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Reliability Analysis of Composite Power System using FACTS Controllers – Combination of TCSC & UPFC

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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, the impact of FACTS controllers on Composite Power System Reliability on IEEE 24 Bus Reliability Test System (RTS) is examined by incorporating the controller devices. A novel approach of composite power system has been presented by incorporating FACTS controllers in the RTS system in all the transmission lines for determining the system reliability. In this paper, an attempt is made to study the impact of Thyristor Controlled Series Capacitor (TCSC) & Unified Power Flow Controller (UPFC) combination on composite power system by using state space enumeration techniques. In order to improve system performance the impact of the combination of TCSC & UPFC has been considered. Investigation results show a significant improvement in the Load point, system indices, probability of failure & Expected Energy Not Supplied (EENS) in all transmission lines & generation capacity.

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.

Unified Power Flow Controllers (UPFC) and Thyristor Controlled Series Capacitor (TCSC) [1-3] are the most versatile FACTS [2] devices that has emerged for the control and optimization of power flow in electrical power transmission systems [4-5]. They offer major potential advantages for static and dynamic operation [6-8] of transmission lines.

In this paper, the impact of the combination of UPFC & TCSC on composite electric power system reliability is examined. Load point & system indices [9-11] performances are presented to examine the impact of the combination on the IEEE 24 Bus RTS.

2. Reliability Analysis of UPFC & TCSC

The Single diagram of IEEE 24 Bus Reliability Test System (RTS) is shown in Fig. 1.

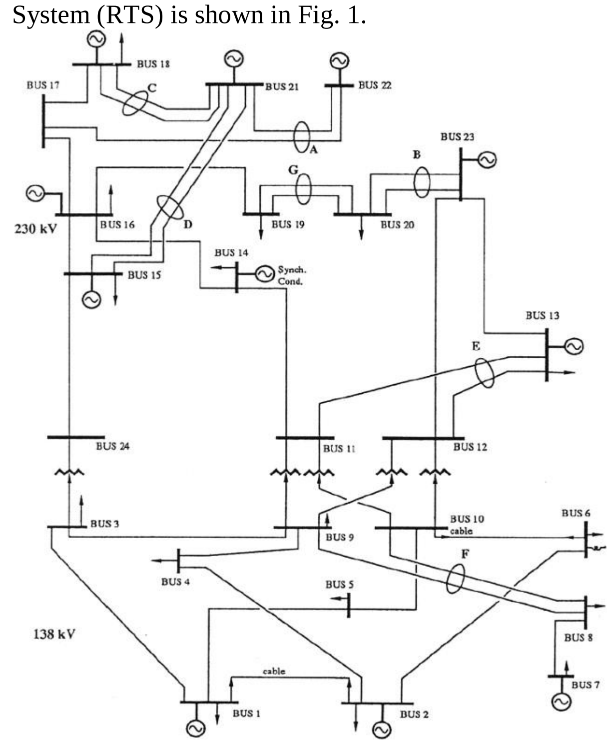

Fig 1: Single Line diagram of IEEE 24 Bus – Reliability Test System

Average load at the buses is 235.87MW. Depending on the with stand capacity, repair rate and failure rate, it is feasible to have the combination of 3 module UPFC & 3 module TCSC in all the transmission line except in 1 to 2, 1 to 4, 1 to 5, 2 to 2, 2 to 4, 2 to 5, 3 to 2, 3 to 4 and 3 to 5 lines. In these lines the maximum power transmitted is only 97 MW throughout the year. Based on the above criteria, only 1 module TCSC & 1 module

UPFC are incorporated in the above 9 transmission line with 20 % increase in their individual capacities.

Stage 1: 3 Modules TCSC – 3 * 40MW – 120MW
3 Modules UPFC – 3 * 40MW – 120MW
Total – 240MW

Stage 2: with 20% increase in the individual capacity of TCSC & UPFC (for 1 to 2, 1 to 4, 1 to 5, 2 to 2, 2 to 4, 2 to 5, 3 to 2, 3 to 4 and 3 to 5 transmission lines only)

1 Module TCSC – 1 * 48MW – 48MW
1 Module UPFC – 1 * 48MW – 48MW
Total – 96MW

Stage 1 and Stage 2 are incorporated in the 24 Bus System independent of the load demand. The reliability analysis is carried out by incorporating Stage 1 and 2 simultaneously in the system. Availability and unavailability of the two stages are calculated by State Space representation.

