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A Novel Cloud-Based Platform for Implementation of Oblivious Power Routing for Clusters of Microgrids

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ABSTRACT There has been an increasing demand for connectivity of the clusters of microgrids to increase their flexibility and security. This paper presents a framework for implementation, simulation, and evaluation of a novel power routing algorithm for clusters of microgrids. The presumed cluster is composed of multiple direct current (dc) microgrids connected together through multi-terminal dc system in a meshed network. In this structure, the energy is redirected from the microgrid with excessive power generation capacity to the microgrid which has power shortage to supply its internal loads. The key contribution of this paper is that each microgrid in the cluster is unaware of the current state and other flows of the cluster. In this approach, the optimal power flow problem is solved for the system while managing congestion and mitigating power losses. The proposed methodology works for both radial and non-radial networks regardless of the network topology, scale, and number of microgrids involved in the cluster. Therefore, it is also well suited for large-scale optimal power routing problems that will emerge in the future clusters of microgrids. The effectiveness of the proposed algorithm is verified by MATLAB simulation. We also present a comprehensive cloud-based platform for further implementation of the proposed algorithm on the OPAL-RT real-time digital simulation system. The communication paths between the microgrids and the cloud environment can be emulated by OMNeT++.

INDEX TERMS Clusters of microgrids, cloud computing, congestion management, oblivious network design, optimal power routing, real-time simulation platform.

I. INTRODUCTION

A. MOTIVATION

Smart microgrids can be defined as a new generation of smart power networks that incorporate actions from all connected end-users. Many researchers have investigated different aspects of microgrids, including their penetration into electric power system, integration issues of distributed energy resources (DERs), role of power electronics, stability and reliability of microgrids [1]–[10]. Although all of these investigations and their associated models are very useful in understanding the performance and operation of the system, little or no efforts have been done in co-simulation of the communication network and power systems. The communication platform is an essential factor, which is unexploited in most of researches in the areas related to microgrids, such as [2]. The role of information and communication technology (ICT) and the required infrastructures in the future power systems simulation is investigated in [11].

In [3], a comprehensive energy management system for off-grid and on-grid microgrids is described. The proposed approach is very competent when the power system under test is operating in steady state mode. However, disregarding the transient response of power systems may lead to the instability and cascading failures of the network. In an efficient energy management system, there is a bidirectional flow of data between the DERs. Therefore, communication delays added to the transient conditions may deteriorate the stability margin of the network in the transient period. In [4]–[6], a state-of-the-art planning method is proposed for AC and DC microgrids. This method investigates the economic viability of microgrids deployment and optimal generation of DERs. Khodaei *et al.* [6], addressed the microgrid planning under uncertainty. The cooperative control of power electronics converters within a power network consisting of several microgrids and sub-grids is investigated in [7]–[9]. The proposed algorithms can provide a robust optimization approach for the planning and operation of the old fashioned AC and DC microgrids. However, the advent of cloud computing has brought the networking and optimization principals to the next era, which is a highly integrated centralized controllers within a microgrids or amongst multiple interconnected microgrids in a cluster.

There has been an increasing demand for connectivity of the microgrids to establish a secure cluster of power networks. The idea of self-sustaining energy islands that can stay on even during grid-wide blackouts is of obvious value to entities and consumers that cannot let power outages keep them from performing their missions. In a typical microgrid system, two main types of uncertainty affect the reliable and secure operation: outage of the generation units and deviation from the forecasts [12], [13]. The outage of generation units can lead to a supply shortage in system, which is usually met from both spinning and non-spinning operating reserves. Departures from the forecasts resulting from uncertain loads and the integration of intermittent sources of energy, i.e. DERs introduce additional operational uncertainty. Wind and solar generation depend on wind speed and solar irradiance, respectively, which are difficult to predict accurately. Indeed, the effects of the uncertainty associated with wind and solar generation are more significant in microgrids due to the high penetration levels of such resources and typically small intertia. There are numerous reports of a variety of methods that take into account the uncertainties arising from load, wind, and solar power forecasting errors [13]–[15]. These uncertainties may lead to partial or overal blackout in the migrogrid system. In order to provide more resilience to such uncertainties, the promotion of the clusters of several interconnected microgrids are becoming more popular [16]. The new concept of cluster of microgrids introduced based on the idea of accommodating the excesses and shortfalls of power between *prosumers* (producers and consumers), which enable the system to be able to accept more than 50% of required power from renewable energy without system stabilization and defines a highly secure system that is independent from blackouts.

