Cascading Line Outage Prevention with Multiple UPFCs

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***Abstract*— Flexible AC Transmission System (FACTS) have been recognized to be effective in regulating network power flow and enhance system dynamic performance. In this paper, multiple UPFCs are integrated into a network and controlled according to the Max Flow algorithm to avoid possible cascading line outage. The dynamic response of UPFC controllers and generator performance are investigated with potential cascading critical line outage. Cascading blackout prevention is investigated not only for steady state power flow overload problem but also for system dynamic stability problem. Generator performances of speed deviation, angle deviations and bus voltage profile as well as dynamic power flows are shown. A classical generator model is used in the simulation program. The IEEE 118-bus 20-generator system is used for testing. A cascading line trip sequence is expected to be prevented immediately after the first grid component outage.**

***Index Terms*—Cascading outage, blackout, FACTS, power system dynamic performance, line overload, line security**

I. Introduction

CASCADING blackouts in power systems is a process, in which an initial disturbance or component outage increases the stress on other system components, and then a series of critical components are subsequently tripped either as a direct consequence or due to hidden blackouts [1], [2]. Recently cascading blackouts in power systems around the world underscore the need for researchers to identify probability distribution of blackouts and find ways to prevent potential cascading blackouts [3], [4].

There is no systematic method for analyzing the risk of cascading blackout considering system dynamic response [5]. One possible option for blackout prevention is to develop a strategy to allow systems keeping their N-1 security state. FACTS controller application is one useful method to reach this objective. Instead of looking at overall risk of cascading blackouts in power systems, this paper deals with individual blackout prevention by multiple UPFC controllers. The IEEE 118-bus, 20-generator mid-western US power grid system is selected as the test system.

The concept of FACTS was first introduced by NG Hingorani in 1988 [6]. Since then, FACTS controller are being increasingly investigated and used in power system to control power flow, improve system stability, and enhance power quality. The unified power flow controller (UPFC) is the most sophisticated and versatile FACTS device. With the application and control of back to back chain link converter, UPFC can independently adjust real power and reactive power to the grid [7], [8]. In this study, multiple UPFCs will be controlled to regulate line active power flow so as to prevent line overloads following an initiating outage event. This will lead to preventing cascading outages of overloaded lines. Some control strategies have been published for optimizing power flow in power system, damping power flow oscillation and improving system dynamic performance [9], [10]. This study uses multiple UPFCs equipped with a new control strategy described in reference [9]. The strategy is meant to manage the power flows on key lines immediately after a critical line failure. UPFC placement and the amount of power flow control on the key lines are pre-determined by a series of max-flow simulations [11-12].

Optimal FACTS placement, size and the type of FACTS device are complex questions for FACTS application for the purpose of maximizing total system transfer capacity. A generic algorithm approach is proposed in [13] to solve the N-1 security problem with optimal FACTS location, FACTS types and their rates. The optimal FACTS settings in the power grid are determined by an optimal power flow algorithm incorporating N-1 security consideration in [14].

In this study, a max flow algorithm is used to achieve desired line flows on certain lines by UPFC controllers after the loss of a critical line. This technique is capable of managing the power flows such that none of the lines become overloaded in the N-1 state. The location of the UPFCs and their optimized settings are obtained directly from the max-flow algorithm [11-12].

These existing UPFC placement and settings for cascading outage prevention focuses initially on steady state analysis. However, sometimes steady state analysis does not provide the complete picture of how the system evolves in a cascading blackout scenario. In the advanced stages of a blackout, uncontrollable system separation, angle instability and voltage collapse can occur. It is necessary to study system transient stability in more detail with adequate representation of synchronous generators and FACTS in the 118 bus test system. System dynamic performance is compared for classical generator model and the detailed generator model in [15]. It was reported there that for most transient stability case studies, the classical model is adequate, This paper emphasizes on investigating system dynamical performance with classical generator model and dynamic UPFC controller, while trying to prevent cascading line outages. The simulation software

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MATLAB is used for system modeling and simulation.