2.1 RLD using State Space representation

Stage 1

The Reliability Logic Diagram (RLD) of IEEE 24 Bus RTS for the combination of TCSC & UPFC with 3 modules each using state space representation is shown in Fig. 2.

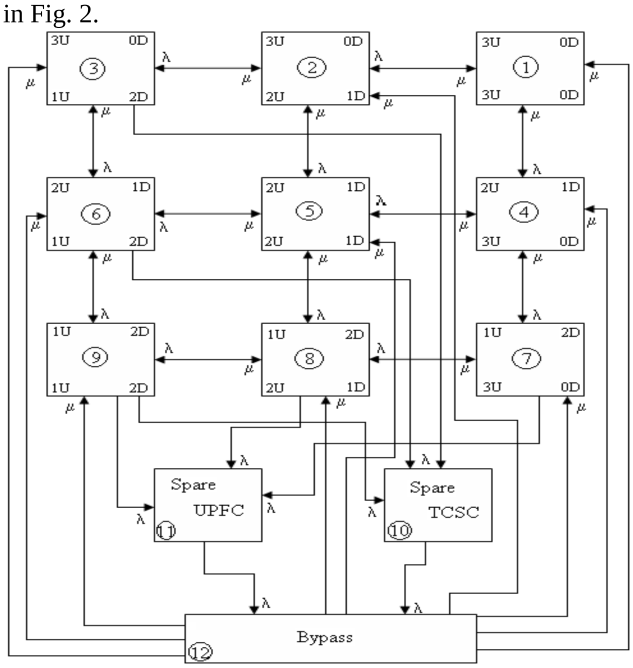

Fig. 2: RLD for Combination of TCSC & UPFC (Stage 1) using State – Space Representation

Results

From the above, the Limiting State Probabilities [5] can be obtained.

Consider the data:

Failure rate (**λ**) = 0.7 f/yr

Repair Rate (**μ**) = 150 hrs of each component,

Individual LSPs are:

$P_1 = 0.97642$ $P_2 = 0.012402$ $P_3 = 0.00025$
$P_4 = 1.3548*10^{-3}$ $P_5 = 2.709*10^{-4}$ $P_6 = 5.4194*10^{-5}$
$P_7 = 3.847*10^{-7}$ $P_8 = 4.6684*10^{-8}$ $P_9 = 6.7134*10^{-9}$
$P_{10} = 0.008524$ $P_{11} = 0.008524$ $P_{12} = 8.3216*10^{-12}$

$P_{UP} = P_1 + P_{10} + P_{11} = 0.97642 + 0.008524 + 0.008524$
$= \mathbf{0.985666}$

$P_{DOWN} = 1 - P_{UP} = \mathbf{0.014334}$

Stage 2

The state space representation for stage 2 of combination of TCSC and UPFC is shown in Fig. 3. In Fig. 3, the blocks 1 to 7 represent transition states. The upper transition rates are of UPFC and lower transitional rates are of TCSC. Here, 4 states are considered because the remaining states will represent the failed states as they cannot withstand rated capacity. Stage 2: (for 1 to 2, 1 to 4, 1 to 5, 2 to 2, 2 to 4, 2 to 5, 3 to 2, 3 to 4 and 3 to 5 transmission lines only)

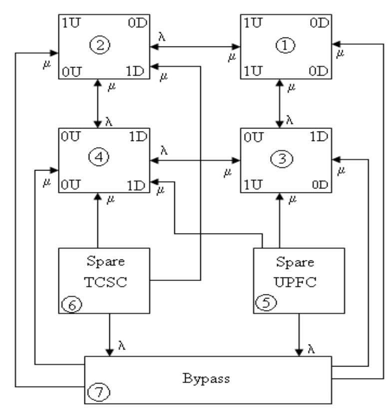

Fig. 3: RLD for Combination of TCSC & UPFC (Stage 2) using State – Space Representation

Results

Considering the data of **λ** and **μ** as given above

Individual LSPs are:

$P_1 = 0.979347$ $P_2 = 0.005871$ $P_3 = 0.001405$
$P_4 = 0.000932$ $P_5 = 0.005989$ $P_6 = 0.005989$
$P_7 = 0.000467$

$P_{UP} = P_1 + P_5 + P_6 = 0.979347 + 0.003946 + 0.003946$
$= \mathbf{0.991325}$

$P_{DOWN} = 1 - P_{UP} = \mathbf{0.008675}$

In Table 1, the results of availability and unavailability of IEEE 24 bus RTS for stage 1 & stage 2 are presented.

