IMPACT OF THE APPLICATION OF PROCESS IMMUNITY TIME ON DISTRIBUTION EXPANSION PLANNING

Juan Carlos CEBRIAN
University of São Paulo – Brazil
cebrian@ieee.org

Jovica V. MILANOVIC
University of Manchester – The UK
jovica.milanovic@manchester.ac.uk

Nelson KAGAN
University of São Paulo – Brazil
nelsonk@pea.usp.br

ABSTRACT

This paper proposes to broaden the classical concepts of multi-stage distribution expansion planning in order to consider the financial losses related to process trip (FPT) which are caused by electric faults. The process immunity time (PIT) is applied during the FPT assessment for each alternative planning. The proposed function fitness joins topics such as: investment costs and FPT according to the process sensitivity in each customer. The best investment schedule obtained ensures an economical and reliable energy supply, and the minimum FPT during the planning horizon.

INTRODUCTION

Currently, the constant change in operational conditions on distribution networks, such as new consumers, new power systems equipment and changing weather conditions, has been affecting significantly the operational and planning actions on distribution systems. This type of problem is known, in the literature, as multi-stage distribution expansion planning (MDEP) [1]-[4]. This problem copes with different economical and electrical variables which must be addressed in order to find solutions that ensure good service to consumers with acceptable investment costs of electric utilities.

On the other hand, the assessment of financial losses (FPT) due to interruption and voltage sags has been studied by different authors [5]-[8]. The FPT obtained allows electric utilities to select the best corrective and preventive actions to improve the power quality supplied to customers. However, these proposed methods don't consider the process immunity time (PIT) during their assessment.

The Process Immunity Time or PIT is defined by [9]. At the occurrence of voltage sags or interruptions, some devices can be shut down or disconnected from the supply. After disconnection, the PIT will define if the whole process will have to be shut down as well [10].

This paper, the application of PIT concept is inserted into the distribution expansion planning context in order to analyze its impact when the best investment schedule is obtained to ensure an economical and reliable energy supply under the constraints of line capacities, voltage limits, and load demands. An optimization technique is used in order to find the best solution. The impact of the application of PIT is shown on a representative distribution network. The planning horizon is analyzed by stages, thus, for each stage, financial losses and investment costs are calculated.

ASSESSMENT OF FINANCIAL LOSSES

To calculate FPT, it is crucial to verify if a fault in the distribution network (due to short-circuit current and duration) causes an interruption (LDI) or a voltage sag to different consumers. For a LDI, the location of protective devices and their time-current curves (CTCP) can define which set of customer can be disconnected after a short-circuit condition. On the other hand, whether a fault has a short duration, customers will notice a voltage sag. The probability of LDI ($Prob_{LDI}$) and the probability of sag or swell ($Prob_{sag/swell}$) can be obtained by the correlation between CTCP and the cumulative probability of voltage sag duration (CPSD) which can be estimated using historical data. While the time-current curve correlates information about the fault (position, type of fault, impedance of fault and duration); the probabilistic sag curve can successively provide probability values for each event.

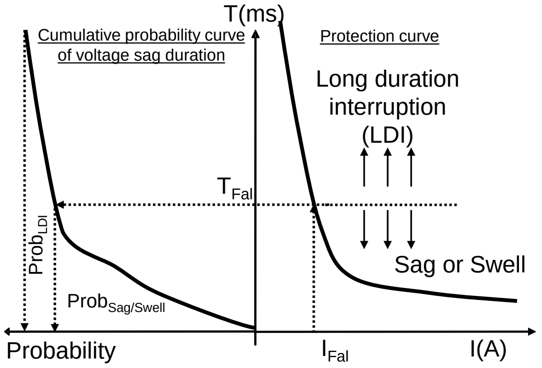
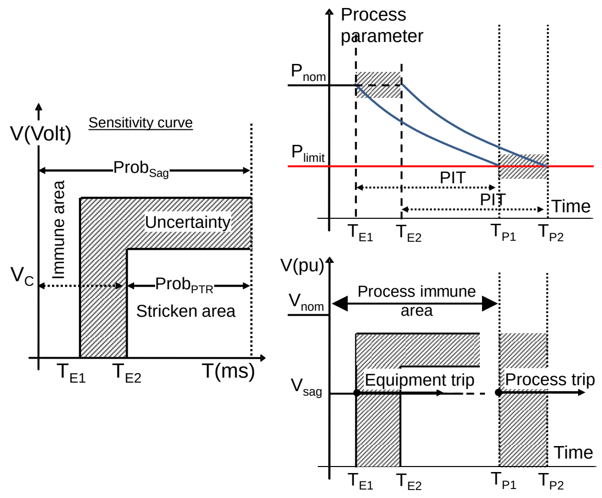


