Composite Power System Reliability Improvement using TCSC

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Abstract— FACTS technologies can have major positive impacts on power system reliability performance and the actual benefits obtained can be assessed using suitable models and practice. Emerging techniques for composite power system reliability evaluation mainly focus on conventional generation and transmission facilities. In this paper, improvement of Reliability in composite electric power system is examined by incorporating Thyristor Controlled Series Capacitor (TCSC). A 6 bus RBTS (Roy Billinton Test system) is considered to show major improvement in reliability. A state space reliability model of multi-module TCSC has been developed and incorporated in the system. Load point & System indices performances are presented to examine the impact of TCSC on the composite electric power system reliability. Investigation results show a significant improvement in the Load point & system indices when utilizing TCSC.

Index Terms—TCSC; RBTS; Load Indices, System Indices, State Space, Composite Power System.

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1 Introduction

Flexible AC transmission system (FACTS) technology is the ultimate tool for getting the most out of existing equipment via faster control action and new capabilities. The most striking feature is the ability to directly control transmission line flows by structurally changing parameters of the fast switching.

Thyristor Controlled Series Capacitor (TCSC) is an important FACTS component which makes it possible to vary the apparent impedance of a specific transmission line so as to force power flow along a path. This controlled impedance [1] can be programmed to react in a planned way to contingencies so as to greatly enhance power system security. Using this approach [2] it is possible to operate stably at power levels well beyond those for which the system was originally intended. Addition of capacitors in series with the transmission line is called series compensation, it can be fixed, and i.e. capacitance in the line remains fixed and cannot be altered [3-4]. It is also possible to provide alteration of series capacitance by means of thyristors [5-6]. Such a system becomes Flexible AC Transmission System (FACTS) [7-8].

In this paper, the impact of TCSC on composite electric power system reliability of 6 bus RBTS is examined. TCSCs are employed in a system to adjust the transmission infeed impedances and therefore, increase the transmission system capacity without increasing the system fault current levels [9-10]. Load point & system indices performances are presented to examine the impact of TCSC on the 6 bus RBTS test system.

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2 Thyristor Controlled Series Capacitor

Fig. 1 shows a TCSC module [1] with different protection elements. Basically it comprises a series capacitor C, in parallel with a Thyristor Controlled Reactor (TCR) Ls. A Metal Oxide Varistor (MOV) essentially a nonlinear resistor is connected across the series capacitor to prevent the occurrence of high capacitor over voltage. Not only does the MOV limit in the circuit even during fault conditions, it helps to improve the transient stability. A circuit breaker is also installed across the TCSC module to bypass it if a severe fault or equipment malfunction [1] occurs. A current limiting inductor, L_d is incorporated in the circuit to restrict both the magnitude and the frequency of the capacitor current during the capacitor bypass operation.

It consists of series compensating capacitor shunted by a thyristor controlled reactor. In a practical TCSC implementation, several such basic compensators may be connected in series to obtain the desired voltage rating and operating characteristics. Basic idea behind the TCSC scheme is to provide a continuously variable capacitor by means of partially canceling the effective compensating capacitance by the TCR.

TCR at fundamental system frequency [7] is continuously variable reactive impedance, controllable by delay angle α. The steady state impedance of the TCSC is that of a parallel LC circuit, consisting of a fixed capacitive impedance, X_C, and a variable inductive impedance $X_L(\alpha)$, i.e.,

$$X_{TCSC}(\alpha) = \frac{X_C X_L(\alpha)}{X_L(\alpha) - X_C} \tag{1}$$

$$X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - \sin 2\alpha} \qquad X_L \le X_L(\alpha) \le \infty \tag{2}$$

$X_L = \omega L$ and α is delay angle measured from the crest of the capacitor voltage.

In each module, the capacitor bank is provided with a parallel thyristor controlled inductor that circulates current pulses which add in phase with the line current. This boosts the capacitor voltage beyond the level that would be obtained by the line current alone. Each thyristor is triggered once per cycle and has a conduction interval that is shorter than a half cycle of the rated frequency.