Since the microgrids can act as both demand side and generator side, power flows among them can be significant. Therefore, the cluster of microgrids may face power congestion issue in some transmission lines connecting microgrids. As a result, it is critical to design power routing algorithms which prevent or mitigate power congestion in clusters of microgrids. To this end, there are some studies such as [17]–[19] which have proposed different congestion management techniques.

B. RELATED WORK

A smart power system requires modern monitoring, analysis and control to deliver the electricity in a more reliable, economical, and sustainable way. Advent of the phasor measurement units (PMUs) and modern supervisory control and data acquisition (SCADA) systems resolved some of the conventional issues related to the monitoring and control of the smart grids. However, without a seamless communication technology, operators (computerized or hand-operated) cannot get an insight in the current grid states and use the monitored data to operate the system effectively [26]. Therefore, there is a need to analyze the performance of the proposed communication algorithm. However, due to multiple types of latency in the communication links, simulation should be considered as an exigent tool to give a realistic insight to the performance of the system. OMNeT++ is a discrete event simulator for modeling the communication network and distributed systems that can be used for modeling and testing the wide-area communication protocols, where the data propagation delays become significant. OMNeT++ was initially introduced in [27] and [28] as a design tool for wired and wireless networks of computer clusters, telecommunications and distributed/parallel systems. OMNeT++ have been used by many researchers to simulate different events on the smart grid [29]. In [30], OMNeT++ has been used to simulate the cyber layer of the smart grid. In [31] and [32], a methodology for co-simulation of OMNeT++ and OpenDSS (electric power Distribution System Simulator) has been proposed, in which OMNeT++ and OpenDSS are running in parallel and the events are synchronized at certain time slots. The authors in [33] have utilized the OMNeT++ to analyze the measurements from a real testbed. NREL (National Renewable Energy Laboratory) have utilized OMNeT++ as a network simulator-in-the-loop, which simulates the network and links with real computers and virtual hosts [34]. OMNeT++ platform was later used in [35]–[41] to model and simulate their proposed communication protocols. This helps to ensure the proposed methodology can be utilized in the real world applications.

The key components of microgrid include loads, distributed energy resources, master controller, smart switches, and protective devices. Furthermore, communication networks, control and automation systems play a pivotal role in microgrid operation [1]. In our application, due to the fact that the microgrids within a same cluster may be located hundreds of meters away from each other, the instant communication between the nodes (microgrids) is required to ensure seamless power flow between the nodes. Therefore, OMNeT++ is used to check on the practicality of our proposed method. The schematic view of the clusters of microgrids along with the cloud environment is depicted in Fig. 1.

Economic Dispatch (ED) is one of the most studied optimization problems in power systems and microgrids operation [20]–[25]. The goal of ED is to obtain the efficient scheduling of the clusters of microgrids. Furthermore, in large-scale power systems, we need to deal with the unit commitment (UC) problem which is solved on a day-ahead basis. In this context, ED is normally solved at each hour using the results of UC as the main input [42], [43]. The non-convex ED problem is solved utilizing a novel particle swarm

