Enhancing Power System Reliability using Multiple FACTS Devices

N.Mahiban Lindsay[1], A.K.Parvathy[2].

[1]nmlindsay@hindustanuniv.ac.in, Hindustan University

[2]akparvathy@hindustanuniv.ac.in, Hindustan University

***Abstract*— This paper discusses various aspects of multiple FACTS devices of control modes and settings and evaluates their impacts on the power system reliability. Two UPFC's are used for the reliability evaluation in a test system. Multiple UPFC's can control various power system parameters, such as bus voltages, reactive power and line flows effectively. The impact of UPFC control modes and settings on the power system reliability has not been addressed sufficiently yet. The various control modes of UPFC and the optimal settings of UPFC with respect to reliability is proposed. The remedial action cost (RAC) can be minimized associated with the reliability index evaluation. The proposed method is applied to the IEEE nine bus system in this paper. The performance of multiple UPFC's also analysed in detail.**

***Index Terms*—Composite system reliability, optimal control mode and settings, unified power flow controller (UPFC), Remedial Action cost (RAC).**

I. INTRODUCTION

The unified power flow controller (UPFC) is one of the most versatile flexible ac transmission systems (FACTS) devices that has ever been used for the control and optimization of power flows [1]. In addition, reliability of protection systems has emerged as an important topic because protection failures have critical impact on the reliability of power systems [4]. A unique concept for the analysis of protection system reliability was introduced by the idea of uneasiness probability [5] The techniques for the reliability evaluation of conventional power systems have been well developed [4]–[6]. In a conventional power system, similar reliability and regulated price for the same type of customers are implemented. Ac or dc power flow techniques are usually used in reliability evaluation to determine network violations for contingency states. The ability to control power flow in an electric power system without generation rescheduling or topology changes can improve the power system performance. Using controllable components, the line flows can be changed in such a way that thermal limits are not exceeded, losses are minimized, stability margins are increased and contractual requirements are fulfilled without violating the economic generation dispatch. The possibility of operating the power system at the minimal cost while satisfying specified transmission constraints and security constraints is one of main current issues in stretching transmission capacity by the use of controllable flexible AC transmission system (FACTS). The conventional OPF program must undergo some changes such as inclusion of new control variables belonging to FACTS devices and the corresponding load flow solutions.

This paper is aimed at finding the optimal UPFC control mode and settings to improve the composite reliability of power systems when all UPFC components are available. The proposed approach will minimize ESRAC for improving the system reliability. A selected set of contingencies are analyzed and the optimal power flow (OPF) is used to minimize RAC and calculate the optimal UPFC injections and the sensitivity of RAC to UPFC injections. The results of contingency analyses are used to calculate post-contingency injections of UPFC and to estimate the ESRAC associated with control modes and settings. The optimal UPFC control mode and settings are obtained by solving the proposed mixed-integer nonlinear optimization problem.

II. POWER SYSTEM RELIABILITY EVALUATION

Generally, the term of reliability refers to the ability of a component or a system to perform its intended function. In field of power system, such evaluation can be defined as analyzing the ability of the system to satisfy the load demands. Therefore, power system reliability assessment is performed in two main domains; system adequacy and system security.

A. Reliability evaluation domains

A power system can be divided into three main functional regions designated as generation, transmission and distribution systems. The term of system adequacy relates to existence of sufficient facilities within a system to meet the consumers demand, whereas system security refers to the ability of the system to respond to disturbances arising within a system. Although these concepts are not independent of each other, the reliability evaluation is conducted only in one of the mentioned domains, either adequacy or security, and mostly in adequacy

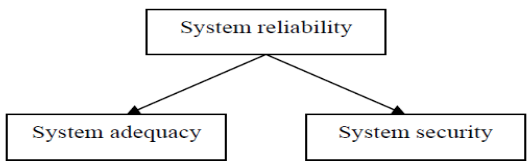

Fig. 1. Reliability evaluation domains

B. Hierarchical levels for reliability evaluation

Reliability evaluation of the power systems can be performed in either each individual functional zone or at the hierarchical levels obtained from combining the functional regions as shown in the figure 2.

