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Spinning Reserve Based Topology Control in Holonic Distribution Grids

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SUMMARY

The evolution of smart grid concept requires rethinking of the current structure of distribution grids, as that is a key element to achieve the emerging functionalities that the smart grid can provide. An innovative idea in restructuring the distribution grids is to move towards a holonic architecture. Holonic distribution grids are highly flexible and structurally controllable grids that can promote the connectivity among the grid entities, such as prosumers and microgrids, to realize the highest reliability and resilience benefits. This paper investigates and discusses the holonic distribution grids and their importance in the future power systems, and further examines how the spinning reserve in microgrids can impact the connections among the integrated entities in holonic distribution grids. Numerical simulations conducted on a test system show the effectiveness of the holonic distribution grids in improving the customer- and system-level reliability.

KEYWORDS

Holonic distribution grid, provisional microgrids, distributed energy resource, islanding.

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1. INTRODUCTION

Microgrids are autonomous entities and one of the key enablers to fully realizing the potential of smart grids and producing a host of benefits, including enhanced grid reliability and resilience. Geographically-close microgrids can form an integrated microgrid system, or clustered microgrid and enhance the overall operational performance of the system by taking full advantage of local power exchange among microgrids [1]-[3]. In addition, integrated microgrids can broaden the merits of microgrids via increasing renewable energy resources penetration in distribution systems [4]-[6] and mitigating the congestion during peak hours by creating additional paths to supply local demand. While current centralized platform for operating distribution grids may not provide enough flexibility to transform into smarter grids, integrating microgrids is a strategic effort to accommodate emerging technologies and making smart choices in delivering electricity in a more reliable and sustainable manner.

A new concept for distribution power grids, called holonic distribution grids, has recently emerged and is projected to be significantly utilized in the future due to their capability in boosting the connectivity among autonomous entities [7]-[9]. Holonic distribution grids can potentially i) optimize the overall system performance through dynamic reconfiguration; ii) promote the diversity of resources, autonomy, and connectivity; iii) facilitate the information and energy exchange among the integrated systems; and iv) contribute to balancing the local customer and global system objectives. The holonic architecture is to some extent investigated and discussed in the literature. In [9] a generic architecture of smart grids is proposed based on the holarchy concept. The suggested architecture of the system involves various independent prosumers with a bottom-up organization in a recursive manner to form various aggregation layers that contribute in a dynamic system reconfiguration. The study in [10] proposes a holonic control architecture to address the smart grids control challenges for attaining global and local objectives at the macro- and micro-levels, respectively. A proof-of-concept implementation is exemplified to investigate the use of the proposed holonic architecture by integrating basic control solutions. The study in [11] presents a goal-based holonic multi-agent system to support the power distribution systems in operating as cyber-physical systems, and further provides details on its design and operation. In addition, it demonstrates the role of the holonic multi-agent system for two applications in power distribution systems including the control of the reactive power at solar PV installations and the system state estimation provided by residential smart meters. In [12] a holonic multi-agent system architecture is presented to control power distribution systems in an adaptive manner. The islanded operation of the distribution system in case of emergencies is further taken into consideration. In [13] a fractal model for power systems based on a holonic structure is presented enabling multiple aggregation layers while maintaining sufficient autonomy of systems. The study in [14] proposes an intelligent control strategy for renewable energy systems based on the holonic structure. In addition, a multi-criteria decision aid method is applied and identified. In [15] an optimal scheduling model of integrated microgrids in holonic distribution grids is proposed, enabling dynamic reconfiguration by determining the optimal connections among the microgrids aiming at enhancing the local and global benefits.

This paper discusses the holonic distribution grids and their role and importance in future power systems. In addition, it investigates the impact of the microgrids' spinning reserve on enabling the local power exchange, and hence its importance in improving the entire system reliability in case of emergencies, i.e. when the system is switched into an islanded mode of operation. The rest of the paper is organized as follows: The concept of holonic distribution grids is discussed in Section 2. The role and importance of spinning reserve in enabling the local power exchange is discussed in Section 3. Section 4 provides an illustrative study on the proposed system. Finally, the paper is concluded in Section 5.

