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Network Reconfiguration for Distribution System with Micro-Grid

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1. Introduction

Nowadays, technologies of distributed generation (DG) and distributed energy resource (DER) are developing rapidly. More and more DG devices, such as photovoltaic(PV), micro-turbine, wind generator, CCHP, energy storage, have been installed to the traditional power system (especially to the distribution system). How to draw more benefits from such DG devices has been paid even more attention than before (EPRI, 2007; IEEE, 2003; EPRI, 2001). A possible solution vision is micro-grid (Barnes et al, 2007; Khan & Iravani, 2007; Dimeas & Nikos, 2005). A micro-grid is a portion of power system that includes one or more DG units capable of operating either parallel with or independent from a distribution system. It is demonstrated to be more reliable and economical that DGs are integrated into a distribution system through micro-grid. So, more and more micro-grids will occur in the distribution system in the future.

Targets of the network reconfiguration in traditional distribution system are to reduce power loss (Civanlar et al, 1988; Baran & Wu, 1989; Song et al, 1997; Kashem et al, 2001; Carpaneto & Chicco, 2004; Sua et al, 2005), balance power supplying and consuming, improve power quality, isolate fault components and restore system quickly under some emergencies (Tu & Guo, 2006; Bhattacharya & Goswami, 2008; Carreno et al, 2008), et al through optimizing the sectionalizing and tie switchers on the feeders. Just as we know, traditional distribution system was constructed and operated radially. In such network, any load only had a single supplying source and power flow on any feeder was in one-way. However, things will be changed once some micro-grids exist in the distribution system. Since a micro-grid may contain various DGs, such as PV, CCHP, wind generator, it can be considered as a power source or a consuming load at different time so that power flow on some feeders will be bidirectional under some conditions (Chen et al, 2008; Yu et al, 2009). It is obvious that reconfiguration for the traditional distribution system and reconfiguration for the distribution system with micro-grids are very different.

In this chapter, we mainly concern the impact of micro-grids on the distribution system reconfiguration. A reconfiguration model suitable for the distribution system with micro-grids is presented. Once a fault occurs, it can be applied to construct some islands. Any island contains one or more micro-grids so as to guarantee power supplying for some important customers and to reduce the power loss at the same time. The problem is then decomposed into a capacity sub-problem and a reconfiguration sub-problem. The former is used to determine the optimal capacity of each island, while the latter is used to find the optimal reconfiguration with less power loss. Finally, some typical distribution systems are employed to validate the effectiveness of the presented method.

Rest of this chapter is organized as following: Section 2 gives the model of the distribution system with micro-grids used in this chapter. Section 3 provides a suitable reconfiguration model and discusses its solving method. Numerical studies and conclusions are given by Section 4 and Section 5.

2. Distribution system model

In this chapter, we will consider the distribution system with parallel operating micro-grids as shown in Fig.1. In the figure, two micro-grids are connected to system at node N_i and N_j. Just as we know, if DG devices are directly installed into the distribution system, they will be tripped quickly once a fault occurs in the system according to the standard of IEEE-1547 (IEEE, 2003) in order to keep the equipments and persons safe. However, if various DGs are first integrated into a micro-grid, and then the micro-grid is connected to the distribution system as a whole, more benefits will be drawn. e.g. if a fault causes some feeder outage, a micro-grid can operate as an isolated island so that it can supply power to some important customers nearby (Barnes et al, 2007; Khan & Iravani, 2007; Dimeas & Nikos, 2005). In this chapter, our aim is to find the optimal islanding scheme so as to guarantee power supplying for more customers with less power loss at the same time.

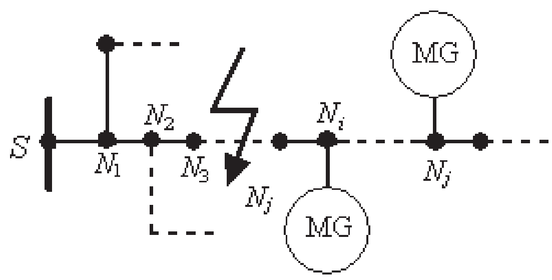

Fig. 1. Distribution system with micro-grids

For the system as shown in Fig.1, we use S to denote the source node and use $\boldsymbol{N}, \boldsymbol{BR}, \boldsymbol{MG}$ for the set of nodes, branches and micro-grids in the system.

