# Performance of FACTS Devices on Power System Reliability

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# Performance of FACTS Devices on Power System Reliability

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**Abstract** Adequacy and security of the power system are authenticated by the reliability index, which is fulfilled by flexible alternating current transmission system (FACTS). This paper confers various features and modes of operation of FACTS devices and evaluates their performance on the power system reliability. The reliability evaluation on reliability test system (IEEE-RTS) is carried out using various FACTS devices like SVC, STATCOM, TCSC, and UPFC. The reliability indices are measured using sequential simulation for each defined FACTS devices. The effects of FACTS devices depend on the system severity. The comparison of each device gives a precise idea for the selection of controlling devices in the power system reliability evaluation. The result implied in the paper gives variation of system reliability in the power system network both steady-state and transient conditions. The system setting up practice using combined adequacy and security deliberation offers a bonus to reliability-based aspects.

**Keywords** System reliability · IEEE-RTS · FACTS · EENS

## 1 Introduction

The system reliability is very important in the power system to empower zero interruptions. The enhancement of system reliability, i.e., the capability to control power flow in an electric power system without altering the system and improve the power system performance is more essential. Many researchers competed the reliability analysis on power system network, but there is no typical evidence on efficient controllers used to measure the power system reliability. The reliability evaluation on vertical-integrated system was examined for bulk electrical system [1]. Power system reliability enhancement using multiple FACTS devices addressed the impact of multiple UPFC in the system reliability [2]. The term "system reliability" can be categorized into the two primary phases of system adequacy and system security. The

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hierarchical levels involved in the power system planning and reliability are classified through the functional regions of generation, transmission, and distribution [3]. The FACTS devices will reduce the failure rate and enhance reliability in the power system network. The optimized model of establishment of FACTS in the test system gives tremendous improvement in the system reliability [4–7]. The FACTS devices can be categorized in to two groups. The first group consists of thyristor switches as controlled devices like Static Var Compensator, thyristor-controlled switched capacitor, phase shifter, etc. The second group consists of self-commutated voltage source converters like static synchronous series compensator, unified power flow controller, interline power flow controller, etc. The reactive power and voltage can be controlled by FACTS devices in the renewable energy sources [8]. The interruptions in the renewable energy sources can be managed by the suitable controllers installed along with the FACTS devices to optimize the performance and to control the fluctuations in the voltage.

In this paper, the effects of FACTS devices on power system reliability are evaluated and compared by testing on an IEEE-RTS system. The dynamic evaluation of reliability through chronological simulation is given in Sect. 2. Section 3 deals with the performance indicators of power system reliability to identify EENS. Section 4 provides the effects of multiple FACTS devices on the test system and reveals the variations in expected energy not supplied. Section 5 implies the significant of results by various FACTS devices and concluded in Sect. 6

## 2 Chronological Simulation

There are many simulation models to evaluate reliability in the composite power system. The Monte Carlo simulation fetches optimal evaluation of reliability through random and stochastic approaches. The sequence or chronological simulation follows the stochastic approach with time dependent variables to achieve the statistical results. Each system state in the chronological simulation is succumbed to the sampling enforced by the previous state and evaluates the success rate. The chronological simulation is one of the highly unswerving tool based on the statistics. The correlation can be done with the samples from the previous state [9]. The complex and nonlinear load models can be characterized with the sequential simulation. If the nonlinear loads and the associated parameters are simulated in a finite time limit acquired from the reliability evaluation in the previous state. The failure and the repair rate for each sequence in the load model can be calculated for different durations through the sequential simulation. The dynamics in the load will be represented in the non-exponential form which will give perfect solution for reliability studies.