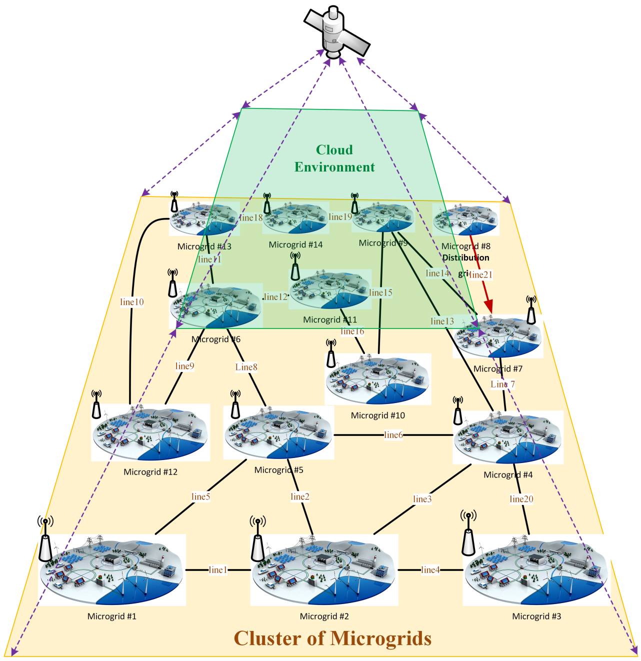

FIGURE 1. Schematic view of the interconnected clusters of microgrids which communicate along with a cloud environment.

optimization proposed by [44]. Amini *et al.* [45] proposed a load manamgement scheme for the smart distribution networks. A graph-based modeling of the power flow problem is introduced in [46]. Several studies explored ED problems [47]–[51]. Boroojeni et al. [47] present a novel oblivious routing economic dispatch ($\mathcal{ORED}$) algorithm for power systems. According to [47], $\mathcal{ORED}$ is the first ED algorithm built based on oblivious network design which is the most fit for networks with oblivious sources and destinations while they are unaware of the current network state and other flows. In our study, every microgrid can either send (source) or receive (destination) power through the available DC lines. In [48] and [49], a Mixed Integer Linear Programming (MILP) is employed in order to solve the ED problem. A demand dispatch in a large penetration of wind power is proposed by Botterud *et al.* [50]. The effect of high penetration of energy storage units under ED problem was investigated in [51]. Liu *et al.* [53] proposed a two-tier pricing scheme for electricity trading between the agents which are responsible for renewable power resources. They also considered both defferable and non-defferable load demands in their optimization problems.

Oblivious Network Routing Design: Despite the traditional Minimum Cost Flow Problems (MCFPs) that are defined with a specific set of commodities (with given source, sink, and size) and pre-defined flow cost in each edge as a function of the flow size in that edge, oblivious network routing design solves a set of MCFP problems in which at-least one of the following conditions hold:

- Source, sink, or size of the commodities are not specified in advance, i.e. there is neither deterministic nor stochastic information regarding the commodities of the problem which are going to be routed through the network. In such circumstances, the MCFP is referred to as *commodity oblivious* [55].
- The cost of flowing commodities in an edge cannot be defined as a deterministic or stochastic function of the flow size in the same edge. In such circumstances, the MCFP is referred to as *flow cost oblivious* [56].

Oblivious routing design provides routing solution to the oblivious MCFPs so that the resulting routing scheme is flexible to the obliviousness of the commodities and flow cost functions. Also, oblivious routing schemes mitigate traffic congestion in small subgraphs of the network by distributing the flow throughout the network. These types of routing schemes provide a low-cost flow routing in long term despite the fact that some elements of the MCFP are not defined either deterministically or stochastically. In other words, oblivious routing design is most suited for the networks in which we have little/no knowledge regarding their current and future states [55]. Therefore, it goes well in line with the microgrid concept, as they are largely independent entities by definition.

Oblivious network routing is considered as a heuristic method as it is utilized to expedite the process of finding a sufficiently low-cost solution for the MCFPs with oblivious elements. In fact, since computing the global optimal solution is too complex to be done practically, oblivious network routing design finds a satisfactory solution for the oblivious MCFPs by deploying a practical means not guaranteed to be globally-optimum, but satisfactory enough for achieving immediate goal of finding a near-optimum approximation of the best solution.

Oblivious network routing is different from Adaptive Routing (AR) as AR responds to any change in the unknown elements of the MCFP by recalculating the solution and possibly providing different solution than the one calculated initially. However, oblivious routing employs a single routing scheme for a wide range of obliviousness in the MCFP in order to sufficiently approximate the best solution of the oblivious MCFP [55]. As a result, in highly oblivious circumstances where AR is not computationally-feasible, oblivious routing can solve the MCFP with much less time complexity.

