased transmission capacity of the lines during full load conditions. This problem is addressed by breaker controlled shunt reactors in many parts of the world. In such cases, the dynamic over voltages and problems evolving from breaker switching of reactors are solved by other technical innovations. The Controlled Shunt Reactor[1] (CSR) which is a thyristor controlled equipment offers a good solution with a fast response time to take care of dynamic conditions. Also the switching problems associated with breakers are completely avoided. An ON/OFF type CSR is in operation at Itarsi substation in India for last five years.

Shunt reactors which are meant to be used for controlling the bus voltage of sub station are known as bus reactors. These are always connected through a circuit breaker and switched on or off, based on the voltage variations. In large switching substations, it is not uncommon to find multiple bus reactors when the total reactor capacity required is large. Due to limited standard ratings of gapped core shunt reactors, it is necessary to provide in multiples of standard ratings along with associated bay equipment and space for accommodating the same. The CSR mentioned above is based on a high impedance transformer known as Reactor Transformer (RT) with a provision to control from the secondary side through thyristor valves. As RT of any large capacity can be realized as a single three phase unit or three single phase units, it is possible to provide variable reactive power support by controlling the firing angle of the thyristor valves. This continuously variable CSR as bus reactor offers following advantages.

1. Continuously variable reactive power based on the voltage variation.
2. Fast Response to dynamic conditions like load throw off
3. Reduced losses with optimized reactive power support.
4. Better economy in terms of sub station space and auxiliary equipment.

Continuous control of CSR was demonstrated successfully on the first prototype without the harmonic filters. The advantage of continuous control can be realized only in a large capacity of CSR. This paper presents a study to visualize the benefits of a continuously variable CSR. A large size CSR with associated power electronics and control requirements is modeled in PSCAD. A suitable power system model is

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realized to study the operation of CSR under different operating conditions. The same power system model is provided with conventional bus reactors for comparative analysis with CSR.

II. Modeling of CSR

CSR is a group of equipment connected in a scheme to realize the desired functionality. The CSR scheme designed for bus voltage control application is as shown in fig.1.The main equipment is the RT which is a three winding transformer. The primary (HV), the secondary (LV) windings are star connected and the tertiary is in delta to facilitate the circulation of triplen harmonics. This is realized from the standard library of PSCAD with appropriate voltage ratings and impedances. The key issue is the 100% impedance between the primary and the secondary windings which has a significant influence on the full load losses of the transformer. The impedance between the secondary and tertiary is important for effective control of harmonics during partial conduction of thyristors. In other words, the coupling between secondary and tertiary is stronger compared to the one between primary and tertiary. The parameters of RT are chosen in line with the practical experience of building the first prototype CSR.

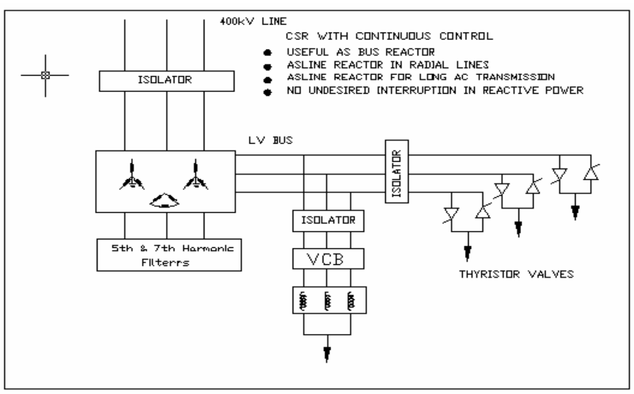

Fig. 1. CSR scheme for continuous control.

The primary terminals of CSR are to be connected to the HV bus (400kV) of the substation through a mechanical isolator. Mechanical isolators are not part of the modeling as they have no significance in the simulation. The voltage ratings of secondary and tertiary are as shown in Fig. 2. Voltage measurement on the primary is provided for voltage feed back. The secondary terminals of RT are connected to an anti parallel pair of thyristors with a bypass path. The bypass path consists of a vacuum circuit breaker in series with a choke. This has a special significance in line reactor application but is retained here as a generic arrangement. For this application while the primary remains connected to the HV bus bar, CSR provides variable reactive power based on the firing angle of the thyristors. The firing angle is varied depending on the bus voltage deviation from the reference value.

