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ADDRESSING CONSUMER-ORIENTED ELECTRICITY NETWORKS WITH EMBEDDED DISTRIBUTED GENERATION

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Small-scale modular generation systems are emerging as profitable solutions for supplying the customers' loads in a decentralized way. The introduction of local resources connected to the distribution system primarily affects the distribution system voltage control, short-circuit capability and protection, that were relatively simple in a radial system supplied by a unique generation point and now is becoming much more complicated. A conceptual framework for analysing the major modifications in operational issues due to the presence of the distributed generation will be provided.

Keywords: *Distributed generation, Electricity distribution systems, Voltage control, Losses*

1. Introduction

The development of new technologies for small-scale generation and the trend towards the adoption of distributed resources is modifying the characteristics of distribution systems [1],[2]. From the reliability point of view, the presence of local generation sources could improve the system performance by allowing temporary islanding, where separate areas are fed by different generators until the repair of the faulted component has been completed. However, feasibility of islanding conditions needs to be accurately verified [3],[4],[5]. This paper deals with the role of local generation resources in improving the overall distribution system reliability after the occurrence of faults in the distribution network. Section II illustrates the basic reliability aspects for distribution systems with local generation and discusses the conditions for successful island operation. Section III presents the overall framework of reliability analysis with local generators. Section IV illustrates the analytical simulation technique used to perform the reliability analysis. Section V shows the results of reliability evaluations performed on a test system.

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2. Reliability aspects of distributed generation and possible islanding

Distribution systems with multiple supply points from HV/MV substations are usually operated with radial configurations, in which each HV/MV substation supplies a radial portion of the system. Additional local generation units can be located into the system, either connected to the network through a transfer switch to provide *backup supply*, or connected in parallel to the system during normal operation [3]. Local generators in parallel to the network operate in *peak shaving* mode if they do not entirely cover the local load, or in *net metering* mode if they are able to exceed the local load. While a generator in peak shaving mode improves reliability by decreasing the network loading, a generator operating in the *net metering* mode impacts the system reliability by inverting some power flows. The local generation should not exceed the contribution of the HV/MV substation, otherwise reverse power flows could be critical for protection coordination and line overloading.

A key issue for reliability is the possibility of forming *islands* supplied by local generators after losing the mains supply from the HV/MV substation. The islands may be *non-intentional* or *intentional*. For several standards (IEEE, and others) non-intentional islanding is not acceptable, since the customers in the island could be supplied with voltage or frequency levels beyond the regulatory limits required. Non-intentional islands must then be detected and eliminated as fast as possible, with local units correctly sensing interruptions and disconnecting the units from the system in a few cycles.

Recent environmental initiatives, enabled by utility deregulation, have strengthened global consumer demand for efficient clean energy sources. Now, fuel cells are being developed for different applications in transportation, communication, and stationary and portable devices.

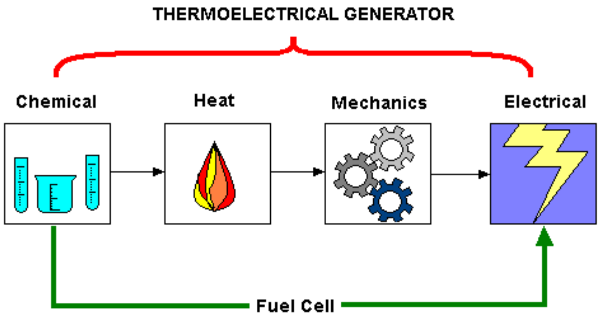

Fig. 1. Comparison between FC and CHP [5]

