

Enhancement of Power System Performance with UPFC under Steady and Dynamic Conditions

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Abstract—Accompanying with many flexible AC transmission system (FACTS) devices put into operation, the safety and reliability of power system operation have been suffering more serious influence and unprecedented challenge. Moreover, it's always difficult to comprehensively and accurately analyze the impacts of UPFC, the most versatile FACTS, on the operation characteristics of power system. This paper presents a framework for UPFC modeling based on the user-defined modeling (UDM) theory as well as a leading-edge stability analysis software named DSATools™. Furthermore, the characteristics of steady-state and dynamic responses are compared and analyzed under the condition of two-machine system. Numerical results from various simulations verify the feasibility and effectiveness of the proposed UPFC in terms of both the independent regulation of power flow and the improvement of transient stability.

Keywords—*dsatools™; flexible ac transmission systems (facts); unified power flow controller (upfc); user-defined modeling (udm); voltage-source converters (vsc)*

I. INTRODUCTION

Unified Power Flow Controller (UPFC), synthesized many flexible control methods, can permit concurrent control of the transmission line active and reactive power besides voltage stability [1]. Currently there are many researches considering the aspect of UPFC at home and abroad [2]-[5]. In [2], the transmission line power flow has been controlled by keeping UPFC controller at the sending end using MATLAB. Using UPFC based on feedback linearization technique was introduced in [3] to regulate the active power demand. The UPFC location optimization using the immune PSO is investigated in [4] to enhance power system capacity. In [5], the critical clearing time of SMIB system has increased after the occurrence of UPFC.

Due to the complicated internal structure, UPFC modeling has always been the difficulty and hotspot in research. In [6], the steady-state model of UPFC is built by use of power injection method in PSASP. A dynamic model of UPFC has been implemented by PSCAD to enhance the active power flow and bus voltage in [7]. According to [8], the electromechanical transient model of UPFC is established in PSS/E surrounding. However, there are only a few researches on UPFC dynamic modeling based on user-defined modeling (UDM) method. The fundamental thought of UDM is that, on the premise of not understanding the internal architecture of program and going through additional compilation processes, user can build various models with reference to their own preference using familiar concept and methods. This paper

presents a dynamic model of UPFC with UDM approach in DSATools™, which is a leading-edge security assessment software developed by Powertech Labs Inc. This reduces the difficulty in modeling process and consider the influence of system nonlinear parts on UPFC dynamic performance. The established UPFC is conducive to the enhancement of the flexibility and controllability for power system parameters.

The rest of this paper is organized as follows: Section II and Section III respectively give a brief introduction about FACTS and UPFC. In the next section, the security assessment software DSATools™ is introduced first, and then the detailed application of UDM for UPFC is explained emphatically. This section is followed by Section V in which the simulation setup is presented. It fully describes an overview of a test system and the assessment simulation results. Finally, conclusions are outlined in Section VI.

II. OVERVIEW OF FACTS

Flexible AC Transmission System (FACTS), firstly put forward by Dr Narain. G. Hingorani of EPRI in 1986 [9], is a novel power system controlling technology based on the installation of power electronic devices in the main positions of the transmission system. FACTS are primarily classified into three categories as follows with reference to various functions and connection mode in different conditions. All of thyristor controlled Series capacitor (TCSC), static synchronous series compensator (SSSC) and Interphase Power Controller (IPC) have affiliation to the series FACTS controller. These controllers could be employed to enhance the network power flow distribution by means of changing the line impedances. Static var compensator (SVC), thyristor controlled braking resistor (TCBR) and static synchronous compensator (STATCOM) are regarded as subordinate to the shunt FACTS controller, which have ability to control the reactive power flow as well as bus voltage for the transmission capacity improvement and system stability enhancement. Additionally, unified power flow controller (UPFC), interline power flow controller (IPFC), general unified power flow controller (GUPFC) and convertible static compensator (CSC) are parts of the hybrid FACTS controller, a combination of various series and shunt controllers. Most of them perform the characteristics of adjusting multiple power parameters, either simultaneously or independently, through the control of the related all-controlling power electronics device [10].

