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VOLTAGE STABILITY ENHANCEMENT USING UNIFIED POWER FLOW CONTROLLER IN DEREGULATED POWER SYSTEMS

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Abstract

The maximum loading capability (MLC) is a measure to identify voltage stability margin (VSM) of the power system before voltage collapse happens. Under line outage contingency, the reduction in VSM can use an indicator to validate the importance of that line in network for stability management. This paper presents a novel approach for unified power flow controller (UPFC) location to maximize VSM in deregulated environment. The decoupled power injection (DPIM) modeling is adopted and the Continuous Power Flow (CPF) method is used for MLC calculation. The case studies are performed on IEEE 14-bus and IEEE 30-bus test systems and results are encouraged for real-time

***Keywords*:**Deregulated power system; MLC; VSM; UPFC

1 INTRODUCTION

The major goal of a deregulated power system is to supply continuously the market cleared quantities to all market participants. This is a difficulty of highly complicated power system operation where the following dispatchable issues must be observed: (1) the maintenance of acceptable voltage profile at each bus and system frequency must be kept within specified margins; (2) the congestion management of transmission system considering thermal and stability constraints; (3) adequate power quality in electrical supply; and (4) the sustainability of preventive and control actions under abnormalities in the system. Moreover, because of the highly competitive environment with the open access power market, transmission cost must be kept as low as possible. The regulatory constraints on the expansion of the transmission network has resulted in reduction of stability margins and increased the risks of cascading outages and blackouts. Many of the researchers are already focused on this technique to mitigate intolerable operating states transmission system for security maintenance. This problem can be effectively tackled by the introduction of high power electronic controllers for the regulation of power flows and voltages in AC transmission networks. This allows flexible operation of AC transmission systems whereby the changes can be accommodated easily without stressing the system. Power electronic based systems and other static equipment that provide controllability of power flow and voltage are termed as FACTS Controllers. FACTS devices control the power flow in the line by supplying or absorbing reactive power, controlling the phase angle or series impedance and increasing or decreasing bus voltages [1]. Depends upon control attributes, the FACTS devices classified such as series compensators, shunt compensators and series-shunt/combined compensators. The series compensators like Static Synchronous Series Compensator (SSSC), Thyristor-Switched Series Capacitor (TSSC), Thyristor-Controlled Series Capacitor (TCSC), Thyristor-Controlled Voltage and Phase Angle Regulators (TCVRs and TCPARs), the shunt compensators like Static Var Compensators SVC and STATCOM and combined compensators like Unified Power Flow Controller (UPFC) and Interline Power Flow Controller (IPFC) etc., can be found in literature.

Among all the FACTS devices, UPFC is one of the versatile FACTS devices for power flow control, since it can either simultaneously or selectively control the active and reactive power flow along the lines [2]. In 1981, Dr. Laszlo Gyugyi was introduced the concept of Unified Power Flow Controller (UPFC) [3, 4]. Similarly, the application of other FACTS devices for various technical benefits can be found in literature. For available transfer capability (ATC) enhancement [5-8], for total transmission capacity enhancement [9], for transmission system loadability enhancement [10], for voltage stability margin enhancement [11], for transient stability enhancement [12], for system reliability [13] and for load flow control [14-16] are some of the examples of FACTS application in deregulated environment.

2 STATIC MODELING OF UPFC

In literature various models can be found for UPFC in power flow studies like Power Injection Modeling (PIM), Decoupled PIM, and Coupled PIM for Conventional Power Flow, PST Equivalent Model, Static Modeling of UPFC. Each model has its own advantages and disadvantages. Because of simple and easiness to implement in Newton-Raphson load flow program without modifying Jacobian matrix, Decoupled Power Injection Model (DPIM) has chosen in many works. The brief description on DPIM of UPFC is presented here. As far as power flow solutions concerned, the only restriction with this model may have is that the UPFC converter valves are taken to be lossless [17].

Consider a transmission line connected between bus i and j as shown in Figure 1. The net injected power at bus i is 50 MW and the same is flowing through line. The withdrawal at bus j is 50 MW. Assume that the line having a capability of 40 MW, then the situation is termed as overloading or congestion in the network.

In order to overcome this problem, the desired solution by the compensation device is illustrated in Figure 2. An amount of 10 MW power has been withdrawn at bus i and hence the remaining surplus power i.e. 40 MW at bus i is transferring to bus j through line. But the net required withdrawal at bus j is 50 MW and so an amount of 10 MW power has been injected by a generator at bus j. Under this condition, the incoming bus i has become PQ bus and the outgoing bus j has become PV bus.