Fig. 1. Obtaining probability of sag/swell and long duration interruption for a given fault current [8].

The Fig. 1 shows the procedure to correlate CPSD and CTCP curves. I_{Fal} represents a short circuit current. Thus, using I_{Fal} and the protective curve, T_{Fal} (protection time) can be obtained. Whether the duration of this event is below T_{Fal}, downstream customers will notice a voltage sag. If the duration of this event is above T_{Fal}, downstream customers will notice an interruption. Therefore, each short circuit simulated has a probability of sag/swell ($Prob_{SAG/Swell}$) and a probability of interruption ($Prob_{LDI}$). Although, it is possible to analyze voltage swells, this paper is focused on analyzing only voltage sags.



(a) (b)

Fig. 2. Equipment and process sensitivity curve: a) with uncertainty areas and b) applying process immunity time.

In order to assess process trip probability (Prob_{PTR}), it is necessary to include the electronic equipment sensitivity curve (ESC) as shown in Fig. 2(a). The ESC has an approximation coming of the CBEMA curve (Computer Business Equipment Manufacturers Association) or ITIC (Information Technology International Council) [11], in particular cases some manufacturers offer their curves as a result of laboratory tests. From Fig. 2(a), the value of Prob_{PTR}, for a short circuit condition and for a voltage level Vc, is only the value below the sensitivity curve (affected area).

The probability trip evaluation of the whole process can be obtained by knowing the probability trip of individual equipment and their mutual connections (serial or parallel) as proposed in [6].

Applying process immunity time

The Fig. 2 (a) shows how uncertainty areas of sensitivity curves and PIT can be linked. Considering that this equipment controls a process, at the occurrence an interruption or voltage sag with duration longer that TE1, this equipment can be shut down or disconnected from the supply, consequently, the process parameter starts to deviate from its normal value. Due to equipment has an uncertainty area between TE1 and TE2, the start point of deviation may be between TE1 and TE2 as well. Whether this variation follows after of the lower frontier Plimit, the process normal operation cannot be preserved. Fig. 2(b) shows two time values TP1 and TP2, between these values there is the same uncertainty area such as between TE1 and TE2. After any time between TP1 and TP2 the process no longer operates as intended and must be shut down, or restarted, or otherwise corrected.

Process Immunity Time is an important variable that define if a process can support a short circuit event. Therefore, In order to determine PIT value is important to know the interconnection between "equipment and parameter" for each process or subprocess. For an existing process, historical information as disturbances and their effects on the process can be used. For new processes, simulation or experience from similar processes can be a helpful tool.

Two interesting areas are shown in Fig. 2(b), process immune area and process trip area. The first one, between 0 and T_{P1}, represent short circuit event which not affect the normal process function. In contrast, the process trip area represents events which the process may trip because of a combination of voltage sag (V_C) with duration greater than T_{P1}.