2. HOLONIC DISTRIBUTION GRIDS – DEFINTION AND SIGNIFICANCE

The penetration of the distributed energy resources (DERs) is continuously growing in distribution systems [7], [9]. However, current distribution systems may not be able to adequately handle the new dynamics offered by the DERs, especially in case of high penetrations, which necessitate the transition into more dynamic and adaptive distribution networks. The concept of a holonic distribution grid is proposed to address such challenges and to create an intelligent environment for the next generation of smart grids. Holonic structure is based on a dynamic hierarchy concept of holons, where each holon represents a self-contained and autonomous system (e.g., a microgrid or a prosumer with decision-making capability). Nonetheless, each holon in a holonic distribution grid may be composed of several subsystems or can be part of other holons in the system, where this topology adapts for the benefit of the individual systems and the aggregated system of systems [7]-[10]. Connected holons in the system can create an aggregated holon called a super-holon. The provided topology by the holonic distribution grids can therefore be recognized as a hybrid between the centralized and distributed approaches, where the self-contained subsystems can be adapted within the holonic system autonomously and managed by a supervisory controller. Figure 1 shows a holonic distribution grid structure.

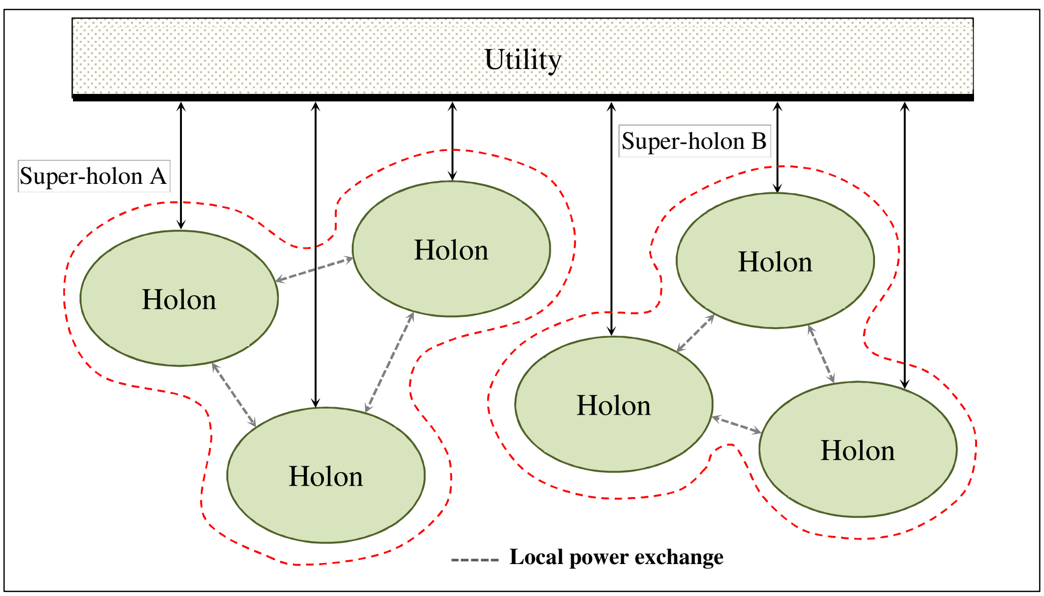

Figure 1. A holonic distribution grid structure

The holons in the holonic distribution grid can be dynamically reorganized or reconfigured to adapt themselves in an active environment. In addition, the holons can interact through cooperation and competition to create an intelligent setting that promotes local and global benefits [7], [15]. Hence, the holonic distribution grids would optimally identify the optimal connection or reconfiguration of the integrated microgrids that can enhance the individual and the entire system objectives.

3. SPINNING RESERVE – A KEY ELEMENT IN SUCCESSFUL IMPLEMENTATION OF HOLONIC DISTRIBUTION GRIDS

The spinning reserve capacity is a significant requirement to ensure power systems reliability without having to resort to undesirable supply-demand balance solutions such as load shedding. The spinning reserve is considered as an ancillary service that can provide the system with an immediate supply of power once a credible contingency takes place [16]-[18]. It supports the withstanding of the system towards the uncertainty of the non-dispatchable units' generation, the unforeseen increase in load, and the sudden outages. Therefore, preserving an appropriate amount of spinning reserve is fundamental in power systems operation. The spinning reserve requirement is typically set as a base component plus a fraction of the high operating limit of the largest committed unit or a fraction of the load in bulk energy systems. The spinning reserve requirement is defined as follows:

$$sr_{it} = \min\left\{10MSR_i, P_i^{\max} - P_{it}\right\} \tag{1}$$

$$0 \le sr_{it} \le 10MSR_i I_{it} \tag{2}$$

where sr_{it} is the spinning reserve requirement, MSR_i is the 10-minute maximum sustained rate, and $P^{\max}$ and P_{it} are the maximum capacity and current generation of the on-line unit i, respectively, at a specific operating period t. The binary variable I represents the commitment state of dispatchable units in the holon. In a super-holon, the aggregated and net spinning reserves can be defined and calculated as follows:

$$SR_h = \sum_{i \in H_h} sr_i \tag{3}$$

$$PD_h = \sum_{i \in H_h} pd_i \tag{4}$$

$$SR_h^N = SR_h - PD_h \ge 0 \tag{5}$$

where SR and PD are the total spinning reserve and power deficiency in the super-holon, respectively, index h refers to the super-holon, and H is the set of holons. The superscript N indicates the net spinning reserve in a super-holon. Positive net spinning reserve in a super-holon indicates that the load shedding in that super-holon is zero, while a negative value shows that there is no adequate generation capacity to fully supply loads within the super-holon.

