

Assessment of Optimal Location of Unified Power Flow Controller Considering Steady-State Voltage Stability

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Abstract-- In this paper, UPFC is modeled as two reactive power injections and a bypass circuit of active power in parallel with connecting series transformer of the UPFC. UPFC has three parameters, which can be controlled within the range of inverter limited capacity. Therefore, UPFC can be assumed to be the constant power load in the power flow calculation. Steady-state voltage stability can be evaluated using maximum loading of P-V curves, but also by the total reactive power loss of the power system. In this paper, a new methods are proposed, which can estimate how much UPFC at a given location improves the voltage stability, based on the information on line power flow and bus voltage in the network without installing the UPFC at the location. The proposed method can determine the optimal location of UPFC efficiently from the computational viewpoint. Optimal location of UPFC may be affected by power system configurations and load conditions. In this paper, many types of power system configurations and load conditions are considered when UPFC location is given. UPFC can not only improve the voltage stability but also control active power flow resulting in active power loss reduction and overload alleviation. The optimal location of UPFC depends on the selected objective function.

Index Terms--flexible AC transmission systems (FACTS), optimal location, optimal power flow controller (OPF), steady-state voltage stability, unified power flow controller (UPFC).

I. INTRODUCTION

IN recent years, the demand for electric power is gradually increasing, and some power system apparatus are used almost at its maximum thermal capacity. Furthermore, new construction of transmission lines is very difficult from a view point of construction cost and environment problems. Therefore in a power system, the voltage stability may be detracted due to increasing power flow on transmission lines [1]. A large-scale blackout following the voltage instability was experienced in North America, 2003. There are many previous studies on the application of unified power flow controller (UPFC), a kind of FACTS devices [2], to the power system stability enhancement. At present, however, the installed capacity of UPFC is only 320MVA for commercial use throughout the world. In these studies, it is recognized that

it is very important to determine the optimal location of UPFC in the planning stage. Therefore, this paper proposes a new method for determining the optimal location of UPFC considering steady-state voltage stability.

II. MODELING OF UPFC

A. Configuration of UPFC

Unified power flow controller (UPFC) consists of two transformers and VSCs, and a DC capacitor. One transformer is connected in series to transmission line, and the other is connected in parallel with lines on power system [3]. UPFC model is shown in Fig. 1. The series site of UPFC is the same as SSSC, and the shunt part is the same as STATCOM.

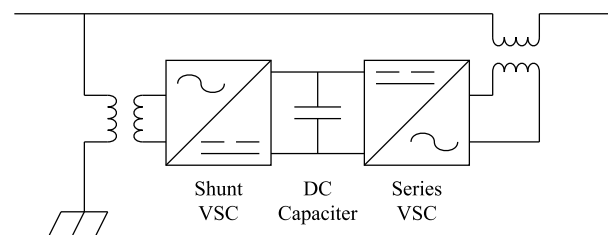


Fig. 1. Configuration of UPFC.

UPFC can control not only reactive power but also active power flow, because DC capacitor has two connections to a power system, and the active power can go through DC capacitor. STATCOM also has shunt VSC and DC capacitor, but DC capacitor cannot supply active power in the steady state.

UPFC is modeled as two ideal voltage sources and leakage reactance. Fig. 2 shows the equivalent circuit of UPFC. Two injection voltages are E_{se} and E_{sh} . Both voltage sources can inject active and reactive power independently, but the sum of the two injecting active power should be zero. The VSC losses are ignored here.

VSC and transformer have the maximum capacity. In this paper, other limits for voltage, current, etc. are ignored.

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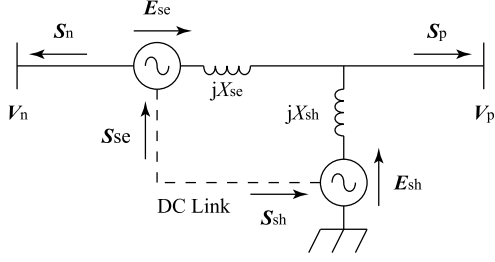


Fig. 2. Equivalent circuit of UPFC.

B. Steady-State UPFC Model

The main purpose of UPFC is to regulate active and reactive power flow in the power system. In this paper, UPFC in the steady state is modeled as a voltage source (P-V constant bus). Fig. 3 shows the UPFC model in the steady state. The bus connected with UPFC bus interacted as a PV-constant bus. When load demands change, UPFC parameters such as E_{se} and E_{sh} are controlled to keep the voltages V_n and V_p , and power flow P_{np} on the transmission line constant. Furthermore, the setting value of active power flow is changed in proportion to the total load demand.

