A procedure for the computation of the spot price component associated to transient instability.

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Abstract.

The present trend towards power system deregularitation has brought the need to accurately compute the costs associated with the different services provided by the electric utilities. Among these costs is the cost related to maintain an adequate level of security face to the contingencies which the power system may suffer, and specifically face to the possibility of loss of synchronism because of transient instability.
This paper shows that this computation is feasible in the framework of marginal pricing theory. In fact, a procedure to compute the value of the component of the spot price associated to the transient instability is shown, as well as a numerical example in the well-know 31-buses New England network.

Keywords: Spot price, transient instability.

1. Introduction.

The cost of electric energy is the sum of several factors with different origin. Among the main factors that form this price, it can be found the cost of generation (it depends basically on the type of predominant power plants -nuclear, coal, fuel, hydro...-, and therefore, on the price of combustible), the cost related to the market of complementary services (secondary and tertiary regulation), and among other possible elements, the factor analysed in this paper, which is the cost related to the stability of the system. So the total cost can be expressed in the following way:

$$C_{TOTAL} = C_{Gen} + C_{CCSS} + ... + C_{Stab} \tag{1}$$

The energy spot price (cost related to the production of an additional unit of the service), will be obtained by calculating the derivative of the total cost with respect to the demanded power in a given bus:

$$\rho_{TOT} = \frac{\partial C_{TOT}}{\partial P_{DEMAND}} \tag{2}$$

This derivative of a sum can be expressed as a sum of derivatives, being the last element the one that is of interest in this development:

$$\rho_{TOT} = \frac{\partial C_{Gen}}{\partial P_{DEMAND}} + \frac{\partial C_{CCSS}}{\partial P_{DEMAND}} + \ldots + \frac{\partial C_{Stab}}{\partial P_{DEMAND}} = \rho_{Gen} + \rho_{CCSS} + \ldots + \rho_{Stab} \tag{3}$$

This paper proposes a methodology to compute the above quantity. The next section explains the chosen approach. Section 3 shows a model, which incorporates the stochastic nature of the protective relays and the rest of the power system. Section 4 explains the proposed algorithm. An example is shown in section 5. Finally, conclusions are stablished in section 6. The used data and other relevant parameters are shown in the Appendix.

2. Reliability Spot Price Computation.

It is proposed to compute the stability spot price by using finite differences:

$$\rho_{Estabilidad} = \frac{\partial C_{Stab}}{\partial P_{DEMAND}} = \frac{\Delta C_{Stab}}{\Delta P_{DEMAND}} \tag{4}$$

In order to calculate the spot price related to the stability of the system, a probabilistic evaluation of the impact of this instability will be used. The stability probability variation from one scenario to another one with a higher demand in a given bus will provide the cost increase related to the power increase for each case:

$$\rho_{Stab} = \frac{\Delta C_{Stab}}{\Delta P_{DEMAND}} = \sum_{\forall fault} \frac{\Delta \Pr[Stab.] \cdot \Pr[fault] \cdot E.N.S. \cdot Cost_{E.N.S}}{\Delta P_{DEMAND}} \tag{5}$$

where ΔPr[Stab.] is the stability probability variation between the base case and another case with different load, Pr[fault] is the probability of occurrence of the analysed fault in the system, and E.N.S. is the Non Supplied Energy. It is calculated as the product of the power existing in the system in the instant of the fault, times the service recovery time. $\text{Cost}_{E.N.S.}$ is the price of the non-supplied energy.

3. Models.

3.1. Modelling the system.

In order to analyse the system stability, the group formed by the swing equations in the generators, the electric equations in the grid, and the additional equations in the different elements of the system (A.V.R., turbine-governor, etc.) must be solved.
The objective of the study is to obtain the critical clearing times of the faults in the system. This can be achieved by direct methods (Lyapunov), although in this case, it has been done by indirect methods, integrating numerically the group of algebraic and differential equations mentioned above. The Power System Toolbox [4] (a MATLAB Toolbox) will be used for this. The Toolbox has been slightly modified to adapt it to our needs.
For a given fault, simulations assuming different opening times of breakers in both ends of the line are performed, and the stability of the system (stable or unstable) assessed. The results, a scatter plot, will be fitted by a polynomial of third or fourth degree, in a least-squares sense, as shown in figure 1.

