

SUGGESTED ANALYTIC APPROACH TO TRANSMISSION RELIABILITY MARGIN

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Abstract

Transmission Reliability Margin (TRM) is the component of available transfer capability that accounts for uncertainties and safety margins. We suggest an analytic framework for TRM calculation using transfer capability sensitivity formulas and a probabilistic characterization of the various uncertainties. Preliminary results on a simple example show how we plan to test the TRM calculation and validate it with a Monte Carlo method. This draft report is produced in order to seek comment from PSerc members on the practicality and usefulness of this approach to TRM.

1 Introduction

Successful implementation of electric power deregulation requires the determination of the available transfer capability of a power system. The available transfer capability indicates the amount by which interarea power transfers can be increased without compromising system security. The available transfer capability is the total transfer capability minus the base case transfer together with adjustments such as the Transmission Reliability Margin (TRM) to allow some margin of safety. The transmission reliability margin takes account uncertainties and provides safety margins. This report suggests an analytic framework for computing the transmission reliability margin.

The approach exploits formulas for the first order sensitivity of transfer capability which have been developed by PSerc [7, 4]. These formulas can be quickly and easily computed when the transfer capability is determined. The formulas essentially determine a linear model for changes in transfer capability in terms of changes in any of the power system parameters. This report assumes that the uncertainty of the parameters can be estimated or measured. Using this information, the report shows how to estimate the corresponding uncertainty in the transfer capability. A formula for TRM is then developed based on the uncertainty in the transfer capability and the degree of safety required.

2 Summary of available transfer capability

For this report we use the main features of the NERC 1995 and 1996 definitions [8, 9]: The power system is judged to be secure for the purpose of interarea transfer

if “all facility loadings are within normal ratings and all voltages are within normal limits”, the system “remains stable following a disturbance that results in the loss of any single element”, the post-contingency system ... has all facility loadings within emergency ratings and all voltages within emergency limits” [10]. In this report we do not address some of the finer points of the transfer capability definition.

The power system is partitioned into areas, each of which is defined by a set of buses. The transfer between two areas is the sum of the real powers flowing on all the lines which directly connect one area to the other area. A list of contingencies is chosen and a nominal transfer schedule is chosen. A secure base case is chosen. A base case transfer including existing transmission commitments is determined. The transfer is then gradually increased starting at the base case transfer until the first security violation is encountered. The real power transfer at the first security violation is the total transfer capability.

The available transfer capability is then defined as

$$\begin{aligned} \text{Available Transfer Capability (ATC)} = & \\ & \text{Total Transfer Capability (TTC)} \\ & - \text{Existing Transmission Commitments (ETC)} \\ & - \text{Transmission Reliability Margin (TRM)} \\ & - \text{Capacity Benefit Margin (CBM)} \end{aligned}$$

The following limits are accounted for in the transfer capability computation:

- power flow or current limits (normal and emergency)
- voltage magnitude upper and lower limits (normal and emergency)
- voltage collapse limit

Our framework accounts directly only for limits which can be deduced from static model equations. Oscillation and transient stability limits are assumed to be studied offline and converted to surrogate power flow limits. However, treating dynamic limits with power flow limit surrogates will not produce correct sensitivity information.

3 Purpose and definition of TRM

According to NERC [9], “The determination of ATC must accommodate reasonable uncertainties in system conditions and provide operating flexibility to ensure the secure operation of the interconnected network”. There are two margins defined to allow for this uncertainty: The *transmission reliability margin* is defined in [9] as “that amount of transmission capability necessary to ensure that the interconnected transmission network is secure under a reasonable range of uncertainties in system conditions”. The *capacity benefit margin* ensures access to generation from interconnected systems to meet generation requirements. The capacity benefit margin is calculated separately from the transmission reliability margin.

Since the uncertainty increases as conditions are predicted further into the future, the transmission reliability margin will generally increase when it applies to times further into the future.

4 Quantifying TRM

4.1 Parameters and their uncertainty

The transfer capability is a function A of many parameters p_1, p_2, \dots, p_m :

$$\text{transfer capability} = A(p_1, p_2, \dots, p_m) \quad (1)$$

The parameters p_i are chosen to satisfy the following conditions:

1. The uncertainty in the parameters p_i causes the uncertainty in available transfer capability that is accounted for by the transmission reliability margin.
2. The uncertainty in the parameters is accounted for by regarding each parameter p_i as a random variable with known mean $\mu(p_i)$ and known standard deviation $\sigma(p_i)$.
3. The parameters are statistically independent.

