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TECHNICAL NOTE

Probabilistic Evaluation of Transient Stability of a Power System Incorporating a Unified Power Flow Controller

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Abstract. This paper presents a probabilistic based approach to evaluate transient stability of power systems incorporating a Unified Power Flow Controller (UPFC). In this application, the UPFC is employed to boost the transmission system capacity and the system voltage after fault clearing and, therefore, enhances the system stability. In this context, investigations have been conducted on a sample multi-machine power system taking into consideration the uncertainty of several factors associated with the practical operation of a power system. A risk index that reflects the likelihood that the system encounters an instability problem is presented. The effect of load forecast certainty on such an index is also investigated.

Keywords: Transient stability, Stochastic techniques, Unified power flow controller, Flexible ac transmission systems (FACTS).

Introduction

Electronic control of power system will revolutionize the power system operation. The installation of FACTS devices will allow the control of load flow, which reduces losses and help identify where the purchased energy coming from. This would result in the development of more realistic wheeling charges. Another promises is the improvement of transient stability through the modulation of line impedance, which permit higher line loading in normal conditions. The expected significant effect of FACTS technology on power system calls for intensive research in planning and operating electric power systems. Traditionally, power systems are planned and operated using deterministic transient stability criteria in which the system should withstand the worst case scenario. In such a scenario, the system should maintain synchronism following three phase short circuits near generator terminals under full load operating conditions. Deterministic approaches have been widely and successfully used and adapted for many years in most of the international standards. However, the introduction of the open electricity market has created the need of power system utilities to adjust the power supply quality based on the customer needs. This cannot be fulfilled by traditional stability studies. Probabilistic techniques, however, reflect the stochastic nature of the operating condition as well as system component in a set of probabilistic indices. A stochastic approach can, therefore, be used to obtain a realistic appraisal of the expected performance of the system.

In general, there are two main published techniques for probabilistic assessment of transient stability, The first technique utilizes the conditional probability theorem in analytically evaluating the probability of stability [1-5]. The second utilizes the Monte-Carlo simulation approach [6,7]. Analytical evaluation of transient stability was introduced in a series of papers [1, 2]. The major concern of these papers is with the probabilistic aspects of fault type, fault location, fault clearing phenomenon and system operating conditions which affect transient stability. A practical model for the protection system is utilized [2]. The stochastic nature of the system prefault operating conditions was studied in more details in [3]. Billinton and Aboreshaid [4] presented a stochastic model for high-speed simultaneous reclosing and reported the impact of employing such a reclosing on probabilistic transient stability. Aboreshaid, *et al*. introduced [5] a bisection algorithm was introduced that reduces the computation time required to conduct probabilistic transient stability studies. Anderson and Bose 6 explored the nature of the transformations required to determine the probability of transient stability defined in terms of the stability margins and demonstrated that such transformations cannot be easily defined. McCalley *et al*. [7] presented a new risk based security index for determining the operating limits in stability limited electric power systems. Monte-Carlo simulation technique, which is suitable for the analysis of complicated events, can require considerable computational effort.

This paper presents a probabilistic based approach to evaluate transient stability of power systems incorporating a Unified Power Flow Controller (UPFC). The modern development of such a FACTS device provides system planners and operators with new alternatives to consider for systems which are limited in their transfer capability by transient stability considerations. In this application, the UPFC is employed to boost the transmission system capacity and the system voltage after fault clearing and, therefore, enhances the system stability**.** The analytical approach is adopted in the studies reported in this paper.

System Under Study

The system used for the investigations in this paper is shown in Fig. 1. This sample multi-machine power system represents a situation that is similar to that found in large interconnected systems. It consists of three control areas, namely Area 1, Area 2 and Area 3. Area 1 represents a typical utility where its generation is located at bus 1. Area 2 represents the total generation and peak load in a nearby region. Area 2 is connected to Area 1 by two 500 kV transmission lines (L_1 & L_3). Area 3, which represents also a neighboring power system, is connected to Area 1 utility by a 500 kV double-circuit transmission line (L_4 & L_5). A UPFC is connected between buses 4 and 5 as shown in Fig.1. The system deterministic and probabilistic data are given in the Appendix.