$$\boldsymbol{N} = \{N_1, N_2, N_3, \cdots, N_n\} \tag{1}$$

$$\boldsymbol{BR} = \{BR_1, BR_2, BR_3, \cdots, BR_m\} \tag{2}$$

$$\boldsymbol{MG} = \{MG_i(N_j)\}, i = 1, 2, ..., k; N_j \in \boldsymbol{N} \tag{3}$$

Where, n, m, k are numbers of the system nodes, branches and micro-grids. In Eq.(3) $MG_i(N_j)$ means that the i-th micro-grid is connected to node N_j. Normally, distribution system is operated radially, so the following equation holds n=m+1. Further $\overline{\boldsymbol{U}}, \underline{\boldsymbol{U}}$ are used for the upper and lower voltage limits of $\boldsymbol{N}$, and $\overline{\boldsymbol{SB}}$ for the upper power limit of $\boldsymbol{BR}$.

$$\overline{\boldsymbol{U}} = \{\overline{U}_1, \overline{U}_2, \overline{U}_3, \cdots, \overline{U}_n\} \tag{4}$$

$$\underline{\boldsymbol{U}} = \{\underline{U}_1, \underline{U}_2, \underline{U}_3, \cdots, \underline{U}_n\} \tag{5}$$

$$\overline{\boldsymbol{SB}} = \{\overline{S}_1, \overline{S}_2, \overline{S}_3, \cdots, \overline{S}_m\} \tag{6}$$

A micro-grid can be treated as a load or a generator under different operating conditions. When it is operated as a load, it only draws power from distribution system just like a normal load. While, if it is operated as a generator, it can send power into the distribution system. Once a fault occurs in the distribution system, some loads may be interrupted without micro-grid. However, if there are some micro-grids connecting to the system, things may be changed. A micro-grid with "extra power" can form an island and send its extra power to some nearby loads temporarily just like a local generator. And, loads interruption may be avoided. In this chapter, we use $\boldsymbol{SMG}$ to denote the maximum extra power (maximum capacity) of the micro-grids that can be used under a fault condition.

$$\boldsymbol{SMG} = \{SMG_1, SMG_2, SMG_3, \cdots, SMG_k\} \tag{7}$$

Further, $\boldsymbol{SS}, \boldsymbol{TS}$ is used to denote sets of the sectionalizing switchers and tie switchers as following:

$$\boldsymbol{SS} = \{SS_i(BR_j)\}, i = 1,2,...,K_s, BR_j \in \boldsymbol{BR} \tag{8}$$

$$\boldsymbol{TS} = \{TS_i(N_j, N_k)\}, i = 1,2,...,K_t, N_j, N_k \in \boldsymbol{N} \tag{9}$$

where K_s, K_t are numbers of the sectionalizing switchers and tie switchers. $SS_i(BR_j)$ means the *i*-th sectionalizing switcher is located on branch BR_j, and $TS_i(N_j, N_k)$ means the *i*-th tie switcher is located between node N_j and N_k.

3. Network reconfiguration

3.1 Reconfiguration model

Switchers of $\boldsymbol{SS}, \boldsymbol{TS}$ can be optimized so as to reduce the power loss and the customer interruption at the same time in an emergency condition. The reconfiguration model used in this chapter is given as following:

$$\min\left\{W_1[\sum_{i=1}^{IS}(SIS_i - LDIS_i)] + W_2(P_{loss}^{sys} + \sum_{i=1}^{IS} P_{loss,i}^{Island})\right\} \tag{10}$$

$$\text{s.t. } n_0 = m_0 + 1 \tag{11}$$

$$n_i = m_i + 1, \ \ i = 1,2,3,...,IS \tag{12}$$

$$IS \le k \tag{13}$$

$$S_i \le \overline{S}_i, BR_i \in \boldsymbol{BR} \tag{14}$$

$$\underline{V}_i \le V_i \le \overline{V}_i, N_i \in \boldsymbol{N} \tag{15}$$

$$SIS_i - LDIS_i \ge 0, \ \ i = 1,2,3...,IS \tag{16}$$

where, *IS* is number of the islands formed by the micro-grids. An island can consist of more than one micro-grid, so *IS*≤*k*, *k* is number of the micro-grids. SIS_i is the total extra power of the *i*-th island. When there is a single micro-grid in the island, SIS_i equals to its *SMG*. While, if there are more than one micro-grid, SIS_i equals to the *SMG* sum of all micro-grids in the island. $LDIS_i$ is the total loads in the *i*-th island. P_{loss}^{sys} is the power loss of the distribution system exclusive of all islands, and $P_{loss,i}^{Island}$ is the power loss of the *i*-th island.