Table 1: Availability & Unavailability of different Stages

Stage	Modules		Availability	Unavailability
	TCSC	UPFC		
1	3	3	0.985666	0.014334
2	1	1	0.9991325	0.008675

From Table 1, it can be observed that as the no. of stages increase, the availability will decrease although it satisfies the required performance

3. System Indices

System Indices like BPSD, BPII & BPECI [1-3, 5] are calculated for IEEE 24 bus RTS system by incorporating the combination of FACTS devices.

Bulk Power Supply average curtailment / disturbance (BPSD),

$$BPSD = \frac{\sum_{k} \sum_{j \in x,y} L_{kj} F_j}{\sum_{j \in x,y} F_j} \quad (1)$$

$$= \frac{268833 * 0.98912}{3.632} = 732.18 \text{ MW/disturbance}$$

Bulk Power Interruption Index (BPII),

$$= \frac{\sum_{k} \sum_{j \in x,y} L_{kj} F_j}{L_s} \quad (2)$$

$$= \frac{5939609 * 0.98912}{3405} = 1.7254 \text{MW / MW-yr}$$

Bulk Power Energy Curtailment Index (BPECI),

$$= \frac{\sum_{K} \sum_{j \in x,y} L_{Kj} D_{Kj} F_j * 60}{L_s} \quad (3)$$

$$= 60 * \frac{43139695 * 0.986451 * 25.47}{3405} = 1909.94$$

MWh/MW-yr

The system indices for IEEE 24 Bus RTS are presented in Table 2.

Table 2: System Indices with different FACTS Components

System Indices	Original	TCSC	UPFC	TCSC & UPFC
BPSD	817.22	784.56	780.19	732.128
BPII	2.620	2.0156	1.9987	1.7254
BPECI	2211.640	1987.41	1924.65	1909.94

From Table 2, it can be observed that the system indices viz. BPSD, BPII & BPECI are reducing when using FACTS controllers in the system (IEEE 24 bus). It can be noted that when the combination of TCSC & UPFC [1] is incorporated in the system at different locations, the system indices are gradually reduced when compared with other components.

System Indices (BPSD, BPII and BPECI) are further calculated [4] at each bus as shown in Tables 3 to 5. The graphical forms of the Tables 3 to 5 are shown in Figs. 4 to 6.

Table 3: BPSD at each Bus with different FACTS

Bus No.	BPSD			
	Original	TCSC	UPFC	UPFC & TCSC
1	817.22	784.56	780.19	732.128
2	817.22	784.56	780.19	732.128
3	817.22	784.56	777.18	729.118
4	817.22	784.56	780.09	732.028
5	817.22	784.56	780.19	732.128
6	817.22	784.56	780.19	732.128
7	816.45	783.79	779.42	731.358
8	817.22	784.56	780.19	732.128
9	817.22	784.56	778.24	730.178
10	817.22	784.56	780.19	732.128
11	817.22	784.56	780.19	732.128
12	817.22	784.56	780.01	731.948
13	817.22	783.91	779.54	731.478
14	817.22	784.56	780.19	732.128
15	817.22	784.56	780.19	732.128
16	817.22	784.56	780.19	732.128
17	817.22	784.56	779.12	731.058
18	817.22	784.56	780.19	732.128
19	817.22	784.56	780.19	732.128
20	817.22	784.56	780.19	732.128
21	817.22	784.56	780.19	732.128
22	817.22	784.56	780.19	732.128
23	817.22	784.56	776.92	728.858
24	817.22	784.56	780.19	732.128