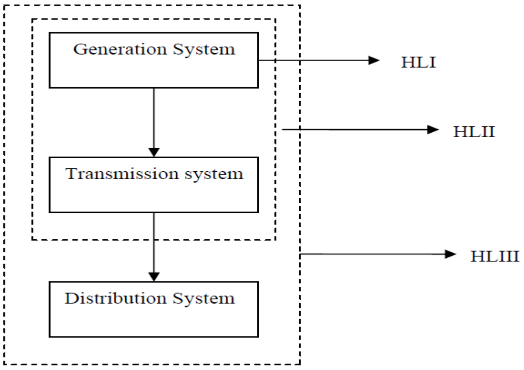

Fig. 2. Hierarchical levels for reliability evaluation

HLI analyses refer to evaluating the generation systems and its ability to supply the load points. In this level, the transmission systems and their associated influences on the reliability of the overall system are disregarded. The adequacy indices in this level are loss of load expectation (LOLE), loss of energy expectation (LOEE), failure frequency and its relevant duration

HLII studies can be used to assess the adequacy of an existing or proposed system including the impact of various reinforcement alternatives at both the generation and transmission levels. The adequacy evaluation in this level, results in achieving two different set of indices related to the system load points and the overall system. The most important indices in this level are failure frequency and its duration.

Finally the level associated to the overall power system analysis including all the functional zones, starting from generation units and terminating at costumers load points is known as HLIII evaluation. Generally, due to complexity of a practical power system, assessment in this level is not performed by considering all three functional zones; instead, the distribution system which receives its reliability data from the load point indices of HLII is evaluated. The common reliability indices in this level are system average interruption frequency index (SAIFI), the system average interruption duration index (SAIDI) and the customers average interruption duration index (CAIDI). Reliability assessment in this thesis work has been conducted in adequacy domain with main focus on transmission system.

Such analyses include many aspects such as load flow analysis, contingency assessment, generation rescheduling, transmission overload alleviation, load curtailment and etc. In this thesis work it has been tried to cover all the procedures required in analytical approach

C. System reliability performance indicators

System reliability indices indicate the system performance, or more precisely, the system's shortcomings in form of undelivered energy, the average number of interruptions and the average outage duration. There are generally two types of indices that are used to indicate power system performance: Customer-weighted and capacity-weighted. The indices relevant to this thesis are presented in equations (1) to (7). *Uj* refers to the unavailability (h/yr), the failure rate (f/yr), *Nj* the number of customers and P the average capacity demand (kW) in load point *j*

System Average Interruption Duration Index =

$$\frac{\sum_{j\epsilon M}(U_j N_j)}{\sum_{j\epsilon M}(N_j)} \qquad (1)$$

System Average Interruption Frequency Index =

$$\frac{\sum_{j\epsilon M}(\lambda_j N_j)}{\sum_{i\epsilon M}(N_j)} \qquad (2)$$

Customer Average Interruption Duration Index=

$$\frac{\sum_{j\epsilon M}(U_j N_j)}{\sum_{j\epsilon M}(\lambda_j N_j)} \qquad (3)$$

Customer Average Interruption Frequency Index =

$$\frac{\sum_{j\epsilon M}(\lambda_j N_j)}{\sum_{i\epsilon M}(N_j)} \qquad (4)$$

Average System Interruption Duration Index =

$$\frac{\sum_{j\epsilon M}(\lambda_j N_j)}{\sum_{j\epsilon M}(N_j)} \qquad (5)$$

Average System Interruption Frequency Index=

$$\frac{\sum_{j\epsilon M}(U_j P_j)}{\sum_{j\epsilon M}(\mathrm{P}_j)} \qquad (6)$$

Energy Not Supplied =

$$\sum_{j\epsilon M}(U_j P_j) \qquad (7)$$

M is a set containing all of the system's load points, *K* is a set containing those load points that have been affected by at least one interruption. Aggregated system reliability performance indices are suitable for determining overall system performance for uniform system. However, when applying aggregated indictors on systems with uneven performance the mean values are misleading. While customer weighted indicators tends to value areas containing large quantities of customers, capacity weighted indicators tends to value high consuming areas, which usually means a rather uniform valuation between different areas.

III. UPFC: STRUCTURE, OPERATION AND OPTIMIZATION OF CONTROL MODES

A UPFC consists of two identical inverters which are connected in parallel and series to power systems through corresponding power transformers. The net active power exchange of inverters is zero if we neglect power losses in inverters. Each inverter is equipped with a control unit for firing commands according to measured signals and control modes of the inverter. The designated power system parameters are regulated at the associated settings.

A. Operating principle of UPFC

The basic components of the UPFC are two voltage source inverters sharing a common dc storage capacitor, and connected to the power system through coupling transformers. One VSI is connected to in shunt to the transmission system via a shunt transformer, while the other one is connected in series through a series transformer. The series inverter is controlled to inject a symmetrical three phase voltage system, of controllable magnitude and phase angle in series with the line to control active and reactive power flows on the transmission line. So, this inverter will exchange active and reactive power with the line.