It can be found that, in the above model, there are two optimal objects: one is to maximize the uninterrupted loads and the other is to minimize the power loss of the whole system, including distribution system exclusive of micro-grids and all islands. In the model, Eq.(11) and Eq.(12) guarantee that the distribution system exclusive of micro-grids and all islands are operated radially. Eq.(14) and Eq.(15) guarantee all system limits not to be violated. Eq.(16) guarantees that there is no load interrupted in any island, i.e. power supply is larger than the power demand in any island.

3.2 Solving of the reconfiguration model

Since the reconfiguration model used in this chapter is a multi-objective optimization model, it can be decomposed into two sub-problems: capacity sub-problem and reconfiguration sub-problem.

Capacity sub-problem is a typical combinatorial optimization model. It is used to determine the optimal capacity of each island, i.e. optimal values of $LDIS_i$ and SIS_i for each island. The model is given as below:

$$\min\sum_{i=1}^{IS}(SIS_i - LDIS_i) \tag{17}$$

$$\text{s.t. } n_0 = m_0 + 1 \tag{18}$$

$$n_i = m_i + 1,\ \ i = 1,2,3,...,IS \tag{19}$$

$$SIS_i - LDIS_i \geq 0,\ \ \ i = 1,2,3...,IS \tag{20}$$

After optimization, the capacity sub-problem will yield the islanding scheme $ISLD_i^o, i = 1,2,3,...,IS$. It tells us which micro-grid and which node are included in an island.

Reconfiguration sub-problem is used to minimize the power loss of whole system including the rest distribution system exclusive of micro-grids and all islands. The model is given as following:

$$\min(P_{loss}^{sys} + \sum_{i=1}^{IS} P_{loss,i}^{Island}) \tag{21}$$

$$\text{s.t. } ISLD_i = ISLD_i^o, i = 1,2,3,...,IS \tag{22}$$

$$n_0 = m_0 + 1 \tag{23}$$

$$n_i = m_i + 1,\ \ i = 1,2,3,...,IS \tag{24}$$

$$S_i \leq \overline{S}_i, BR_i \in \boldsymbol{BR} \tag{25}$$

$$\underline{V}_i \leq V_i \leq \overline{V}_i, N_i \in \mathbf{N} \tag{26}$$

Since the rest distribution system exclusive of all micro-grids and all islands in the above model are all operated radially, Eq.(21)–Eq.(26) just form a typical distribution network reconfiguration model. Its objective is to minimize the power loss of the whole system. It can be solved effectively by some existed methods (Civanlar et al, 1988; Baran & Wu, 1989; Song et al, 1997; Kashem et al, 2001; Carpaneto & Chicco, 2004; Sua et al, 2005; Tu & Guo, 2006; Bhattacharya & Goswami, 2008; Carreno et al, 2008). In this chapter, we just use an improved branch exchange method given by (Kashem et al, 2001) to solve this problem. Details of the method can be referred to (Kashem et al, 2001; Baran & Wu, 1989).
The above two sub-problems are called iteratively, the whole reconfiguration problem given by Eq.(10)-Eq.(16) can be solved finally (Chen et al, 2008; Yu et al, 2009).

4. Case studies

In this chapter, IEEE 33-node system and PG&E 69-node system(Baran & Wu, 1989, Chen et al, 2008; Yu et al, 2009) are employed to validate the presented method.

4.1 IEEE 33-node system

IEEE 33-node system is shown in Fig.2. It consists of 33 nodes and 5 tie lines all with switchers. The first node is treated as the source node. And, it is assumed that all branches have sectionalizing switchers. In this chapter, a fault occurring on branch 11-12 is considered. It will cause this branch out of service after fault.