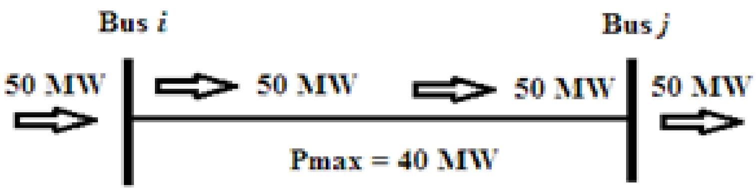


Figure 1: Situation of congestion in line i-j

It is also observable that the net flow in line reduced by 10 MW and hence this amount of power has been considered as counter-flow in the line. If the withdrawal at bus i is 20 MW and injected power at bus j is also 20 MW, then the flow in transmission line will become only 30 MW which is less than its rated capacity. So we can control the power in congested line by changing the network configuration as shown in Figure 2. This type of compensation is possible only by the power injection modeling of UPFC. The major advantage of this model is not required to change the Jacobian matrix and in addition to this, the absolute mismatch to the market driven schedule with the rescheduling approach, can also be minimize in the event of unsolvable situation with UPFC control. A similar explanation for DPIM for UPFC can be found in [18].

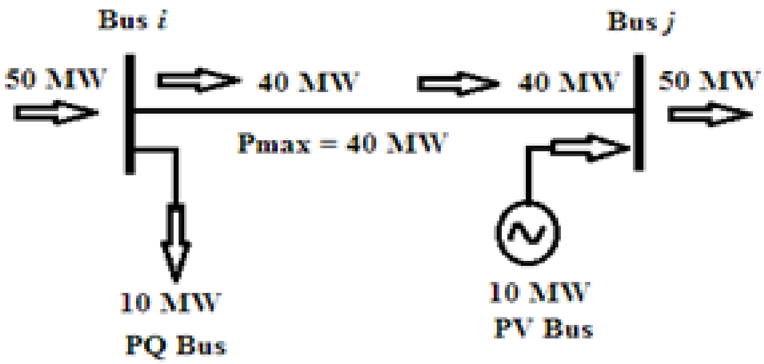


Figure 2: Congestion relief in line i-j

3 OPTIMAL LOCATION OF UPFC

In order to meet high security margin, the location should satisfy certain prerequisites for satisfactory operation of the system. In general, the system stability, network loadability, transmission losses and power quality issues are some of the considerable objectives for optimization problem of FACTS devices. As given in [19], the optimal location approaches can classified in to (1) approaches based on heuristic optimization algorithms, (2) approaches based on analytical methods, (3) approaches based on single-type FACTS device allocation, (4) approaches based on multi-type FACTS devices allocation. However, the best choice of FACTS devices and their optimal location is not a simple optimization problem due to their distinguished advantages and disadvantages of each device, size and number. So, the solution is mainly dependent on the concerned objective function. In this paper, a novel strategic approach is proposed to maximize transmission loadability based on reduced critical loading margin under (N-1) line contingency.

Since all FACTS devices are passive in nature, they can inject/withdraw required reactive power in to the system rapidly.

The voltage instability is mainly dependent on lack of reactive power support. The network loading capability at unsolvable condition of power flow equations is known as Critical Loading Margin (CLM) [20]. This will drastically decrease with the worst contingencies. Contingency analysis is an important aspect to the secure operation of a system, since contingencies may have a vast and negative impact on voltage stability margin, and can eventually lead the system to a voltage collapse [21]. So the validation of FACTS devices support can more pronounced at this stage. P-V and V-Q curve power flow programs were popular for many years. Due to divergence problem with conventional methods, we cant generate complete P-V and V-Q curves. These curves are determined by stressing each bus load independently and the selection of bus to analyze is also very important. Later Continuous Power Flow (CPF) method was introduced to determine maximum loading condition [22]. The method gives the information of voltage drooping nature at a specified bus with the increment of load either only at one bus or on the entire system.

In order to identify week load buses as well as to rank (N1) line outage contingencies and as a part in new approach for optimal location of FACTS devices, CPF is adopted. The reduced system loadability is considered as a measure to understand the severity of a particular (N1) line contingency. Using this information, the lines have been ranked to integrate UPFC device optimally. To reduce computational effort while (N1) line contingency ranking, the voltage sensitive geographical zone has been identified using Network Visualization approach. The Network Visualization technique in Power System Analysis Toolbox (PSAT) can easily visualize all voltage sensitive zones buses [23]. The lines incident to sensitive zone buses are only selected in contingency analysis. With this, the computational effort can reduce significantly.