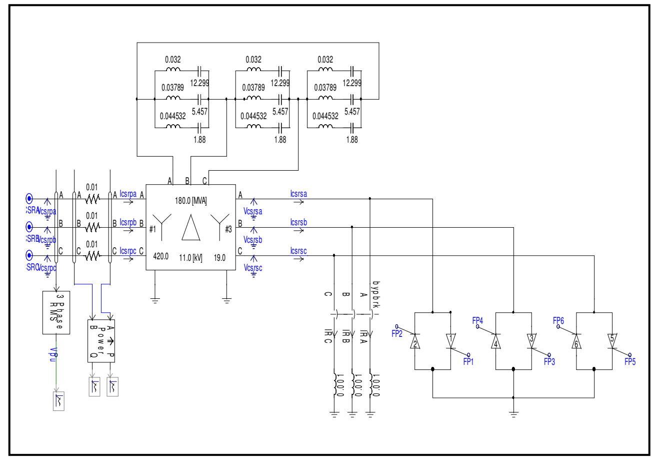

Fig. 2. Model of CSR power circuit in PSCAD

The tertiary connected in delta takes care of third harmonic and the other significant harmonics the 5^{th},7^{th}, and 11^{th} are mitigated by providing suitable LC filters across the same. The complete modeling of CSR is converted into a user defined component as shown in Fig. 2.

The control system of CSR comprises a Proportional Integral (PI) block available in the PSCAD library. The bus voltage is compared with the reference value and the deviation becomes the error signal or actuating signal to the PI block. The output of PI block is scaled to suit the operational range of thyristors which is between Π/2 and Π with reference to the zero crossing of voltage waveform. The output of the controller is used for generating firing pulses for each thyristor based on the reference derived from individual phase voltages. Voltage, power and current meters are provided at appropriate locations to capture the operation of CSR. The Fast Fourier Transform (FFT) block is used to estimate the magnitude of harmonics and the distortion factor due to the same is also calculated using the Harmonic Distortion (HD) block. The control system and the thyristor firing pulse generation block are shown in Fig. 3.

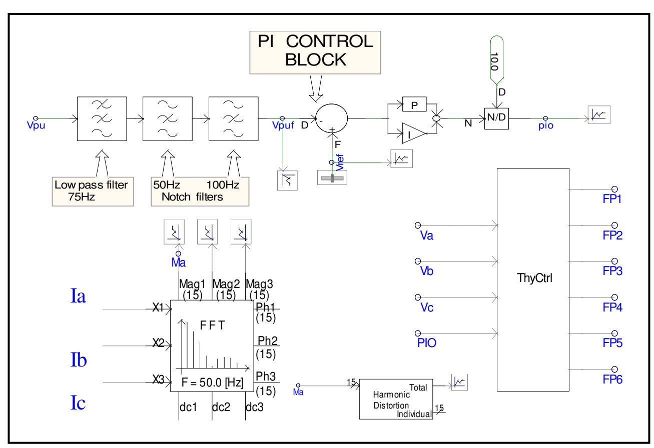

Fig. 3. PSCAD model of control system for CSR in continuous mode.

III. Power System Model

The CSR modeled is to be used for the control of a 400kV bus voltage in an EHV sub station. The power system model should facilitate over voltage condition during line charging, bus voltage variations due to changes in the load demand on the substation and sudden load throw off condition which can lead to sudden increase of the bus voltage. The scheme shown in fig.4 is realized in PSCAD by using the standard library blocks and user defined components of CSR. The power system represents a typical 400kV system in Indian power system network.

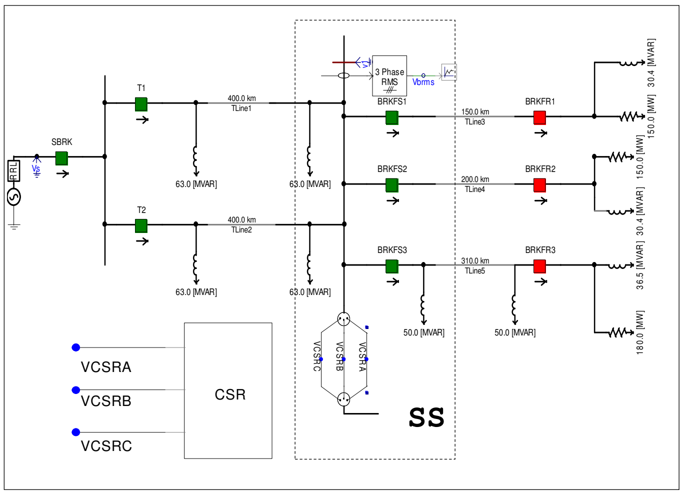

Fig. 4. 400kV Power system network model in PSCAD.