III. UNIFIED POWER FLOW CONTROLLER

A. Fundamental Principle of UPFC

The schematic diagram of UPFC is displayed in Figure I. UPFC is actually the synthesis of STATCOM and SSSC. It consists of two power-electronic based voltage-source converters (VSC) coupled through a common capacitor in DC side.

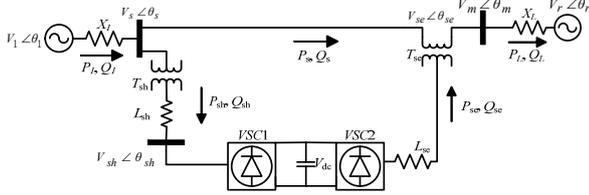


FIGURE I. SCHEMATIC DIAGRAM OF UPFC

These two converters are connected respectively in shunt with transmission line through a shunt transformer T_{sh} and in series with the transmission line through a series transformer T_{se} . The shunt converter VSC1 is utilized to independently manipulate reactive power flow to regulate the voltage at the connected point of AC system. Besides, it also has a capability of providing the active power flow exchanged between the series converter and the transmission line. The series converter VSC2, as the main function parts, injects a voltage \dot{V}_{se} in series with the system through the transformer T_{se} , which controls the active and reactive power flow in the transmission line by the variation of the voltage with controllable magnitude V_{se} and phase angle θ_{se} at power frequency. The DC link provides a path to exchange active power between these two converters [11].

B. Mathematical Model of UPFC

1) Shunt part

The shunt part of UPFC can be regarded as an ideal controllable voltage source \dot{V}_{sh} connected with a leakage reactance of shunt transformer X_{sh} shown in Figure II.

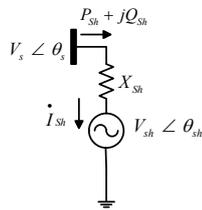


FIGURE II. EQUIVALENT CIRCUIT OF SHUNT PART

Taking the sending-end voltage \dot{V}_s as the reference vector, the output voltage of shunt converter \dot{V}_{sh} can be expressed in terms of two orthogonal vectors V_{sh-d} and V_{sh-q} . That is,

$$\dot{V}_{sh} = V_{sh-d} + jV_{sh-q} = V_{sh} \cos \theta_{sh} + jV_{sh} \sin \theta_{sh} \quad (1)$$

The current flowing through the shunt converter from the AC system is \dot{I}_{sh}

$$\begin{aligned} \dot{I}_{sh} &= I_{sh-d} + jI_{sh-q} = \frac{\dot{V}_s - \dot{V}_{sh}}{jX_{sh}} \\ &= \frac{V_s - V_{sh} \cos \theta_{sh} - jV_{sh} \sin \theta_{sh}}{jX_{sh}} \\ &= -\frac{V_{sh} \sin \theta_{sh}}{X_{sh}} - j\frac{V_s - V_{sh} \cos \theta_{sh}}{X_{sh}} \end{aligned} \quad (2)$$

Where I_{sh-d} and I_{sh-q} are the direct-axis and quadrature-axis component of the injected current respectively.

Therefore, the power absorbed from the AC system to the shunt converter is given as

$$\begin{aligned} P_{sh} + jQ_{sh} &= \dot{V}_s \dot{I}_{sh}^* = V_s I_{sh-d} - jV_s I_{sh-q} \\ &= -\frac{V_s V_{sh} \sin \theta_{sh}}{X_{sh}} + j\frac{V_s^2 - V_s V_{sh} \cos \theta_{sh}}{X_{sh}} \\ &= -\frac{V_s V_{sh-q}}{X_{sh}} + j\frac{V_s^2 - V_s V_{sh-d}}{X_{sh}} \end{aligned} \quad (3)$$

2) Series part

The series part of UPFC can also be equivalent to an ideal controllable voltage source \dot{V}_{se} both in magnitude and phase angle as seen in Figure III. Thus, the current \dot{I}_{line} flowing through this voltage source results in exchange of power flow between it and AC system. \dot{V}_m represents an imaginary voltage located between the series reactance X_{se} and the line reactance X_L .