The objective of this study is to bring the system back into secure state by applying multiple UPFC controllers when a potential cascading trigger event is instigated. The outline of this paper is as follows: the steady state power flow analysis first introduces ten cascading line outage contingency scenarios which will finally lead to a system blackout of the 118 bus test system [16]. Then, two solvable scenarios, that is, those cascading outages that can be prevented by using steady state techniques, is investigated by dynamic simulations. The UPFC dynamic model is described in section III. The dynamic response of the UPFC and generator performance is presented in section IV and V. Finally we draw conclusions and propose relevant future work.

II. CASCADING BLACKOUTS IDENTIFIED AND UPFC SETTING

In the dynamic simulations of cascading outages reported in this study, we assume that the outages are caused by line overloads and its resulting outage are considered in cascading blackout; load shedding and generator control are not investigated. The ten critical line trip sequences which eventually lead to system blackout as presented in [16] and repeated in Table I are considered for the dynamic simulations. The tripped line is defined with bus numbers in the table. The first line is tripped at 0.1s and subsequent lines are tripped at 2s, 4s, 6s, 8s and 10s.

Similarly, using steady state analysis and only line power flows considered, refs [11-12] describe the placement of UPFCs to achieve maximum performance. A max-flow algorithm is applied to calculate the maximum possible flow between each generation and load. Each contingency is analyzed separately using a greedy strategy. A FACTS device is placed on the greatest overloaded line and its capacity is set to the value determined by the max-flow algorithm. This process is repeated for the given contingency until either all the lines operate within their specified flow limits or the maximum number of FACTS devices has been placed. Then, the algorithm is repeated for the next contingency. For this study, this method was used to determine the location and settings of multiple UPFCs to prevent two of the ten potential cascading outages. For two solvable cases: 4 and 9 shown in Table II, cascading line outage could be prevented by UPFCs regulating line active power. By regulating the overloaded line directly, line power flow of every line on the system operates below active power limits.

III. THE 118 BUS TEST SYSTEM MODEL AND UPFC DYNAMIC MODEL

Cascading blackout simulations with only steady state power flow calculation cannot capture dynamic response details of a blackout because it doesn't consider the dynamics of power system such as generator trip, load shedding and other dynamic elements. The dynamic response of generators and UPFC controllers plays a key role in system stability and blackout events. To emphasize the fast contribution of UPFC controllers, the generator is modeled in a classical fashion in this study load tap changing transformers are replaced by fixed transformers. All loads are assumed to be constant power static loads. The system map is shown in the Appendix.

Classical generator model neglects the amortisseur effects with constant mechanical power and constant generator internal voltage. The differential algebraic equation (DEA) model of classic model is given as equation (1)-(2) :

$$\dot{\delta} = \omega_r - \omega_s \tag{1}$$

$$\frac{2H}{\omega_s}\dot{\omega}_r = P_m - (\frac{EV}{x_{dp}}\sin(\delta-\theta)) \tag{2}$$

Where δ is the power angle of generator, ω_r is rotor speed, ω_s is the rated synchronous speed, H is inertia constant, P_m is the mechanical power, E is internal voltage of generator, V is generator terminal voltage, x_{dp} is transient reactance, θ is bus voltage angle.

TABLE I
TEN CRITICAL CONTINGENCIES

Case no.	1st Line	2nd Line	3rd line	4th line	5th line	6th line	7th line
1	48-49	47-46	45-49	34-43			
2	64-65	62-67	66-62	56-58	54-56	54-55	56-57
3	69-70	74-75	70-75	72-24			
4	4 - 5	5 - 11	7-12	3-5	16-17	14-15	
5	34-37	35-36	43-44				
6	5 - 8	14-15	16-17				
7	37-38	15-33	19-34	43-44			
8	47-69	47-49	46-48	45-49			
9	37-39	37-40	40-42	40-41			
10	89-92b	82-83	91-92	100-101	94-100	96-95	96-94