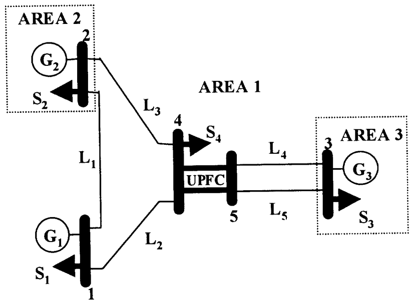

Fig. 1. System under study.

For time-domain simulation studies, the synchronous generators are represented in the d-q-0 reference frame. The transmission lines are modeled using the equivalent π circuit of a long transmission line. Each circuit breaker is represented as an ideal switch that can open at current zero crossings. Dynamics of the governor system of the generators are neglected and the input mechanical torque is assumed to remain constant corresponding to the steady-state operating conditions. Dynamics of the generators excitation system are included in the simulation model. System loads are represented in the present study by constant impedances.

The Unified Power Flow Controller

The UPFC [8-12] shown in Fig. 2 consists of two switching converters where each converter is a voltage-sourced inverter using gate-turn-off (GTO) thyristor valves. These inverters, labeled “Inverter 1” and “Inverter 2” in the figure, are operated from a common dc link provided by a dc storage capacitor. This arrangement functions as an ideal ac to ac power converter in which the real power can flow freely in either direction between the ac terminals of the two inverters and each inverter can independently generate (or absorb) reactive power at its own ac output terminal. Inverter 2 provides the main function of the UPFC by injecting an ac voltage V_i with controllable magnitude and phase-angle α at the power frequency, in series with the line via an insertion transformer T_1. This injected voltage can be considered essentially as a synchronous ac voltage source. The transmission line current flows through this voltage source resulting in real and reactive power exchange between it and the ac system. The real power exchanged at the ac terminal (i.e., at the terminal of T_1) is converted by the inverter into dc power which appears at the dc link as positive or negative real power demand. The reactive power exchanged at the ac terminal is generated internally by the inverter.

The basic function of Inverter 1 is to supply or absorb the real power demand by Inverter 2 at the common dc link. This dc link power is converted back to ac and coupled to the transmission line via a shunt connected transformer T_2.

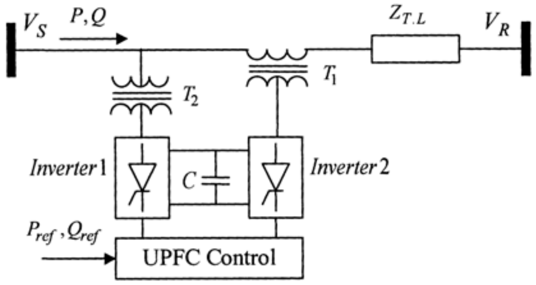

Fig. 2. Simplified transmission system and UPFC model.

Simulation Results

In order to demonstrate the effectiveness of UPFC in improving power system transient stability, the time simulation results of the following case study are presented in this section.

Case study

Disturbance:	An unsuccessful reclosing of a 4-30-4 cycle three-phase fault on line L_2 near bus 1.
Scheduled interarea power transfer:	Area 2 exports 100 MW to Area 1 and 900 MW to Area 3.
UPFC:	± 150 MVA series converter (SSSC) and ± 50 MVA shunt converter (STATCOM).

As it can be seen from Fig. 3, in the case of no UPFC, the generator swing angles, measured with respect to Generator 1 are increasing indicating system instability. The reason is that with the removal of line L_2 (due to fault clearing and unsuccessful reclosing), generator G_1 must serve its load in Area 1 (S_4) by transmitting its output power over a higher impedance path, consisting of lines L_1 and L_3 in series. This becomes critical for generator G_1 to remain in synchronism with generator G_2 in Area 2. If the UPFC is employed in this case where line L_2 is opened, its series converter can compensate line L_3 as it will be in series with it in such a case. Moreover, the UPFC shunt converter can boost the voltage of bus 4. Figure 4 shows that the system transient stability is significantly improved by employing the UPFC.