Intentional islanding during scheduled interruptions or outages could be allowed, by adopting reliable local units and careful coordination of the protection devices. In order to operate an island, one or more generators should be able to support voltage supply to the islanded portion of the network, and local units must be able to satisfy loads and load variations without experiencing dynamic problems in their voltage and frequency control systems. In addition, power quality aspects in the island should not exceed specific limits. If a fault occurs in the island, the local units must switch the island off, and the islanding circuit breaker connecting the island to the external system must be blocked to avoid reclosure of the faulted island on the external system. During the transition from parallel to island operation, it is important to avoiding mis-operations due to incorrect interpretation of phenomena such as sudden load variations or capacitor switching. In reliability analysis, a probability of islanding failure (PIF) is taken into account. Once the island is formed, automatic reconnection of the island without proper resynchronization must be avoided. In order to perform resynchronization, voltage and phase regulation must be available inside the island. When several local units are connected to the network, only one unit at a time must be selected for re-synchronizing the island, taking care of the variations needed in the control variables. A control logic based on two control loops (amplitude and phase) has been proposed in [6] for inverter-type network interface. Islanding control is expensive and should be able to exchange information with the local units enabled to drive the island synchronization. The number of islanding controllers is then limited, and their location in the system should be carefully identified. The extra time needed to reconnect the island to the external system must be taken into account while computing duration-dependent reliability indicators [7]. A reliability model with Petri nets to represent the fault location and the restoration process is used in [4], in which the time sequential Monte Carlo simulation is adopted for reliability evaluations in the presence of local generation. In order to improve reliability, additional resources can be connected to the of the island formed, or load shedding schemes could be studied, evaluating the reliability improvement with the method used for small isolated power systems [2] or, with a more recent view, exploiting the concept of *microgrids* [8] for carefully studying the interaction between the island and the external network.

3. Reliability model of systems with distributed generation

The reliability analysis performed in this paper assumes that some portions of the system under analysis can be aggregated into a few equivalent networks, each of which containing the components subject to the same interruption in case of fault. These networks are represented by their equivalent reliability parameters [4]. The effect of a DG unit on reliability is investigated by considering the feeder to which the DG unit is connected (Fig.2) and representing two equivalent networks with their failure rates, namely, λ_U for the *upstream* network and λ_D for the *downstream* network, and with the corresponding load powers C_U and C_D. The two equivalent networks can be connected to other supply sources during the system restoration after a fault by closing the switches S_U and S_D. Then, the service restoration after a fault in the downstream network requires opening the circuit breaker B_D and performing manual operations. For a fault in the upstream network, the service restoration requires performing manual operations. The presence of the local DG unit can assist the restoration process, by opening the circuit breaker B_S and connecting the DG unit to the downstream network.

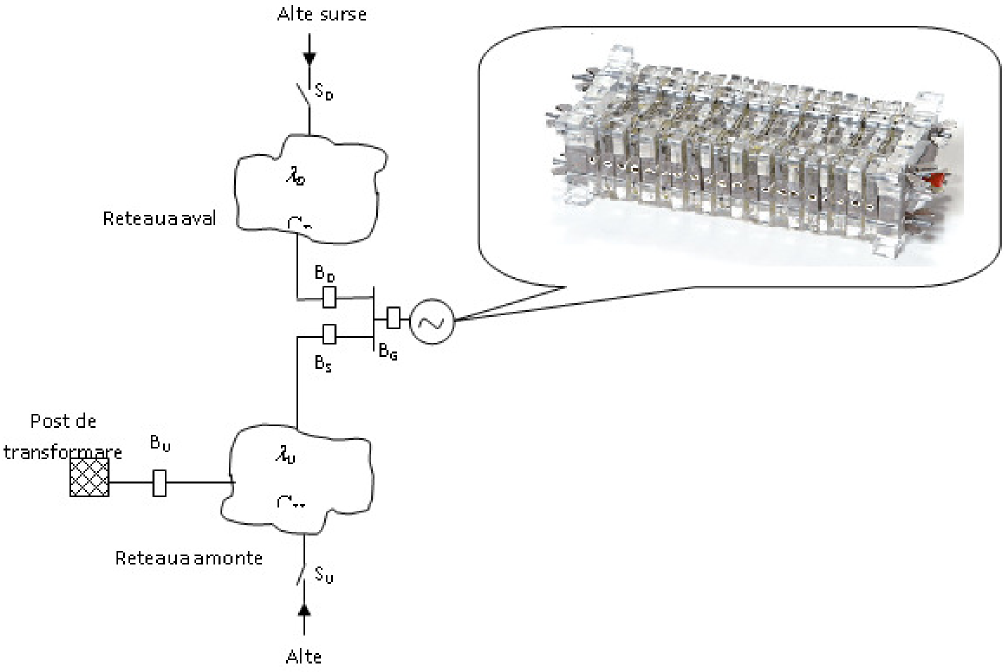

Fig. 2. Scheme of the test system for reliability study of a distribution system with DG.