The source is realized as a 3 phase, 50 Hz , 400kV infinite source with an equivalent impedance represented through a series-parallel R-L circuit for a short circuit level of 27000MVA. The source is transmitting power to the substation SS through two parallel transmission lines of length 400km. The 400kV transmission line is modeled as a frequency dependent model with suitable conductor configuration. Each line is compensated by permanently connected line reactors at sending and receiving ends. The capacity of the line reactors is chosen as 63 MVAR in line with the existing practice of 60% permanent compensation and standard shunt reactors ratings in India. Both the lines are provided with breakers (T1&T2) at the sending end.

The substation dispatches power to three different load centers through different lengths of 400kV transmission lines. Only one of the lines which is of 310km is provided with permanently connected shunt reactors of 50MVAR in line with the existing practice. All the three lines are provided with breakers at the sending and receiving ends to facilitate selective switching of loads and load throw off. The load connected to each line, line length and reactor capacity are as shown in Table I.

TABLE I
Transmission Lines and Loads

Line	Length in km	Reactor capacity MVAR	Load	
			P MW	Q MVAR
Tline1	400	126	-	-
Tline2	400	126	-	-
Tline3	150	0	150	30.44
Tline4	200	0	150	30.44
Tline5	310	100	180	36.53

CSR is rated for 180 MVAR capacity based on the simulation of the above network under different conditions. As shown in Fig .4, CSR is connected to the substation (SS) bus and a three phase RMS voltmeter is used for monitoring the bus voltage. If the same amount of compensation is to be provided with breaker controlled shunt reactors, it will be through three units of 60 MVAR capacity. This case is also studied for comparison with CSR. A case without any bus reactor compensation is also studied and compared with the above.

IV. Simulation Studies

The simulation studies are intended to investigate the following cases:

1. To study the bus voltage of substation SS during line charging of lines 1& 2 from the sending end , during loading of the lines emanating out of the SS and also during switching off of the same loads. The loads on line 3, line 4 and line 5 are selected in such a way that the bus voltage at SS swings below and above the reference value of 1 p.u.

2. To study the bus voltage for the same situation described above with the bus SS supported with shunt reactor bank of 3x 60 MVAR switched through circuit breakers. To simulate the delay involved with circuit breakers a delay of 100ms is introduced for each switching. In this case, the number of shunt reactors are introduced as per the predetermined requirement. For example, only 60 MVAR is connected during line charging. Further, with the increase of load this is also switched off to keep the voltage within permissible limits. During load throw off, all the three shunt reactors are brought in sequentially to control the over voltage.

3. By connecting a CSR of continuously variable type with 180 MVAR capacity at the bus SS and study the voltage of the same during the above described conditions.

A. Simulation sequence

A common simulation sequence shown in Table II applicable to all the three cases is formulated to facilitate the study.

In the case of CSR, Thyristor valve de-blocking and bypass breaker (BYBRK depicted in Fig. 2) opening are the two additional operations required to bring CSR in to operation. From the instant of bypass breaker opening the automatic operation of CSR becomes effective thereby providing the required reactive power support to the SS bus.

TABLE II
SIMULATION SEQUENCE

Time Instant (Secs)	Description Of Operation	Case		
		1 Without Reactors	2 Switched Reactors	3 CSR
0.2	Close SBRK	✓	✓	✓
0.3	Deblock thyristors	-	-	✓
0.4	Open BYBRK	-	-	✓
0.5	Close Tl	✓	✓	✓
1.0	Close T2	✓	✓	✓
1.5	Close BRKFS2	✓	✓	✓
2.0	Close BRKFS1	✓	✓	✓
3.0	Close BRKFS3	✓	✓	✓
3.5	Open BRKFS1 and BRKFR1	✓	✓	✓
6.0	Open BRKFS2 and BRKFR2	✓	✓	✓
6.5	Open BRKFR3	✓	✓	✓
7.0	Simulation ends	✓	✓	✓

B. *Bus voltage management*

In Fig. 5, the bus voltage of SS plotted against the above sequence and time base is shown for comparison. The plot 1 is with no bus reactor support. During line charging the bus voltage is 1.04 p.u, at full load drops to 0.945p.u and with full load throw off it raises to 1.24p.u.