4.2 Transfer capability sensitivity

The uncertainty U in the available transfer capability due to the uncertainty in all the parameters is:

$$U = A(p_1, p_2, \dots, p_m) - A(\mu(p_1), \mu(p_2), \dots, \mu(p_m)) \quad (2)$$

The mean value of the uncertainty is zero:

$$\mu(U) = 0 \quad (3)$$

Approximating the changes in available transfer capability linearly in (2) gives

$$U = \sum_{i=1}^m \frac{\partial A}{\partial p_i} (p_i - \mu(p_i)) \quad (4)$$

$\frac{\partial A}{\partial p_i}$ is the sensitivity of the transfer capability to the parameter p_i evaluated at the nominal transfer capability.

When the available transfer capability is limited by voltage collapse, $\frac{\partial A}{\partial p_i}$ can be computed using the formulas of [5]. (Topology changes can also be accommodated with limited accuracy using the fast contingency ranking techniques in [6].) When the available transfer capability is limited by voltage magnitude or thermal limits, $\frac{\partial A}{\partial p_i}$ can be computed using the formulas of [7, 4]. In each case a static, nonlinear power system model is used to evaluate the sensitivities. The computation of $\frac{\partial A}{\partial p_i}$ is very fast and the additional computational effort to compute $\frac{\partial A}{\partial p_i}$ for many parameters p_i is very small [5, 7, 4].

4.3 Formula for TRM

Since the parameters are assumed to be independent,

$$\sigma^2(U) = \sum_{i=1}^m \sigma^2 \left(\frac{\partial A}{\partial p_i} (p_i - \mu(p_i)) \right) \quad (5)$$

$$= \sum_{i=1}^m \left(\frac{\partial A}{\partial p_i} \right)^2 \sigma^2(p_i) \quad (6)$$

and the standard deviation of U is

$$\sigma(U) = \sqrt{\sum_{i=1}^m \left(\frac{\partial A}{\partial p_i} \right)^2 \sigma^2(p_i)} \quad (7)$$

Under suitable conditions which are discussed in the appendix, the uncertainty U is approximately a normal random variable with mean zero and standard deviation given by (7). This approximation gives a basis on which to define the transmission reliability margin. The conditions described in the appendix are mild and require little knowledge of the distribution of the parameters.

We want to define the transmission reliability margin large enough so that it accounts for the uncertainty in U with rare exceptions. More precisely, we want

$$\text{probability}\{-U \leq \text{TRM}\} = P \quad (8)$$

where P is a given high probability. This can be achieved by choosing the transmission reliability margin to be a certain number K of standard deviations of U :

$$\text{TRM} = K\sigma(U) \quad (9)$$

K is chosen so that the probability that the normal random variable of mean zero and standard deviation 1 is less than K is P . (That is, $\frac{1}{\sqrt{2\pi}} \int_{-\infty}^K e^{-t^2/2} dt = P$.) It is straightforward to calculate K from P by consulting tables of the cumulative distribution function of a normal random variable [2]. For example, if it is decided that the transmission reliability margin should exceed the uncertainty $-U$ with probability $P=95\%$, then $K = 1.65$. (Another way to state this result is that

a normal random variable is less than 1.65 standard deviations greater than the mean 95% of the time.) If it is decided that the transmission reliability margin should exceed the uncertainty $-U$ with probability $P=99\%$, then $K = 2.33$.

Combining (7) and (9) yields a formula for transmission reliability margin:

$$\text{TRM} = K \sqrt{\sum_{i=1}^m \left(\frac{\partial A}{\partial p_i} \right)^2 \sigma^2(p_i)} \quad (10)$$

In order to use formula (10) we need:

- A choice of uncertainty parameters p_1, p_2, \dots, p_m satisfying the three conditions above.
- The standard deviation $\sigma(p_i)$ of each parameter.
- Calculation of the sensitivity of the transfer capability to each parameter $\frac{\partial A}{\partial p_i}$.

5 Uncertainty parameters

The available transfer capability is computed from a base case constructed from system information available at a given time. There is some uncertainty or inaccuracy in this computation. There is additional uncertainty for future available transfer capabilities because the available transfer capability computed at the base case does not reflect evolving system conditions or operating actions. These two classes of uncertainty are examined in the following two subsections.

5.1 Uncertainty in base case ATC

- inaccurate or incorrect network parameters
- effects neglected in the data (eg effect of ambient temperature on line loading limits)
- approximations in ATC computation

5.2 Uncertainty due to evolving conditions

These uncertainties increase when longer time frames are considered.