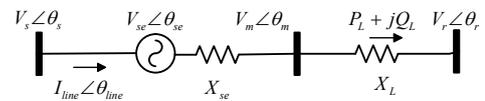


FIGURE III. EQUIVALENT CIRCUIT OF SERIES PART

Hence, the line power flow of the series part is formulated as follows,

$$P_L = \frac{V_m V_r \sin \theta_{mr}}{X_L} = \frac{V_m V_r \sin(\theta_m - \theta_r)}{X_L} \quad (4)$$

$$Q_L = \frac{V_m^2}{X_L} - \frac{V_m V_r \cos(\theta_m - \theta_r)}{X_L} \quad (5)$$

Where \dot{V}_s and \dot{V}_r are the sending-end and receiving-end voltage space vector respectively. Besides, θ_{mr} is the phase difference between \dot{V}_m and \dot{V}_r . Supposing $\theta_s = 0$, the above formulae (4) and (5) are further deduced like the equations (6) and (7) in accordance with the relationship between control vectors of series part shown in Figure IV.

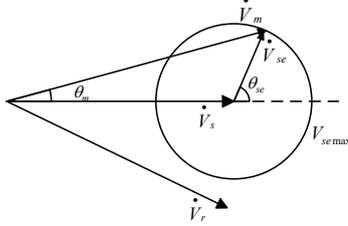


FIGURE IV. VECTOR GRAPHIC OF UPFC SERIES PART

$$P_L = \frac{V_m V_r}{X_L} \sin(\theta_m - \theta_r) = \frac{V_r}{X_L} V_{se} (\sin(\theta_{se} - \theta_r)) - \frac{V_r}{X_L} V_s \sin \theta_r \quad (6)$$

$$Q_L = \frac{V_r^2}{X_L} - \frac{V_m V_r}{X_L} \cos(\theta_m - \theta_r) = \frac{V_s^2}{X_L} - \frac{V_s V_r}{X_L} \cos \theta_r + \frac{V_{se}^2}{X_L} - \frac{V_{se} V_r}{X_L} \cos(\theta_{se} - \theta_r) + \frac{2V_s V_{se}}{X_L} \cos \theta_{se} \quad (7)$$

IV. UDM OF UPFC IN DSATools™

A. Overview of DSATools™

In this paper, the steady-state simulation is carried out based on PSAT in DSATools™ to investigate the influence of UPFC on the system power flow. TSAT plays a vital role in evaluating the dynamic performance of UPFC on the power system. TSAT can not only give accurate responses of various types of disturbances, but also have complete assessments of transient security problems of large interconnected power system. Together with PSAT, scenarios in TSAT are used to specify different power flow condition, dynamic component models, computation parameters and multiple contingencies.

B. UDM Modeling of UPFC

1) Overview of user-defined modeling

UDM Editor in DSATool™ provides a comprehensive library of math, control functions and physical device models in building UDMs. UDM Editor has the capability of creating all types of UDM including converter-based FACTS devices. With regard to UPFC modeling, UDM Editor will work in the mode of DC UDM or UDC which provides a flexible operating environment to converter-based FACTS model. The general structure of a UDC model is shown in Figure V. User can group DC control blocks into sub-diagrams based on the corresponding physical link connection by their functionality, or just put all the DC control blocks in a sub-diagram [12].

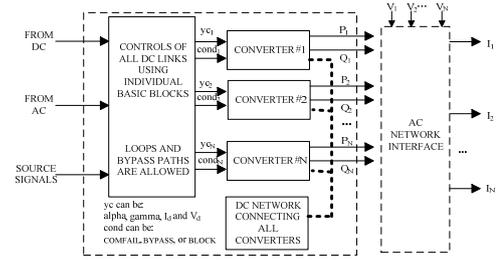


FIGURE V. THE GENERAL STRUCTURE OF USER-DEFINED DC MODEL

2) Application of UDM to UPFC

During the process of UPFC modeling, user can implement a customized control function in UDM using general blocks available in the element library, as well as a set of special blocks and end blocks. There is mainly composed of three essential parts in UDM Editor described below.