The reactive power is electronically provided by the series inverter, and the active power is transmitted to the dc terminals. The shunt inverter is operated in such a way as to demand this dc terminal power (positive or negative) from the line keeping the voltage across the storage capacitor Vdc constant. So, the net real power absorbed from the line by the UPFC is equal only to the losses of the inverters and their transformers. The remaining capacity of the shunt inverter can be used to exchange reactive power with the line so to provide a voltage regulation at the connection point.

B. Control modes

The Control modes associated with series and parallel inverters can control reactive power, voltage and phase angle. The two VSI's can work independently of each other by separating the dc side. So in that case, the shunt inverter is operating as a STATCOM that generates or absorbs reactive power to regulate the voltage magnitude at the connection point. Instead, the series inverter is operating as SSSC that generates or absorbs reactive power to regulate the current flow, and hence the power flows on the transmission line. The parallel inverter can operate either as a constant reactive power source or a voltage controller. The series inverter can operate as Power Flow control Mode or Voltage Control Mode or Voltage Injection Mode The control modes are as follows

1) Reactive power Control Mode

The parallel inverter can operate as a constant reactive power source. A constant positive or negative reactive power is injected at PB. The reference input is an inductive or capacitive VAR request. The shunt inverter control translates the var reference into a corresponding shunt current request and adjusts gating of the inverter to establish the desired current. For this mode of control a feedback signal representing the dc bus voltage.

2) Automatic Voltage Control Mode

The shunt inverter reactive current is automatically regulated to maintain the transmission line voltage at the point of connection to a reference value. For this mode of control, voltage feedback signals are obtained from the sending end bus feeding the shunt coupling transformer.

3) Power Flow control Mode

UPFC regulates Real power and Reactive power independently at associated settings. This control mode distinguishes UPFC from STATCOM and SSSC. The reference inputs are values of P and Q to maintain on the transmission line despite system changes.

4) Voltage Injection Mode

Voltage and phase angles are determined to maintain V_d at associated settings The reference inputs are directly the magnitude and phase angle of the series voltage source Inverter. The series inverter simply injects voltage as per the order specified.

IV. COMPARISON OF RELIABILITY INDICES

A. Deterministic Criteria

The probabilistic methods are far superior to the percentage reserve and other rules of thumb often used. They provide analytical basis to consistently define system risk for different configurations. Deterministic criteria are insensitive to factors that significantly influence system reliability, such as unit size, failure rates or load characteristics. In fact, the reliability of two systems with same percentage reserve but different unit composition may be quite different. Moreover, the percentage reserve conveys the misguiding idea that all the risk can be removed keeping a fixed amount of reserves.

B. LOLP/LOLE

This is the probability of system failure (to serve the load) based on a load duration curve or daily peak load curve. Depending on which load model is used the LOLP have different meanings. This index is often expressed as the expected fraction of time, LOLE, on which the system will be observed undergoing an outage event that leads to load of loss. All loss-of-load events count for its time contribution and not for the magnitude of the loss. LOLP/LOLE is easy to calculate and understand but it does not differentiate small capacity outages from large ones.

C. FAD

The frequency of system failure measures the average number of failure occurrences per unit time. The corresponding duration indicates the average residence time on the failure states. This information is not provided by LOLP, but FAD does not either give information about the size of the outages when they occur. The frequency and duration of capacity outages have a greater physical significance than LOLP, but the FAD models require more detailed information about each generating unit and more computational effort.

D. LOEP

It measures the expected fraction of system energy not served due to capacity outage events. The loss-of-energy approach has much greater physical relevance than the other approaches and takes into account the magnitude of the different outage events.

The component's life history is determined by the probability distributions fU (t) and fD (t). Where fU (t) is the density function of up times TU, and fD (t) is the density function of down times TD. If **Xt** is the state of the component at time t, then the following definitions apply:

i) Probability of being in the up state: PU (t) = P [up at t] = P [**Xt** = U]
ii) Probability of being in the down state: PD (t) = P [down at t] = P [**Xt** = D]

V. SIMULATION RESULTS AND DISCUSSIONS

In order to demonstrate the impact of UPFC control modes and settings on reliability, the IEEE nine-bus test system is used in Fig. 3. The system is modified by adding a 230 kV transmission line from B4 to B8. Since the IEEE reliability data are unavailable, those of the IEEE reliability test system are used. A composite reliability evaluation has identified that the loading of L48 is the main source of system unreliability.

So, in order to improve the system reliability, a UPFC is installed on L48 at B4 to reduce L48 loading. Fig. 3 shows that PB is directly connected to B4 and L48 is connected between BS and B8. The UPFC is assumed to have two identical 160 MVA inverters interconnected by a DC link. The specification of the inverters and transformers are presented in Table I.

