A STUDY OF EQUIPMENT SIZES AND CONSTRAINTS FOR A UNIFIED POWER FLOW CONTROLLER 12 h 19	NGHIÊN CỨU KÍCH THƯỚC THIẾT BỊ (THAM SỐ THIẾT BỊ) VÀ CÁC RÀNG BUỘC ĐỐI VỚI BỘ ĐIỀU KHIỂN DÒNG CÔNG SUẤT TÍCH HỢP
Abstract - Tbis paper provides a quantitative measurement of the	Tóm tắt-Bài báo này đánh giá định lượng lợi ích của Bộ Điều Khiển

benefit that a Unified Power Flow Controller (UPFC) can provide to increase firm power transfer between two large power systems. Included is a complete model for a UPFC control system that contains bus voltage control by the shunt inverter, real power transfer between the shunt and series inverters, and real and reactive power control for the transmission line into which the series inverter is inserted. A significant part of the model is representation of dynamic limits that coordinate injected current limits for the shunt inverter, power transfer limits between inverters, voltage injection limits for the series inverter, current limits for the series inverter, and line voltage limits for the transmission line. This paper contains a simple system simulation to demonstrate the coordinated dynamic control and illustrate issues that system planning engineers must consider in defining applications for a UPFC.	Dòng Công Suất Tích Hợp (UPFC) trong việc tăng cường khả năng truyền tải điện bền vững giữa hai hệ thống điện lớn. Chúng tôi sẽ đề cập đến một mô hình hoàn chỉnh về hệ thống điều khiển UPFC có tính năng điều khiển điện áp bus thông qua bộ nghịch lưu shunt, truyền tải điện thực giữa bộ nghịch lưu shunt và bộ nghịch lưu nối tiếp, và điều khiển công suất thực và công suất phản kháng của đường dây truyền tải được lắp đặt bộ nghịch lưu nối tiếp. Một phần quan trọng của mô hình trình bày các giới hạn động học chi phối các giới hạn dòn tiêm của bộ nghịch lưu shunt, các giới hạn truyền tải điện giữa các bộ nghịch lưu, các giới hạn tiêm điện áp, các giới hạn dòng đối với bộ nghịch lưu nối tiếp, và các giới hạn điện áp đường dây đối với đường dây truyền tải. Bài báo này chứa đựng một mô phỏng hệ thống đơn giản để minh chứng cho tính năng điều khiển động học phối hợp và minh họa các vấn đề mà những kỹ sư thiết kế hệ thống phải xét đến trong quá trình xác định các ứng dụng cho UPFC.
KEYWORDS: Power Flow Control, Voltage Control, Static Synchronous Compensator, Unified Power Flow Controller, Voltage Sourced Inverters	TỪ KHÓA: Điều khiển dòng công suất, điều khiển điện áp, bộ bù đồng bộ tĩnh, bộ điều khiển dòng công suất hợp nhất, bộ nghịch lưu nguồn áp
I. INTRODUCTION A number of products centered around voltage sourced inverters are being developed under the Electric Power Research Institute's Flexible AC Transmission System (FACTS) initiative. The first of these products, the static synchronous compensator (STATCOM) is in demonstration at	[redacted]

the Tennessee Valley Authority's Sullivan Station [1], The second, the Unified Power Flow Controller, is scheduled to be demonstrated at the American Electric Power Company's Inez Station [2]. These devices have generated a significant amount of research interest and they show a great amount of promise for fast and accurate control of transmission system voltages, currents, impedance, and power flow [3,4,5].

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The UPFC combines two voltage sourced inverters to control the voltage at a transmission substation and at the same time control the real and reactive power flow on a transmission line [6]. Figure 1 shows the general circuit arrangement for a UPFC. Reactive power is generated or absorbed by the shunt inverter to control bus voltage and by the series inverter to control the real and/or reactive power flow on the transmission line.