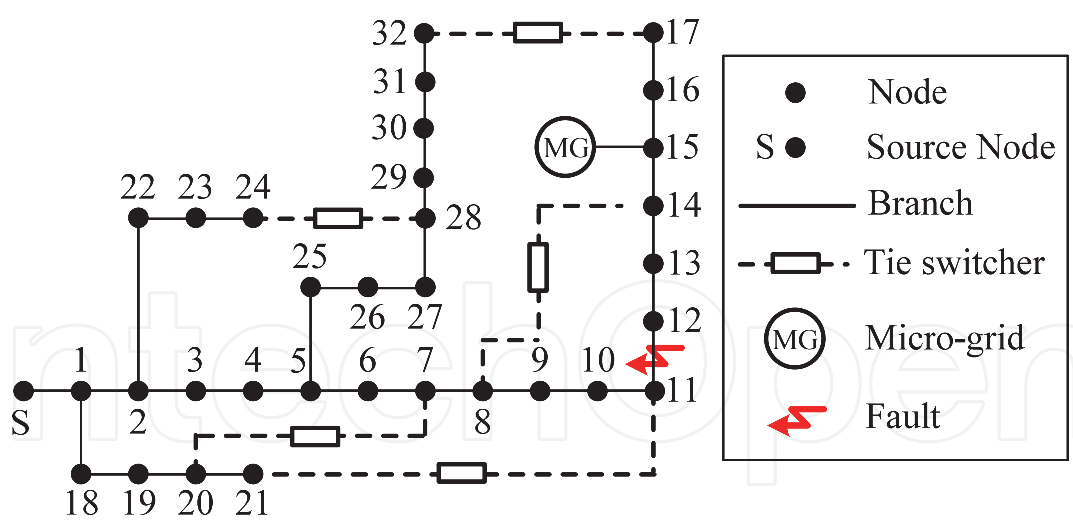

Fig. 2. IEEE 33-node system

1. Reconfiguration without micro-grid

When there is no micro-grid in the system, we can get the reconfiguration result as shown in Fig.3. Five sectionalizing switchers are opened after optimization. They are switchers of 6-7, 8-9, 11-12, 14-15, 27-28, and all tie switchers are closed at the same time. Power loss changes from 134.98kW to 153.14kW after reconfiguration. The power loss increasing is caused by the fault.

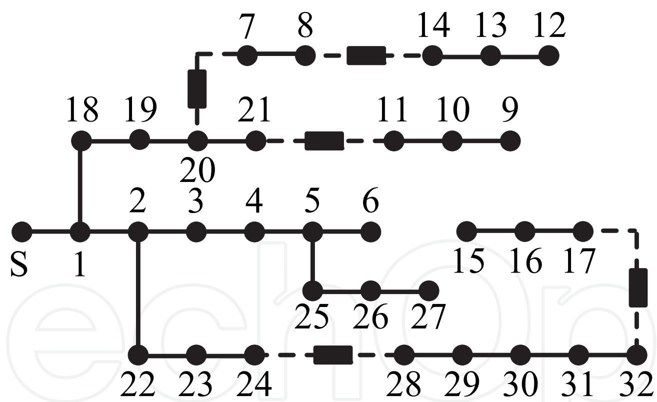

Fig. 3. Reconfiguration result of IEEE 33-node system without micro-grid

2. Reconfiguration with a micro-grid and *SMG*=900kW

When a micro-grid with *SMG*=900kW is installed to node 15 just as shown in Fig.2. After reconfiguration, we can get the optimization result shown in Fig.4. It can be found that an island is formed. It consists of the micro-grid and 9 nodes: 8, 12, 13, 14, 15, 16, 17, 31 and 32. The rest part consists of all the other nodes and is supplied by the original source. Power loss after reconfiguration turns to 80.03kW, which is less than the one without micro-grid. And, the lowest voltage is also changed from 0.9143 p.u.(without micro-grid) to 0.9545 p.u (with a micro-grid).

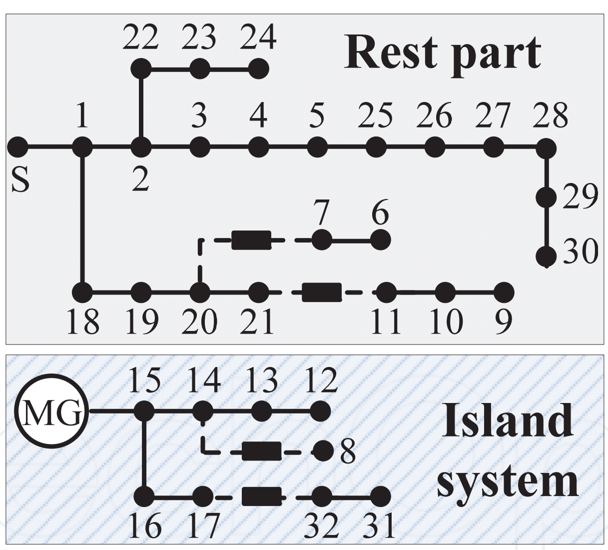

Fig. 4. Reconfiguration result of IEEE 33-node system with a micro-grid and *SMG*=900kW