4 PROBLEM FORMULATION

A. Formulation of Mathematical Problem

- Equality constraints: Power flow equations corresponding to both real and reactive power balance equations are the equality constraints that can be written, for all the buses except buses p and q in which UPFC is connected, as

$$P_i = P_{g,i} - P_{d,i} = \sum_{k=1}^{NB} |V_i||V_k||Y_{ik}|\cos(\theta_{ik} - \delta_i + \delta_j) \tag{1}$$

$$Q_i = Q_{g,i} - Q_{d,i} = -\sum_{k=1}^{NB} |V_i||V_k||Y_{ik}|\sin(\theta_{ik} - \delta_i + \delta_j) \qquad i = 1,2,\ldots,NB \text{ ; but } i \neq p,q \tag{2}$$

For buses p and q, the quality constraints can be written as

$$P_p = \sum_{k=1}^{NB} |V_p||V_k||Y_{pk}|\cos(\theta_{pk} - \delta_p + \delta_j) - P_{p,inj} \tag{3}$$

$$Q_p = -\sum_{k=1}^{NB} |V_p||V_k||Y_{pk}|\sin(\theta_{pk} - \delta_p + \delta_j) - Q_{p,inj} \tag{4}$$

$$P_q = \sum_{k=1}^{NB} |V_q||V_k||Y_{qk}|\cos(\theta_{qk} - \delta_q + \delta_j) + P_{q,inj} \tag{5}$$

$$Q_q = -\sum_{k=1}^{NB} |V_q||V_k||Y_{qk}|\sin(\theta_{qk} - \delta_q + \delta_j) + Q_{q,inj} \tag{6}$$

For lossless operation,

$$P_{p,inj} = P_{q,inj} \tag{7}$$

- Real power generation limits: This includes the upper and lower real power limit of generators.

$$P_{g,i}^{\min} \leq P_{g,i} \leq P_{g,i}^{\max}, \qquad i = 1,2,\ldots,NG \tag{8}$$

- Reactive power generation limits: This includes the upper and lower reactive power limit of generators.

$$Q_{g,i}^{\min} \leq Q_{g,i} \leq Q_{g,i}^{\max}, \qquad i = 1,2,\ldots,NG \tag{9}$$

- Voltage limits: This includes the upper and lower limits on the bus voltage magnitude.

$$V_i^{\min} \leq V_i \leq V_i^{\max}, \; i = 1,2,\ldots,NB \tag{10}$$

$$\delta_i^{\min} \le \delta_i \le \delta_i^{\max}, \qquad i = 1, 2, \ldots, NB \qquad (11)$$

- Phase angle limits: This includes the upper and lower limits on the bus voltage phase angle.
- Tap-Changers limits: This includes the upper and lower limits on the tap positions in tap-changing transformer lines.

$$a_i^{\min} \le a_i \le a_i^{\max} \qquad i = 1, 2, \ldots, NTCL \qquad (12)$$

- MVAr injection limits: This includes the upper and lower limits on the MVAr injections at voltage controlled buses.

$$Q_{inj,i}^{\min} \le Q_{inj,i} \le Q_{inj,i}^{\max}, \qquad i = 1, 2, \ldots, NVCB \qquad (13)$$

- Line flow limits: These constraints represent the maximum MVA power flow in a transmission line

$$S_l \le S_l^{\max}, \qquad l = 1, 2, \ldots, NL \qquad (14)$$

- UPFC Operating Constraints: These constraints represent the maximum power injections of UPFC incident buses. The base case complex power flow of line p q selected to integrate UPFC, is added at PQ bus of UPFC and same is injected at PV bus of UPFC. While optimizing the objective function, these parameters are scaled up to maximum without violating MVA rating of line rating p q.

$$P_{p,inj} = real\left(S_{l,pq}\right) \qquad (15)$$

$$Q_{p,inj} = imag\left(S_{l,pq}\right) \qquad (16)$$

$$\sqrt{P_{p,inj}^2 + Q_{p,inj}^2} \le \left|S_{l,pq}\right| \qquad (17)$$

$$P_{q,inj} = P_{p,inj} \qquad (18)$$

Since bus q is modeled as PV bus, the reactive power injection adjusts within limits.

$$Q_{g,q}^{\min} \le \left(Q_{g,q} = Q_{q,inj}\right) \le Q_{g,q}^{\max} \qquad (19)$$

B. Voltage Stability Assessment

The continuation power flow (CPF) analysis is robust and flexible and suited for solving load flow problems with convergence difficulties. However, the method is very slow and time consuming. Hence the better approach is to use combination of conventional load flow method i.e. NR or FD and continuation method. Starting from the base case, load flow is solved using a conventional method to compute power flow solutions for successively increasing load levels until a solution cannot be obtained. Hereafter, the continuation method is restored to obtain the load flow solutions. Normally, the continuation method is required only if solutions are required exactly at and past the critical point [24].