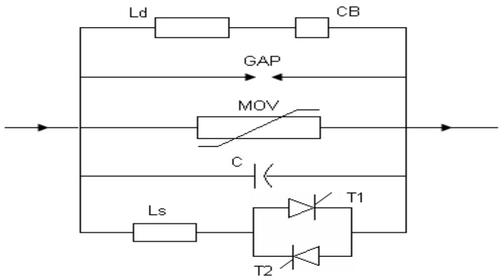

Fig. 1: Practical TCSC

If the additional voltage created by the circulating current pulses is controlled to be proportional to the line current, the transmission system will perceive to the TCSC as having a virtually increased reactance beyond the physical reactance [6] of the capacitor. The control and protection of TCSC are partitioned in two levels, common and module [2]. Common level protection detects problems affecting all modules; bypass breaker is used for bypassing all modules. Modules level protection detects problems affecting a single module.

3 Reliability Analysis of TCSC

The availability and reliability of a TCSC depends on the performance of each element in the TCSC. For a multi module TCSC, two different types of failure modes can be assigned to each module. The cause of outage in only the module itself refers to first cause eg. capacitor failure, the cause of outage of all M-modules refers to second cause eg. Varistor failure.

The reliability analysis of TCSC is determined by the state-space model. In the state space model, only the first failure mode is considered to cause the module to be transferred to the down state. Based on the two state models, once a module is declared failed, it is not available for line compensation. The steady state probabilities P_1 & P_2 for the up & down states are:

$$P_1 = \frac{\mu}{\mu+\lambda} \qquad P_2 = \frac{\lambda}{\mu+\lambda} \qquad (3)$$

where λ is failure rate, μ is reapir rate

In Fig. 2, the state space representation of single module TCSC is shown. Each state is represented by rectangle block which enclosed left side number which is state number. Emergency state, state 3 is a transition state between states 1, 2 & 4. The number of states is increased as the number of modules increases.

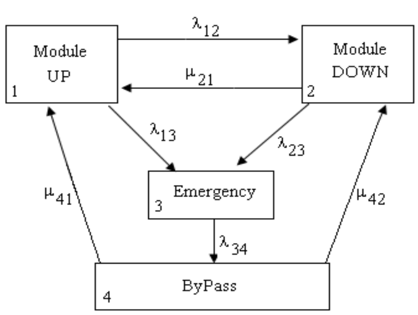

Fig. 2: State Space Representation of TCSC

A control circuit is present in the TCSC model so that all the components are controlled by using the controller. If the controller fails the TCSC goes into bypass [1] state. The entire system may be in state 3 when the bypass (i.e. tripping circuits, relays etc.) fails, where the component is replaced by using a spare component. As one module is insufficient for power transmission, analysis is carried out for different modules like 2, 3 etc.

Fig. 3, 4, 5, 6, 7 & 8 shows the state space diagram of 2, 3, 4, 5, 6 & 7 modules TCSC with bypass and emergency states respectively.