Plot 2 of Fig. 5 which is the case of switched reactors the line charging voltage is limited to 0.98p.u with one 60 MVAR connected. However with increase of load at t=2.0 sec the reactor is switched off, thereby the bus voltage improves to 1.048p.u. But with disconnection of loads, the shunt reactors are to be switched in one by one, to maintain the bus voltage within permissible limits. It may be noted that the required capacity of reactors and switching instants are possible only in simulation.

The simulation with CSR as bus reactor is shown in plot 3 of Fig. 5. From t =0.3 s CSR adjusts the reactive power support to the bus based on the voltage feed back. The switching-in and switching-off the loads do not affect the bus voltage. Even during load throw off, the maximum bus voltage is maintained at 1.02 p.u. This is possible by varying the reactive power support to the SS bus continuously. As the response is immediate the delays imminent with switched shunt reactors are avoided.

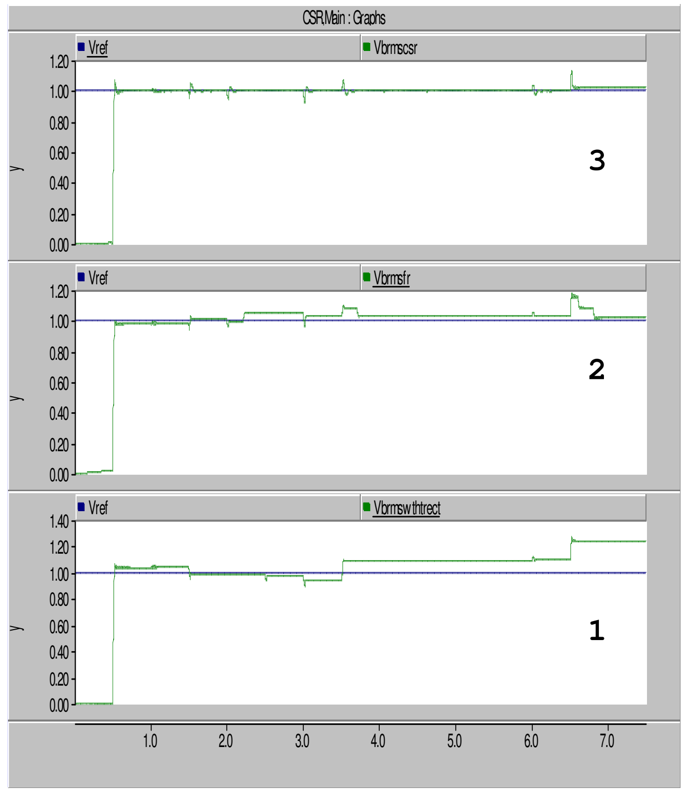

Fig. 5. RMS bus voltage for complete simulation sequence. Without Reactors (1), Switched Reactors (2), CSR (3)

It can be seen from the above plots, the bus voltage follows the reference setting quite closely. The variation of reactive power (Q) and active power (P) consumption by CSR through the simulation cycle is seen in fig.6. The reactive power consumed, varied from 37 to 180 MVAR with five other values in between. Such precise compensation can not be obtained with a bank of breaker controlled shunt reactors.

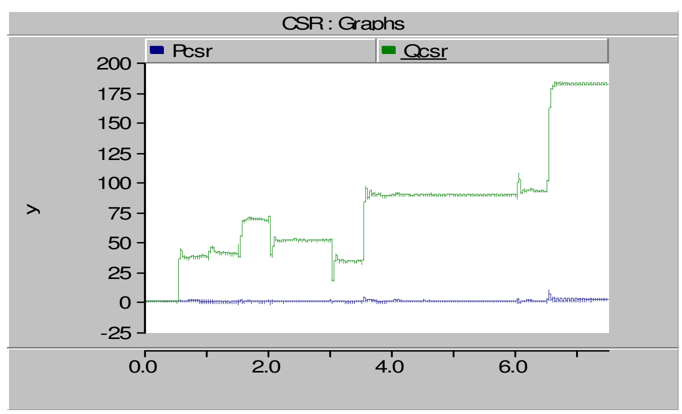

Fig. 6. P, Q Variation in CSR during the simulation sequence.

The variation of CSR primary currents corresponding to the reactive power consumption is shown in fig.7. As explained in section II, this is the result of triggering the thyristors at appropriate firing angles calculated by the control system.