Figure 1 UPFC connected to the system

A portion of the real power flow on the transmission line drawn from the bus by the shunt inverter charges the DC capacitor that forms the DC bus. This real power is inserted into the line through the series inverter. Several alternate arrangements can be used to control the DC bus voltage and allow two different AC voltages. One method is to divide the DC

[redacted]

[redacted]

capacitor and provide a boost converter to maintain DC voltage proportional to the AC voltage of each inverter.	[redacted]
Specification of a UPFC requires definition of the sizes for each of the components. These include the voltage and VA rating for the shunt inverter, the current rating, VA rating, and insertion transformer leakage reactance for the series inverter and the power transfer through the DC bus. With these ratings defined, the related quantities, shunt inverter current and injected voltage for the series element can be easily calculated. The shunt inverter rating must be large enough to provide both the reactive current needed to support system voltage and the real power required for insertion by the series inverter. It should be noted that the series inverter current rating may be the limiting element for current flow on the transmission line. This value must be carefully specified because the transient overload characteristics of the power semiconductors in the inverters are much different from those of more traditional transmission system equipment.	[redacted]
II. UPFC CONTROL SYSTEM The operation of the UPFC is defined by its internal control system. The UPFC control system establishes the gating commands for the GTO thyristor valves so that the two inverters can perform their designated functions correctly under normal	[redacted]

conditions. The controller is also responsible for taking action to prevent the equipment from operating in any region that would be damaging for the inverters or undesirable for the power system. During normal operation of the shunt inverter, the UPFC control system regulates its output ac voltage to draw a desired level of current from the line. This current has a real power component required to regulate the dc bus voltage in the UPFC and a reactive component to regulate line voltage at the substation bus where the shunt inverter is connected. The automatic voltage control is very similar to that which is commonly employed on conventional static var compensators providing a voltage reference input and a droop factor that determines the voltage error versus the reactive current load of the shunt inverter. In the case of the series inverter under normal operation, the UPFC control system determines the voltage to be injected in series with the transmission line. The injected voltage is a positive sequence vector quantity having magnitude and phase angle and its purpose is to influence the real and reactive power flow on the line. The phase angle reference is chosen to be the phase of the positive sequence voltage at the substation bus where the UPFC is installed. The injected voltage and line current can be separated into two components, VP and Ip which are in phase with the bus voltage and VQ and IQ which are defined to lag the bus voltage by 90°. Then the injected voltage of the series	[redacted] [redacted]

inverter V; (= VtZ8,), is computed as follows:

The UPFC control system achieves these objectives by means of carefully structured automatic feedback control algorithms. These algorithms are executed in high speed digital processors with sample times of a few tens of microseconds. These control actions are so rapid that they would not limit the response of the UPFC to transient and dynamic oscillations in power systems.

A block diagram representation of the UPFC control system is shown in Figure 2. Functions within the blocks labeled shunt and series inverter control would be chosen to coordinate operation of the two inverters and maintain the charge of the dc bus. For purposes of system studies using transient and dynamic stability simulation programs, they can be represented as shown in Figures 3a and 3b. Gains and time constants used for the study discussed below are given in the Appendix.

The block entitled system control can be used to define additional dynamic functions that would supplement the shunt and series control. Since these functions are computed using digital processors, they can be tailored to meet requirements for specific applications such as inter-area oscillation damping. For the study in this paper, algorithms that coordinate the multiple limits encountered with the UPFC are programmed in this block. Its output modifies the reference settings for the shunt and series controllers.

Figure 3b Power control block of a UPFC series inverter

III. CONSTRAINT RESOLUTIONS

There are six constraints imposed to the operation of a UPFC.
These are:
1. series injected voltage magnitude
2. line current through series inverter
3. shunt inverter current
4. minimum line-side voltage of the UPFC
5. maximum line-side voltage of the UPFC
6. real power transfer between the series and shunt inverters

The voltage constraint on DC-link related to the constraint for the shunt inverter voltage will be handled by the basic control of a UPFC. To make full use of a UPFC, the constraint resolutions need to be developed so that when the UPFC control is in limit, a best compromise of control and power system operation is sought. For a UPFC, real power flow control is very important during both steady-state and transient operation. Therefore, the objective chosen when limits are reached is to maximize the real power transfer of the line.

