Applied Energy xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Enabling resilient distributed power sharing in networked microgrids through software defined networking

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HIGHLIGHTS

- An SDN-enabled control and communication architecture is established for NMGs.
- A resilient distributed power sharing control strategy is devised for NMGs.
- Novel event-triggered communication is deployed through an SDN architecture.
- A cyber-physical HIL testbed is built to validate NMGs' control and communication strategies.

ARTICLE INFO

Article history:
Received 31 March 2017
Received in revised form 22 May 2017
Accepted 7 June 2017
Available online xxxx

Keywords:
Networked microgrids
Software-defined networking
Event-triggered communication
Distributed power sharing

ABSTRACT

Networked Microgrids (NMGs) offer a new, more resilient alternative to traditional individual Microgrids (MGs). Even though networking existing microgrids presents clear advantages, the scalable and resilient communication and control infrastructure necessary for supporting this innovation does not yet exist. This paper addresses this challenge by developing a Software-Defined Networking (SDN) enabled architecture that can achieve fast power support among microgrids, transforming isolated local microgrids into integrated NMGs capable of achieving the desired resiliency, elasticity and efficiency. Equipped with a novel event-triggered communication scheme, the SDN-based architecture enables distributed power sharing among microgrids in both the transient period and the steady state, a capability that is unattainable using existing technologies. Extensive experiments on a cyber-physical Hardware-in-the-Loop (HIL) NMGs testbed have validated the effectiveness and efficiency of the SDN-enabled distributed power sharing method.

1. Introduction

A microgrid normally refers to a localized autonomous distribution network designed to supply electrical and heat loads for a local community (e.g., a university campus [1], a commercial building [2] or a residential area [3]). It can be connected with the main grid (*grid connected mode*) or isolated during main grid emergencies (*islanded mode*). Because microgrids offer the following benefits, they have attracted increased interest in the last few years: they enable integration and coordination of renewable energy resources; they enhance the resilience of electrical system for customers; and they reduce economic and emission costs [4]. These benefits are particularly important given the rapid development of power electronics technologies as well as primary, secondary and tertiary control techniques in recent years [5].

The swift growth of microgrid research and development are leading to increased penetration of microgrids [6]. For instance, in urban areas where populations and critical loads are concentrated, microgrids are being increasingly deployed. A smart city (or smart and connected communities) zone is expected to have many microgrids operated by various stakeholders. It is therefore natural to ask whether coordinated networked microgrids can offer a more resilient system than individual microgrids. Indeed, our preliminary research [7] shows that, when local microgrids are networked, this not only enables faster distribution grid recovery during a main grid blackout but also significantly improves the system's day-to-day reliability. In fact, the U.S. Department of Energy

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http://dx.doi.org/10.1016/j.apenergy.2017.06.006
0306-2619/

Please cite this article in press as: Ren L et al. Enabling resilient distributed power sharing in networked microgrids through software defined networking. Appl Energy (2017), http://dx.doi.org/10.1016/j.apenergy.2017.06.006

Nomenclature

Acronyms

NMGs	networked microgrids
MG	microgrid
SDN	software-defined networking
HIL	hardware-in-the-loop
DG	distributed generator
ACA	average consensus algorithm
LC	local controller
PCC	point of common coupling
DAPI	distributed-averaging proportional-integral
VM	virtual machine
VSC	voltage source converter
PWM	pulse-width modulation
K-NN	K-nearest neighbors

Indices

i	index for MGs
j	index for DGs
l	index for neighboring DGs
k	index for neighboring MGs

Sets

$\mathscr{V}$	set of MGs
$\mathscr{V}_i$	set of DGs in the ith MG
$\mathscr{L}_j$	Set of neighboring DGs of the jth DG
$\mathscr{K}_i$	Set of neighboring MGs of the ith MG

anticipates that researching and developing of networked microgrids will usher in the next wave of smart grid technology. This innovative approach promises to meaningfully modernize the nation's grid system in response to issues such as climate change and the need for greater grid resilience [8].