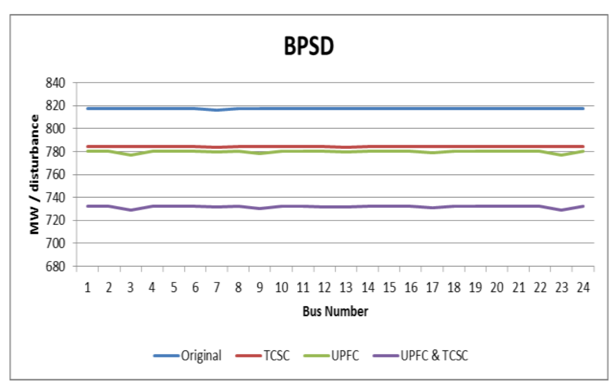

Fig. 4: BPSD at each Bus with different FACTS Components

From Table 3, it can be observed that, Bulk Power Supply Disturbance is decreasing when the combination of TCSC & UPFC is incorporated into the system rather than the system when incorporated by TCSC, UPFC independently. From the graphical form in Fig. 4 it can be clearly seen that there is a reduction in BPSD.

Table 4: BPII at each Bus with different FACTS

Bus No.	BPII			
	Original	TCSC	UPFC	UPFC & TCSC
1	2.62	2.0156	1.9987	1.7254
2	2.62	2.0156	1.9987	1.7254
3	2.62	2.0001	1.9832	1.7099
4	2.62	2.0156	1.9987	1.7254
5	2.62	2.0156	1.9987	1.7254
6	2.62	2.0156	1.9987	1.7254
7	2.611	2.0066	1.9734	1.7001
8	2.62	2.0156	1.9987	1.7254
9	2.62	2.0156	1.9987	1.7254
10	2.62	2.0156	1.9987	1.7254
11	2.62	2.0156	1.9987	1.7254
12	2.62	2.0156	1.9987	1.7254
13	2.62	2.0072	1.9903	1.717
14	2.62	2.0002	1.9833	1.717
15	2.62	2.0072	1.9903	1.717
16	2.62	2.0156	1.9987	1.7254
17	2.62	2.0156	1.9987	1.7254
18	2.62	2.0156	1.9987	1.7254
19	2.62	2.0156	1.9987	1.7254
20	2.62	2.0156	1.9987	1.7254
21	2.62	2.0156	1.9987	1.7254
22	2.62	2.0156	1.9987	1.7254
23	2.62	2.0156	1.9753	1.702
24	2.62	2.0156	1.9987	1.7254

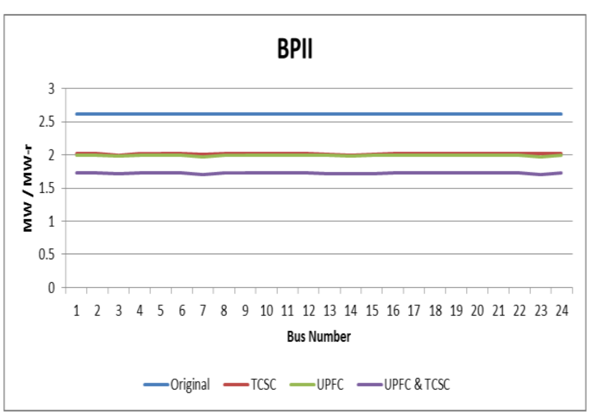

Fig. 5: BPII of IEEE 24 Bus at each Bus with different FACTS Components

From Table 4, it can be observed that, Bulk Power Interruption Index is decreasing when the combination of TCSC & UPFC is incorporated into the system rather than the system when incorporated by TCSC, UPFC independently. Once the Interruption Index is decreasing obviously the system performance increases. The graphical form in Fig. 5 shows clearly the reduction in BPII.

Table 5: BPECI at each Bus with different FACTS

Bus No.	BPECI			
	Original	TCSC	UPFC	UPFC & TCSC
1	2211.64	1987.41	1922.78	1908.07
2	2211.64	1987.41	1924.65	1909.94
3	2211.04	1985.67	1922.91	1908.2
4	2211.64	1987.41	1923.91	1909.2
5	2211.64	1987.41	1924.65	1909.94
6	2211.64	1986.22	1923.46	1908.75
7	2205.82	1979.24	1916.48	1901.77
8	2211.64	1987.41	1924.65	1909.94
9	2211.64	1987.41	1918.44	1903.73
10	2211.64	1987.41	1924.65	1909.94
11	2211.39	1987.16	1924.4	1909.69
12	2211.64	1985.91	1923.15	1908.44
13	2211.64	1987.41	1924.65	1909.94
14	2207.87	1983.64	1920.88	1906.17
15	2211.64	1987.41	1924.65	1909.94
16	2211.64	1987.41	1924.65	1909.94
17	2211.64	1987.41	1924.65	1909.94
18	2211.64	1986.22	1923.46	1908.75
19	2211.64	1986.22	1923.46	1908.75
20	2211.64	1986.22	1923.46	1908.75
21	2210.32	1986.22	1910.11	1895.4
22	2211.64	1986.22	1923.46	1908.75
23	2211.64	1986.22	1912.33	1897.62
24	2211.64	1986.22	1923.46	1908.75