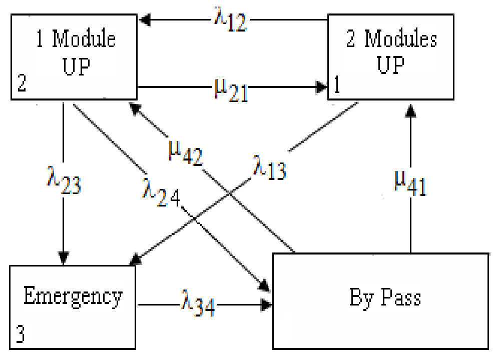

Fig. 3: State space diagram of 2 modules TCSC

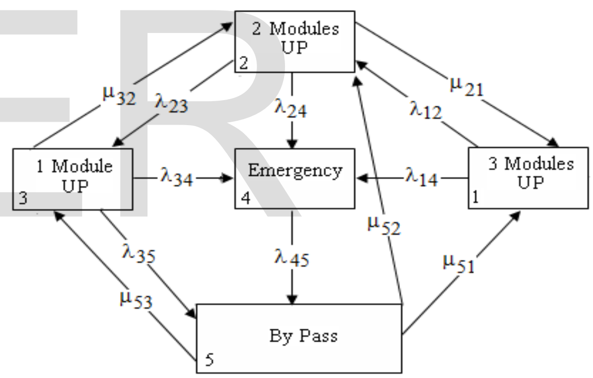

Fig. 4: State space diagram of 3 modules TCSC

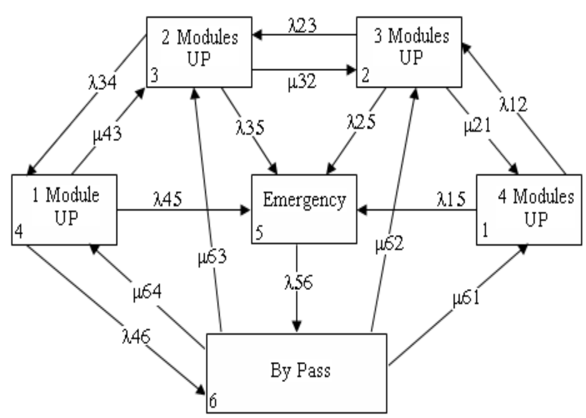

Fig. 5: State space diagram of 4 modules TCSC

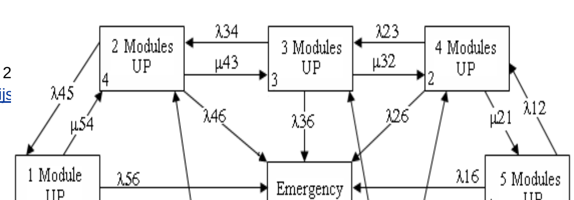

Fig. 6: State space diagram of 5 modules TCSC

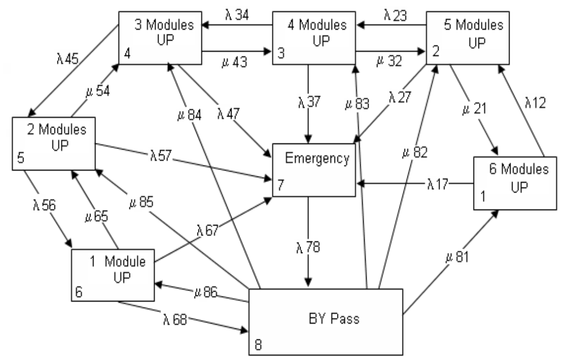

Fig. 7: State space diagram of 6 modules TCSC

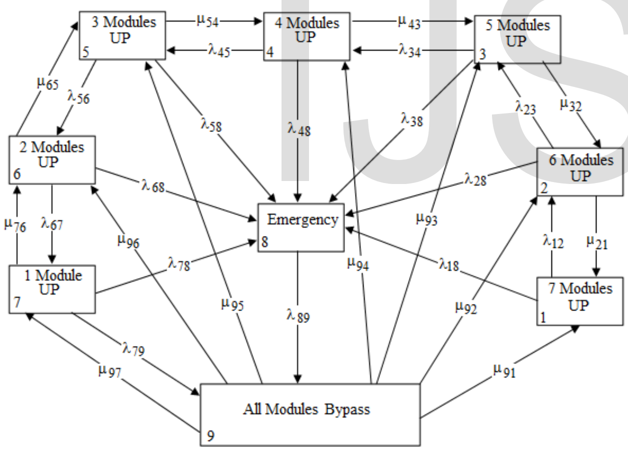

Fig. 8: State space diagram of 7 Modules TCSC

The transition rates i.e., λ and μ are considered as 0.7 f/yr and 150hr respectively [3]. Availability & unavailability of different modules of TCSC is shown in Table 1.

TABLE 1
AVAILABILITY & UNAVAILABILITY OF DIFFERENT MODULES

Modules	Availability	Unavailability
2	0.995371	0.004629
3	0.994594	0.005406
4	0.993628	0.006372
5	0.992594	0.007406
6	0.991834	0.008166
7	0.990346	0.009654
8	0.980671	0.019329

The availability of different modules is decreasing as the number of elements in the state is increasing. Depending on the capacity of the transmission line it is justified to use 7 modules UPFC depending on the Limiting state probabilities which are calculated but not presented here..

