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Distribution Network Reconfiguration in a Smart Grid Context with Fault Occurrence

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Abstract

Two of the most important characteristics of a Smart Grid are: a) working optimally, i.e., using the optimal topology and using optimally all available resources in order to minimize the overall planning costs; b) the capability to adapt itself to a contingency, for instance, a load increase/decrease, a fault (automatic repair or removal from service the component in an outage situation, etc). In these cases the reconfiguration of the distribution system must be performed to reroute supplies of energy to sustain power to all customers. This paper proposes a deterministic method based on DC Optimal Power Flow for distribution network reconfiguration with high penetration of distributed generators when a fault occurs. A case study based on a real 201-bus distribution network located in Zaragoza, Spain is presented to illustrate the application of the proposed method.

Keywords: Distribution network reconfiguration, Optimal power flow, Distributed generators, Non-supplied power.

1. Introduction

Three dominant factors are impacting future electric distribution systems: governmental, customer needs, and new intelligent computer software and hardware technologies. In addition, environmental concerns are driving the entire energy system to efficiency, conservation, and renewable sources of electricity.

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Customers are becoming more proactive and are being empowered to engage in energy consumption decisions affecting their quotidian. At the same time, energy needs are continually expanding. Consumer behavior changes will include extensive use of electric vehicles, remote control of in-home appliances, ownership of distributed generation from renewable energy sources, and energy storage. The availability of new technologies such as distributed sensors, two-way secure communication, advanced software for data management, and intelligent and autonomous controllers has opened up new opportunities for changing the distribution energy system.

Today, the distribution network is transforming and evolving into a faster-acting, potentially more controllable grid than in the past, the so-called "Smart Grid" (SG) [1][2][3]. In this context new digital and intelligent devices will be incorporated in the distribution networks. These new devices will allow two way communications, providing an opportunity for new control schemes and algorithms [1][2].

A distribution system in a Smart Grid context must have the following characteristics [4]:

- Flexible: the rapid and safe interconnection of distributed generation, energy storage and other distributed energy resources;
- Predictive: use of machine learning, weather impact projections, and stochastic analysis to provide predictions of the next most likely events;
- Interactive: appropriate information regarding the status of the system is provided not only to the operators, but also to the customers;
- Optimized: knowing the status of every major component in real or near real time and having control equipment to provide optional routing paths provides the capability for autonomous optimization of the flow;
- Secure: considering the two-way communication capability of the Smart Grid covering the end-to-end system;
- Self-healing: automatic repair or removal from the service the component, in a potentially outage situation or in outage situation, and reconfiguration of the distribution system to reroute supplies of energy to sustain power to all customers.

Distribution networks are normally meshed in design but operated radially. Their configuration may be varied with manual or automatic switching operations with diverse goals such as supplying loads at the minimum cost, increasing system security and reliability and enhancing power quality [5][6]. Reconfiguration consists in changing the status of sectionalizing and tie-switches so that the network becomes radially operated.

This paper proposes a deterministic method base on DC Optimal Power Flow for distribution network reconfiguration in presence of a fault. To illustrate the application of the proposed method, a case study based on a real 201-bus distribution network located in Zaragoza, Spain [7] considering high penetration of distributed generators is presented.

This paper is organized as follows: Section II explains the method proposed for distribution network reconfiguration with a fault occurrence. Section III presents the case study and the discussion of the obtained results. Finally, in Section IV, the most relevant conclusions are presented.

2. Proposed Method

This paper proposes a method for distribution networks reconfiguration with high penetration of distributed generators in order to minimize the expected non-supplied power cost in presence of a fault. Figure 1 presents the scheme of the proposed method.

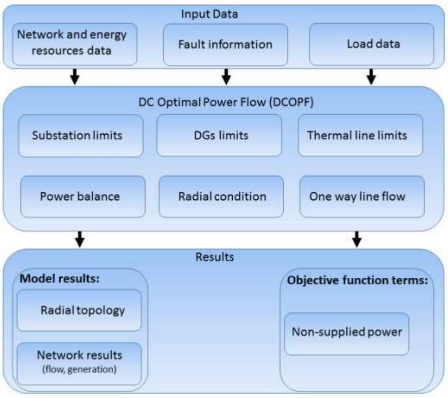

Fig. 1. Diagram of proposed method

The proposed method has three main aspects, which are presented in more detail as follows:

2.1. Input data

All network data with all energy resources and load information (at time of fault occurrence) as well as the fault location are the main basis of the proposed method.