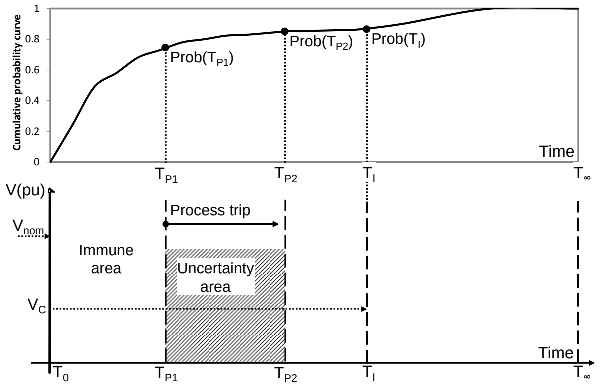


Fig. 3. Evaluation of process trip probability.

The procedure to obtain process trip probability by different time values is shown in Fig. 3. The cumulative probability curve is the same (CPSD) used to obtain Prob_{SAG} and Prob_{LDI}. The variable T_I denote the protection time, in other words, before T_I the process may be affected by voltage sag (supply voltage ≠ zero), but after T_I the process only is affected by LDI (supply voltage = zero).

The relationship between the fault rate per year and the cumulated Prob_{LDI} value is applied to determine the annualized correction factor (ACF). The number of process trip for each consumer per year is obtained from multiplying ACF with the cumulated Prob_{PTR} value. This method can be extended using not only a single year of study, but the whole duration of each analyzed planning stage as well.

PROBLEM FORMULATION

In order to compare each planning alternative, it is necessary to formulate an adequate fitness function. In this paper, financial losses related to process trips is assessed and included in each stage of planning. Thus, the proposed fitness function (FO) can be formulated:

Minimization:

$$FO = \sum_{k=1}^{n} \left[\left(C_{Inv(k)} + 1 \right) \times C_{FPT(k)} \times \delta_k^{inv} + 10^6 \times TotPen_{(k)} \right]$$

$$\delta_k^{inv} = 1 \big/ \left(1 + I \right)^{t_{k+1} - t_k}$$

$$TotPen_{(k)} = \sum_{p=1}^{N_f} pen\left(f_{p,k}\right) + \sum_{j=1}^{Nb} pen\left(V_{j,k}\right)$$

$$pen(f_{p,k}) = \begin{cases} 0 & \left|I_{p,k}\right| \le I_{\max\ p,k} \\ \left(1 + \dfrac{\left(\left|I_{p,k}\right| - I_{\max\ p,k}\right)}{I_{\max\ p,k}}\right)^2 & \left|I_{p,k}\right| > I_{\max\ p,k} \end{cases}$$

$$pen(V_{j,k}) = \left\{ \begin{array}{cc} 0 & V_{min} \le V_{j,k} \le V_{max} \\ \left(1 + \frac{(V_{j,k} - V_{max})}{V_{max}}\right)^2 & V_{j,k} > V_{max} \\ \left(1 + \frac{(V_{j,k} - V_{min})}{V_{min}}\right)^2 & V_{j,k} < V_{min} \end{array} \right\}$$

Where: $C_{Inv(k)}$: total investment costs during stage k; I: interest rate; t_k: final time for stage k; n: number of stages during planning horizon; $C_{FPT(k)}$: total financial losses due to sags and interruptions during stage k; δ^{inv}_k: conversion factor during stage k: *pen(V), pen(f)*: voltage and current penalties; V_{min}, V_{max}: minimum and maximum voltage; f_{max}: maximum current go through each line. The considered constraints are: Kirchhoff's laws; voltage limits and loading of lines; network radiality. Thus, the planning alternative with the lowest fitness function value will be more attractive than others and, it has to treat all technical and economic restrictions during normal operating conditions and electric faults.

Genetic Algorithm

In order to solve MDEP problem, the GA proposed in [12], is used. Each investment schedule is represented as a chromosome. Each chromosome is constituted by a set of genes. One gene is formed by a set of planning options for a respective line. When a chromosome is completed, an investment schedule will be formed.

In this paper, to generate the initial population, different chromosomes are created. Their genes are randomly chosen. In order to reduce a computational efforts, previous results obtained in [12] [13] are inserted in the initial population.