TABLE II
TWO SOVLABLE CASE

Case no.	UPFC NO.	UPFC location	P_{line} before outage	P_{line} after outage if no UPFC	P_{set} for UPFC
Case4	UPFC1	5-11	0.7867	1.3179 (overloaded)	1.158
	UPFC2	7-12	0.1775	0.4266	0.2098
	UPFC3	13-15	0.0249	-0.0402	-0.0558
	UPFC4	70-75	-0.0061	-0.009	0.0067
Case9	UPFC1	37-40	0.4172	0.7959 (overloaded)	0.6615
	UPFC2	65-66	0.1275	0.2118	0.1290

The UPFC consist of a combination of a shunt branch (STATCOM) and a series branch (SSSC) connected through the dc capacitor as shown in Fig.1. The active and reactive power of the transmission line can be controlled by converter2 with series connected transformer voltage magnitude and phase angle controlled by parameter k_2 and α_2. The bus voltage can be controlled by converter1 and the reactive power regulated by k_1 and α_1. The shunt connected converter provides the active power drawn by series branch and the losses on UPFC.

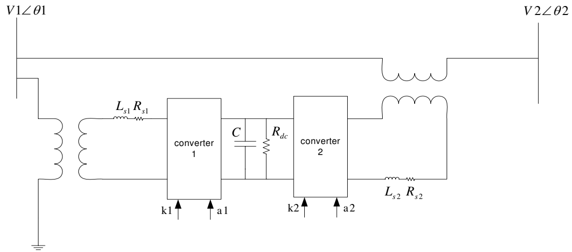

Fig. 1. UPFC diagram

The UPFC dynamic model used in this study is repeated here as follows [17]:

$$\frac{1}{w_s}\frac{di_{d1}}{dt} = \frac{k_1 V_{dc}}{L_{s1}}\cos(\alpha_1+\theta_1) + \frac{w}{w_s} i_{q1} - \frac{R_{s1}}{L_{s1}} i_{d1} - \frac{V_1}{L_{s1}}\cos\theta_1 \quad (3)$$

$$\frac{1}{w_s}\frac{di_{q1}}{dt} = \frac{k_1 V_{dc}}{L_{s1}}\sin(\alpha_1+\theta_1) - \frac{w}{w_s} i_{d1} - \frac{R_{s1}}{L_{s1}} i_{q1} - \frac{V_1}{L_{s1}}\sin\theta_1 \quad (4)$$

$$\frac{1}{w_s}\frac{di_{d2}}{dt} = \frac{k_2 V_{dc}}{L_{s2}}\cos(\alpha_2+\theta_1) + \frac{w}{w_s} i_{q2} - \frac{R_{s2}}{L_{s2}} i_{d2} - \frac{1}{L_{s2}}(V_2\cos\theta_2 - V_1\cos\theta_1) \quad (5)$$

$$\frac{1}{w_s}\frac{di_{q2}}{dt} = \frac{k_2 V_{dc}}{L_{s2}}\sin(\alpha_2+\theta_1) - \frac{w}{w_s} i_{d2} - \frac{R_{s2}}{L_{s2}} i_{q2} - \frac{1}{L_{s2}}(V_2\sin\theta_2 - V_1\sin\theta_2) \quad (6)$$

$$\frac{C}{w_s}\frac{d}{dt}V_{dc} = -k_1\cos(\alpha_1+\theta_1)i_{d1} - k_1\sin(\alpha_1+\theta_1)i_{q1} - k_2\cos(\alpha_2+\theta_1)i_{d2} - k_2\sin(\alpha_2+\theta_1)i_{q2} - \frac{V_{dc}}{R_{dc}} \quad (7)$$

The power balance equations at bus1 are given by

$$0 = V_1((i_{d1}-i_{d2})\cos\theta_1 + (i_{q1}-i_{q2})\sin\theta_1) - V_1\sum_{j=1}^{n} V_j Y_{1j}\cos(\theta_1-\theta_j-\phi_{1j}) \quad (8)$$

$$0 = V_1((i_{d1}-i_{d2})\sin\theta_1 + (i_{q1}-i_{q2})\cos\theta_1) - V_1\sum_{j=1}^{n} V_j Y_{1j}\sin(\theta_1-\theta_j-\phi_{1j}) \quad (9)$$

and at bus2

$$0 = V_2(i_{d2}\cos\theta_2 + i_{q2}\sin\theta_2) - V_2\sum_{j=1}^{n} V_j Y_{2j}\cos(\theta_2-\theta_j-\phi_{2j}) \quad (10)$$

$$0 = V_2(i_{d2}\sin\theta_2 - i_{q2}\cos\theta_2) - V_2\sum_{j=1}^{n} V_j Y_{2j}\sin(\theta_2-\theta_j-\phi_{2j}) \quad (11)$$