The net active and reactive power injections at the load and source buses are functions of and are given by:

$$P_i = P_{i0} + \lambda L_{Pi} \quad (20)$$
$$Q_i = Q_{i0} + \lambda L_{Qi} \quad (21)$$

where is the parameter controlling the amount of injection, is the base case real power injections at the bus, is the base case reactive power injections at the bus, is the real power load participation factor, is the reactive power load participation factors. By maximizing , the maximum loadability of the system constrained by voltage instability limit can obtain. The detailed information about CPF can be found in [22].

5 RESULTS AND DISCUSSIONS

A. Optimal Location in IEEE-14 Bus System

The initial generation schedule is done as per proportional to their maximum generation capacity limit. The base case load of entire system is 259 MW. In this work, the lines which are incident to generator buses (1, 2, 3, 6 and 8) not consider for UPFC location. Similarly, the lines with tap-changing or phase shifting transformers are also not considered for UPFC installation. By performing CPF, the maximum loadability is determined at initial case and equal to 4.592 p.u. The MLC is determined under each line contingency and the results are given in Table 1.

In general, IEEE 14-bus test system has 20 transmission lines and hence there is a need to simulate separately for each line contingency MLC determination. Hence as explained earlier, we have simulated CPF at base case and then by using network visualization technique in PSAT, the critical zone has been identified. From the pictographic representation of critical zone as shown in Figure 3, the critical buses 14, 10, 4, 9 and 7 i.e. which are less than 0.9 p.u. voltage level are identified. The lines incident to these buses are the first priority and based on reduce MLC, line 7 9 is finalized for UPFC location.

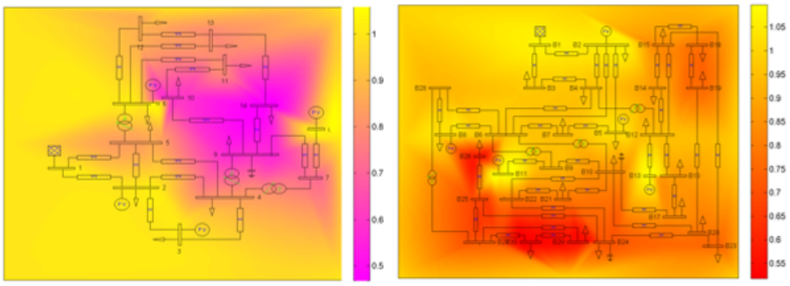
Table 1. (N-1) Line Contingency Ranking as per MLC

IEEE 14-Bus System			IEEE 30-Bus System		
Line	MLC	Rank	Line	MLC	Rank
7 – 9	2.6946	1	28 – 27	1.5753	1
13 – 14	3.1021	2	27 – 29	2.3489	2
9 – 14	3.1090	3	27 – 30	2.3983	3
10 – 11	3.8772	4	9 – 10	2.5535	4
4 – 9	4.1123	5	29 – 30	2.6865	5
4 – 7	4.3220	6	22 – 24	2.9348	6
2 – 4	4.3576	NA	12 – 15	2.9568	7
4 – 5	4.4261	7	10 – 20	2.9844	8
2 – 5	4.4339	NA	15 – 23	3.0361	9
3 – 4	4.4456	NA	10 – 21	3.0720	10
9 – 10	4.5095	8			
7 – 8	NC	NA			

B. Optimal Location in IEEE-30 Bus System

In this system also, the lines which are incident to generator buses (1, 2, 5, 8, 11 and 13) not consider for UPFC location. Similarly, the lines with tap-changing or phase shifting transformers are also not considered for UPFC installation. The CPF is performed for base case load 283.4 MW. The generation schedule is proportional to their maximum generation capacity. The maximum loadability at initial case is 3.2813 p.u. The MLC is determined under each line contingency and the top ten ranked lines are given in Table 1.

In general, IEEE 30-bus test system has 41 transmission lines and hence there is a need to simulate separately for each line



(a) IEEE 14-bus system (b) IEEE 30-bus system

Figure 3: Network visualization of IEEE 30-bus test system at MLC

contingency MLC determination. Hence as explained earlier, we have simulated CPF at base case and then by using network visualization technique in PSAT, the critical zone has been identified. From the pictographic representation of critical zone as shown in Figure 3, the critical buses 10, 14, 15, 16, 17, 18, 19, 20, 21,22, 23, 24, 25 26, 27, 29, 30 i.e. which are less than 0.9 p.u. voltage level are identified. The lines incident to these buses are the first priority and based on reduced MLC, line 28 27 is finalized for UPFC location.