2.2. DC optimal power flow

Base on DC optimal power flow, a mixed integer linear programming is developed (equations (1)-(6)) and applied in order to identify the better topology for the distribution network after a fault occurrence. The main goal is to maximize the reliability, which is presented in the form by minimizing the expected non-supplied power (ENSP). The objective function is subject to all DC optimal power flow constraints, which include the technical constraints. The objective function to be minimized is:

- Non-supplied power cost

$$Minimize \qquad C \cdot \sum_{ij=1}^{NE} FOR_{ij} \cdot S_{ij} \tag{1}$$

The objective function in equation (1) is subject to the following technical constraints:

- Power balance

$$\sum_{i=1}^{N} Sgen_i + \sum_{ij=1}^{NE} S_{ij} - \sum_{ji=1}^{NE} S_{ji} - L_j = 0 \qquad (2)$$

- Generation limits

$$Sgen_i^{min} \le Sgen_i \le Sgen_i^{max} \qquad (3)$$

- Thermal limits of distribution lines

$$S_{ij} \le S_{ij}^{max} \times y_{ij} \qquad (4)$$

Power flow in distribution lines is characterized by double direction between buses, but in the operation of this kind of networks only one of the directions should exist. Constraint (5) shows this idea.

- One direction for the power flow

$$y_{ij} + y_{ji} \le 1 \qquad (5)$$

- Radiality condition

$$\sum_{j \in N} y_{ij}^{j} = 1 \qquad (6)$$

where,

NE	Total number of lines
S_{ij}	Apparent power between bus *i* and bus *j*
FOR_{ij}	Forced outage rate for line *ij*
$Sgen_i$	Apparent power produced in bus *i*
L_j	Load in bus *j*
$Sgen_i^{\min}$	Minimum apparent power generated in bus *i*
$Sgen_i^{\max}$	Maximum apparent power generated in bus *i*
y_{ij}	Binary decision variable associated with the distribution line *ij*
y_{ij}^{j}	Binary decision variable to connect distribution line *ij* to bus *j*

N	Total number of buses
C	Non-Supplied Power cost (€/kVA)

2.3. Output results

As outputs the model will present the new network radial topology (without the network component in fault state) and also the power flow through the lines and the resources selected to supply the network. The new value for the expected non-supplied energy is also obtained.

3. Case Study

The proposed method has been tested on a real 201 buses distribution network adapted from [7]. This network is a 11 kV system with three feeders, one substation, 201 buses, and 168 load points. In this case study occurs a fault in period 13 of a summer day. The total load in this period is 15,245 kVA. Also, this network has 119 generation units (1 substation, 4 co-generations, 1 small hydro, 1 biomass, 30 winds and 82 photovoltaic). MATLAB with TOMLAB Optimization Environment [8] has been used to develop the reconfiguration problem based on DC optimal power flow. The solver used in this case study is the CPLEX. The cost for the non-supplied power is 3€ per kVA.

A computer with one processor Intel Core i7 1,7GHz, 8GB of Random-Access-Memory (RAM) and Windows 8.1 Professional 64-Bit Operating System was used for this case study.

Figure 2 depicts the diagram of the 201 buses distribution network [7]. The substation unit it is in bus 201. All buses have switches that can open or close in order to make the network radial in operation. Table 1 presents the apparent power of the load. Figure 3 presents the normal operation of the 201-bus distribution network in radial topology. This operation condition is for period 13 which have the active resources presented in Table 2. The ENSP for this period is 126 kVA.