3. Reconfiguration results with a micro-grid and various *SMG* values

When there is a single micro-grid in the system and its *SMG* changes in the range 0~1700kW, reconfiguration results are shown in Tab.1, Fig.5 and Fig.6. Following conclusions can be drawn from the calculation results:

1. When there is a micro-grid in the distribution system, it can form an island so as to supply power to the nearby loads under the emergency condition. Comparing with the result without micro-grid, we can find that the power loss is reduced and lowest voltage is improved at the same time.

	Initial condition	*SMG* of the micro-grid					
		0 kW	100 kW	200 kW	300 kW	400 kW	500 kW
Switchers to be opened	7-20 (T) 8-14 (T) 11-21 (T) 17-32 (T) 24-28 (T)	6-7 (S) 8-9 (S) 11-12 (S) 14-15 (S) 27-28 (S)	6-7 (S) 8-9 (S) 14-15 (S) 15-16 (S) 27-28 (S)	6-7 (S) 8-9 (S) 14-15 (S) 16-17 (S) 27-28 (S)	5-6 (S) 7-8 (S) 11-12 (S) 15-16 (S) 24-28 (T)	5-6 (S) 7-8 (S) 11-12 (S) 16-17 (S) 24-28 (T)	5-6 (S) 7-8 (S) 11-12 (S) 17-32 (T) 24-28 (T)
Power loss(kW)	134.98	153.14	141.15	133.65	128.52	121.32	110.10
Node of lowest voltage	17	15	16	17	16	17	32
Lowest voltage (p.u)	0.9143	0.9222	0.9299	0.9335	0.9275	0.9317	0.9378

	SMG of the micro-grid						
	600 kW	700 kW	800 kW	900 kW	1000 kW	1100 kW	1200 kW
Switchers to be opened	5-6 (S) 7-8 (S) 11-12 (S) 9-10 (S) 24-28 (T)	5-6 (S) 7-8 (S) 11-12 (S) 11-21 (T) 24-28 (T)	5-6 (S) 7-8 (S) 8-9 (S) 30-31 (S) 24-28 (T)	5-6 (S) 7-8 (S) 8-9 (S) 30-31 (S) 24-28 (T)	5-6 (S) 7-8 (S) 11-21 (T) 30-31 (S) 24-28 (T)	5-6 (S) 7-8 (S) 11-21 (T) 30-31 (S) 24-28 (T)	5-6 (S) 7-8 (S) 11-21 (T) 29-30 (S) 24-28 (T)
Power loss(kW)	106.24	104.23	81.71	80.03	78.12	78.12	69.57
Node of lowest voltage	32	32	30	30	30	30	29
Lowest voltage (p.u)	0.9379	0.9380	0.9545	0.9545	0.9546	0.9546	0.9627

	SMG of the micro-grid						
	1300 kW	1400 kW	1500 kW	1600 kW	1700 kW		
Switchers to be opened	5-6 (S) 7-8 (S) 11-21 (T) 29-30 (S) 24-28 (T)	5-6 (S) 7-8 (S) 11-21 (T) 28-29 (S) 24-28 (T)	5-6 (S) 7-8 (S) 11-21 (T) 27-28 (S) 24-28 (T)	5-6 (S) 7-8 (S) 11-21 (T) 26-27 (S) 24-28 (T)	5-6 (S) 7-8 (S) 11-21 (T) 5-25 (S) 24-28 (T)		
Power loss(kW)	69.57	63.44	67.71	73.23	80.00		
Node of lowest voltage	29	29	28	26	25		
Lowest voltage (p.u)	0.9627	0.9616	0.9555	0.9488	0.9449		

* In Tab.1, if a switcher is marked by (T), it is a tie switcher, e.g. 11-21(T) means a tie switcher between node 11 and 21. If a switcher is marked by (S), it is a sectionalizing switcher, e.g. 5-6 (S) means a sectionalizing switcher between node 5 and 6.

Table 1. Reconfiguration results for IEEE 33-node system with a single micro-grid and different SMG values.