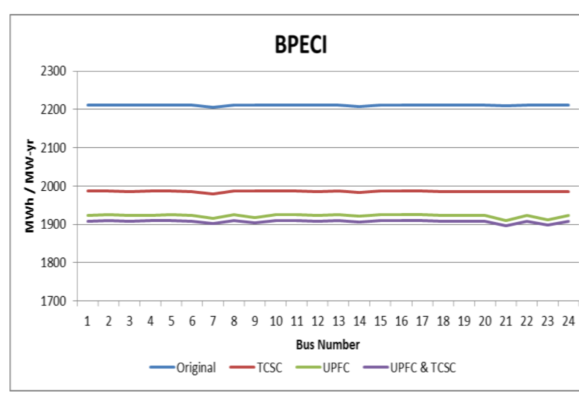

Fig. 6: BPECI of IEEE 24 Bus at each Bus with different FACTS Components

From Table 5, it can be observed that, Bulk Power Energy Curtailment Index is decreasing when the combination of TCSC & UPFC is incorporated into the system rather than the system when incorporated by

TCSC, UPFC independently. Once the Curtailment Index decreases obviously the system performance increases. The graphical form in Fig. 6 shows clearly the reduction in BPECI.

4. Probability of Failure & EENS

Probability of Failure = $Q_K = \sum_j P_j * P_{kj}$ (4)

Where P_j = Probability of existence of outage j

P_{kj} = Probability of the load at bus K exceeding the maximum load that can be supplied at that bus during the outage j.

$EENS = \sum_j L_{kj} * P_j * 8760 (MWh)$ (5)

Further, Probability of Failure & EENS of the system is also calculated at each bus which is presented in Tables 6 & 7 and graphically in Figs. 7 & 8 respectively.

Table 6: Probability of Failure at different Buses

Bus No.	Probability of Failure			
	Original	TCSC	UPFC	UPFC & TCSC
1	0.0752745	0.0751432	0.0749987	0.0741948
2	0.0752745	0.0751432	0.0749987	0.0741948
3	0.0752745	0.0751338	0.0749587	0.0741348
4	0.0752746	0.0751432	0.0747987	0.0741948
5	0.0752746	0.0751534	0.0749987	0.0741958
6	0.0752749	0.0751432	0.0749987	0.0741548
7	0.0752211	0.0750012	0.0747641	0.0740012
8	0.0752745	0.0751432	0.0749957	0.0741948
9	0.0752745	0.0751232	0.0747987	0.0741978
10	0.0752745	0.0751402	0.0749987	0.0741248
11	0.0752745	0.0751432	0.0749977	0.0741948
12	0.0752745	0.0751132	0.0747985	0.0741948
13	0.0752745	0.0751432	0.0749987	0.0741941
14	0.0752746	0.0751302	0.0748947	0.0741949
15	0.0752745	0.0751432	0.0749981	0.0741748
16	0.0752745	0.0751487	0.0749987	0.0741948
17	0.0752745	0.0751432	0.0748967	0.0741942
18	0.0752745	0.0751432	0.0749987	0.0741448
19	0.0752745	0.0751439	0.0749981	0.0741944
20	0.0752745	0.0751432	0.0749984	0.0741947
21	0.0752745	0.0751431	0.0748987	0.0741748
22	0.0752746	0.0751402	0.0749967	0.0741949
23	0.0752746	0.0751412	0.0749787	0.0740949
24	0.0752745	0.0751432	0.0749987	0.0741948