Increasing the spinning reserve requirement can significantly reduce the potential of load shedding. However, it would increase the system total cost due to the need for committing additional units. Therefore, the spinning reserve requirement is determined based on a tradeoff between the economics and the reliability objectives [16], [19]. Although the spinning reserve could help improve reliability, it could further offer additional intelligent paths to improve the economic benefits by exploiting those unused capacities.

4. ILLUSTRATIVE STUDY

A holonic distribution grid with five microgrids is used to demonstrate the impact of the microgrids' spinning reserve on enabling the local power exchange among the integrated players, and consequently enhancing the player-specific and system-wide reliability and economic benefits. These microgrids include two typical microgrids (named Microgrid 1 and Microgrid 2) and three provisional microgrids (named Provisional Microgrids 1, 2, and 3). Provisional microgrids are elevated prosumers, as described in [4], [6]. Similar to microgrids, provisional microgrids have clearly defined electrical boundaries and a master controller to manage available resources. However, provisional microgrids do not have the ability to be islanded on their own and are dependent on one or more electrically connected microgrids for switching to an islanded mode.

The initial spinning reserve and unmet power in each holon (microgrid or provisional microgrid) in the holonic distribution grid are provided in Figure 2 for a given operating hour. Those unused capacities provided by the microgrids' spinning reserve and the additional requirement of power in the provisional microgrids create a motivated environment for the power exchange among the players for mutual benefits. Since the investigated holonic distribution grid contains five holons, several rational combinations (i.e., super-holons) can be created within the holonic distribution grid. Figure 3 shows six different super-holons combinations and further shows the net spinning reserve of the super-holons once they are created. Even though several super-holon solutions can be generated in the holonic distribution grid, the optimal topology would be the one that best matches spinning reserve to deficient load, i.e., a minimum net spinning reserve solution. In the created six examples, in Figure 3(a), provisional microgrid 3 experiences a load curtailment of 0.8 MW; in Figure 3(b) either provisional microgrid 2 or 3 would experience a load curtailment of 0.3 MW; in Figure 3(c) none of the provisional microgrids would face load curtailment since the spinning reserve in these two super-holons is equal to their power deficiency; in Figure 3(d) provisional microgrid 1 experiences a load curtailment of 1 MW; in Figure 3(e) provisional microgrid 3 experiences a load curtailment of 0.8 MW; and in Figure 3(f) provisional microgrid 2 experiences a load curtailment of 0.5 MW.

Based on the discussion and demonstrated figures, the combination in Figure 3(c) seems to be the most desirable solution as (1) microgrids can fully use their unused capacity and benefit from selling power to provisional microgrids in the islanded mode, and (2) provisional microgrids can fully supply their local load through power exchange with microgrids in their super-holon, thus reducing load curtailment and increasing their reliability.

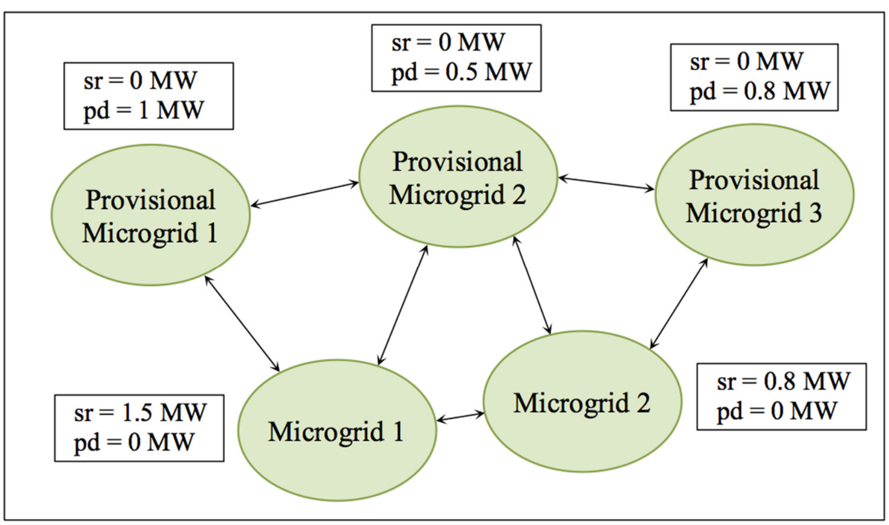

Figure 2. Spinning reserve and power deficient in each holons in the holonic distribution grid