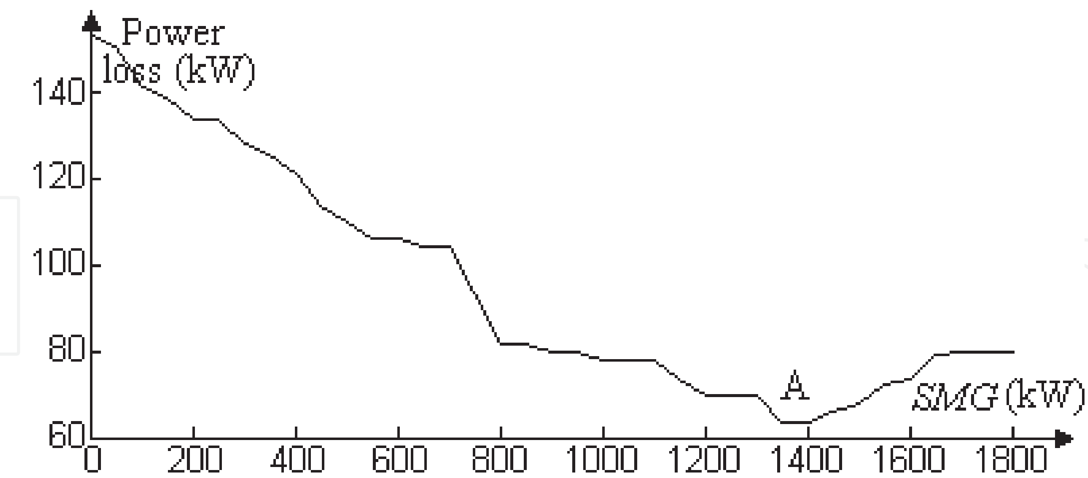

Fig. 5. Power loss changes with *SMG* (IEEE 33-node system)

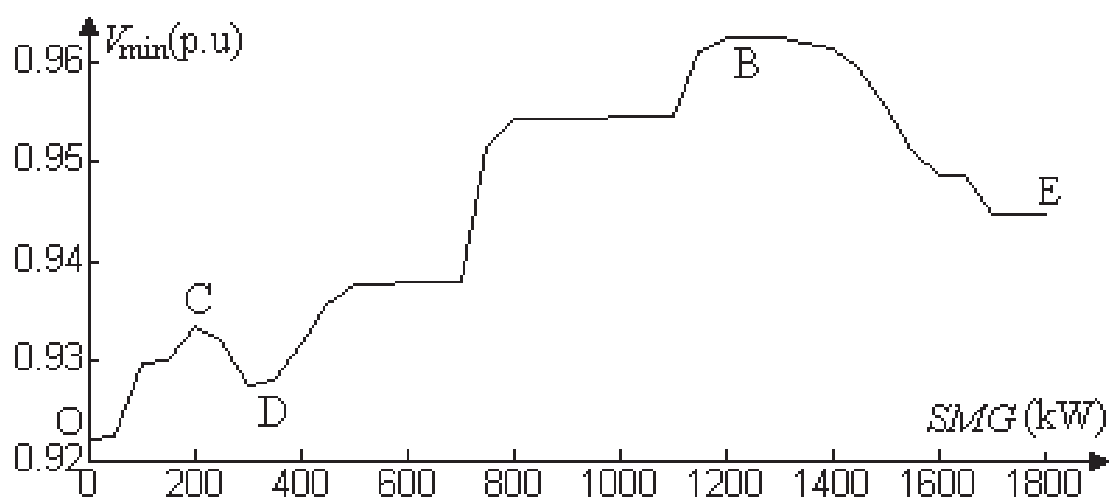

Fig. 6. Lowest voltage changes with *SMG* (IEEE 33-node system)

2. Power loss and lowest voltage (V_{min} in Fig.6) both change with the *SMG* value of micro-grid. For power loss, the minimum value occurs at point A in Fig.5 with (1400kW, 63.44kW), while the maximum value of V_{min} occurs at point B with (1200kW, 0.9627p.u.). It is very interesting that the *SMG* values of point A and point B are not equal.
3. Power loss and V_{min} both change with *SMG* nonlinearly. e.g. In Fig.6, when *SMG* increases in the interval of O-C and D-B, V_{min} also increases. While *SMG* increases in the interval of C-D and B-E, V_{min} decreases. For power loss, it is interesting that there is a minimum point at *SMG* =1400kW. When the *SMG* is less than 1400kW, the power loss decreases with *SMG* increasing. When *SMG* is larger than 1400kW, the power loss increases with *SMG* increasing.