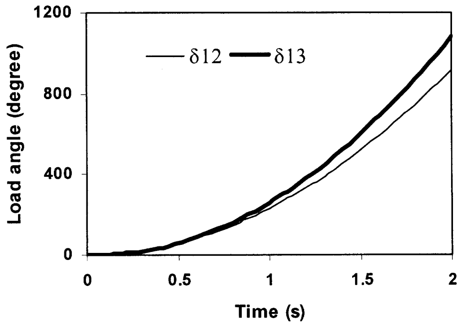

Fig. 3. Generator load angle responses during unsuccessful reclosing of a 4-30-4 cycle three-phase fault on line L_2 near bus 1.

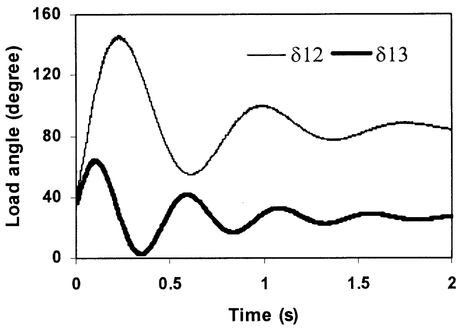

Fig. 4. Generator load angle responses during unsuccessful reclosing of a 4-30-4 cycle three-phase fault on line L_2 near bus 1 (UPFC is employed).

Stochastic Models and Probabilistic Transient Stability Indices

The analytical approach [1-5] is utilized in this paper to predict the probability distributions of the risk index, probability of instability. The basic five uncertainty factors recognized in a probabilistic assessment of transient stability are [1-7]: fault type, fault location, fault clearing time, line reclosing time, and fault duration.

System stability is seriously affected by fault clearing and line reclosing times. Several papers show that fault clearing time values are normally scattered about the setting value to some extent [1-7]. This distribution of fault clearing and line reclosing times is caused mainly by the fact the fault detecting time of a protective relay depends on the phase angle of the voltage at the instant of fault occurrence and that a circuit breaker interrupts the current at its zero crossing point. Most system faults are transitory in nature and a ten-step approximated Rayleigh distribution is used to model the fifth uncertainty factor, fault duration. Figure 5 shows the probability distributions of the factors causing uncertainty in practical operation of a power system. It is assumed in this paper that the relay and breaker operating times, fault location and duration can be represented by approximate discrete probability distributions (a seven-step discrete approximation was used for the fault clearing and reclosing times, a three-step approximation of the uniform distribution was used for the fault location and an eleven step-approximation was used for the fault duration). The fault type probability distribution is also shown in Fig. 5. The required probabilistic data for each of these distributions are given in the Appendix.