a) Workspace

The information of workspace is organized in a tree with three layers of Data File, Simulation Parameters and DC Link. Data File shows the UPFC modular blocks loaded in the Editor when creating a new data file as "UDC File.dat". Simulation Parameters shows the first data containing the dc system solution parameters. DC Link(DL) shows all DC links and the functional diagrams within the corresponding DC link models in the data file. Sub-diagrams incorporated into each DC link are groups of related UDC control blocks which can define the functionality of each part of UPFC model.

b) Model canvas

Model canvas is where we actually add the relevant components to build UPFC project. A new canvas is created after selecting the model type that UPFC belongs to. Then, any available function blocks can be utilized to the model type to build UPFC model by means of dragging from the block tree and dropping on the working model canvas. Meanwhile, blocks are added to individual sub-diagrams within a DC Link.

c) Function blocks

The operation logics of UPFC model behave diversely so that multitudes of function types should be available to satisfy the requirements of UPFC's various functions. There mainly exists several basic procedures for UPFC user-defined modeling. User-defined controls of UPFC are built by interconnecting input signals and various control function blocks with drag-&-drop approach.

V. SIMULATION SETUP

A. Test System

The single line diagram of a two-machine AC system is as shown in Figure VI designed in DSA/PAST. This incorporates two synchronous generators in each area of 18000 and 19000 MVA rating respectively, connected by several parallel tie lines. And the detailed parameters are same as that in [13].

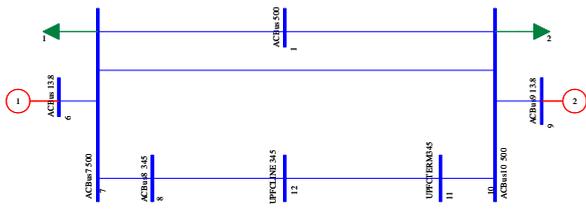


FIGURE VI. TWO-MACHINE AC SYSTEM

UPFC is installed between the 345 kV buses B11 and B12, which is used to control the power flow and voltage of the line L11-12. B11 is the sending end bus connected to the shunt VSC1 of UPFC, while the receiving end bus B12 is in conjunction with the series VSC2. Thus, the L10-11 and L8-12 will be influenced by the installation of UPFC.

B. Simulation Results

1) Power flow analysis

The steady-state model of UPFC in PSAT is made utilizing rectifier and inverter network based on the VSC converter model. Here, VD (DC voltage) and QA (reactive power) method will be selected for the shunt VSC1 of a UPFC model, while the variables of series VSC2 will be set to PA (active power) and QA (reactive power) in PSAT.

The power flow during the steady-state analysis cannot be controlled without UPFC. With the presence of UPFC across the L11-12, all the transmitted active and reactive power of lines have remarkably changed. For example, when setting VD=10 kV, QA=5 MVAR for VSC1 as well as PA=370 MW, QA=25 MVAR for VSC2, the actual values of power flow have become 369.932+j25.0677 MVA and 369.981+j61.3306 MVA for L12-8 and L10-11 respectively. Simulation results demonstrate the feasibility of UPFC in controlling the power flow through the transmission lines.

From Table I and Table II, both can be observed that the active and reactive power of L11-12 are controlled independently by adjusting the series VSC2 of UPFC. Besides, for L12-8 in Table I, the actual reactive power remains basically unchanged at QA=25 MVAR, but the active power varies in accordance with the set point PA. Similarly, the actual active power is always keeping P=370 MW while the reactive power changes with the variation of QA shown in Table II. Additionally, the voltage magnitude and phase for the receiving end B12 present regular change, along with the active and reactive power changing separately in both situations. Sending end B11 is basically not changed at this moment. In a word, UPFC has the capability of influencing the voltage magnitude and phase of transmission line.