RESULT

The representative network is composed by: 18 bars (2 substations and 16 consumers), 24 lines and 6 protection devices (3 per each substation). The network topology shown in Fig. 4 is obtained from [13]. The nominal voltage is 13.8 kV. In Fig. 3, the types of traits represent: existing lines in the initial network (continuous trace) and candidate lines for addition (dotted trace). Information about load demands and line impedances can be seen in [13].

The planning horizon is analyzed for four years, which are divided into three stages. The first two are 1 year and the third is two years. The interest rate adopted (I) is 10% per year. Using this value, the conversion factors of each investment costs are: $\delta^{inv}_1 = 1$, $\delta^{inv}_2 = 0.9091$, $\delta^{inv}_3 = 0.8264$. The voltage limits are $V_{min} = 13110$ V and $V_{max} = 14490$ V.

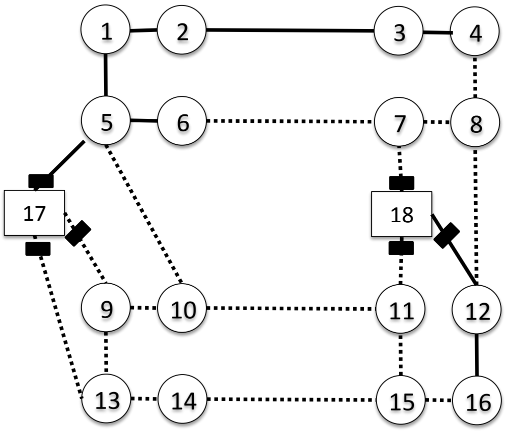
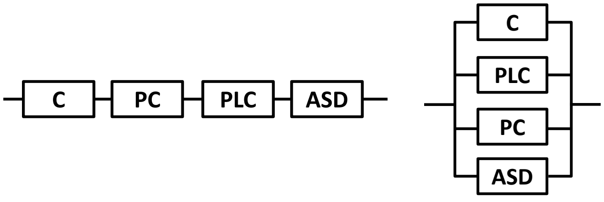


Fig. 4. Topology of 18 bars network [13].

TABLE I
INFORMATION OF BARS

Bar	Customer type	Process type	PIT (s)	Bar	Customer type	Process type	PIT (s)
1	IN	I	2	9	LC	II	1
2	IN	I	2	10	IN	I	2
3	IN	I	2	11	LC	II	1
4	IN	I	2	12	LC	II	1
5	IN	I	2	13	IN	I	2
6	LC	II	1	14	IN	I	2
7	IN	I	2	15	IN	I	2
8	LC	II	1	16	IN	I	2

* IN: Industrial; LC: Large customer



Type I Type II

Fig. 5. Two representative processes used during assessment of annual process trip: C-contactor, PC, PLC and ASD.

A set of 1000 short circuits conditions is created using the Hybrid method proposed in [8]. In order to assess FPT, customer/process type and PIT values are assigned, they are shown in TABLE I. The fault occurrence conditions are adopted from [12]. This paper uses only two process types as shown in Fig. 5. Each type of process uses one equipment AC contactors, PLC, PC and ASD. Their sensitivity curves considering uncertainty areas can be seen in [14]. For all equipment, a high sensitivity is assumed, such as [7], in order to consider the worst case.

The parameters of GA are: population = 50, maximum and minimum for recombination and mutation rate are 0.9 and 0.1 respectively.

Three planning alternatives are compared in TABLE II. In relation to investment costs, the reference [13] shows the lowest value. However, in terms of financial losses, the proposed methodology shows the lowest value. Although, the solution obtained using the proposed methodology needs 22.4% more investment that [13], it reduces 23.5% the financial losses of the customers. As electrical utilities are responsible by normal energy supply, these financial losses can be reflected in fines and penalties which can increase the total cost.