The probability p_I = 1-PIF of forming the island to supply the power C_D depends on the local generator availability, on the probability that $C_G > C_D$ and on the probability successful transition from parallel to island mode of operation. The reliability model considered in this paper takes into account the probability of successful island formation p_I, the probability p_S of selective operation of the circuit breaker B_D with respect to the supply circuit breaker B_U for faults occurring in the downstream network, and the probabilities p_U (or p_D) of successful switching S_U for the upstream network (S_D for the downstream network) to connect the corresponding network to the other supply when faults in the upstream (downstream) network occurs. All these probabilities are used to compute the probability of successful restoration p_R and the interrupted power C_{int}, by considering different restoration modes, corresponding to independent events, as in Table 1.

Table 1.

Probabilities of successful restoration (restoration mode with initial letter U for faults in the upstream network, D for faults in the downstream network).

restoration mode	successful island formation	successful $\mathrm{S_U}$ switching	successful $\mathrm{S_D}$ switching	successful $\mathrm{B_D}/\mathrm{B_U}$ selective operation	interrupted power C_{int} (p.u.)	probability of successful restoration p_R
U1	yes	yes	---	---	C_U	$p_I\, p_U$
U2	yes	no	---	---	C_U	$p_I\, (1\text{-}p_U)$
U3	no	yes	yes	---	$C_U + C_D$	$(1\text{-}\, p_I)\, p_U$
U4	no	no	no	---	$C_U + C_D$	$(1\text{-}\, p_I)\, (1\text{-}\, p_U)$
D1	---	---	yes	yes	C_D	$p_S\, p_D$
D2	---	---	yes	no	C_D	$p_S\, (1\text{-}p_D)$
D3	---	---	no	yes	$C_U + C_D$	$(1\text{-}\, p_S)\, p_D$
D4	---	---	no	no	$C_U + C_D$	$(1\text{-}\, p_S)\, (1\text{-}\, p_D)$

4. Application to a test system

The reliability indices computation has been performed on a test system composed of M = 10 equal feeders. Each feeder has the structure indicated in Fig.1. Failure rates are $\lambda_U = 0.5$ and $\lambda_D = 0.3$. Loads are C_U = 2 p.u. and C_D = 1.5 p.u. The probabilities of successful operations are $p_I = 0.8$, $p_S = 0.95$, $p_U = 0.9$ and $p_D = 0.9$. The parameters of the Gamma PDFs are μ_{τ_S} = 30 min and $\alpha_{\tau_S} = 3$ for the switching time, μ_{τ_R} = 360 min and $\alpha_{\tau_R} = 5$ for the repair time. The time interval of analysis is T = 1 year. The probability of successful restoration in the various restoration modes are shown in Table 2.

Using the characteristic functions-based approach provides the whole PDF and CDF of the total duration of the interruptions. The number of samples used in the IDFT to obtain the PDF for the feeder is 1024 and the maximum duration d_{max} = 1400 min, while the number of samples for the system, for which the PDF is simpler to sample, is 256 and the maximum duration d_{max} = 200 min. The computational errors shown in Table III witness the effectiveness of the approach. Results for the various portions of the system are presented in Table IV. In addition to expected value and variance, other useful results include the probability for which an indicator does not exceed a specified value, such as a limit imposed by a regulation (e.g., the duration d_{lim} = 30 min). Fig. 2a) shows the results for the upstream and downstream networks and for the entire feeder. The effect of the Dirac pulse in the origin is clearly identified in the CDF. The final

PDF for the whole system is compared in Fig.2b to Gamma and Normal PDFs with the same expected value and variance. The Gamma PDF better approximates the “true” PDF obtained from the numerical procedure.

Table 2.