## 3 Reliability Enactment Pointers

The interruptions associated with the frequency and duration due to the outages and blackouts are reflected in the evaluation of reliability indices [10]. The performance of the power system network will be indicated by the enactment pointers which includes capacity-weighted and customer-weighted indices. The indices used to calculate expected energy not supplied are given from Eqs. (1)–(7). $U_j$, λ, $N_j$ and $P$ are unavailability (h/y), letdown rate (f/h), number of customers ($N_j$), and average load capacity (KW), respectively. The uninterrupted power supply to the customers can be authenticated by the reliability index, EENS.

$$\text{Expected Energy Not Supplied (EENS)} = \sum_{j\epsilon M}\left(U_j P_j\right) \tag{1}$$

To calculate EENS, the associated reliability indices which implies on the system interruption with respect to the duration and the frequency can be calculated

$$\text{System Average Interruption Duration Index} = \frac{\sum_{j\epsilon M}\left(U_j N_j\right)}{\sum_{j\epsilon M}\left(N_j\right)} \tag{2}$$

$$\text{System Average Interruption Frequency Index} = \frac{\sum_{j\epsilon M}\left(\lambda_j N_j\right)}{\sum_{i\epsilon M}\left(N_j\right)} \tag{3}$$

$$\text{Customer Average Interruption Duration Index} = \frac{\sum_{j\epsilon M}\left(U_j N_j\right)}{\sum_{j\epsilon M}\left(\lambda_j N_j\right)} \tag{4}$$

$$\text{Customer Average Interruption Frequency Index} = \frac{\sum_{j\epsilon M}\left(\lambda_j N_j\right)}{\sum_{i\epsilon M}\left(N_j\right)} \tag{5}$$

$$\text{Average System Interruption Duration Index} = \frac{\sum_{j\epsilon M}\left(\lambda_j N_j\right)}{\sum_{j\epsilon M}\left(N_j\right)} \tag{6}$$

$$\text{Average System Interruption Frequency Index} = \frac{\sum_{j\epsilon M}\left(U_j P_j\right)}{\sum_{j\epsilon M}\left(\mathrm{P}_j\right)} \tag{7}$$

The nonlinear load points in the system are given as $M$,n and the load points that have been affected by at least one interruption are noted as $j$. The above interruption indices were checked for the IEEE-RTS system and the energy-based index EENS will be calculated at the required location. The expected energy not supplied is based on the system interruption which incorporates the duration, frequency, and forced outage rate [11]. The EENS depends on the probability of outage and the load curtailment which includes the repair rate and the failure rate of the components [12]. Lessening the EENS can be done through various FACTS devices and the sensitivity of FACTS on EENS was examined [13]. The complete power system reliability is evaluated from the system indices which can give the solutions for system adequacy. The capacity and customer weightage indices indicate the average interruption at the weaker portions identified in the test system [14]. Uniform valuation will be examined in different loading conditions in the test system.

# 4 Implementation of FACTS

In the IEEE-RTS system, FACTS controllers can be added at the weakest portion [15]. The iterative power flow analysis is carried out through electrical transient analysis programming (ETAP) for the IEEE-RTS and identified the weakest portion. According to the power flow solution, the buses **6, 9, 10, 11, and 12** are the weakest buses, which are having poor voltage profile and more losses. EENS for the weakest buses were calculated through the composite reliability analysis using the reliability indices. The values of EENS for the each selected bus without any FACTS device are shown in Table 1.

## *4.1 Effects of SVC*

Static Var Compensators can be fixed at the selected buses of the IEEE-RTS. The ultimate objective is to minimise EENS, so that the system reliability will be improved. The MVAR rating for SVC is chosen as 200 for enhancing power system reliability. SVC is the shunt-connected compensator which can inject or absorb reactive power. By controlling the reactive power in the selected buses, the reliability indices can be calculated. At each selected bus, the expected energy not served will be calculated by the composite power system reliability assessment. The thyristor-switched capacitor and thyristor control reactor present in the SVC control the reactive power in the specified limit. The impact of SVC for the selected buses in the IEEE-RTS system is listed in Table 1.