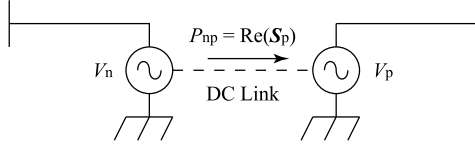


Fig. 3. Steady-state UPFC model for P-V constant bus control.

C. UPFC Installation

UPFC is typically located at the salutation bus in the power system. For each transmission line, there are two location for UPFC, and each location has two directions based on the connections of series VSC and shunt VSC. In this paper, UPFC installation mode is represented as a pair of "Location" and "Direction" as shown in Fig. 4.

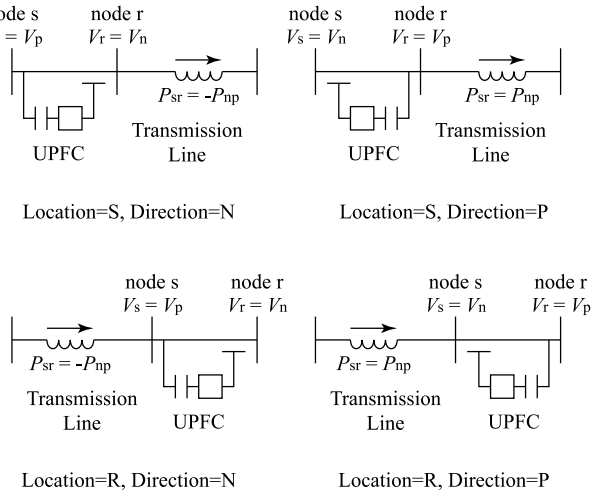


Fig. 4. Mode of UPFC installation.

In the initial state, every transmission line has active power flow on it, and the direction of actual active power flow is defined as the transmission line direction. When UPFC is installed on transmission line, the power sending side is denoted "S", and the receiving side is denoted "R".

On the other hand, UPFC series voltage source has its own direction to inject the voltage. In details, the direction from series side to shunt side is defined as the UPFC direction. If the transmission line direction and UPFC direction are the same, it will be denoted by "P", and if opposite, denoted by "N". UPFC has a symmetric characteristic if PV constant type controller is equipped and no capacity limit of VSC is assumed.

Other locations such as the middle of transmission lines is not considered in this paper.

D. Voltage Stability Analysis

In this paper, voltage stability is analyzed using the maximum loading of PV-curve [4]. In fact, the analysis of voltage collapse requires dynamic numerical simulations. In the previous works, dynamic load can be approximated by constant power sources in a short time after the fault [5]. Therefore, the larger the maximum loading of PV-curve is, the further the power system is from voltage collapse. The maximum loading can be calculated by repetitive power flow calculation, but it requires a great amount of time to calculate the optimal solutions in the OPF control. In the previous works, the maximum loading is evaluated by a sum of reactive power losses in power system. Thus in this paper, the OPF control for voltage stability is to minimize the sum of reactive power losses, and the actual maximum loading is recalculated after the OPF control.

E. OPF Control

The objective function of the OPF control is as follows:

$$f(x) = \sum Q_{\text{loss}} \rightarrow \text{minimize} \quad (1)$$

There are also limits of injected power by VSC. Other limits such as bus voltage and line current are ignored because the calculation of power system transfer capability such as TTC is not the main purpose of this research. The maximum loading is one of the steady-state voltage stability indices. Parameters x in (1) are the steady-state parameters, i.e. P_{sr} , V_s , and V_r . Q_{loss} includes only reactive power loss of transmission lines, not of UPFC leakage reactance losses.

Only three parameters of UPFC are controllable, and the power output of generators is always proportional to load demand except for the swing bus generators.

F. Test System

In this paper, the 7-machine 23-bus system is used as a test system. Fig. 5 shows the test system model. As mentioned previously, the possible locations of STATCOM and UPFC installation are buses 8 to 23, and lines 8 to 27 except lines 11, 13, and 24 respectively.

III. CONTRIBUTION OF SHUNT AND SERIES VSC TO MAXIMUM LOADING EXTENSION

Table I shows the best six solutions obtained from the OPF control, which are in descending order of the maximum loading of PV curves. Note that no limit of UPFC injected voltage and VSC capacity are considered. The numbers of lines and buses are shown in Fig. 5. Even though Q_{loss} is the objective function of OPF control, but it is not used for selecting the optimal UPFC location.