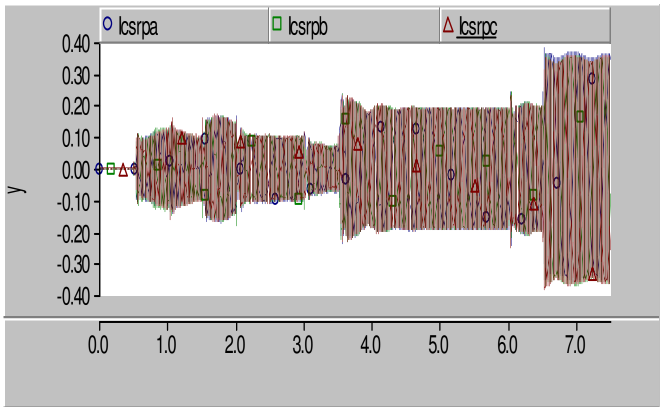

Fig. 7. Primary currents variation in CSR during the simulation sequence.

C. *Suppression of Harmonics*

The partial conduction of thyristors gives raise to the generation of harmonics in the current .The dominant harmonics are the 3rd, 5th, 7th and 11th harmonics. The tertiary winding (Δ) provided in the RT takes care of the 3rd while the 5th, 7th and 11th harmonic filters connected across the tertiary mitigate the corresponding harmonic frequencies. The harmonics are analyzed using the FFT block in PSCAD and are found to be much lower than the permissible limits. The same can be observed visually by comparing the primary and the secondary waveforms during the same time interval. Fig. 8 shows both secondary and primary current waveforms between t=2.380s to 2.480s during which CSR is consuming around 51 MVAR which is 28.3% of the actual capacity. Under full conduction i.e. at 180 MVAR capacity primary and secondary current waveforms of are shown in fig.9 for comparison. It can be seen that secondary and primary currents are totally free from harmonics.

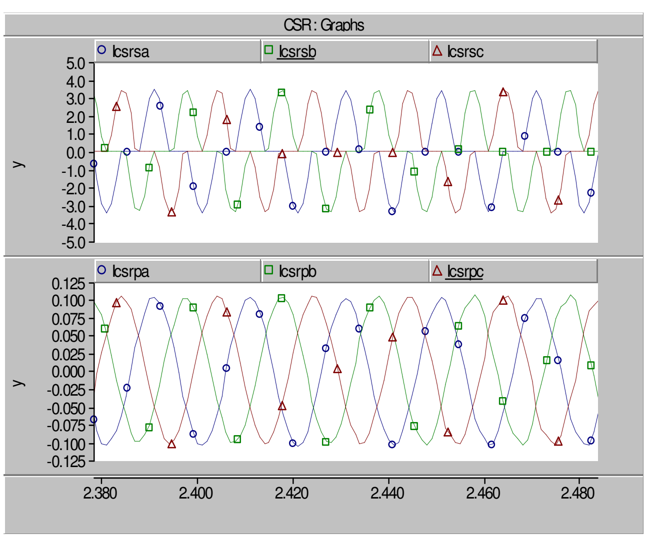

Fig. 8.Chopped secondary currents (Icsrsa, Icsrsb, Icsrsc). Corresponding primary currents (Icsrpa, Icsrpb, Icsrpc).

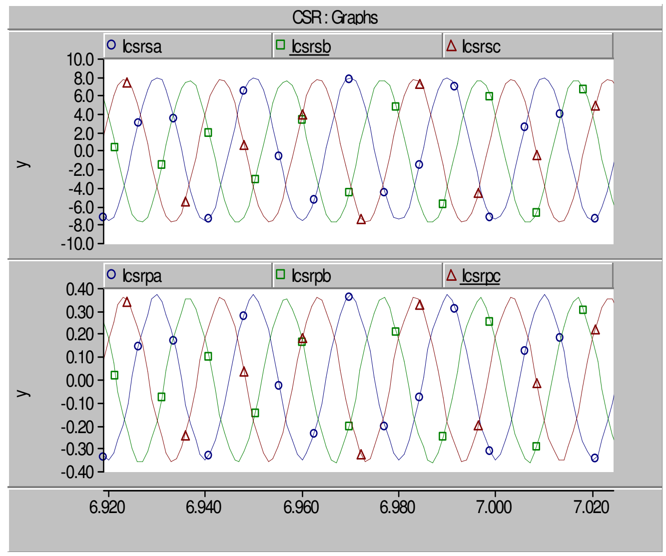

Fig. 9. Secondary currents at full conduction (Icsrsa, Icsrsb, Icsrsc). Corresponding primary currents (Icsrpa, Icsrpb, Icsrpc).