4.2 PG&E 69-node system

PG&E 69-node system consists of 69 nodes, 5 tie lines all with tie switchers. All branches have sectionalizing switchers. Details of the system can be referred to (Baran & Wu, 1989, Chen et al, 2008; Yu et al, 2009). It is assumed that there is a micro-grid connecting to node 25. When a fault occurs, it causes branch 14-15 out of service. Using the presented method in section 3, we calculate the power loss and lowest voltage when *SMG* of the micro-grid changes. The result is shown in Tab.2, Fig.7 and Fig.8. Discussion to the result is similar to that of IEEE 33-node system, which is omitted here for simplification.

	Initial Condition	*SMG* of the micro-grid					
		0 kW	100 kW	200 kW	300 kW	400 kW	500 kW
Switchers to be opened	11-66(T) 13-21(T) 15-69(T) 27-54(T) 39-48(T)	11-66(T) 13-21(T) 14-15(S) 50-51(S) 47-48(S)	11-66(T) 21-22(S) 15-69(T) 27-54(T) 47-48(S)	11-66(T) 14-15(S) 18-19(S) 27-54(T) 47-48(S)	11-66(T) 13-21(T) 15-69(T) 27-54(T) 47-48(S)	11-66(T) 13-21(T) 15-69(T) 53-54(S) 47-48(S)	11-66(T) 13-21(T) 63-64(S) 53-54(S) 47-48(S)
Power loss(kW)	188.53	129.08	121.96	118.15	117.32	110.32	110.01
Node of lowest voltage	54	50	54	54	54	53	53
Lowest voltage (p.u)	0.9140	0.9236	0.9254	0.9261	0.9261	0.9297	0.9297

	SMG of the micro-grid						
	600 kW	700 kW	800 kW	900 kW	1000 kW	1100 kW	1200 kW
Switchers to be opened	11-66(T) 13-21(T) 3-59(S) 53-54(S) 47-48(S)	11-66(T) 13-21(T) 15-69(T) 52-53(S) 47-48(S)	11-66(T) 21-22(S) 15-69(T) 51-52(S) 47-48(S)	11-66(T) 14-15(S) 3-59(S) 50-51(S) 47-48(S)	11-66(T) 21-22(S) 3-59(S) 50-51(S) 47-48(S)	11-66(T) 14-15(S) 3-59(S) 50-51(S) 47-48(S)	11-66(T) 10-11(S) 67-68(S) 50-51(S) 47-48(S)
Power loss(kW)	109.60	83.77	83.78	83.80	83.80	83.81	84.81
Node of lowest voltage	53	52	51	50	50	50	50
Lowest voltage (p.u)	0.9297	0.9412	0.9416	0.9425	0.9425	0.9425	0.9426

Table 2. Reconfiguration results for PG&E 69-node system with a single micro-grid and different SMG values.

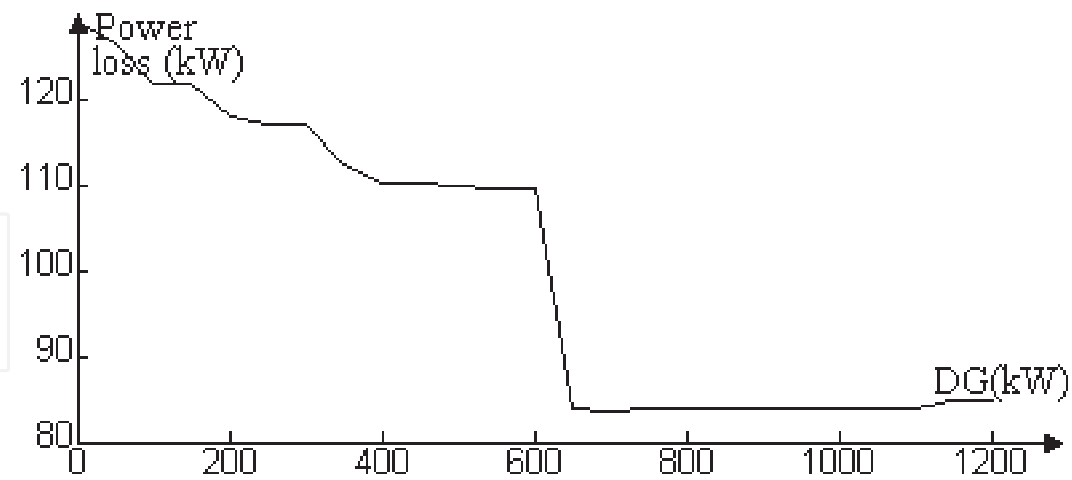

Fig. 7. Power loss changes with *SMG* (PG&E 69-node system)