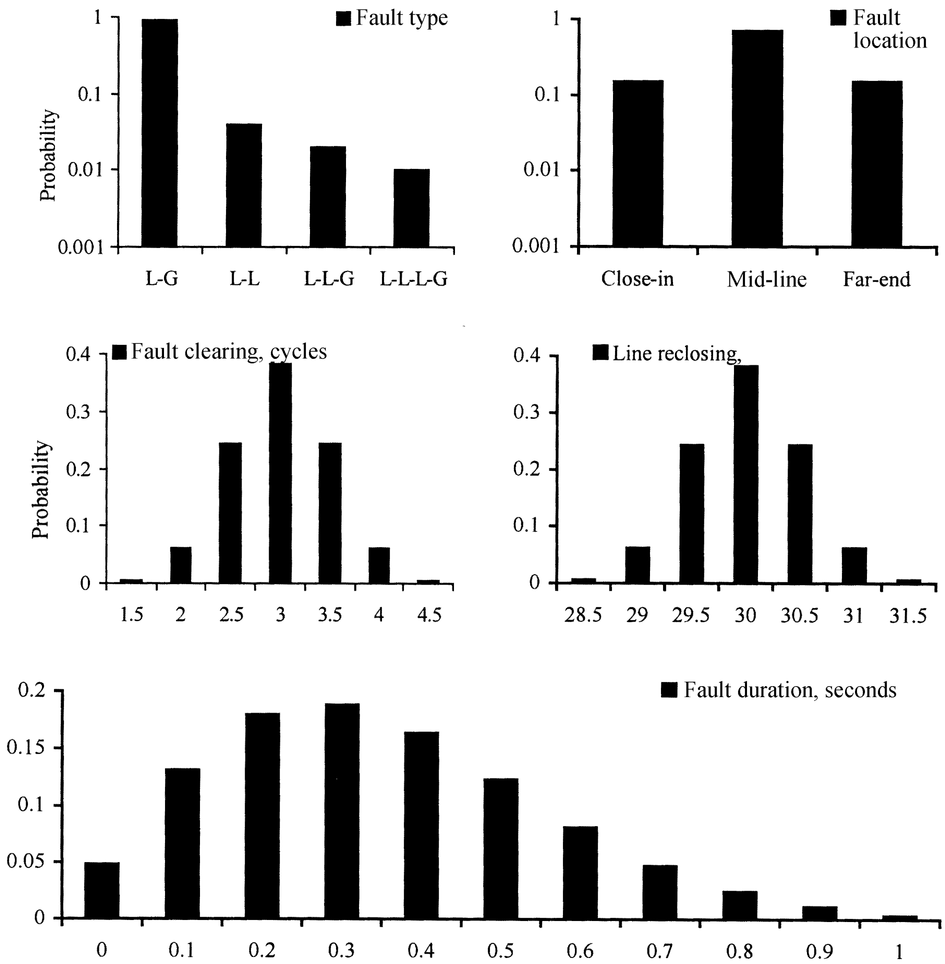

Fig. 5. Stochastic models for the case of system faults.

A. Effect of the fault type and basic results

Figure 6 shows the risk indices, probability of instability, for all fault types in the test system when the UPFC is not employed in the system. In the case of single line-to-ground faults, single-pole switching is considered for clearing and reclosing such faults. It is clear from this figure that three phase faults have the highest probability of instability values while single phase-to-ground faults have less impact on the system instability. It can be also see from this figure that lines L_2 and L_3 have the highest risk indices and this is due to the fact that most of the power are transmitted through these two lines. One way to improve this, of course, is to provide a quicker clearing time for faults on these two lines and increase the probability of successful reclosing by employing, for example, adaptive reclosing.

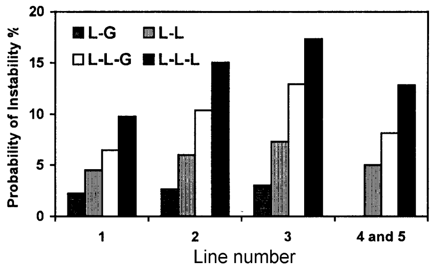

Fig. 6. Risk indices associated with fault types (UPFC is not employed in the system).

Figure 7 shows the impact of employing the UPFC on the risk indices of different fault types. In this case, the transmission system capacity and bus 4 voltage are boosted after clearing a fault on any line by the UPFC. Figure 7 shows that a considerable reduction in the risk indices has been achieved with employing the UPFC. The figure shows also that with employing UPFC, single line-to-ground faults on any transmission line will not cause system instability. This is also the case for line-to-line faults on the double circuit transmission line (L_4 & L_5).

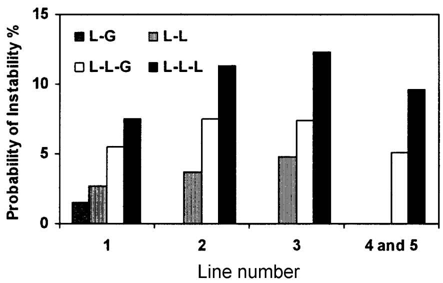

Fig. 7. Effect of employing UPFC on the risk indices associated with fault types.

B. Overall system and line results

The weighted indices for the probability of instability for the five transmission lines are shown in Fig. 8. It can be seen from this figure that significant reductions in the risk index, probability of instability for all transmission lines are achieved using the UPFC. The overall system probability of instability is reduced by approximately 86% (from 2% to 0.28%)

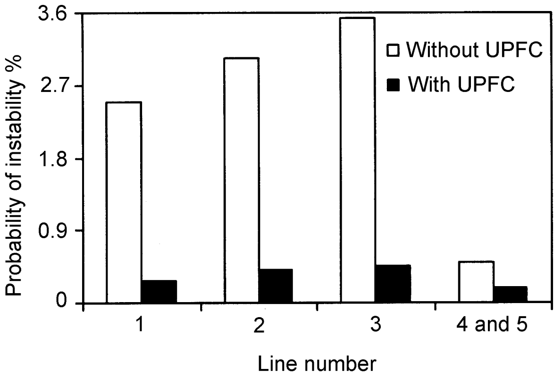

Fig. 8. Probabilistic transient stability indices for different transmission lines of the test system.