In Tables I and II, the utilization of the loss minimization as the objective function does not always provide the best maximum loading. However, the almost same but in obtained for both STATCOM and UPFC. For example, bus 10 is the optimal location for both UPFC and STATCOM. In addition, V_{sh} and S_{sh} are larger than V_{se} and S_{se} . This signifies that the

Line	Location	Bus	V_s	V_t	P_{st}	Q_{loss}	P_{max}	Direction	E_{se}	E_{sh}	S_{se}	S_{sh}	S_{sum}
L9	R	10	1.069	1.075	0.735	0.970	2.227	P	0.0445	1.131	0.0386	1.255	1.294
								N	0.0533	1.124	0.0479	1.248	1.296
L16	S	10	1.075	1.060	0.408	0.970	2.219	N	0.0256	1.130	0.0106	1.255	1.266
								P	0.0677	1.115	0.0700	1.239	1.309
L10	S	10	1.066	1.081	0.324	0.969	2.182	N	0.0389	1.122	0.0205	1.252	1.272
								P	0.0231	1.137	0.0172	1.268	1.286
L10	R	11	1.085	1.066	0.334	0.964	2.165	P	0.0476	1.133	0.0266	1.502	1.529
								N	0.0326	1.152	0.0299	1.527	1.557
L12	R	11	1.036	1.089	1.164	0.954	2.160	P	0.0697	1.155	0.0824	1.523	1.605
								N	0.1158	1.102	0.1657	1.453	1.619
L17	S	11	1.074	1.055	0.687	0.965	2.126	N	0.0389	1.141	0.0295	1.518	1.548
								P	0.0770	1.121	0.0881	1.493	1.581

Bus	V_b	Q_{loss}	P_{max}	E_{sh}	S_{sh}
10	1.073	0.970	2.117	1.128	1.254
9	1.068	0.962	2.027	1.125	1.271
11	1.071	0.966	2.023	1.137	1.513
16	1.071	0.995	1.956	1.110	0.875
17	1.067	1.026	1.936	1.097	0.650
8	1.046	0.999	1.899	1.106	1.343

Bus Solution : 1st to 17th	10	10	10	11	11	11	9*	9	9	16	16*	16	8	17*	17*	17	18
18th to 34th	18	18*	13	8	20	20	13	15*	15*	23	23*	23	19	19*	19*	22	22

Bus Solution : 1st to 16th	10	9	11	16	17	8	18	20	13	15	23	14	21	19	12	22
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shunt side of UPFC plays an important role in controlling the maximum loading of power system. The UPFC direction has an influence on the capacity of inverters. For example, if the shunt site of UPFC, which is important part of UPFC, is installed to bus directly, it results in the smaller capacity of VSC.

Based on the results, UPFC is more effective for extending the maximum loading than STATCOM. Nonetheless, the total inverter size of UPFC is slightly larger than that of STATCOM.

C. PV Curve

The PV curves of buses 14 and 23 where the steady-state voltage stability is the severest are shown in Fig. 6. UPFC is installed in line 9R, which is the best position as shown in Table I. "OPF" in fig. 6. denotes the PV curve obtained from the OPF control shown in Table I and it provides the better solutions among the others. "UPFC" in Fig. 6. denotes that

UPFC is installed in the line and the parameters of UPFC are controlled to keep the voltage of the installed bus and power flow of the installed line at their initial values.

UPFC itself can extend the maximum loading. However, OPF control increases not only the maximum loading, but also the bus voltage, which is not preferable.

D. Effect of UPFC Installation and OPF Control

At can be seen from the PV curves that, contribution of UPFC installation and OPF control shows the different PV curve characteristics. Table V shows how much UPFC installation and OPF control contribute to the maximum loading extension. In these cases, OPF control can increase the maximum loading in only about 4-7% whereas UPFC installation can increase up to approximately 20% in some cases. When comparing total contribution and individual contribution, OPF control has a small contribution to the maximum loading extension.