Where ω_s is the rated synchronous speed, i_{d1} and i_{q1} are the dq components of the shunt current while i_{d2} and i_{q2} are the series current components. $V_1\angle\theta_1$, $V_2\angle\theta_2$ are voltages on the two sides of the UPFC. $R_{s1}, R_{s2}, L_{s1}, L_{s2}, R_{dc}$ and C are UPFC device parameters as shown in Fig 1.

The control strategy described in [7] is implemented in this study to control the UPFC active power.

IV. Dynamic Performance with Two UPFC

In this section, two UPFCs are applied for cases 9. The system performance and UPFC response are investigated. The dynamic response of series branch active power and dc link capacitor voltage of two UPFCs are presented. The voltage profiles on UPFC shunt bus sides are also provided. Speed deviations and power angle deviations of the 20 generators in the system are also calculated to evaluate system stability.

For case 9, two UPFCs are integrated into line 37-40 and line 65-66. When line 37-39 is tripped at 0.1s, the line active powers on UPFC series branch are regulated as Fig. 2. Voltages on the UPFC DC link capacitor and shunt side bus are shown in Figs. 3 and 4.

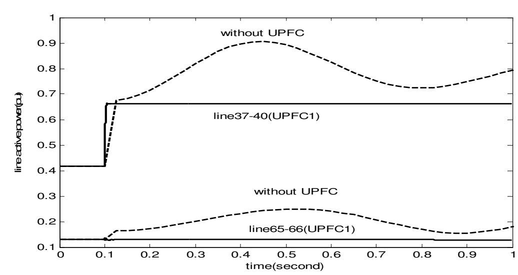

Fig. 2. Controlled active power on UPFC series branch

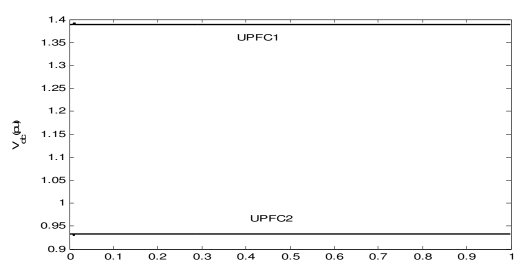

Fig. 3. DC voltage on UPFC capacitor

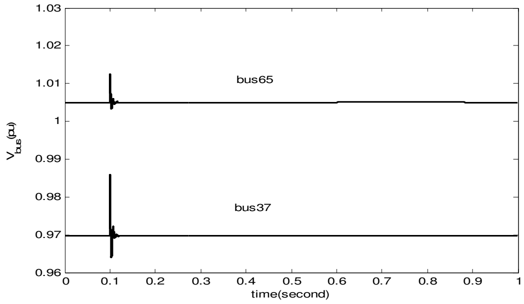

Fig. 4 Bus voltage on UPFC shunt side and the other side bus

The speed deviation and angle deviation of all 20 generators are shown in Figs. 5 and 6 respectively.