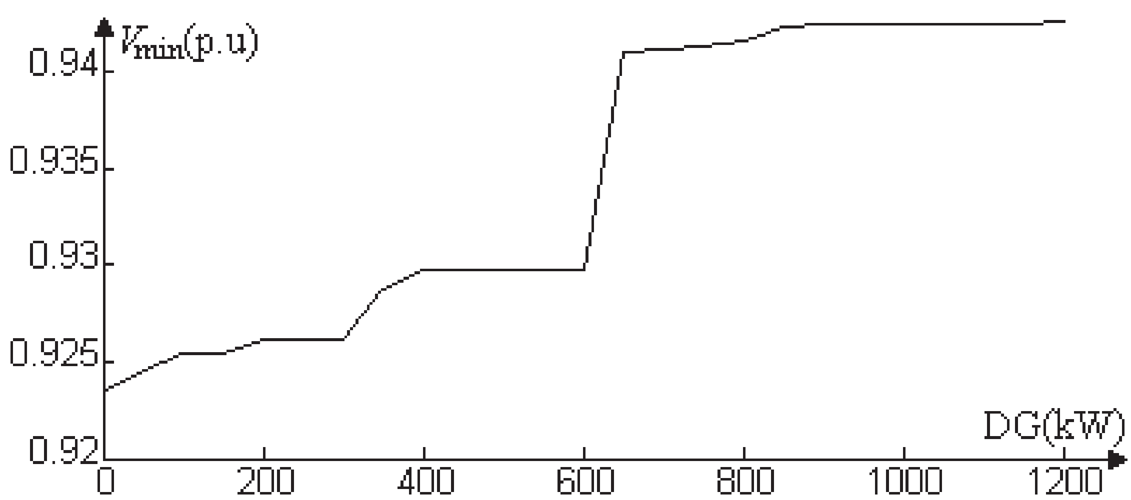

Fig. 8. Lowest voltage changes with *SMG* (PG&E 69-node system)

5. Conclusion

This chapter presents an optimal model for reconfiguration analysis of distribution system with micro-grids. Once a fault occurs in a distribution system, it can be applied to construct some optimal islands so as to guarantee power supplying to some important loads and to reduce power loss at the same time. The model is then decomposed into a capacity sub-problem and a reconfiguration sub-problem. The former is used to determine the optimal capacity for each island, and the latter is used to find the optimal reconfiguration with less power loss. Two sub-problems are called iteratively to get the optimization solution. Finally, IEEE 33-node system and PG&E 69-node system are employed to validate the effectiveness of the presented method. Studies of this chapter are helpful to find the optimal integration scheme for various DG devices connecting to distribution system in the future.

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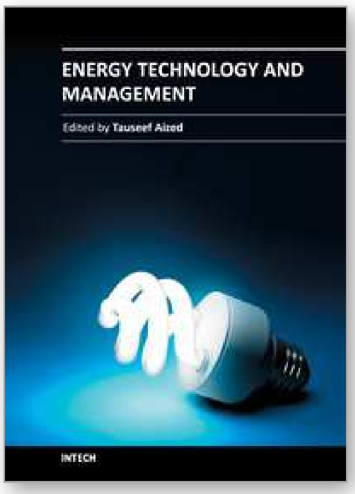

Energy Technology and Management
Edited by Prof. Tauseef Aized

ISBN 978-953-307-742-0
Hard cover, 228 pages
Publisher InTech
Published online 30, September, 2011
Published in print edition September, 2011

The civilization of present age is predominantly dependent on energy resources and their utilization. Almost every human activity in todayâ€™s life needs one or other form of energy. As worldâ€™s energy resources are not unlimited, it is extremely important to use energy efficiently. Both energy related technological issues and policy and planning paradigms are highly needed to effectively exploit and utilize energy resources. This book covers topics, ranging from technology to policy, relevant to efficient energy utilization. Those academic and practitioners who have background knowledge of energy issues can take benefit from this book.

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