The objective function and its constraints can be described as follows with quantities defined by the typical one-line diagram of a UPFC installation shown in Fig. 4. In this figure the series inverter is modeled as a voltage source [7]: max

[redacted]

[redacted]

PD subject to Vt < LVj (LI) where Vt is the magnitude of the series injected voltage, I is the magnitude of line current through series inverter, Pdc is the real power transfer between series and shunt inverter, Ish is the magnitude of the reactive current of the shunt inverter and VD is the voltage magnitude at UPFC line side.	[redacted]
, LVD max and Lv min are the corresponding	[redacted]
For the system shown in Fig. 4, assume that Vs = 1.015Z10°pu, VR = 1.0Z0°pu, ZL = O.Ol+jO.l pu, and the magnitude of series injected voltage is 0.25 pu (F?=0.25 pu). From Eq. (1) and (2) the variations of line flow PD and QD are illustrated in Fig. 5 and 6 with respect to the phase angle 0,-.	[redacted]
Figure 5 Real power flow vs. injected voltage angle Figure 6 Reactive power flow vs. injected voltage angle Applying Eq. (4), the PD and QD, characteristics are an ellipse as shown in Fig. 7.	[redacted]
Figure 7 Power flow of the line versus series injected voltage (no constraints) Assume that with the present UPFC, none of six constraints are violated at t=t0. By having Vw, 0/o and system input, the UPFC controller would generate a new Vu and 6,7 based on the requested bus voltage and power	[redacted]

flow of the line. Given Vu, 9,7 and the bus voltage VSj where the shunt inverter is connected and the calculated bus voltage at the end of the transmission line, Vm, h, Pda, ISh and VDi can be easily computed and whether or not any constraints are violated can be checked. If none of the constraints are violated, then inject Vu and 0;j to the system at ti=to+At and continue to find out the Vu and 0a through the UPFC controller; otherwise, search the feasible ranges of 0*; which make the violated variables stay within the feasible ranges while keeping Vu unchanged. . Among the feasible ranges, the optimal 0,7 can be found which maximizes the real power flow of the line. If no feasible ranges exist, then reduce the Vu based on the violated constraints while keeping 0l7 unchanged. The flow chart of this constraint resolution is illustrated in Fig. 8.

Figure 8 One step flow chart of UPFC constraint resolutions Similar strategies to relieve a UPFC from the limits could be applied to the UPFC controller if different objective functions are defined based on system operation needs.

For any given Vt within the limit, the feasible ranges of 0; can be found as follows.

Define:

The line current can be calculated using Eq. (6),

If the magnitude of the line current is less:than the li mit Lj, or m-r, (7)

Based on Eq. (5) and (6) it is apparent that (7) is equivalent to the following:

where cp 2 and <p/o are the phase angles , of the ZL and I0, respectively. For the system shown in Fig. 4, with V; = 0.25 pu and the series current limit Lj= 4.15 pu the allowable ranges for 0; are O°<0,- <66° and 115°<0,- < 360°, shown in Fig. 9 where the line flow plotted in solid lines is the same as the flow in Fig. 7 without any constraints and the line flow in dashed lines is the flow with the fixed line current 4.15 pu.

Figure 9 Line flow with a current-limited UPFC ,

Similarly, we know that the real power transfer between series inverter and shunt inverter can be written as follows:

Applying Eq. (6) into (9), P; is equal to

where

(12)

The constraint |Prfc|^ LPj^ is equivalent to the following set of two inequalities:

system shown in Fig. 4, with Vj = 0.25 pu and the real power transfer limit Lpjc = 0.27 pu the allowable ranges for 0,- are

68° < 6, < 145° and 227° <0;- < 304°, shown in Fig. 10.

Figure 10 Line flow with a UPFC having limit for \Pdc\

The line-side voltage of a UPFC, VD, can be computed as Eq. (15).

constraint LVijmin < VD < LV]_max is equivalent to

(16)

Figure 11 Line flow with a UPFC having limits for Vo

For the system shown in Fig. 4, with

[redacted]

[redacted]

[redacted]

Vt = 0.25 pu and the limits of the line-side voltage of a UPFC, Lv^max = 1.1 pu and

LyDmin ~ 0.90 pu, the allowable ranges for 0,- are

87°<0 j < 133° and 247°<0Z < 293° , shown in Fig. 11.

Figure 12 Line flow with a UPFC constrained by six limits

The shunt inverter size must be at least as large as the real power transfer between the two inverters. Additional capability will usually be required to provide the reactive current needed to regulate bus voltage. This rating establishes the limit for shunt inverter current and the bus voltage regulation must be relaxed to avoid exceeding this current level. In summary, the feasible ranges of 0;- can be obtained by combining the five inequalities (8), (13), (14), (16) and (17) and the solutions of different optimal problems can be found within these feasible ranges.

IV. POWER SYSTEM STUDY

A simple power system is used to illustrate the considerations that influence equipment ratings for the UPFC. It represents two large systems that exchange power over two transmission lines which have unequal transfer capability as shown in Fig. 13.