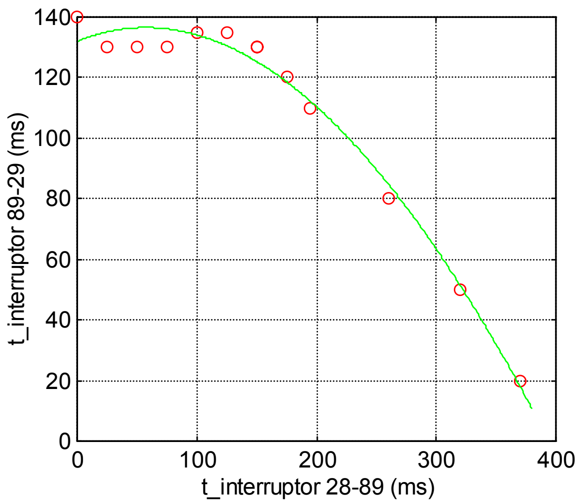

Fig.1

3.2. Modelling the Protective Relays.

When the curves that provide the critical clearing times of a fault have been obtained, they must be translated into a probability value. To reach that value, the operation times of the protections will be considered as random variables, which can be modelled using continuous probability density functions.
The operation time of a protection can be decomposed in two parts: the operation time of the relay, and the operation time of the breaker. For the distance protections simulated in this paper, these times can be represented by normal distributions.
So the distribution function of the total clearing time of a fault can be obtained through the sum of two random variables, which follow a normal distribution and are considered independent one of each other. The convolution of two normal distributions is another

normal one, whose mean is the sum of means, and whose variance is the sum of variances:

$$N_a(\alpha_a, \sigma_a^2) + N_b(\alpha_b, \sigma_b^2) = N(\mu = \alpha_a + \alpha_b, \sigma^2 = \sigma_a^2 + \sigma_b^2) \tag{6}$$

Then, the total operation time of a protection will be represented by the following probability density function:

$$f(t) = \frac{1}{\sqrt{2\pi} \cdot \sigma} \cdot e^{-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2} \tag{7}$$

where t is the value of the random variable, μ its mean, and σ its standard deviation.
It is assumed that the breakers placed in both ends of the line have opening times which are independent random variables (t_1 and t_2). Therefore, their operation can be described by the joint distribution function:

$$f(t_1, t_2) = \frac{1}{2\pi \cdot \sigma_1 \cdot \sigma_2} \cdot e^{-\frac{1}{2}\left[\left(\frac{t_1-\mu_1}{\sigma_1}\right)^2 + \left(\frac{t_2-\mu_2}{\sigma_2}\right)^2\right]} \tag{8}$$

Its shape is shown in figure 2. On the other hand, the stabilty probability is the integral of this distribution function over the region of stability described above (see figure 1). The computation of the integral is done numerically, given the interpolating polynomial.

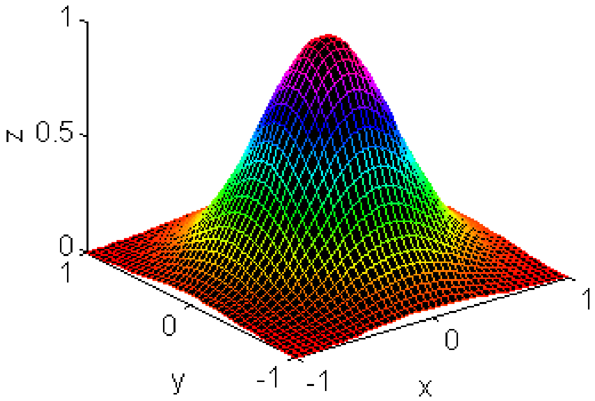

Fig.2

4. Proposed Algorithm.

The sequence used to calculate the spot prices related to the stability of the system can be divided in three steps:

1.- Probabilistic evaluation of stability for a certain fault, in a determined place, and under certain load conditions.

2.- Probabilistic evaluation of stability for the same fault, in the same place, but under new load conditions.
3.- Economic quantification of the instability increase caused by the load increase.