TABLE II
COMPARISON AMONG OTHER ALTERNATIVES

	C_{Inv}(k\$)	C_{FPT}(k\$)
Reference [13]	1110	464
Reference [12]	1657	358
Proposed	1359	355

TABLE III
THE BEST OBTAINED SOLUTION

Line	Stage 0	Stage 1	Stage 2	Stage 3
1-2	0	-1	0	0
2-3	0	-1	0	-1
3-4	0	-1	-1	0
1-5	0	0	0	0
5-6	0	0	0	0
5-17	0	0	2	2
12-16	0	0	0	0
18-12	0	0	1	1
4-8	-1	1	1	1
5-10	-1	-1	1	1
6-7	-1	-1	1	1
7-8	-1	-1	-1	-1
7-18	-1	-1	-1	-1
8-12	-1	1	1	1
9-10	-1	-1	-1	-1
9-13	-1	1	1	1
9-17	-1	2	2	2
10-11	-1	-1	-1	-1
11-15	-1	-1	1	1
11-18	-1	2	2	2
13-14	-1	-1	1	1
13-17	-1	-1	-1	-1
14-15	-1	-1	-1	-1
15-16	-1	-1	-1	-1
C_{Inv}(k\$)		945	414	0
C_{FPT}(k\$)		74	147	134
Total(stage)		1019	561	134
Total(\$)		1714		

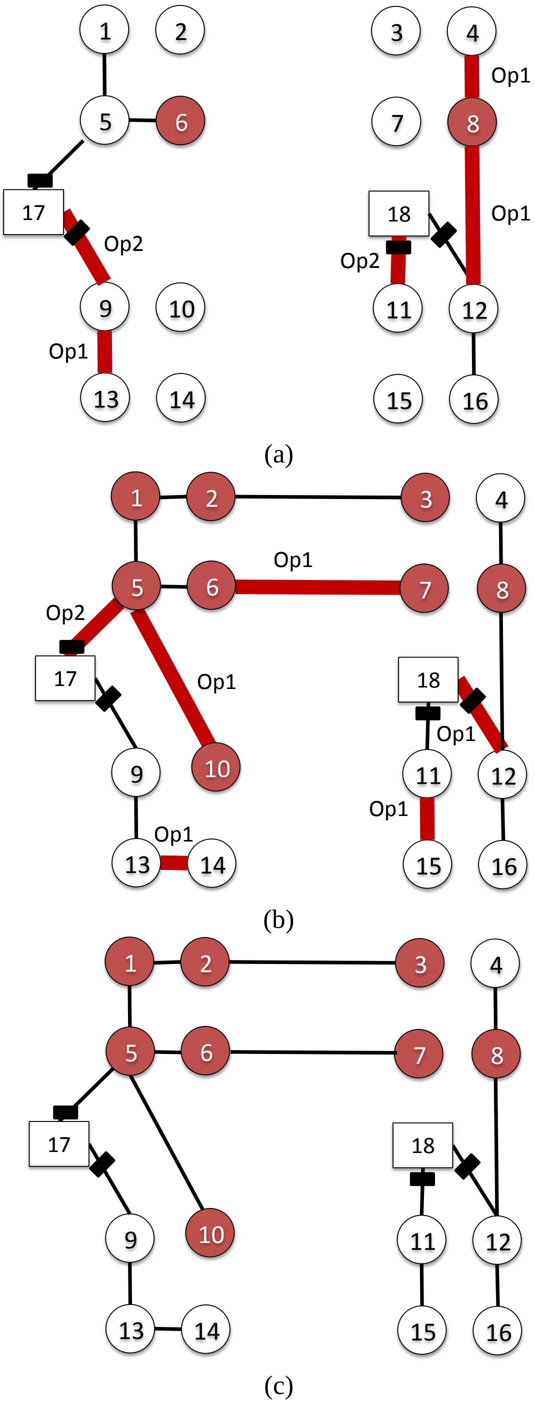
Table III shows the chromosomal structure for the best obtained result after 40 evolutionary cycles during 655 minutes. The value -1 represents a disconnected line and 0, 1, 2 and 3 represent planning options. The obtained topologies can be seen in Fig. 6. The thicker lines represent some change with respect to prior planning stage. The highlighted bars represent customers with highest values of FPT.