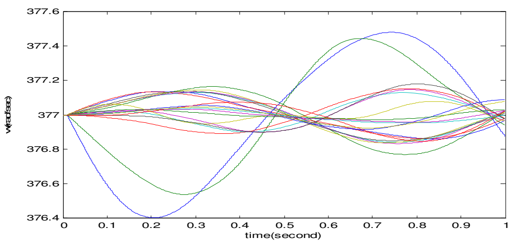

Fig. 5 Generator speed variations

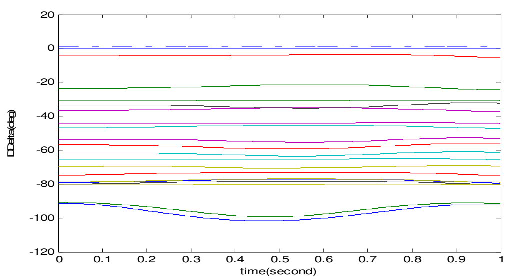

Fig. 6 Generator angle deviations

Based on the above results, we can draw conclusion that, with the proposed scheme, the two UPFC controllers can regulate line active power to the commanded value immediately after the initiating line outage. Any potential line overload is thus prevented and all generators remain stable and the power grid is N-1 secure.

V. DYNAMIC PERFORMANCE WITH FOUR UPFC

For case 4 with line 4-5 tripped, four UPFCs are needed to regulate line active powers.

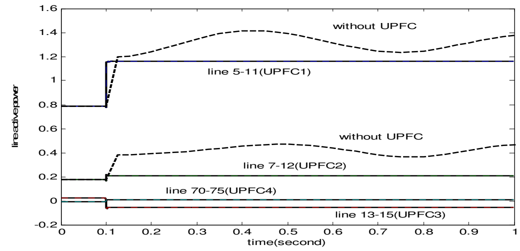

Fig. 7. Controlled active power on UPFC series branch

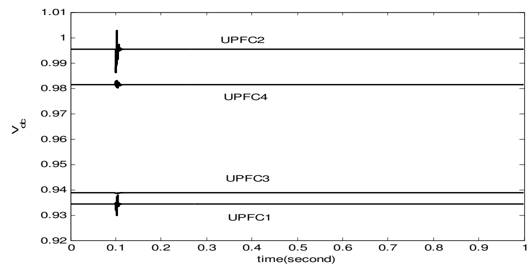

Fig. 8. DC voltage on the UPFC capacitor

The locations and settings of four UPFCs are shown in Table II. The dynamic responses of the four UPFCs and generator performance are shown in Figs. 7-11.

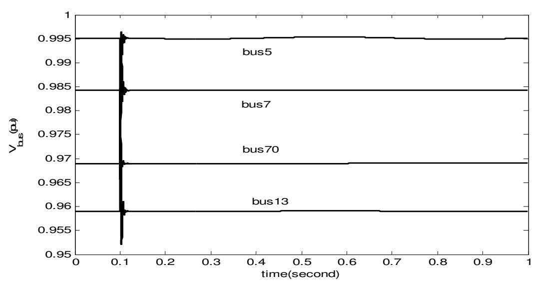

Fig. 9. Bus voltage on the UPFC shunt side and the other side bus

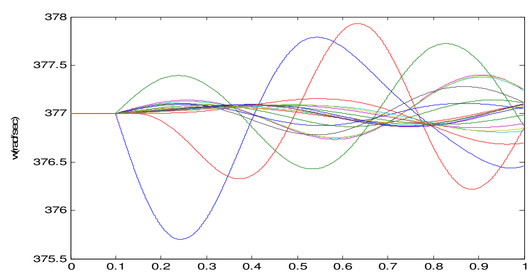

Fig. 10. Generator speed variations

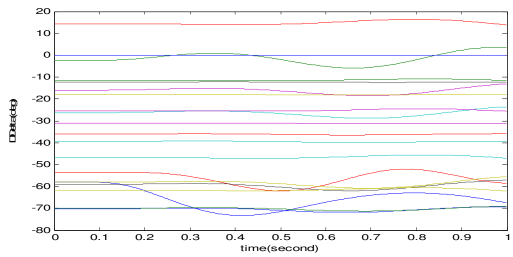

Fig. 11. Generators angle deviations

VI. Conclusion

Dynamic investigations provide an insight into generator performance and UPFC response to prevent cascading line outages. Therefore, potential blackouts can be prevented. With the proposed UPFC control strategy and preferred locations and settings, the system can avoid further line overloading and possible outages. The system is able to maintain stability even after a critical line outage that otherwise would have caused a series of cascaded line trips.