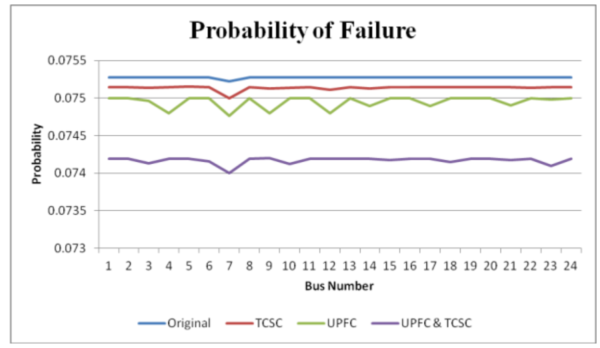

Fig. 7: Probability of Failure at different bus

From Table 6, it can be observed that, Probability of Failure is decreasing when the combination of TCSC & UPFC is incorporated into the system rather than the system when incorporated by TCSC, UPFC independently. Decrease in Probability of Failure indicates increase in the availability of the system, which leads to increase in system performance. The graphical form in Fig. 7 shows clearly the decrement of Probability of Failure at each and every bus.

Table 7: EENS at different Buses

Bus No.	EENS			
	Original	TCSC	UPFC	UPFC & TCSC
1	3981.03	3802.9	3583.68	3382.41
2	3575.56	3387.43	3168.21	2966.94
3	6635.01	6456.88	6237.66	6036.39
4	2727.83	2549.7	2330.48	2129.21
5	2617.23	2439.1	2219.88	2018.61
6	5013.68	4835.55	4616.33	4415.06
7	4605.1	4426.97	4207.75	4006.48
8	6303.26	6125.13	5905.91	5704.64
9	6450.7	6272.57	6053.35	5852.08
10	7187.92	7009.79	6790.57	6589.3
11	6781.65	6603.52	6384.3	6183.03
12	3198.47	3020.34	2801.12	2599.85
13	9768.18	9590.05	9370.83	9169.56
14	7151.29	6973.16	6753.94	6552.67
15	4684.9	4506.77	4287.55	4086.28
16	3686.14	3508.01	3288.79	3087.52
17	4368.59	4190.46	3971.24	3769.97
18	4274.7	4096.57	3877.35	3676.08
19	6671.88	6493.75	6274.53	6073.26
20	4718.24	4540.11	4320.89	4119.62
21	5719.24	5541.11	5321.89	5120.62
22	3687.19	3509.06	3289.84	3088.57
23	6781.92	6603.79	6384.57	6183.3
24	7014.67	6836.54	6617.32	6416.05

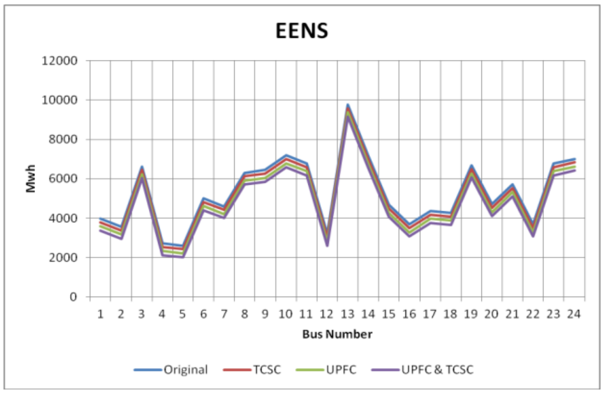

Fig. 8: EENS at different bus

From Table 7, it can be observed that, Expected Energy not supplied is decreasing when the combination of TCSC & UPFC is incorporated into the system rather than the system when incorporated by TCSC, UPFC independently. Decrease in EENS indicates increase in the availability of the system, which leads to increase in system performance. From the graphical form in Fig. 8 it can be seen clearly the decrement of EENS at each and every bus.

5. Conclusions

In this paper, the reliability analysis of IEEE 24 Bus RTS when using the combination of TCSC & UPFC is presented. Depending upon the generation & transmission line capacity, the combination of TCSC & UPFC is divided into 2 stages. Stage 1, consist 3 Modules each of TCSC & UPFC, where as Stage 2, consists 1 module of TCSC & UPFC each. Reliability analysis of the two stages is determined by using state space representation. System Indices, Probability of Failure & EENS are also calculated.

In IEEE 24 bus RTS system stage 1 & 2 are incorporated simultaneously depending on the transmission line capacity connected between different buses. System Indices, Probability of Failure & EENS are calculated for all the combinations of FACTS controllers of the system and found the combination of TCSC & UPFC is found to be best suitable for the system rather than other combinations.

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