TABLE I. CONTROL VARIABLE PA OF SERIES VSC2

Case 1	VSC1: VD=10, QA=5				VSC2: QA=25			
	PA=350		PA=370		PA=390		PA=410	
Power Flow	P(MW)	Q(MVAR)	P(MW)	Q(MVAR)	P(MW)	Q(MVAR)	P(MW)	Q(MVAR)
L11-12	350	25	370	25	390	25	410	25
L12-8	349.931	25.0727	370.004	24.9936	389.927	25.0727	407.156	25.0214
L10-11	349.99	65.8937	370.051	61.2307	389.961	55.6014	407.18	49.6163
Bus Voltage	V(p.u.)	Angle	V(p.u.)	Angle	V(p.u.)	Angle	V(p.u.)	Angle
Bus 11	0.97474	-5.464	0.97483	-5.4697	0.97493	-5.4753	0.97503	-5.4802
Bus 12	1.02664	-13.5377	1.01998	-12.2532	1.01287	-10.9437	1.00602	-9.7734
Vse	0.14982	65.834	0.12647	65.6798	0.10212	65.479	0.08044	65.1756

TABLE II. CONTROL VARIABLE QA OF SERIES VSC2

Case 2	VSC1: VD=10, QA=5				VSC2: PA=370			
	QA=10		QA=20		QA=30		QA=40	
Power Flow	P(MW)	Q(MVAR)	P(MW)	Q(MVAR)	P(MW)	Q(MVAR)	P(MW)	Q(MVAR)
L11-12	370	10	370	20	370	30	370	40
L12-8	370.071	9.92906	370.075	19.921	370.076	29.9189	370.072	39.9163
L10-11	370.091	45.69501	370.113	56.0556	370.135	66.1586	370.159	76.0155
Bus Voltage	V(p.u.)	Angle	V(p.u.)	Angle	V(p.u.)	Angle	V(p.u.)	Angle
Bus 11	0.97498	-5.4693	0.97488	-5.4696	0.97478	-5.4699	0.97468	-5.4701
Bus 12	1.00406	-11.9218	1.01467	-12.1411	1.02502	-12.3507	1.03514	-12.5518
Vse	0.11511	72.1593	0.12241	67.7214	0.13007	63.8799	0.13802	60.5347

In Table III, it can be easily found that the DC voltage of both converters will follow the change of VD from the data of V_{DC_VSC1} and V_{DC_VSC2}. However, the actual values of active and reactive power maintain unchanged for both sending and receiving end, same with the connected bus voltage. This demonstrates, in steady-state operation, UPFC keeps the DC capacitor voltage constant for the initial setting. And there is no active power exchange between UPFC and AC transmission system. That is, the active power on the shunt VSC1 is totally equal to that on the series VSC2.

In Table IV, the change of reactive power injected into the shunt converter, QVSC1, will take place under the condition of different QA set point. Apparently, the reactive power through the shunt line L10-11 has an obvious alteration, including both the magnitude and the direction. At the same time, the power flow passing through the series line L12-8 always stay the same as the set point of PA and QA. What's more, it's evident from the table that the voltage of B11 responds to the change of QA while the voltage of B12 remains unchanged all the time. In brief, the bus voltage of sending end can be adjusted by regulating the reactive power flow with UPFC.

TABLE III. CONTROL VARIABLE VD OF SHUNT VSC1

Case 3	VSC1: QA=5				VSC2: PA=370, QA=25			
	VD=10		VD=20		VD=30		VD=40	
Power Flow	P(MW)	Q(MVA _r)	P(MW)	Q(MVA _r)	P(MW)	Q(MVA _r)	P(MW)	Q(MVA _r)
L11-12	370	25	370	25	370	25	370	25
L12-8	370.004	24.9936	370.041	24.9546	370.006	24.9991	370.011	24.9867
L10-11	370.051	61.2307	370.053	61.1723	370.012	61.2228	370.014	61.2226
Bus Voltage	V(p.u.)	Angle	V(p.u.)	Angle	V(p.u.)	Angle	V(p.u.)	Angle
Bus 11	0.97483	-5.4697	0.97483	-5.4697	0.97483	-5.4697	0.97483	-5.4697
Bus 12	1.01998	-12.2532	1.01992	-12.2499	1.01997	-12.2531	1.01997	-12.2526
V _{bc_vsc1} (p.u.)	10		20		30		40	
V _{bc_vsc2} (p.u.)	10		20		30		40	