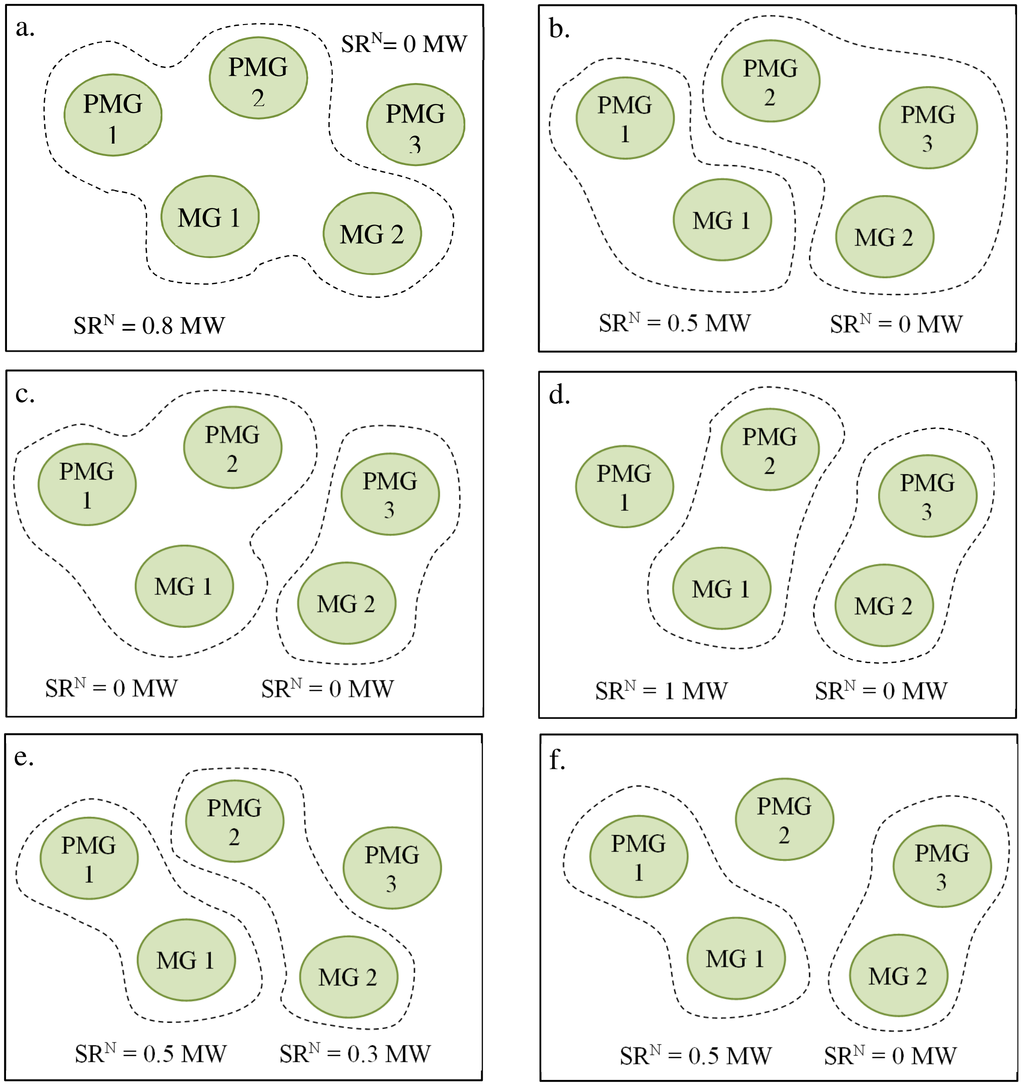

Figure 3. Different super-holons reconfigurations.

5. CONCLUSION

Holonic distribution grids promote the systemic features of diversity, autonomy, and connectivity in the system, and further boost local and global objectives through identifying the optimal distribution network reconfiguration and proper connection of autonomous entities. This concept was investigated in this paper, and the microgrids' spinning reserve impact on the local power exchange in holonic distribution grids was further discussed. An illustrative study was implemented to show the impact of optimal system reconfiguration and the microgrids' spinning reserve on enabling the optimal local power exchange, and therefore improving the entire system reliability and economic objectives. The results and conclusions in this study can be extended to develop an optimization problem that can determine the optimal system topology without the need for examining all possible combinations. The objective function of such optimization problem would be to minimize the aggregated net spinning reserve in super-holons within the distribution grid.