VII. Future work

Future work will focus on system dynamic performance considering large disturbances such as three phase faults on line and generator trips. More sophisticated UPFC control strategy should be developed for damping inter-area system power oscillations and further improving the transient stability.

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Biographies

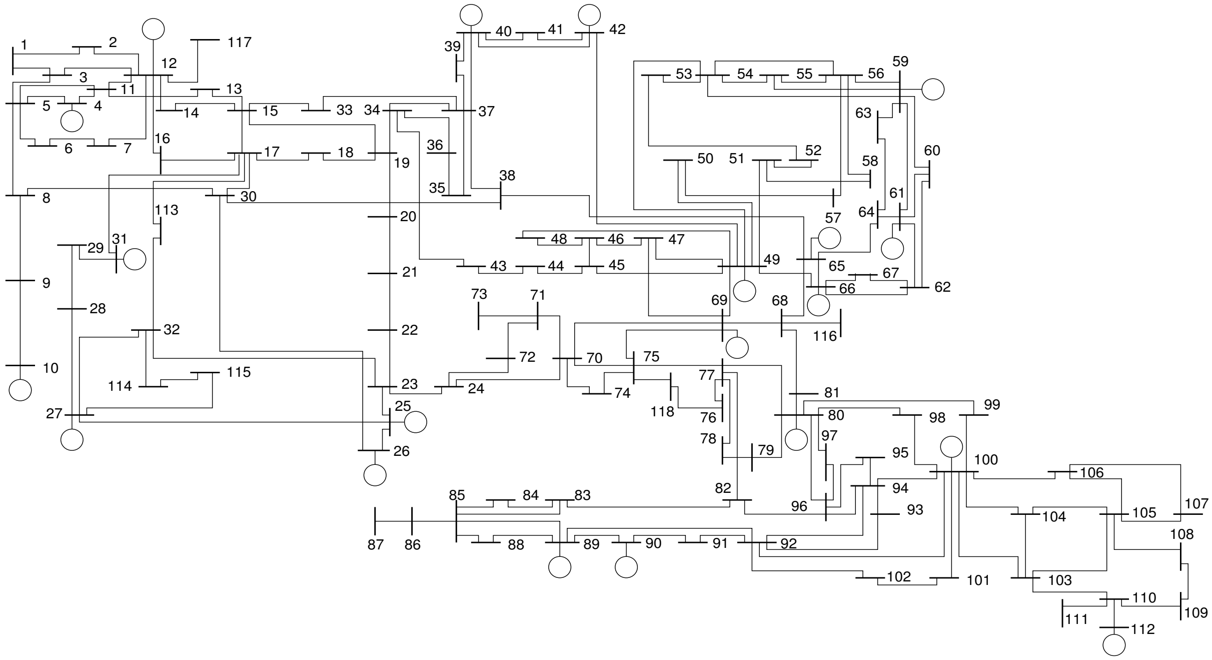
Hong Tao Ma received his BS and MS degrees in Electrical Engineering in 1999 and 2003 respectively from the Huazhong University of Science & Technology, Wuhan, China. His research interests are in power system modeling, distributed energy resources, and FACTS.

Mariesa L. Crow received her BSE degree from the University of Michigan, and her Ph.D. degree from the University of Illinois. She is the F. Finley Distinguished Professor of Electrical and Computer Engineering at the University of Missouri-Rolla. Her area of research interests have concentrated on developing computational methods for dynamic security assessment and the application of power electronics in bulk power systems.

Badrul H. Chowdhury obtained his M.S. and Ph.D. degrees in Electrical Engineering from Virginia Tech, Blacksburg, VA in 1983 and 1987 respectively. He is currently a Professor in the Electrical & Computer Engineering department of the University of Missouri-Rolla. From 1987 to 1998 he was with the University of Wyoming's Electrical Engineering department. Dr. Chowdhury's research interests are in power system modeling, analysis and control and distributed and renewable energy resources.

Adam Lininger is an undergraduate student in the Computer Science Department of the University of Missouri-Rolla. His research interests are in distributed computing and power system simulation.

Appendix



The 118-bus 20-generator test system