TABLE IV. CONTROL VARIABLE QA OF SHUNT VSC1

Case 4	VSC1: VD=10				VSC2: PA=370, QA=25			
	QA=5		QA=35		QA=65		QA=95	
Power Flow	P(MW)	Q(MVA _r)	P(MW)	Q(MVA _r)	P(MW)	Q(MVA _r)	P(MW)	Q(MVA _r)
L11-12	370	25	370	25	370	25	370	25
L12-8	370.004	24.9936	370.009	25.0637	369.982	25.0637	370.065	24.9316
L10-11	370.051	61.2307	370.055	31.2627	370.029	1.26508	370.112	-28.8803
Q _{vsc1} (MVA _r)	5		35		65		95	
Q _{vsc2} (MVA _r)	-40.5							
Bus Voltage	V(p.u.)	Angle	V(p.u.)	Angle	V(p.u.)	Angle	V(p.u.)	Angle
Bus 11	0.97483	-5.4697	0.97483	-5.4697	0.97483	-5.4697	0.97483	-5.4697
Bus 12	1.01998	-12.2532	1.01992	-12.2499	1.01997	-12.2531	1.01997	-12.2526

2) Contingency analysis

A symmetrical three-phase short circuit is considered for being applied at the B10 in the two-machine AC system. At time $t=0.5$ s, the three-phase fault occurs at B10 and then will be cleared after removing the line between B1 and B10 at 0.567s in test system 1. Figure VII (a) and (b) individually show the voltage magnitude of B11 and B12 respectively without/with the insert of UPFC. As can be seen from these two figures, after clearing the fault, the designed UPFC provides damping of the voltage oscillation. And, the waveforms of both voltages with UPFC die out in a short time as compared to when the UPFC was not connected. Besides, Figure VIII (a) and (b) show the power flow of L8-12 and L10-11 without/with UPFC respectively, where the occurrence of designed UPFC effectively suppresses the active and reactive power oscillation of both transmission lines. So, the dynamic stability of this power system can be improved to some extent with UPFC.

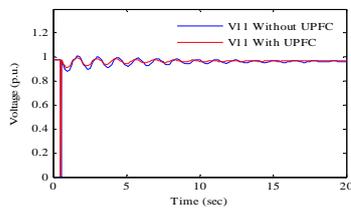


FIGURE VII (A) VOLTAGE MAGNITUDE OF BUS B11

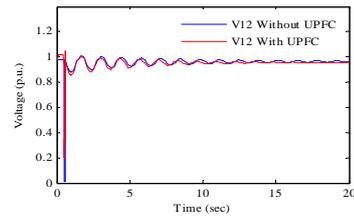


FIGURE VII. (B) VOLTAGE MAGNITUDE OF BUS B12

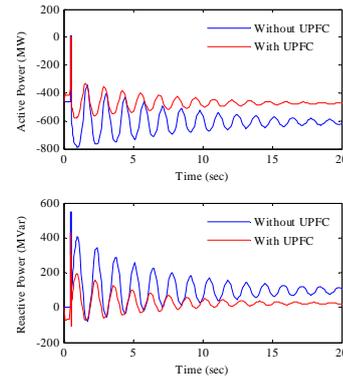


FIGURE VIII (A) POWER FLOW OF LINE L8-12

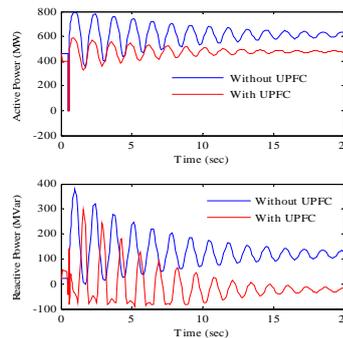


FIGURE VIII. (B) POWER FLOW OF LINE L10-11

VI. CONCLUSION AND FUTURE WORK

In this paper, the steady-state model of UPFC is firstly established based on VSC modular in PSAT. User-defined modelling method has been implemented to build UPFC in UDM Editor and TSAT. And, simulation results in the steady and dynamic analysis present the flexible control of lines power flow and rapid response of oscillation damping after inserting the UPFC, which prove the feasibility and effectiveness of the established UPFC.

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