C. Effect of load forecast uncertainty

An important task in power system operation and planning is to predict the load level over the next period of time. It is extremely unlikely that the forecast load will be the same as the forecast value. Load forecast uncertainty can be reasonably described by a normal distribution. The normal distribution can be divided into class intervals whose number depends on the required accuracy. The area of each class represents the probability of load being at the mid-value of the class interval. The load forecast uncertainty in the test system is approximated by a seven-step histogram.

The probabilistic transient instability indices after the incorporation of load forecast uncertainty are presented in Fig. 9. It is assumed that the forecast load has a standard deviation of 5%. By comparing the results presented in Fig. 9 with the ones in Fig. 8, one can see that the probability of instability indices with load forecast uncertainty are higher than those obtained with zero load forecast error (basic results). Figure 8 shows also that significant reductions in these indices are also achieved with the employing of UPFC in the system.

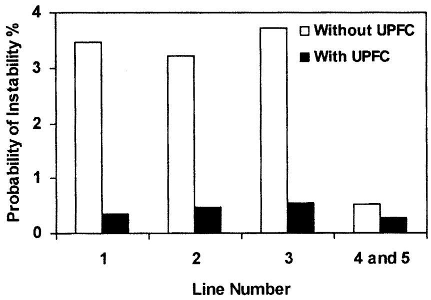

Fig. 9. Probabilistic transient stability indices for different transmission lines after incorporating load forecast uncertainty.

Figure 10 shows the adverse effect of increasing the standard deviation of the system load on the expected probability of instability risk index for the overall system. It can be seen from Fig. 10 that the probability of Instability for the overall system increases when increasing the standard deviation of the system load. It can be also seen from this figure that utilization of UPFC provides an improvement in system stability especially for the cases when the standard deviation of the forecasted load is high. This improvement ranges from 86% in the case of zero standard deviation to 83.4% when the standard deviation of the system load is 10%.

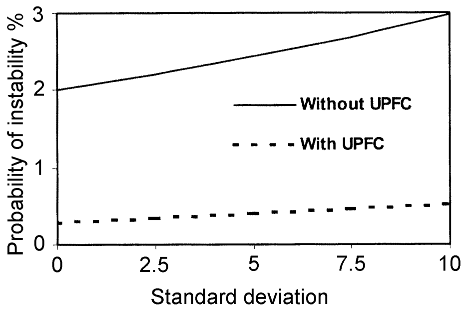

Fig. 10. Effect of standard deviation on the overall system probabilistic transient stability indices.

Conclusion

This paper presents a probabilistic approach to evaluate the transient stability of a multi-machine power system incorporating a UPFC considering the uncertainties associated with the occurrence of disturbances and their attendant protective switching sequences. The UPFC is employed in the system to boost the transmission system capacity and the system voltage after fault clearing. The results of the investigations reported in this paper have shown that the UPFC reduces the risk index, probability of instability of the system. The basic concepts presented in this paper can be easily extended to include several UPFC located at different locations as well as other stability enhancement FACTS devices.

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Appendix

Probabilistic Data

Fault type probability distribution:

Single Phase-to-Ground, 93% Phase-to-Phase, 4%
Double Phase-to-Ground, 2% Three Phase, 1%

Fault location probability distribution:

Close-in faults, 15%, Far-end faults, 15%, Mid-line faults, 70%

Fault duration probability distribution:

Rayleigh distribution, K = 10.

Fault clearing probability distributions:

Normal distribution, mean =3 cycles, standard deviation = 0.5 cycle.

Line reclosing probability distributions:

Normal distribution, mean =30 cycles, standard deviation = 0.5 cycle.