System data and probabilities of successful restoration for the test system

mode	μ_{τ_R} (min)	λT	interrupted power C_{int} (p.u.)	probability of successful restoration p_R	mode	μ_{τ_R} (min)	λT	interrupted power C_{int} (p.u.)	probability of successful restoration p_R
U1	30	0.5	2.0	0.720	D1	30	0.3	1.5	0.855
U2	360	0.5	2.0	0.080	D2	360	0.3	1.5	0.095
U3	30	0.5	3.5	0.180	D3	30	0.3	3.5	0.045
U4	360	0.5	3.5	0.020	D4	360	0.3	3.5	0.005

Table 3

Computational errors on average value and standard deviation of the total duration of the interruptions.

	system results			feeder results		
	numerical (min)	analytical (min)	error (%)	numerical (min)	analytical (min)	Error (%)
expected value μ_d	29.333	29.340	-0.02	29.360	29.340	0.07
standard deviation σ_d	22.236	22.261	-0.11	70.582	70.396	0.26

Table 4

Total duration of the interruptions and related probabilities (d_{lim} = 30 min)

network	C_{int} (p.u.)	expected value μ_d (min)		standard deviation σ_d (min)		Prob{d=0}	Prob{$d > \mu_d$}	Prob{$d > d_{lim}$}
		analytical	numerical	analytical	numerical			
upstream	2.0	32.45	32.43	92.55	92.35	0.598	0.223	0.241
downstream	1.5	25.20	25.19	81.57	81.43	0.670	0.216	0.190
feeder	3.5	29.34	29.34	70.40	70.40	0.449	0.216	0.216
system	35.0	29.34	29.38	22.26	22.14	0.0004	0.394	0.382

A dedicated analysis has been performed to investigate the variation of the total duration of the interruptions in function of the probability of successful island formation and of the probability of successful selective operation for the B_D and B_U circuit breakers. Fig.3 and Fig.4 show that the total duration of the interruption for the whole system decreases as the two probabilities increase.

5. Conclusions

An overall scheme for addressing the impact of the distributed generation to reliability analysis of distribution systems has been presented. Including the impact of local generation resources and possible islanding operation into this scheme requires taking into account the probabilities of successful islanding operation, selective protection and successful switching of the upstream and downstream networks to other supplies. Results have been shown for a simple but general test system using an effective approach based on the characteristic functions and on the properties of the compound Poisson process. Further investigations are in progress to perform comprehensive reliability evaluations on large real distribution systems.

6. References

1. N.Hadjsaid, J.F.Canard and F.Dumas, "Dispersed Generation Impact on Distribution Networks", *IEEE Computer Applications in Power*, Vol.12, No.2, April 1999, pp.22-28.
2. R.Billinton and R.Karki, "Maintaining supply reliability of small isolated power systems using renewable energy", *IEE Proc. Gener. Transm. and Distrib.*, Vol.148, No.6, Nov.2001, pp.530-534.
3. R.E. Brown, *Reliability of distribution systems*, Dekker, New York, 2002.
4. M.Megdiche, Y.Besanger, J.Aupied, R.Garnier and N.Hadjsaid, "Reliability assessment of distribution systems with distributed generation including fault location and restoration process", *17th CIRED*, Barcelona, Spain, May 12-15, 2003, paper 4.74.
5. P.P.Barker and R.W.de Mello, "Determining the Impact of Distributed Generation on Power Systems: Part I – Radial Distribution Systems", *IEEE/PES Summer Meeting*, 2000, Vol.3, pp.1645-1656.
6. S.Barsali, G.Celli, M.Ceraolo, R.Giglioli, P.Pelacchi and F.Pilo, "Operating and Planning Issues of Distribution Grids Containing Diffuse Generation", *16th CIRED*, 2001, paper 4.20.
7. R.E.Brown and L.A.A.Freeman, "Analyzing the reliability impact of distributed generation", *IEEE/PES Summer Meeting*, 2001, Vol.2, pp.1013–1018.
8. B.Lasseter, "Microgrids", *IEEE/PES Winter Meeting*, 2001, Vol.1, pp.146-149.
9. R.Billinton and R.N.Allan, *Reliability Evaluation of Power Systems*, Plenum Press, New York, 1984.
10. E.Carpaneto and G.Chicco, "Evaluation of the probability density functions of distribution system reliability indices with a characteristic functions-based approach", submitted for publication.
11. A.Papoulis, *Probability, Random Variables, and Stochastic Processes*, McGraw Hill, Singapore, 1991.
12. W.Feller, *An introduction to probability theory and its applications*, 2 Voll., Wiley, New York, 1971.
13. E.Carpaneto, G.Chicco, A.Mosso and A.Ponta, "Analytical Evaluation of the Probability Distributions of Reliability Indices for Large Distribution Systems", *Proc. PMAPS*, Napoli, Italy, 2002, pp.31-36.