Though networking existing microgrids offers a number of advantages, there is one major challenge that has not been addressed: a scalable and resilient communication and control infrastructure does not yet exist. Furthermore, given the standardized control architecture of individual microgrids (e.g., droop control, secondary control), it is highly desirable to establish a network-level control architecture that does not significantly modify the communication and control layers in individual microgrids. This paper aims to address these challenges by developing an SDN-enabled architecture that can readily network microgrids at the cyber layer in a simple and economically efficient way, transforming isolated local microgrids into integrated smart microgrids capable of achieving the desired resiliency, elasticity and efficiency. In particular, this novel method will enable a provably correct and previously unattainable distributed power sharing among microgrids in both the transient period and the steady state.

Related work: Networked microgrids, or coupling microgrids, can be defined as a cluster of microgrids interconnected in close electrical or spatial proximity with coordinated energy management and interactive support and exchange. Recently, the feasibility of coupling microgrids through common AC buses [9], utility feeders [10] and DC links [11] has been discussed. Ref. [12] presents a power dispatch strategy for maintaining islanded microgrids' power balances through microgrid generation reallocation triggered by power deficiency events. Ref. [13] presents the use of networked microgrids to improve the self-healing of the distribution network under power outages, where microgrids are designed to pick up external loads with minimum switch operations. Further, an economic dispatch strategy for networked microgrids is developed [14], where the surplus capacities in individual microgrids are aggregated to fulfill the power requirements. Apart from facilitating power system restoration, networked microgrids can also participate in global frequency regulation by providing extra frequency control reserves [15]. The interaction between the distribution network operator and local microgrids has also been investigated [16,17]. These studies focus on the longer-term coordination of interconnected microgrids at a time scale of minutes, hours or longer. In the real world, however, microgrids usually have low inertia and intermittent renewable generation. Thus, it is critically important to ensure fast power sharing while maintaining transient stability in networked microgrids. In order to adequately control such a complex system, a high-speed, resilient cyber infrastructure is indispensable, but this remains an open challenge.

In networked microgrids, one of the most important functions is to share power demands among the networked Distributed Generators (DGs). Power sharing in a single microgrid is achieved in tandem with voltage and frequency recovery either in a centralized or a distributed way [18,19]. The latter has been attracting more attentions in recent years due to the potential benefits of avoiding the single point of failure and reducing communication overhead [20,21]. In [22], a distributed control requiring only local communication is presented, which is capable of achieving proportional active power sharing and frequency restoration. This paper also identifies the conflict between voltage control and reactive power sharing for DG units with a droop-based primary control. An alternative approach for fast voltage recovery without considering reactive power sharing is developed in [23]. Among various distributed power sharing schemes, the Average Consensus Algorithm (ACA) is a popular choice for solving the problem in a fully distributed fashion. ACA, however, can compromise network resilience by requiring continuous intensive data transmissions which may cause bandwidth shortage, congestion, and processor overuse. Moreover, there is a lack of distributed power sharing schemes for networked microgrids in the existing literature.

Our contributions: To enable resilient networked microgrids and close the aforementioned gaps, we are introducing a novel SDN-based cyber architecture with a distributed event-triggered communication scheme. The authors have pioneered the use of SDN in enabling resilient microgrids [24] by devising a novel SDN-based cyber architecture for individual microgrids and developing SDN functions such as delay management, automatic failover, and traffic prioritization. The unprecedented flexibility and dynamic programmability of SDN [25–27] supports on-the-fly network updates and enables the interoperability of local microgrids. Therefore, the SDN-based architecture in [24] is further expanded to enable networked microgrids. We also integrate the event-triggered communication in the SDN-based communication architecture such that a microgrid only shares information with its neighbors when the specific states exceed predefined thresholds. Recent research into networked control systems has mathematically proven the effectiveness of the event-triggered communication in enabling more efficient and robust ACAs [28–30]. This paper makes three main contributions:

- It devises a layered cyber and control architecture that supports the plug-and-play of networked microgrids. The local layer includes the primary and secondary controllers within individual microgrids while the global layer is responsible for the