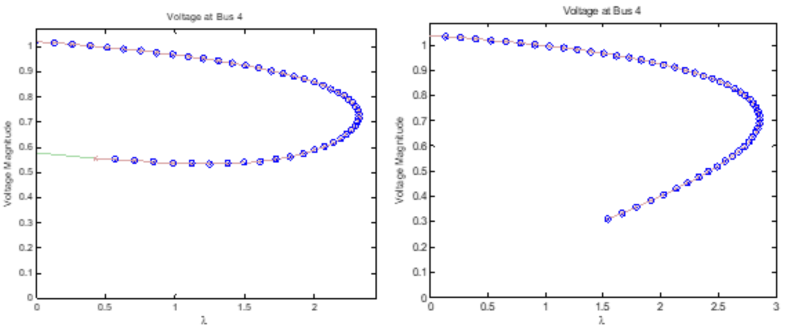
C. MLC Calculation in IEEE-14 Bus System under Electricity Market Environment

With an assumption of various generation schedules with different bidding scenarios in deregulated environment, the case studies are performed. The various generation schedules for the same load are given in Table 2. Using CPF method, the MLC value is determined for each generation schedule and corresponding PV curve at critical bus for case # 1 generation schedule is given in Figure 4. By observing results given for without UPFC in Table 2, the MLC is decreased at some cases and increased at some other cases from base case. Hence MLC value is dynamic in nature and strongly dependent on generation schedule as well as system operating constraints.

D. MLC Calculation in IEEE-30 Bus System under Electricity Market Environment

Table 2. Generation schedule (MW) and MLC with UPFC in IEEE 14-Bus System

Case #	PG1	PG2	PG3	PG4	PG5	Without UPFC	With UPFC
1	185.04	36.72	28.74	0	8.5	2.319	2.858
2	7.06	42.80	87.22	62.84	59.09	2.527	4.126
3	156.58	102.43	0	0	0	2.094	2.457
4	133.31	25.69	100.00	0	0	2.381	3.223
5	132.42	26.58	0	100	0	2.425	3.459
6	166.12	32.97	0	0	59.91	2.206	2.952



(a) without UPFC **(b) with UPFC**

Figure 4: PV Curve at MLC for case #1 generation schedule in IEEE 14-Bus System

In this test system, there are 6 generator buses and a total load of 283.40 MW. The base case schedule as case # 1, and its corresponding MLC value is given in Table 3. In addition to this, we have considered (N-1) line contingencies to show their impact on MCL.

Table 3. Generation schedule in MW for IEEE 30-Bus System

Case #	PG1	PG2	PG3	PG4	PG5	PG6
1	200.49	36.23	29.35	12.94	4.39	0
2	4.98	42.07	80.66	52.97	58.94	43.78
3	77.76	40.01	62.17	39.08	39.71	24.66

The considered line outages for a specific schedule and corresponding MLC values are given in the Table 3. By observing the MLC values under line outage conditions, it is decreased significantly at some cases and moderately affected at some other cases. Hence we can conclude that, the MLC is not only dependent on generation schedule as proved in case studies on IEEE 14-bus system and it is also dependent on network configuration. As determined in earlier, the optimal location for UPFC is line 28 27 in IEEE 30-bus system as for both the approaches. Hence line 28 27 is modeled as per DPIM. By observing power flow direction in line 28 27, the bus 27 is modified as PV bus. By comparing without UPFC results, the increment in MLC values with UPFC can be observable in Table 4.

Table 4. MLC Values in p.u for various schedules and line outages in IEEE 30-Bus System with UPFC

Case #	Normal	4 – 12 outage		22 – 24 outage	
		Without UPFC	With UPFC	Without UPFC	Without UPFC
1	2.018	1.457	1.789	1.749	2.586
2	2.126	2.099	3.071	1.850	3.266
3	2.148	2.058	2.890	1.865	3.544

6 CONCLUSIONS

In this paper, the mathematical modeling of decoupled power injection has been reviewed. To integrate UPFC in the network, a novel approach is proposed based on reduced voltage stability margin. The case studies are performed on IEEE 14-bus and IEEE 30-bus test systems. The variation in generation schedule and load withdrawals in deregulated environment is considered in simulations. Under each generation schedule, the change in MLC values is observed. Similarly, the impact of line contingency on MLC is also observed. The enhanced MLC values obtained with UPFC have shown the proposed approach for real-time applications.

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