The total investment cost in the 3 planning stages is 1359 k\$ and the total financial loss is 355 k\$. The sum of both costs is 1714.

CONCLUSION

This paper aims at broadening MDEP in a way to consider financial losses due to interruptions and voltage sag which are provoked by short circuits throughout the distribution networks. Considering the financial losses, it is possible to assess the total investment costs that electric utility will have to prepare to ensure good service to the customers.

The application of process immunity time increases the investment costs. However, it reduces the financial losses on customers. It is possible because the sensitivity of each process is considered.



(a)

(b)

(c)

Fig. 6. Distribution expansion solution: a) stage 1, b) stage 2 e c) stage 3.

ACKNOWLEDGMENT

The authors would like to thank FAPESP for financial support. Process: 2012/05520-0.

REFERENCES

[1] M. L. De Oliveira, "Integrated Planning of Electric Distribution Systems", Ph. D. dissertation. Dept. Electrical Eng. UNICAMP, Campinas, 2010.

[2] N. Kagan, "Electric Power Distribution Systems Planning using Multiobjective and Fuzzy Mathematical Programming", Ph. D. dissertation, University of London, 1993.

[3] F. A. Bazan, "Planning of Electric Distribution Systems Using Tabu Search Algorithm". MSc, UNESP, Ilha Solteira, 2003.

[4] V. Parada, J.A. Ferland, M. Arias, K. Daniels, "Optimization of electrical distribution feeders using simulated annealing". IEEE Trans. on Power Delivery, Vol. 19, No. 3, pp. 1135-1141, 2004.

[5] N. Kagan, N.M. Matsuo, G. Vasconcelos, U.F. Castellano, J.C. Cebrian, L.M. Camilo, S.X. Duarte, H. Arango, W.H. Bernartelli, J.A. Marsulo, "Evaluating the risk of equipment disruption related to voltage sags", Harmonics and Quality of Power, 2004. 11th International Conference on, p. 379 - 384, 2004.

[6] J. V. Milanovic, C. P. Gupta, "Probabilistic assessment of financial losses due to interruptions and voltage sag: Part I: The methodology". IEEE Trans. Power Del. Vol. 21, no. 2, pp. 918-924, Apr. 2006.

[7] J. V. Milanovic, C. P. Gupta. "Probabilistic assessment of financial losses due to interruptions and voltage sag: Part II: The implementation". IEEE Trans Power Del. Vol. 21, no. 2, pp. 925-932, Apr. 2006.

[8] J. C. Cebrian, N. Kagan, “Hybrid Method to Assess Sensitive Process Interruption Costs Due to Faults in Electric Power Distribution Networks”. IEEE Trans. Power Del. Vol. 25, no. 3, pp. 1686-1696, Jul. 2010.

[9] CIGRE/CIRED/UIE Joint Working Group C4.110, Voltage dip immunity of equipment and installations, CIGRE Technical Brochure 412, published in 2010.

[10] K. Van Reusel, K. Stockman, W. Driessens, "“Process Immunity Time” assessment of its practicability in industry," Harmonics and Quality of Power (ICHQP), 2010 14th International Conference on, pp.1,4, 26-29, 2010.

[11] McEachern, "Power Quality: how bad is bad?", Electrical Construction and Maintenance 92(2): 26, 30, 32, 1993.

[12] J. C. Cebrian, N. Kagan, "Distribution expansion planning considering financial losses due to interruptions and voltage sags using genetic algorithms," Energy (IYCE), 2013 4th International Youth Conference on , vol., no., pp.1,6, 6-8 June 2013

[13] S. Haffner, L. F. Pereira, L. A. Pereira; L. Barreto, “Multi-stage optimization model for expansion planning of distribution systems”. SBA Control & Automation.Vol.17, n.4, pp. 478-492, Dez. 2006.

[14] CIGRE/CIRED Joint Working Group C4.107, Economic framework for power quality, CIGRE Technical Brochure 467, published in 2011.