4 RELIABILITY INDICES

4.1 Load Point Indices:

The following are the expressions [4] to determine the load point indices of the given system

$$\text{Probability of Failure} = \sum_j P_j P_{kj}$$

$$\text{Frequency of Failure} = \sum_j F_j P_{kj}$$

$$\text{Expected Load Curtailed} = \sum_j L_{kj} F_j (\text{MW})$$

$$\text{Expected Energy Not Supplied (EENS)} = \sum_j L_{kj} P_j * 8760 \qquad (4)$$

Where: j is an outage condition in the network
P_j is the state probability of the outage event j
F_j is frequency of occurrence of the outage event j
P_{kj} is the probability of load curtailment at bus k during outage event j
L_{kj} is the load curtailment at bus k during outage event j
D_{kj} is the duration in hours of load curtailment at bus k during outage event j.

4.2 System Indices:

$$\text{Bulk Power Supply Disturbances (BPSD)} = \sum_k \sum_j F_j$$

Bulk Power Interruption Index (BPII)

$$= \frac{\sum_k \sum_j L_{kj} F_j}{L_s} (\text{MW / MW} - \text{Year})$$

Bulk Power Energy Curtailment Index (BPECI) (Severity Index) (5)

$$= \frac{\sum_k \sum_j 60 * L_{kj} D_{kj} F_j}{L_s} (\text{system min})$$

Where L_s is the total system load

5 RELIABILITY STUDY RESULTS

It is important to appreciate that, if these indices are calculated for a single load level and expressed on a base of one year, they should be designated as *annualized* values. Annualized indices calculated at the system peak load level are usually much higher than the actual annual indices.

5.1 System Indices

The system indices for a 6 Bus RBTS are calculated by changing the number of modules of TCSC and are tabulated in Table 2 and represented in Fig. 9, 10 & 11

TABLE 2:
SYSTEM INDICES OF 6 BUS RBTS WITH TCSC MODULES

No. of Modules	BPSD	BPII	BPECI
2	17.54	0.3462	284.36
3	17.17	0.3458	284.01
4	16.85	0.3451	283.92
5	16.58	0.345	283.87
6	16.51	0.3448	283.85
7	16.62	0.3452	283.88
8	16.84	0.3456	283.91

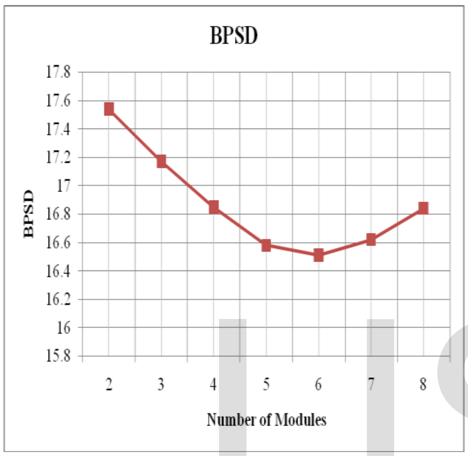

Fig.9: BPSD vs Number of Modules of TCSC in 6 Bus RBTS

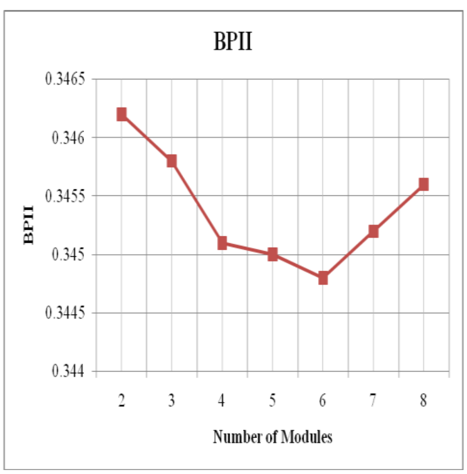

Fig. 10: BPII vs Number of Modules of TCSC in 6 Bus RBTS

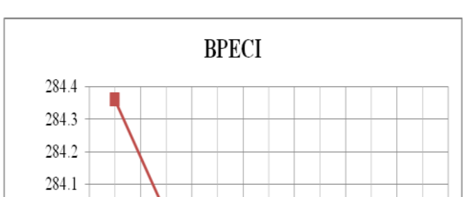

Fig. 11: BPECI vs Number of Modules of TCSC in 6 Bus RBTS

Systems indices via, BPSD, BPII & BPECI are calculated with respect to the generation capacity (MW) by considering 7 modules TCSC for 6 Bus RBTS. The System Indices are tabulated in Table 3.