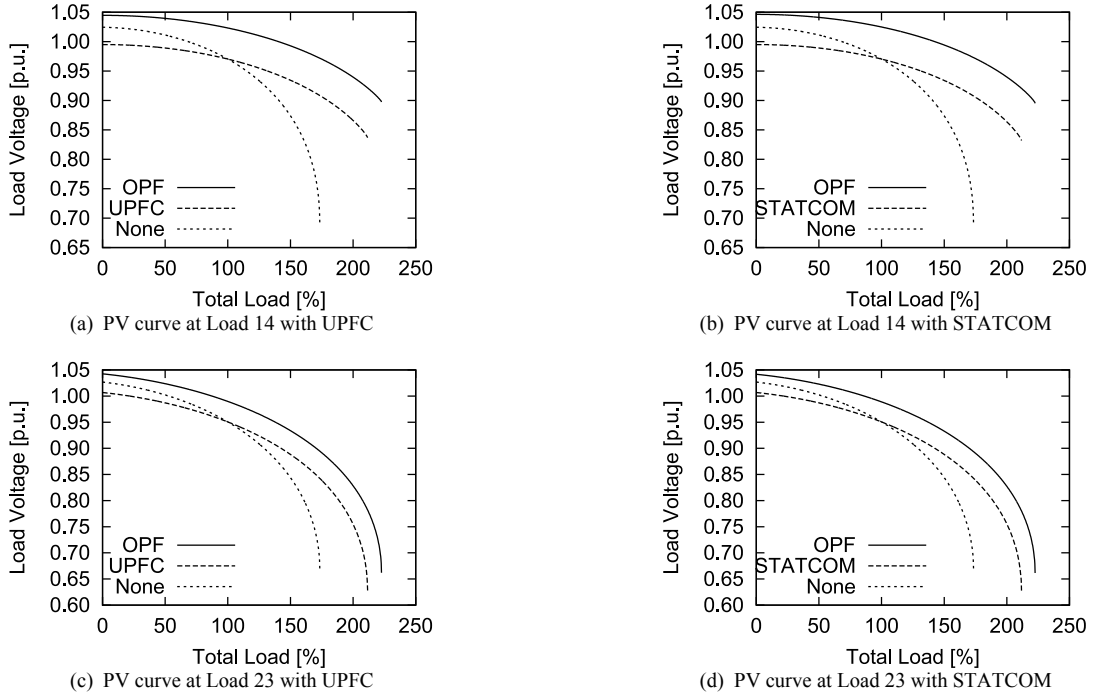


Fig. 6. PV curve at Load 14 and 23 with UPFC and STATCOM installed in line 9R.

TABLE V
CONTRIBUTION OF UPFC INSTALLATION AND OPF CONTROL TO MAXIMUM LOADING EXTENSION

Line	Location	Bus	None	UPFC	OPF	UPFC Effect Contribution [%]	OPF Effect Contribution [%]	Total Contribution [%]
8	S	8	1.734	1.898	2.003	9.47	5.51	15.50
8	R	9	1.734	2.027	2.122	16.90	4.68	22.37
9	R	10	1.734	2.116	2.227	22.00	5.26	28.42
10	S	10	1.734	2.068	2.182	19.26	5.53	25.86
10	R	11	1.734	2.035	2.165	17.35	6.41	24.88
12	R	11	1.734	2.022	2.160	16.62	6.79	24.55
16	S	10	1.734	2.110	2.219	21.69	5.17	27.98
17	S	11	1.734	2.010	2.126	15.94	5.77	22.63

IV. CONTRIBUTION OF INITIAL LOAD CONDITION TO THE MAXIMUM LOADING

A. Load Effect of Initial Condition

As is known, power system load is not always constant. In addition, UPFC optimal location and optimal parameters will be changed. In this research, the maximum loading is obtained by using minimizing the total reactive power losses as the objective function.

Fig. 7 shows the relation between the active power demand in the initial state and the maximum loading when UPFC is controlled to minimize total reactive power losses. It is found that the maximum loading becomes larger when the OPF control is performed at the larger load condition. When the load condition is less than 150%, the installation of UPFC at bus 9 will provide the larger maximum loading than that at bus 12. However, when the load condition is beyond 150%, the installation of UPFC at bus 12 offers the better result.

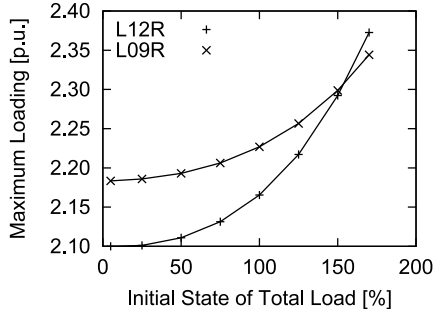


Fig. 7. Initial load changing.