Table 1. Active resources in normal operation

Bus	Resource	Power (MVA)	Bus	Resource	Power (MVA)
19	Biomass	0.3559	128	Co-generation	1.2000
21	Wind	0.0400	131	Wind	0.0160
26	Wind	0.0160	140	Wind	0.0080
29	Wind	0.0400	141	Wind	0.0400
34	Wind	0.0400	142	Wind	0.1201
67	Wind	0.0160	143	Wind	0.0160
70	Wind	0.0400	151	Wind	0.0160
79	Wind	0.0400	154	Wind	0.0400
80	Wind	0.0400	155	Wind	0.0080
81	Wind	0.0040	172	Wind	0.0160
85	Wind	0.0160	174	Co-generation	0.0438
104	Wind	0.0400	201	Substation	13.0249
106	Wind	0.0080		Total	15.2450

A fault in line 20-56 occurs in period 13, and at the same time the model (1) - (6) runs. The problem starts with the meshed design of distribution network which is obtained by considering all switches closed. After 0.712 seconds the model presents the new radial topology with the fault isolated. Figure 4 depicts the new radial topology, which presents 138 kVA for ENSP. Table 3 presents the active resources in this fault condition. It is possible to see that some resources when compared with the normal operation are now actives. Also, the power supplied by substation grows 4.53%. Table 4 presents a comparison between the normal state and fault state results, and it is possible to see an increase of the ENSP. This increase corresponds to a 9.52% in expected non-supplied power.

Table 2. Load Data for Period 13

Bus	Apparent Load (kVA)	Bus	Apparent Load (kVA)	Bus	Apparent Load (kVA)	Bus	Apparent Load (kVA)	Bus	Apparent Load (kVA)	Bus	Apparent Load (kVA)
2	135	39	107	71	134	101	132	136	94	165	41
5	127	40	135	72	43	102	79	137	9	166	171
6	57	41	78	73	132	103	86	138	135	168	23
7	92	42	64	74	54	104	216	139	39	169	87
9	135	44	135	76	55	105	135	140	61	170	23
10	135	45	135	77	49	106	61	141	170	171	30
11	86	46	135	78	91	107	42	142	351	172	114
12	55	47	96	79	147	108	24	143	117	173	135
13	75	48	86	80	216	110	86	144	22	176	135
14	79	50	135	81	23	111	135	145	105	177	216
17	86	51	135	82	135	112	42	146	42	179	86
18	33	52	135	83	3	113	135	147	92	180	91
19	14	54	47	84	58	114	30	148	56	181	59
21	216	55	135	85	114	115	71	149	86	182	135
22	86	56	14	86	23	120	88	150	135	183	71
23	86	57	86	87	23	121	274	151	113	184	96
24	86	58	55	88	23	123	55	152	67	185	91
25	135	60	67	89	6	124	55	153	86	187	186
26	116	61	79	90	23	125	55	154	216	190	146
28	86	62	135	92	23	126	55	155	62	191	23
29	270	63	86	93	20	127	55	156	135	192	23
30	86	64	106	94	135	128	86	158	3	193	23
31	86	65	134	95	129	129	135	159	1	194	23
32	50	66	86	96	8	130	69	160	58	195	23
33	134	67	114	97	71	131	117	161	216	197	23
34	216	68	58	98	54	132	135	162	11	200	58
35	135	69	63	99	18	133	86	163	143		
36	86	70	190	100	86	134	86	164	18		

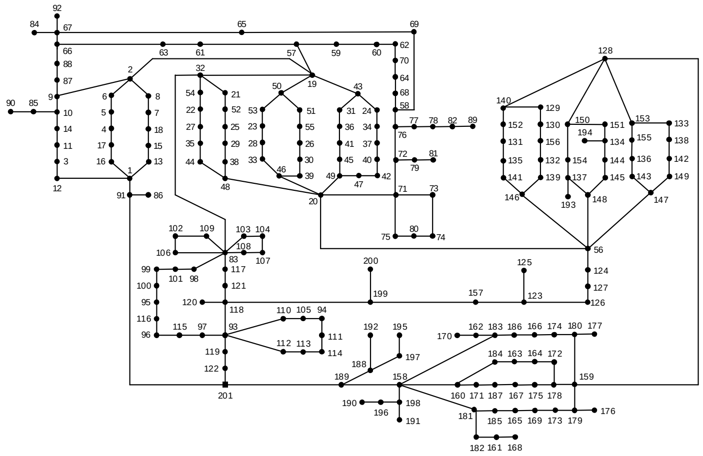

Fig. 2. Single-line 201-bus distribution network [7]