D. *Transient response for load throw off*

The advantage of thyristor control is the fast response which will be of great benefit for sudden changes in the power system conditions. A total load throw off is simulated by switching off the load from 480MW to 0 MW. CSR quickly responds to the changes in the voltage and comes into full conduction as shown in Fig. 10. CSR comes into conduction from the next half a cycle and takes around 30ms to settle.

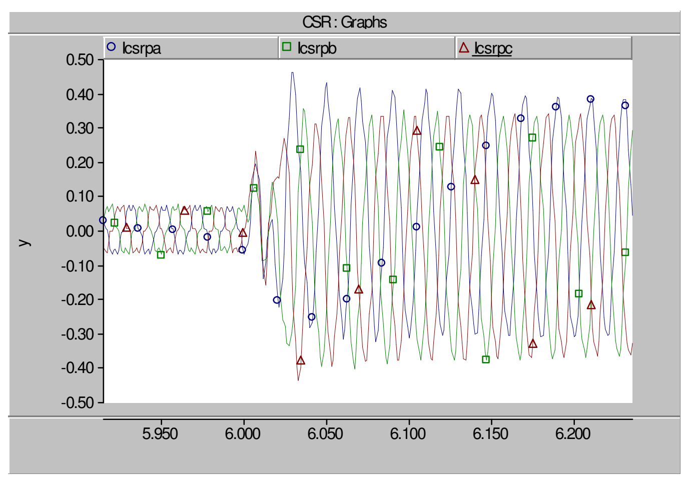

Fig. 10. Response of CSR for sudden load throw off.

The effect fast response is to limit the over voltage on the SS bus. Under the same conditions, breaker switched reactors are used for the same purpose with a minimum delay of 100ms. The corresponding waveform of the bus voltage in this case is compared with the one with CSR as shown in Fig. 11.

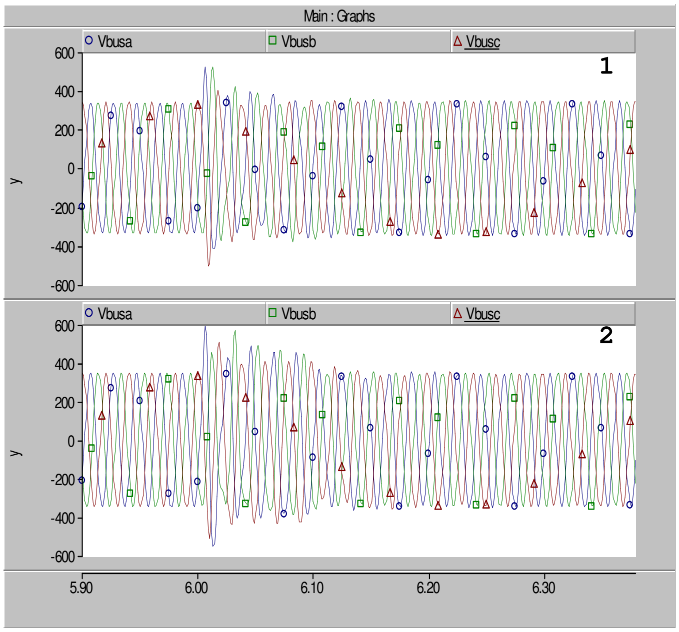

Fig. 11. Load throw off effect on the bus voltage.
1) With CSR 2) With breaker switched reactors.

V. Conclusions

The simulation studies prove that the CSR developed can be effectively used for the management of bus voltage in a EHV sub station. The main equipment RT being a simple transformer type, can be designed as a single three phase unit or as three single phase units. There is no restriction for selecting the suitable capacity of reactor for any specific location.

The application of CSR for this purpose provides economic benefits in terms of space and equipment. As a single large equipment compared to individual shunt reactor units, CSR occupies less space and the individual switchgear, protection and other substation equipment reduce in quantity. The filters required along with CSR are effective in mitigating the harmonics produced during partial conduction of thyristors.

The CSR control system being automatic and local bus voltage dependent, is simple, reliable and fast. Thus it is technically superior to manual switching of shunt reactors which is the existing practice in most of the EHV substations. The problems associated with reactor switching can be averted with the use of CSR.

VI. Acknowledgment

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VIII. Biographies

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