Below, there are some futher remmarks regarding each phase:

1.- The system stability is evaluated for a three-phase fault, because that is the most severe case. If the system remains stable with a three-phase fault, its behaviour will be probably better with a phase-to-phase or a phase-to-ground fault, which are more common, but less severe. In this paper, only line faults have been considered.
2.- Later, the stability of the system will be evaluated again, but with new load conditions, where the demand will be increased in one bus, and the most critical generator will supply this extra load in the system. This generator will be the one who was the first in loosing synchronism in the previous step.
3.- By comparing the two former cases, the stability spot price is computed according the formula derived in Section 2:

$$\rho_{Stab} = \frac{\Delta C_{Stab}}{\Delta P_{DEMAND}} = \sum_{\forall fault} \frac{\Delta \Pr[Stab.] \cdot \Pr[fault] \cdot E.N.S. \cdot Cost_{E.N.S}}{\Delta P_{DEMAND}} \tag{9}$$

In order to obtain Pr[*fault*], the data reported in [2] have been used. It is assumed that the occurrence of any fault of any type in any line is a non-usual phenomenon, which can be modelled by a Poisson distribution:

$$e^{-\lambda t} \cdot \frac{(\lambda \cdot t)^r}{r!} \tag{10}$$

The parameter λ reflects the rate of occurrence or intensity of the Poisson process, and can be estimated using the sample mean. Therefore, the fault probability in the time unit is

$$\Pr[fault] = \lambda \tag{11}$$

The three steps described above should be repeated for several load increases in different buses and for faults in different lines.

5. Study Case.

The proposed methodology has been tested in the New England system, which is shown in figure 3. The total system generation is 5996 MW. $Cost_{E.N.S.}$ is assumed to be 1,000,000 pts/Mw-h. It is assumed that, after transient instability, a system zero happens, and that the reposition time is 3 hours. The used parameters and other relevant information are explained in the Appendix. The results are shown in the table I.Only the buses with a higher component in each case are shown.

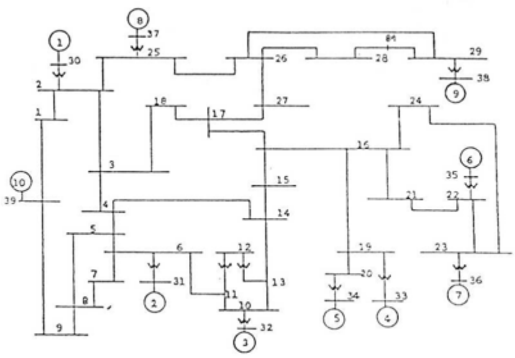

Fig. 3

The energy spot prices related to the system stability are rather high. Some reasons can be taken into account to justify this:

- The system is rather heavily loaded, and in addition the relays have a slow response.
- The load increases in the buses have always been supplied by the most critical generator in the system. As the worst case has always been considered, the obtained costs are higher bounds of the prices related to the system security.
- Another assumption has been made: when a generator losses synchronism, the whole system losses synchronism. Actually, just a part of the grid is affected in real situations, so the real non-supplied energy (E.N.S.) associated to the affected zone would be less than the energy associated to the whole system.

Table I: Example results

Fault in line	28-29		Fault in line	15-16	
	$\frac{\Delta \Pr[Stab.]}{\Delta P_{DEMAND}}$	ρ_{Stab} (pts/MW-h)		$\frac{\Delta \Pr[Stab.]}{\Delta P_{DEMAND}}$	ρ_{Stab} (pts/MW-h)
Bus 26	0,011310	606,331	Bus 16	0,001203	67,414
Bus 29	0,008560	458,903	Bus 4	0,004479	250,997
Bus 16	0,012240	656,188	Bus 26	0,002280	127,563
Bus 4	0,014900	798,791			

6. Conclusions.

A procedure for the computation of the transient stability related spot price component has been shown. This procedure could be used in order to charge the cost of providing an adequate service level.

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Appendix.

The typical fault occurrence values used in this paper have been obtained from the [2]. It is assumed that the three-phase fault are the 8.64 % of all line faults, and that λ for any fault is $34.7 \cdot 10^{-6}$ failures/hour, which translates into 0.3 failures/year.
As stability criterion, it has been assumed that while all the generator angles don't differ one from each other in more than 180º in simulations between 6 and 10 seconds, the system will be considered stable.
The operation time of the protections used in their probabilistic model has a mean of 7 cycles (at 60 Hz), and a standard deviation of 10% of the mean. It must also be considered that, with the used model, the protections have a reliability of 100%, that is, they always work if they are triggered, but their operation time is a random variable. On the other hand, the possibility of actuation of a second or third zone protection has not been considered. Nor has been considered the possibility of reclosing the breakers, because a solid and permanent short-circuit has been applied, so the only way to clear the fault in the system is to isolate the whole affected line with its beginning and end of line breakers. Therefore, the system must be able to keep on working in steady state without that line.
Lastly, in the fault in the line 28-29, it was used the base provided in the distribution of [4]. However, this case was unloaded 2 p.u. (MW) with regard to the original M-file, because the system was too sensitive to a fault in that line with its standard load.