TABLE 3:
SYSTEM INDICES VS GENERATION CAPACITY – WITH 7 MODULES TCSC

Generation Capacity (MW)	Load Demand (MW)	BPSD	BPII	Severity Index
240	185	14.35	0.246	259.86
270	203.5	14.57	0.261	263.66
300	222	15.02	0.269	268.71
330	240.5	16.72	0.283	271.93
345	259	20.63	0.315	288.32
360	277.5	28.146	0.364	297.64

An attempt has been made by increasing the capacity of the TCSC from 100MW to 180MW in step increase of 20MW to determine the System Indices. The System Indices are tabulated in Table 4 and represented in Fig. 12, 13 & 14

TABLE 4:
SYSTEM INDICES FOR MODIFIED 6 BUS RBTS AT GENERATION CAPACITY OF 240MW

TCSC Capacity	BPSD	BPII	Severity Index
100	39.98	0.562	389.16
120	30.62	0.432	343.79
140	28.36	0.416	342.11
160	28.11	0.408	341.86
180	27.86	0.405	340.12

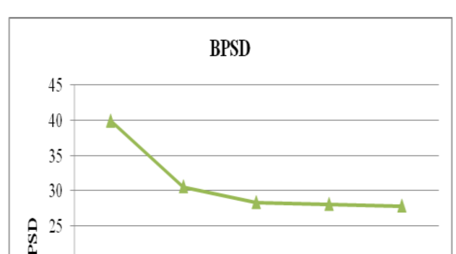

Fig. 12: BPSD vs TCSC Capacity of 6 Bus Modified RBTS

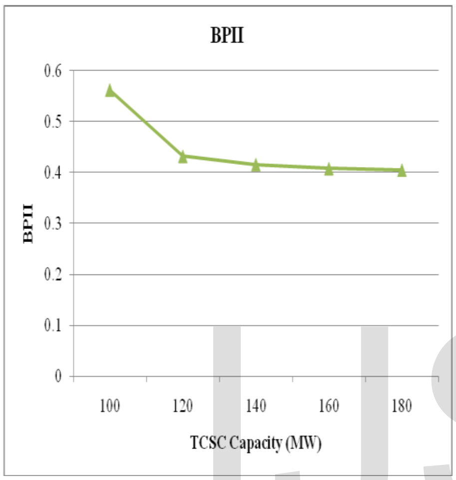

Fig. 13: BPII vs TCSC Capacity of 6 Bus Modified RBTS

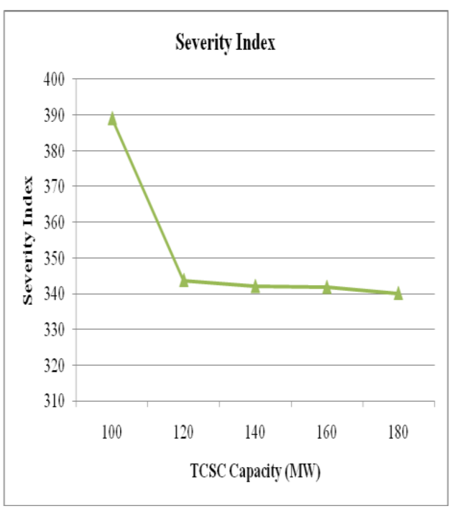

Fig. 14: BPECI vs TCSC Capacity of 6 Bus Modified RBTS

5.2 Probability of Failure & EENS

Probability of failure = $Q_K = \sum_j P_j * P_{kj}$

Expected Energy Not Supplied = $\sum_j L_{kj} * P_j * 8760(MWh)$ (6)

Probability of failure & EENS are calculated for a 6 bus RBTS at each and every bus in the system and tabulated in Table 5 and represented in Fig 15 & 16