Usually, SVC is connected through the coupling transformer to filter the harmonics and to ensure the economic connecting path. The current flow through the SVC depends on the susceptance and the voltage and it is given as

$$I_{\text{svc}} = jB_{\text{svc}}V_i \tag{8}$$

The susceptance of the SVC is contingent with the reactor, coupling transformer, and capacitor and it is represented as

$$B_{\text{svc}} = \frac{B_T(B_{C1} + B_{C2} + \cdots B_{\text{CN}} + B_{\text{TCR}})}{B_T + B_C + B_{\text{TCR}}} \tag{9}$$

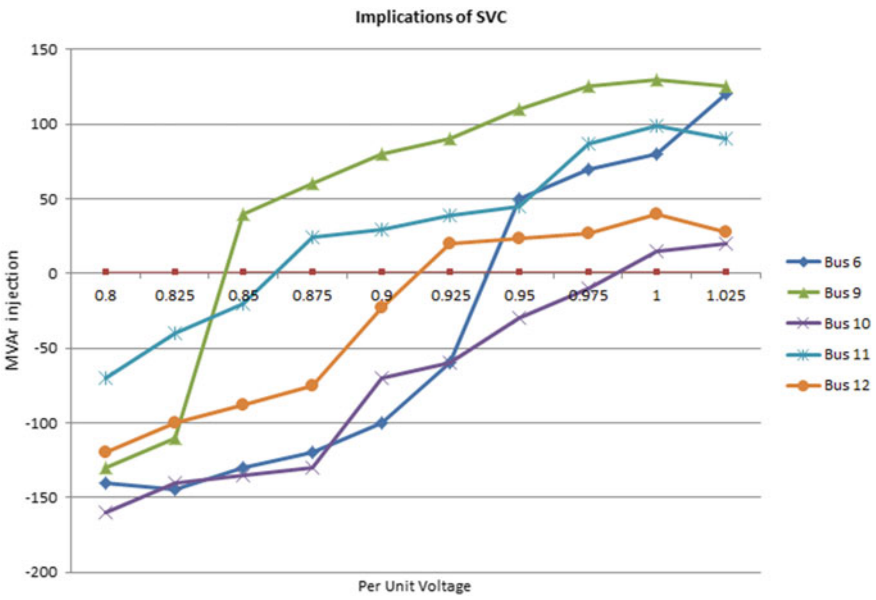


**Fig. 1** Reactive power dynamics with SVC

The optimized value of reactive power can be identified from the limits of susceptance in the SVC.

$$Q_{\mathrm{SVC}} = -V_m^2 B_{\mathrm{SVC}} \tag{10}$$

The insinuations of SVC on the identified weakest were correlated with the EENS. The absorption and injection of reactive power on the various profiles will justify the impacts of SVC. The dynamics of reactive power with respect to the voltage profile is identified and it is shown in Fig. 1.

## 4.2 *Effects of STATCOM*

Static synchronous condenser is a fast acting FACTS device (due to the presence of IGBT's as switching device) which can be incorporated in the IEEE-RTS system to assess the system reliability. STATCOM is a shunt-connected compensator in the power system network which can absorb or inject reactive power. STATCOM is connected at the weakest buses and run the composite power system reliability assessment. The reactive power in the network can be adjusted by the DC capacitor and voltage source converter present in the STATCOM. Also the FACTS device is used to maintain the voltage profile and power factor. The MVAR rating for the device is chosen as 300 to control the reactive power. The reliability index for the