The purpose of UPFC is to reduce the power extraction of L48 from B8 from 17-j8.76 MVA to 12+j6 MVA for reducing the loading of L48 by 18%. Six cases are studied in which six possible combinations of control modes for parallel and series inverters are used. For each case, the settings are determined such that the power extraction of L48 from B8 would be 12+j6 MVA. The pre-contingency condition is the same for all cases.

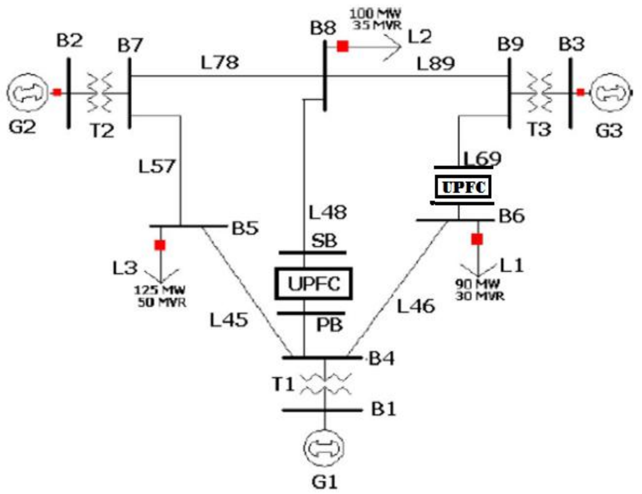

Fig. 3. UPFC applications to IEEE nine bus system.

TABLE I
UPFC SPECIFICATIONS

UPFC Component	Specification
Inverter	100 MVA,10 KV
Series Transformer	100 MVA,10/30 KV,X_{ST}=7%
Parallel Transformer	100 MVA,10/230 KV,X_{PT}=8%

TABLE II
RELIABILITY INDICES WITHOUT AND WITH UPFC

Case No.	Control Mode of Parallel Inverter	Control Mode of Series Inverter	EUEC(K$)	ELC(MW)
1	-	-	1518	230
2	RCM	VIM	1221.98	190.3
3	VCM	VIM	1380.06	209.1
4	RCM	VCM	1425.6	216
5	VCM	VCM	1471.14	222.9
6	RCM	PFM	1749	265
7	VCM	PFM	1768.8	268

Table II shows the study results for the base case (without UPFC, case 1) and the six cases with UPFC (cases 2 to 7). In order to show how UPFC control modes and settings affect the post-contingency following the outage of L57, the injection of line L89 at bus B8 as well as the settings associated with individual cases are shown in Table III. In cases 2 to 5, the injection of L89 is reduced from its original level in case 1, while it is increased from its original level in cases 6 and 7. This shows that the post-contingency condition depends on the UPFC control mode. Post-contingency overloads of L89 in cases 4, 6, and 7 in Table III are mitigated by changing the settings associated with the control modes of these cases. Table IV shows the updated settings and corresponding L89 injections following the outage of L57 in cases 4, 6 and 7. The optimal series injected voltage is determined to minimize the objective function and the limitation on the magnitude of series injected voltage has not influenced the optimal value of series voltage. In these cases, both the magnitude and the angle of the optimal solution would change by increasing the maximum series injected voltage.

TABLE III
OPTIMAL UPFC CONTROL MODE AND SETTINGS

Inverter	Mode	Settings	PS/SS Injections
series	VIM	0.042L-61^{o}	3.5+j4.2 MVA
Parallel	RCM	-21.3 MVAR	-3.5-j21.3 MVA

The best reliability enhancement is achieved when the parallel inverter operates in the RCM mode and the series inverter operates in the VIM mode.

TABLE IV
RAC WITH AND WITHOUT UPFC

Type	EUEC(K$)	ELC(MW)	ESRAC(M$)
SYSTEM WITHOUT UPFC	1518	230	4928040
SYSTEM WIH UPFC	1221.98	190.3	3688020

VI. CONCLUSION

This paper presented the optimal control mode and settings of UPFCs. A two-source power injection model was used for UPFC and the impact of UPFC control modes and settings on reliability indices were investigated. UPFC was installed in the modified IEEE test system and the reliability indices were calculated. The UPFC application enhanced the reliability indices by 31% in the given example. The error in the estimation of RAC was about 4%. The impact of optimal UPFC settings on the dynamic performance of the power system was evaluated.

Reliability indices are calculated to determine the optimal UPFC control mode and settings. The approach estimated the RAC associated with UPFC power injections.. The estimated costs were then used in a mixed-integer nonlinear optimization problem to find the optimal UPFC control mode and settings.

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