BIBLIOGRAPHY

[1] N. Hatziargyriou, H. Asano, M. R. Iravani, and C. Marnay, “Microgrids: An overview of ongoing research, development and demonstration projects” (IEEE Power Energy Mag., vol. 5, no. 4, pp. 78–94, Jul./Aug. 2007).

[2] M. Shahidehpour and J. Clair, “A functional microgrid for enhancing reliability, sustainability, and energy efficiency” (Electricity Journal, vol. 25, no. 8, Oct. 2012, pp. 21-28).

[3] A. Albaker, A. Majzoobi, G. Zhao, J. Zhang, and A. Khodaei, “Privacy-preserving optimal scheduling of integrated microgrids,” (Elsevier Electric Power Systems Research, 163, pp. 164-173, 2018).

[4] A. Khodaei, “Provisional microgrids” (IEEE Transactions on Smart Grid, vol. 6, no. 3, pages 1107–1115, May 2015).

[5] I. Bae and J. Kim, “Reliability evaluation of customers in a microgrid” (IEEE Transactions on Power Systems, vol. 23, no. 3, pages 1416–1422, Aug. 2008).

[6] A. Albaker and A. Khodaei, “Elevating prosumers to provisional microgrids” (IEEE PES General Meeting, Chicago, IL, 16-20 Jul. 2017).

[7] S. Howell, Y. Rezgui, J. L. Hippolyte, B. Jayan, and H. Li, “Towards the next generation of smart grids: Semantic and holonic multi-agent management of distributed energy resources,” (Renewable and Sustainable Energy Reviews, 77, pp. 193-214, 2017).

[8] A. Ferreira, Â. Ferreira, O. Cardin, and P. Leitão, “Extension of holonic paradigm to smart grids,” (IFAC-PapersOnLine, vol. 48, no. 3, pp. 1099-1104, 2015).

[9] E. Negeri, N. Baken, and M. Popov, “Holonic architecture of the smart grid,” (Smart Grid and Renewable Energy, vol. 4, no. 2, p.p 202, 2013).

[10] S. Frey, A. Diaconescu, D. Menga, and I. Demeure, “A holonic control architecture for a heterogeneous multi-objective smart micro-grid,” (IEEE Self-Adaptive and Self-Organizing Systems (SASO), Sept. 2013).

[11] A. Pahwa, S. A. DeLoach, B. Natarajan, S. Das, A. R. Malekpour, S. S. Alam, and D. M. Case, “Goal-based holonic multiagent system for operation of power distribution systems,” (IEEE Trans. on Smart Grid, vol. 6, no. 5, pp. 2510-2518, Sep. 2015).

[12] A. Pahwa, S. A. DeLoach, S. Das, B. Natarajan, X. Ou, D. Andresen, N. Schulz, and G. Singh, “Holonic multi-agent control of power distribution systems of the future,” (Grid of the Future Symposium (CIGRE), 2012).

[13] G. Florea, O. Chenaru, R. Dobrescu, and D. Popescu, “A fractal model for power smart grids.” (IEEE 20th International Conference on Control Systems and Computer Science (CSCS), pp. 572-577, May 2015).

[14] F. Ounnar, A. Naamane, P. Pujo, and N. K. M'Sirdi, “Intelligent control of renewable holonic energy systems,” (Energy Procedia, vol. 42, pp. 465-472, 2013).

[15] A. Albaker and A. Khodaei, “Optimal scheduling of integrated microgrids in holonic distribution grids,” (IEEE North American Power Symposium (NAPS), Fargo, ND, USA, 2018).

[16] M. Q. Wang, and H. B. Gooi, “Spinning reserve estimation in microgrids,” (IEEE Transmission & Distribution Conference & Exposition: Asia and Pacific, pp.1-4, Oct. 2009).

[17] S. Lou, S. Lu, Y. Wu, and D. S. Kirschen, “Optimizing spinning reserve requirement of power system with carbon capture plants,” (IEEE Transactions on Power Systems, vol. 30, no. 2, pp. 1056-1063, Mar. 2015).

[18] M. Amirahmadi and N. Boroomand, “Energy and spinning reserve markets scheduling considering interruptible load and demand-side reserve,” (IEEE Power and Energy International Conference (PECon), pp. 384-389, Nov. 2016).

[19] C. Poomahapinyo and S. Chaitusaney, “Impact of renewable energy on spinning reserve based on economic dispatch,” (IEEE Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology Conference (ECTI-CON), pp. 357-360, June 2017).