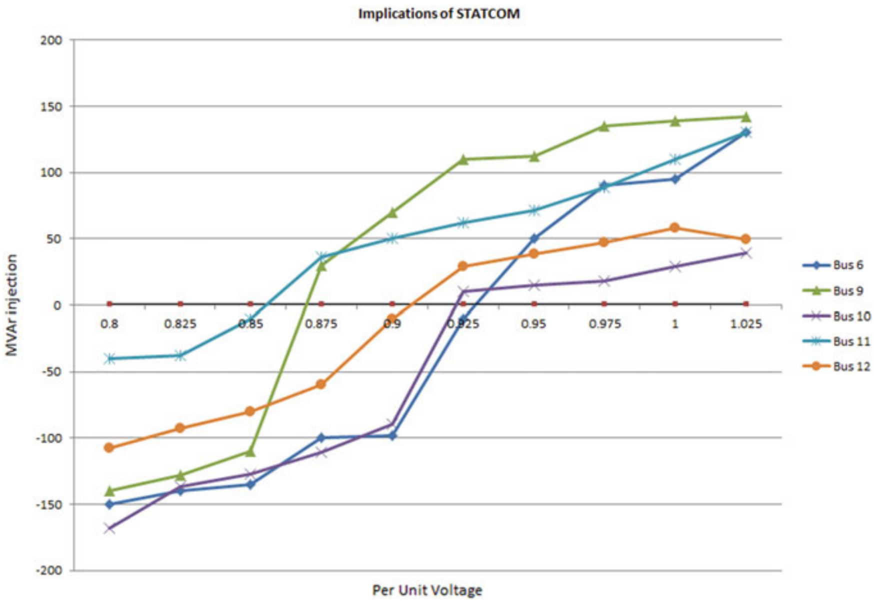


**Fig. 2** Reactive power dynamics with STATCOM

selected buses can be calculated through the sequential simulation. The impact of STATCOM for the selected buses in the IEEE-RTS system is listed in Table 1.

The reactive power flow can be calculated by the bus voltage and the voltage source converter present in the STATCOM and it is represented in Fig. 2. The reactive power injection by the STATCOM ($Q_{SC}$) can be expressed as

$$Q_{SC} = V_{SC}^2 B_{SC} - V_{SC} V_i [G_{sc} \cos(\emptyset_{SC} - \theta_j) - B_{sc} \sin(\emptyset_{SC} - \theta_j) \tag{11}$$

Here, $\varnothing$ and $\theta$ represents the phase angle of each profiles.

## 4.3 *Effects of UPFC*

Unified power flowcontroller can be used to enhance the power system reliability in the IEEE-RTS System. It consists of two voltage source inverters, which is used to control the shunt and series parameters in the power system. The two inverters are operated by a storage capacitor. UPFC will control the real and reactive power flow in the power system through the proper injection or absorption of reactive power. UPFC is having various modes of operation and the optimal mode can be taken into account. With the power flow optimization technique, the combination of voltage injection mode and reactive control mode is identified as suitable modes which gives better result for the IEEE-RTS system. The UPFC can perform the functions of static compensator and static synchronous series capacitor. The control strategy of UPFC in the test system is achieved by formulating through Park's and Inverse Park's transformation with suitable controllers. Here, PI controller is employed to eliminate the steady-state errors and execute the power flow control mode in the UPFC. The control modes UPFC is optimized with the Park's transformation with the assistance of proportional and integral controllers and it is represented in Fig. 3. The proportional gain parameters in the PI controller $K_p$ and $K_i$ are set as 150 and 100, respectively. The control modes and settings in the UPFC are optimized to achieve the minimum EENS. Reactive power coordination controller module is used in the ETAP to obtain the smooth response and control the oscillations.

The power flow constrains in the UPFC are given as

$$Q_{\mathrm{sh}} = -V_i^2 B_{\mathrm{sh}} - V_i B_{\mathrm{sh}}[G_{\mathrm{sh}} \sin(\theta_i - \theta_{\mathrm{sh}}) - B_{\mathrm{sh}} \cos(\theta_i - \theta_{\mathrm{sh}})] \tag{12}$$

$$\begin{aligned} Q_{\mathrm{se}} = {} & -V_{\mathrm{i}}^2 B_{\mathrm{se}} - V_i B_j \left[G_{\mathrm{ij}} \sin\theta_{\mathrm{ij}} - B_{\mathrm{ij}} \cos\theta_{\mathrm{ij}}\right] \\ & - V_i V_{\mathrm{se}}[G_{ij} \sin(\theta_i - \theta_{\mathrm{se}}) - B_{ij} \cos(\theta_i - \theta_{\mathrm{se}})] \end{aligned} \tag{13}$$

The controller can be used in the wind farms to enhance the system reliability. Double feed induction generator can be used to analyze the performance and the