Each large system is represented by a single generator, transfer impedance, shown as a transformer, and load. The generators have typical reactances and inertias in per unit on their bases as well as excitation and speed governing control systems. It is assumed that each generator has 10%

[redacted]

[redacted]

spinning reserve capability. Power is exchanged between the systems primarily over a 100 mile long 345 kV transmission line with a secondary path over the underlying 138 kV system. This system divides the 100 mile distance with two lines, each 60 miles long supplying a load and a single line, 40 miles long to the other end. The generators and system parameters are listed in the Appendix. It is assumed that power transfer is limited by transient stability constraints resulting from a fault on the 345 kV line. The disturbance is a 3-phase to ground fault applied at the center of 345 kV line. The fault is cleared after four cycles with the line left out of service following the fault.

Figure 13 Study System

The base case without a UPFC determined the maximum power that can be transferred between the two systems while maintaining synchronism under this contingency. Various sizes of UPFCs were added at the substation connecting the 138kV lines and new values of the maximum power transfer were defined. In each case, the power flow prior to the fault was defined with no inserted voltage from the series element of the UPFC and with no reactive current supplied by the shunt inverter.

At the instant the fault is applied, the reference power flow for the UPFC was changed to the sum of the prefault line flows for the 345kV line and the single 138kV line. Constraints limiting the maximum transient voltage on the line side of

[redacted]

[redacted]

the UPFC, VDmax, below 1.2 pu and the maximum voltage inserted by the series inverter, Vimax, to 0.3 pu were applied.	[redacted]
Figure 14 Power transfer capability with UPFC	[redacted]
Study results are summarized in Table 1 and 2. Fig. 14 shows the transient power flow on the 40 mile long 138 kV line for Case 1 with no UPFC and Case 4 where the equipment ratings are given in Table 1. In Case 1 further increase in the prefault power flow would result in loss of synchronism between two systems. Although the UPFC operation for Case 4 is constrained by limits, the resulting power flow in the line is well behaved. These cases show that a UPFC with a series element transient rating of 1.26 pu (126 MVA) and a shunt element transient rating of 5.5 pu (550 MVA) allows an increase in firm power transfer of 181 MW (356.8 - 175.7) between two systems.	[redacted]
Table 1 Transient maximum ratings for the UPFC (in pu) * Case 1 has the largest power flow transfer without a UPFC.	
Case 6 shows that firm power transfer can be increased to 450 MW with further increase in UPFC ratings. Each increase in power transfer requires an increase in the transient ratings of the inverters with the increase in the shunt inverter growing rapidly to provide the voltage support required by the 138 kV transmission	

lines. However, the simulations have shown that the half of the shunt inverter rating could be replaced by the capacitors for cost saving. The increase in postfault power flow for the last two cases is much less than the increase in rating for the shunt inverter which suggests that a practical limit for use of the UPFC in this system has been reached.

Table 2 Power transfer of different cases (in MW and Mvar)

Note that the power transfer of Case 5 and 6 may be high for some 138 kV lines, but these post-contingency transfer levels are within the range of short term emergency ratings for many 138 kV lines.

Figure 15 Oscillation damping comparison

When the UPFC is operating below its limits, it provides powerful oscillation damping. This is shown in Fig. 15. For this case, the 3-phase fault to ground is applied at the 138kV line where the load is connected and the disturbance is cleared after 4 cycles. The change in oscillation frequency from the curves in Fig. 14 results from the 345kV transmission line remaining in service for this disturbance. This figure clearly shows that with the same power transfer level the UPFC control provides significant power oscillation damping.

V. CONCLUSIONS

This paper has demonstrated a straightforward methodology for defining a control system for a UPFC.

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[redacted]

This system simultaneously controls bus voltage and real and reactive power flow on a transmission line with coordinated limits for the ratings of the UPFC components and system voltages. Transient simulations show that the strategy chosen to maximize power transfer during limiting conditions results in a smooth transition into and out of limits. The system simulation study illustrated an application of a UPFC to allow increased power transfer while maintaining synchronism during a severe transient disturbance. It showed that significant increases in transfer are possible. It also showed that the amount of increase is related to the MVA ratings of the series and shunt inverters. From the system studied, the increasing requirements for shunt reactive power results in a practical limit on the amount of power transfer that can be achieved.	[redacted]