System Deterministic Data

Table 1. Transmission line data

Line parameters	$z = 0.01864 + j0.3728\ \Omega / km$
	$y = j4.4739\ \mu S / km$
Line length, km	$L_1 = 300$, $L_2 = 400$, $L_3 = 500$, $L_4 = L_5 = 500$
Transmission voltage, kV	500

Table 2. System load data

$S_1 = 340 + j60\ MVA$	$S_2 = 2100 + j400\ MVA$
$S_3 = 1470 + j200\ MVA$	$S_4 = 900 + j150\ MVA$

Table 3: Generators data

Generator	G_1	G_2	G_3
Rating(MVA, kV)	1600, 26	3400, 26	2600, 26
r_a , p.u.	0	0.0045	0.0045
x_l , p.u.	0.13	0.14	0.12
x_d , p.u.	1.79	1.65	1.54
x_q , p.u.	1.71	1.59	1.50
x_d' , p.u.	0.169	0.25	0.23
x_q' , p.u.	0.228	0.46	0.42
x_d'' , p.u.	0.135	0.2	0.18

Table 3. Contd.

Generator	G_1	G_2	G_3
Rating(MVA, kV)	1600, 26	3400, 26	2600, 26
x_q'', p.u.	0.2	0.2	0.18
T_{do}', sec	4.3	4.5	3.7
T_{qo}', sec	0.85	0.55	0.43
T_{do}'', sec	0.032	0.04	0.04
T_{qo}'', sec	0.05	0.09	0.06
x_o, p.u.	0.13	0.14	0.12
H, sec	4.0	3.7	3.6

Excitation system data

$$K_A = 250,\ \tau_A = 0.14,\ \tau_B = 0,\ K_F = 0.06,\ \tau_F = 1$$

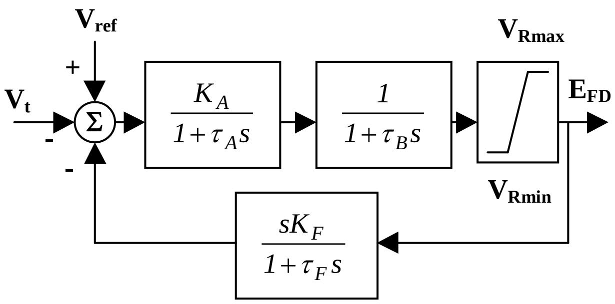

Fig. A1. Excitation system block diagram.

Determination of the UPFC parameters

In order to achieve the maximal UPFC effect on the test system transient stability margin enhancement, during the critical period the UPFC parameters have to be controlled so as to achieve maximal real power flowing from the generator (UPFC rating being, of course, limited: the injected voltage magnitude and parallel branch reactive current should not exceed certain values).. For this purpose, the generator impedances of the test system were taken into consideration as the generator transient reactance, and the lines were modeled as π sections as mentioned earlier. Naturaly, the parameters of the basic model change if the UPFC location or orientation (the positioning of UPFC as faced to the system) is changed. The basic model transmission angle and power correspond to the angle between the generator main field voltage and stiff system voltage and the generator real power of the test system respectively.

التقويم الاحتمالي للاتزان العابر في نظام القدرة المحتوي على حاكم تدفق القدرة الموحد

صالح بن عبدالرحمن أبورشيد

الإدارة العامة للمناهج، المؤسسة العامة للتعليم الفني والتدريب المهني

(قدم للنشر في٢٩/٠٩/٢٠٠١م؛ وقبل للنشر في١٦/٠٣/٢٠٠٢م)

ملخص البحث. تقدم هذه الورقة طريقة تعتمد على الاحتمالية لتقويم الاتزان المرحلي لنظم الطاقة المحتوية على حاكم تدفق القدرة الموحد. في هذا التطبيق، تم استخدام حاكم تدفق القدرة الموحد لدعم الطاقة الاستيعابية للنظام وكذلك لدعم فولتية النظام بعد إزالة العطل مما أثر إيجابيا على تحسين استقرارية النظام. وفي هذا الإطار، تم دراسة الاستقرارية العابرة لمنظومة كهربائية مكونة من عدة آلات كهربائية مع الأخذ في الاعتبار بعض المعاملات الاحتمالية المصاحبة للتشغيل العملي للمنظومة الكهربائية. كما تم تقديم معامل خطر جديد يعكس احتمالية حدوث مشكلة في اتزان المنظومة الكهربائية. وكذلك تم دراسة أثر التقلبات في تقدير الأحمال على الاتزان العابر في نظام القدرة.