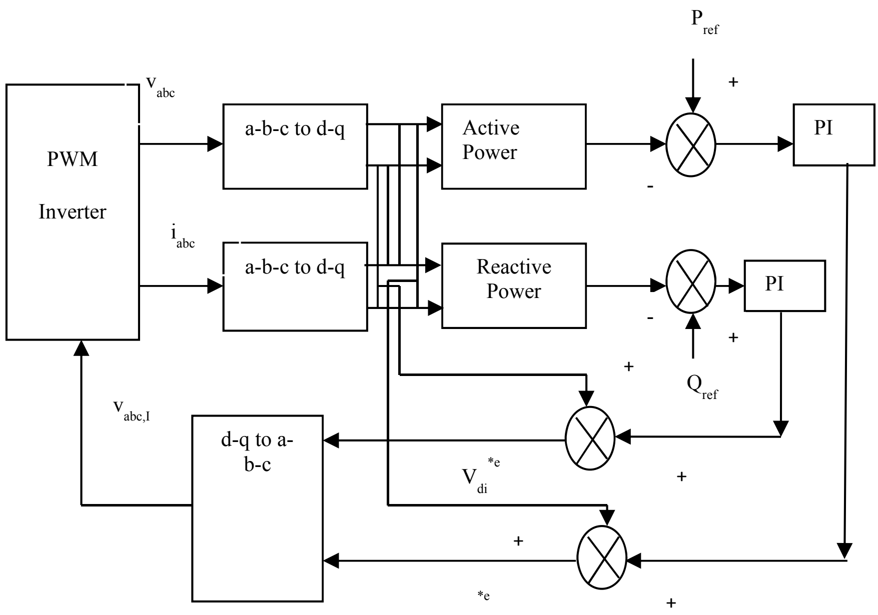


**Fig. 3** Active and reactive power control modes in UPFC

**Table 1** EENS with multiple FACTS devices

| Bus no | EENS without FACTS (MWh/year) | EENS with SVC (MWh/year) | EENS with STATCOM (MWh/year) | EENS with UPFC (MWh/year) |
|---|---|---|---|---|
| 6 | 14,826 | 14,222 | 13,922 | 12,322 |
| 9 | 14,345 | 12,890 | 13,290 | 12,490 |
| 10 | 14,924 | 13,232 | 12,232 | 12,332 |
| 11 | 14,384 | 12,998 | 13,498 | 11,998 |
| 12 | 14,945 | 13,450 | 13,450 | 12,450 |
| $\sum$(EENS) | 73,424 | 66,792 | 66,392 | 61,592 |

impacts. The reactive power variations in the wind farms using SVC and STATCOM are calculated [16]. The composite system reliability is carried out at the each selected bus and the expected energy not supplied is calculated. The impact of UPFC for the selected buses in the IEEE-RTS system is listed in Table 1.

## 5 Significance of Result

Table 1 shows the comparison of various FACTS devices on the reliability index EENS. The effects of various FACTS devices on the IEEE-RTS system provide detailed connotations on reliability assessment in the deregulated power system. FACTS are the fast acting device which can be installed along with the reactor or capacitor bank to provide compensation and improve the system reliability. Black out and Brown out in the power system can be eliminated. The power transfer capability will be improved by fixing right FACTS devices at the precise locations in the power system network. UPFC is having universal control over real power and reactive power and it can be used in composite reliability assessment to minimise EENS. Also the power transmission can be done economically from one end to another with the help of proper power system reliability index, especially EENS. The above assessment can be used for load forecasting and power system planning.

## 6 Conclusion

The effects of various FACTS devices on IEEE-RTS system are carried out and the respective EENS was calculated. The minimal EENS was obtained in the case of adding UPFC with optimal control settings. The results reveal the optimal location of FACTS devices and their effects on IEEE-RTS system. The assessment results can be used for the enhancement of FACTS devices in the renewable energy resources. The results will provide the platform for the researchers to identify the suitable device and connect at the right location. It also enables the dispatch of power supply economically from GENCOs to DISCOs in the deregulated power system. The aggregators or full TSOs can also fix the tariff depend on the EENS calculated through the implementation of FACTS devices.

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