TABLE 5:
PROBABILITY OF FAILURE & EENS VS BUS NUMBER

Bus No.	Probability of Failure	EENS
1	0.008411	129.94
2	0.008463	99.98
3	0.008458	395.43
4	0.008456	183.94
5	0.008457	97.58
6	0.008472	298.66

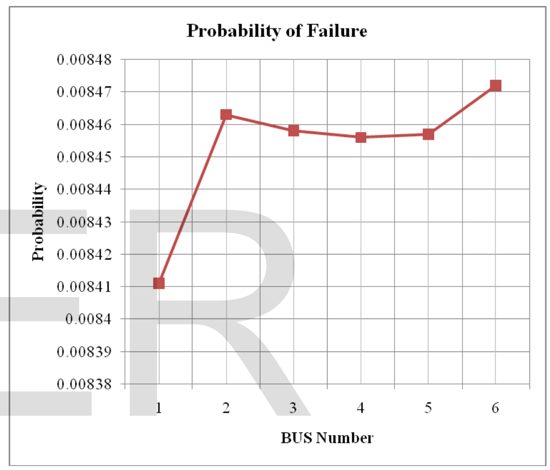

Fig. 15: Probability of Failure vs Bus Number

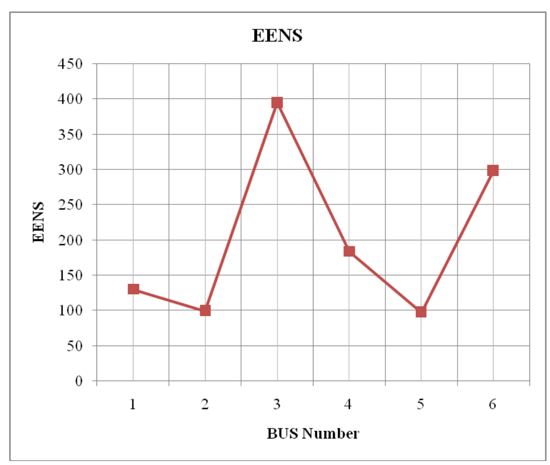

Fig. 16: EENS vs Bus Number

Similarly the probability of failure & EENS for 6 Bus RBTS is calculated with different modules of TCSC which are tabulated in Table 6 & 7 respectively.

Table 6
PROBABILITY OF FAILURE FOR 6 BUS RBTS WITH DIFFERENT MODULES OF TCSC

Module No.	Bus No. 1	2	3	4	5	6
2	0.008536	0.008516	0.008513	0.008511	0.008507	0.008634
3	0.008511	0.008507	0.008501	0.008498	0.008496	0.008602
4	0.008459	0.008498	0.008489	0.008486	0.008489	0.008562
5	0.008416	0.008491	0.008481	0.008479	0.008480	0.008511
6	0.008411	0.008463	0.008458	0.008456	0.008457	0.008472
7	0.008417	0.008475	0.008474	0.008472	0.008470	0.008489
8	0.008426	0.008494	0.008496	0.008494	0.008491	0.008496

Table 7
EENS FOR 6 BUS RBTS WITH DIFFERENT MODULES OF TCSC

Module No.	Bus No. 1	2	3	4	5	6
2	132.64	102.34	398.64	186.42	100.24	302.84
3	132.12	101.96	398.14	185.96	99.38	301.63
4	131.54	101.12	397.58	185.13	98.66	300.75
5	131.08	100.78	396.91	184.66	97.81	299.54
6	129.94	99.98	395.43	183.94	97.58	298.66
7	130.16	100.36	396.16	184.52	98.12	299.18
8	130.84	101.03	396.88	185.66	99.42	300.11

6 CONCLUSIONS

In this paper, the results of studies conducted on a composite electric power system model to investigate the impact of TCSC on the system reliability are presented. The analysis of 6 bus RBTS is determined when using TCSC with different modules in all the bus. From the above results, it can be concluded that seven module TCSC is suitable for the system based on the reliability of different modules depending upon the generation & transmission capacity. Apart from the reliability, system indices, probability of failure & EENS shows a major improvement in the system of different modules for all the buses. Studies are analyzed to help optimize FACTS devices to be used in a system.

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