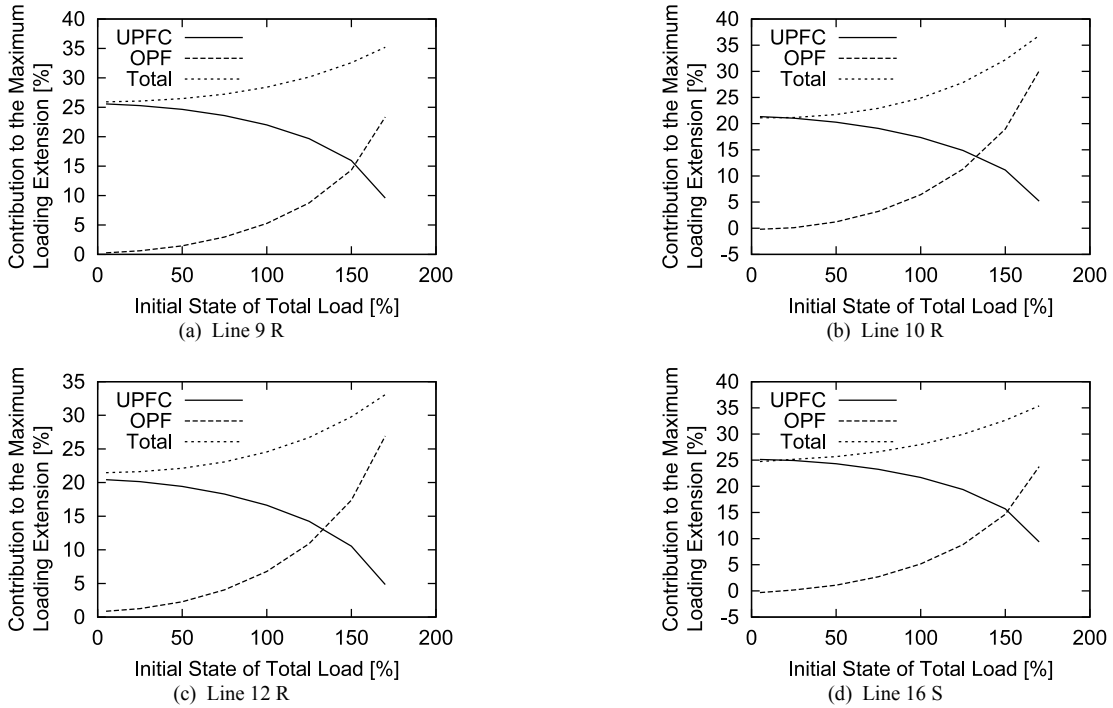


Fig. 8. Contribution of load changing.

B. Contributions of UPFC Installation and OPF Control in Initial Load Condition

Fig. 8 shows the contribution to the maximum loading extension when the initial power demand increases. In these cases, when the load demand increases, contribution of the OPF control also increases, but that of UPFC installation decreases.

When power demand is low, bus voltage becomes relatively higher. Therefore, in this situation, UPFC is controlled to maintain the high bus voltage as the power demand increases. On the other hand, when the power demand is high, the bus voltage becomes lower. In such a situation, UPFC parameters also become smaller unless the OPF control is implemented.

As in seen from Fig. 8. that, the OPF control seems to be effective only when the load demand is heavy. This can be explained as follows. In this paper, the maximum loading is calculated based on the minimization of the total reactive power losses. The reactive power loss on the particular line strongly depends on the difference between voltage magnitudes at two ends. In light load demand condition, bus voltage becomes quite high. Therefore, the bus voltages obtained by the OPF control cannot be increased much. On the other hand, bus voltage becomes quite low at the heavy load demand. In this case, the OPF control can lift the bus voltage to decrease the reactive power losses.

Figures 9 and 10 show the typical characteristics of the PV curves in light and heavy load conditions. In the light load condition, the maximum loading extension from the base case denoted by "None" by UPFC installation is larger than that from the UPFC installation case by OPF control as shown in Fig. 9. However, in the heavy load condition, OPF control from the UPFC installation outperforms UPFC installation in terms of the maximum loading extension as shown in Fig. 10.

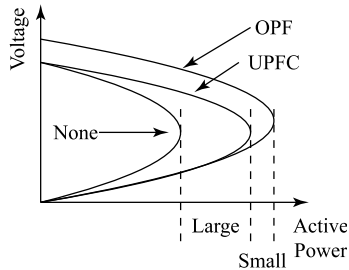


Fig. 9. Typical PV curves on light load condition.

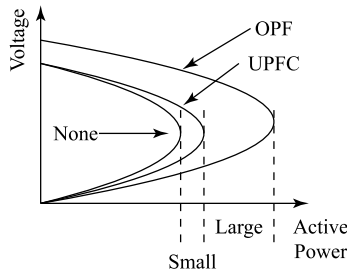


Fig. 10. Typical PV curves on heavy load condition.

V. CONCLUSIONS

In this study, the optimal UPFC location has been examined. It has been found that UPFC has similar characteristics to STATCOM but it has better contribution to the maximum loading extension. In addition, the contribution of UPFC installation to the maximum loading extension is more eminent than OPF control in the light load condition, and vice versa in the heavy load condition.

VI. REFERENCES

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VII. BIOGRAPHIES



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