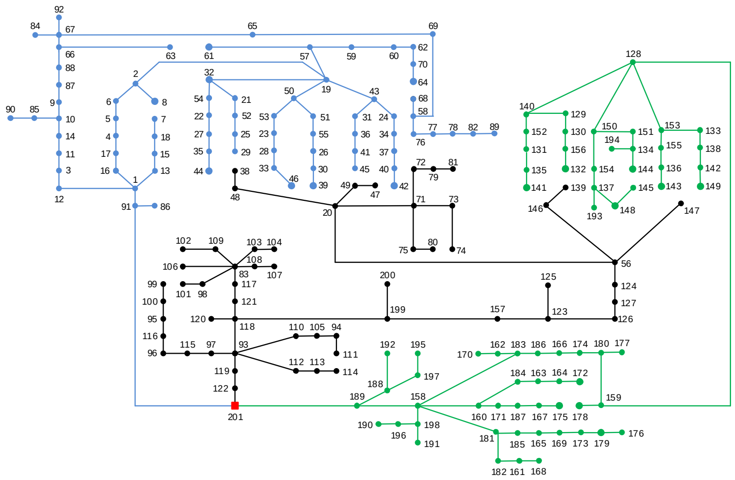

Fig. 3. Radial topolology normal operation in period 13 for 201-bus distribution network

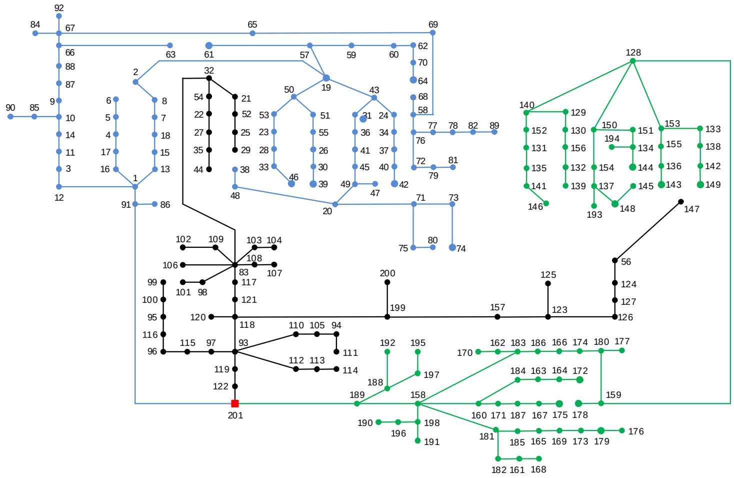

Fig. 4. Radial topolology operation in period 13 for 201-bus distribution network with a fault in line 20-56

Table 3. Active Resources in Fault Condition

Bus	Resource	Power (MVA)	Bus	Resource	Power (MVA)
32	Photovoltaic	0.0043	155	Photovoltaic	0.0086
54	Photovoltaic	0.0043	160	Photovoltaic	0.0086
98	Photovoltaic	0.0043	165	Photovoltaic	0.0043
108	Photovoltaic	0.0043	168	Photovoltaic	0.0043
114	Photovoltaic	0.0043	170	Photovoltaic	0.0043
125	Photovoltaic	0.0043	171	Photovoltaic	0.0043
126	Photovoltaic	0.0043	174	Co-generation	0.0438
128	Co-generation	1.2000	175	Photovoltaic	0.0043
139	Photovoltaic	0.0043	181	Photovoltaic	0.0086
140	Photovoltaic	0.0086	198	Co-generation	0.1683
142	Wind	0.1201	201	Substation	13.6100
146	Photovoltaic	0.0043	Total		15.2450
148	Photovoltaic	0.0086			

Table 4. Active Resources in Fault Condition

Normal State		Fault State	
ENSP (kVA)	ENSP Cost (€)	ENSP (kVA)	ENSP Cost (€)
126	378	138	414

4. Conclusions

This paper proposes a deterministic method for distribution networks reconfiguration aiming the minimization of non-supplied power cost. The proposed reconfiguration method is based on a DC optimal power flow model and it is developed in TOMLAB Optimization Environment. The presented method leads to significant advantages, since it ensures the optimal solution to the problem in real time. The execution time to present a new topology

while minimizing the expected non-supplied power cost is 0.712 seconds. The execution time is an excellent indicator that this method performs well when applied to a large smart grid system, giving a solution in acceptable time. The method proved to be adequate to support the distribution network operator for the reconfiguration of the distribution systems.

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