- ambient temperature and humidity (contributes to loading) and weather
- load changes not caused by temperature
- changes in network parameters
- change in dispatch
- topology changes. This is often referred to as "contingencies." The probabilities of these contingencies can be estimated.
- changes in scheduled transactions

parameter	distribution
line susceptance B_{25}	binary, $\text{Prob}\{B_{25}=5.0\}=0.95,$ $\text{Prob}\{B_{25}=0\}=0.05$
line impedance X_{38}	normal, mean=0.4, $\sigma=0.02$
line impedance X_{67}	normal, mean=0.2, $\sigma=0.01$
system loading p_4	normal, mean=0.0, $\sigma=0.1$
bus 5 generation p_5	normal, mean=0.0, $\sigma=0.01$
flow limit	normal, mean=1.5, $\sigma=0.0748$

Table 1: Parameter distributions

While some of these uncertainties may be quite hard to characterize a priori, it is important to note that it would be practical to collect empirical data on the changes in base cases as time progresses. Then standard deviations and means of the uncertain parameters corresponding to various time frames could be estimated.

It is also important to satisfy the statistical independence assumption when modeling the parameter uncertainty. For example, if the uncertainty of different loads has a common temperature component, then this temperature component should be a single parameter and the load variations should be modeled as a function of temperature.

6 Simulation test results

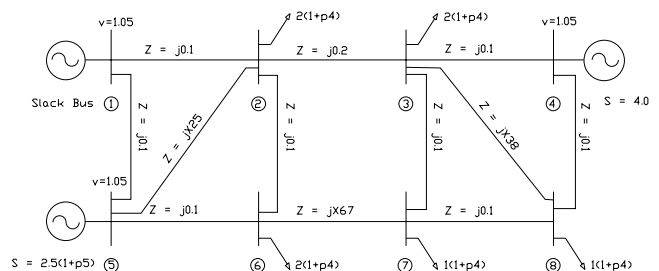


Fig. 1: 8 bus test system

This section shows by a preliminary example how we propose to test the TRM formula by comparing it with Monte Carlo simulations. The 8 bus system shown in Figure 1 is used. The transfer capability from area 1 (buses 1,2,5,6) to area 2 (buses 3,4,7,8) is limited by the power flow limit on the line between bus 2 and 3. The parameters are listed in Table 1. The base case of the system assumes all parameters at their mean values. At the base system, the available transfer capability (ATC) is 2.8338. Sensitivity of ATC to these parameters can be calculated with no difficulty. Given a desired high probability P , TRM defined in (8) is calculated using formula (10). Table 2 list TRMs with respect to different given P s. In the Monte Carlo simulation, 10,000

P	90%	95%	99%	99.5%
TRM formula	0.5817	0.7498	1.0589	1.1725
Monte Carlo	0.5794	0.7425	1.0648	1.1658

Table 2: TRM calculated by formula and Monte Carlo

samples are used.

It is hard to draw firm conclusions from these preliminary results but we are encouraged by these results to proceed with more systematic testing. We expect the performance of the TRM formula to improve as the system size and number of parameters increases.

7 Conclusions

This report suggests a defensible way to estimate TRM with a formula. The formula requires estimates of the uncertainty in parameters, the evaluation of transfer capability sensitivities, and specification of the degree of safety. The formula would be fast to evaluate for large systems (the transfer capability sensitivities are easy and quick to evaluate once the transfer capability is determined). The calculation provides one way to put a value on reducing parameter uncertainty in transfer capability calculations because a given reduction in uncertainty yields a calculable reduction in TRM and this can be related to the profit made in an increased transfer.

8 Appendix

Let X_1, X_2, \dots, X_m be independent, zero mean random variables and write $s_m^2 = \sum_{k=1}^m \sigma^2(X_k)$ for the variance of $\sum_{k=1}^m X_k$. The approximate normality of $\sum_{k=1}^m X_k$ requires a central limit theorem. (Note that the most straightforward version of the central limit theorem does not apply because we do not assume that X_1, X_2, \dots, X_m are identically distributed.) A special case of the Lindeberg theorem [1] states that if

$$\lim_{m \rightarrow \infty} \sum_{k=1}^m \frac{1}{s_m^2} \int_{|X_k| > \epsilon s_m} X_k^2 dF = 0 \quad (11)$$

holds for all positive ϵ then $\frac{1}{s_m} \sum_{k=1}^m X_k$ converges in distribution to a normal random variable of mean zero and variance unity.

One useful class of random variables satisfying the Lindeberg condition (11) is random variables which are both uniformly bounded and whose variance uniformly exceeds some positive constant. It is also straightforward to augment the random variables satisfying (11) with some normal random variables.

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