Since prior art research concerning multiple microgrid clusters has by now been carried out only on conceptual level, interaction of communication interference in microgrids is an important direction for future research. To that end, only the most basic low level control functionalities such as DC link voltage regulation and power flow exchange have been investigated [57]. While this approach provides an invaluable base for further research, it also neglects many practical limitations that may occur in the real world. For instance, it considers only a limited number of DC buses and the power exchange among them is designed to equalized states of charge of local energy storage systems (ESSes). Moreover, the connection of the microgrid cluster to the overhead power system is not considered [58]. In the actual physical system, this might not hold as the future power systems are predicted to be comprised of high number of microgrids which are required to exchange energy among themselves. This exchange of energy makes the overhead system subject to many other metrics. For instance, realistic microgrids cannot be considered to comprise a single ESS but a number of prosumers which can actively complement with ESS [59], [60]. Therefore, state of available energy within the particular microgrids is deemed as more realistic metric than a simple State of Energy (SOE) [61].

C. OUR CONTRIBUTION

This paper presents a novel cloud-based approach for solving optimal power routing problem in clusters of DC microgrids, utilizing oblivious network routing design. The presumed cluster is composed of multiple DC-microgrids connected together through multi-terminal DC (MTDC) system in a meshed network. In this methodology, the energy is redirected from the microgrid with excessive power generation (high state of energy) capacity to the microgrid which has power shortage to supply the internal loads. The key contribution of this work is that all of the microgrids in the cluster are unaware of the current cluster state and other flows, i.e. each microgrid optimized its operation. This approach solves the optimal power flow problem, while managing congestion and mitigating power losses. The proposed methodology works for both radial and non-radial networks regardless of the network topology, scale and number of microgrids involved in the cluster. Therefore, it is well-suited for the large-scale economic dispatch problems that will emerge in the future smart distribution grids. The effectiveness of the proposed algorithm has been verified in MATLAB simulation as well as OPAL-RT real-time digital simulation (RTDS) system. The communication path between the microgrids are implemented on a cloud-based environment emulated by OMNeT++. The results verify the superior performance of the proposed method over the current methods in the literature in terms of congestion management and power loss minimization.

D. ORGANIZATION OF THE PAPER

The rest of the paper is organized as follows. Section II specifies the general overview of the proposed framework. Section III explains how oblivious network design can be utilized in order to solve the optimal power routing problem for clusters of microgrids. Section IV introduces RTDS as a powerful real-time digital power system simulator and addresses how it helps in the process of developing the proposed approach. Section V states the model of the cloud environment in which the proposed method works properly. In Section VI, OMNeT++ is introduced as an effective means for simulating modern communication enabled by several networking protocols. Finally, we present the summary and conclusion of our paper in Section VII.

II. GENERAL OVERVIEW OF THE PROPOSED FRAMEWORK

Here, we provide the schematic view of microgrid and it corresponding cloud system for the communication. As Fig. 2 illustrates, we classify the elements of our proposed system into two layers: power network layer and communication network layer. In the first layer, we aim to solve the optimal power routing problem for the clusters of microgrids utilizing an oblivious routing scheme provided by the communication layer. In the communication layer, every microgrid is able to communicate with the cloud environment and send a snapshot of its energy level to the cloud. This communication is performed through the conventional TCP/IP computer network as a subnet of the Internet. After receiving the energy level information of every microgrid, the cloud server utilizes Hadoop and an appropriate oblivious routing algorithm (to be discussed later) in order to obtain an efficient routing scheme which solves the problem of optimal power routing for clusters of microgrids.

III. THE PROPOSED POWER ROUTING METHOD ON CLUSTERS OF MICROGRIDS

A. PRELIMINARIES TO OBLIVIOUS NETWORK DESIGN

First, we explain some basic definitions, assumptions and preliminary data structures needed to construct the oblivious routing scheme, which is responsible for power routing in clusters of microgrids. Assuming that M denotes the set of microgrids and L represents the set of DC power lines connecting neighboringmicrogrids, we model the topology of the clusters of microgrids utilizing the graph (M, L) of vertex set M and edge set L. Additionally, since every line may have different physical characteristics (in general case), we consider a weighted graph (M, L, w) to formulate the clusters of microgrids, where for every line $l \in L$ connecting the couple of neighboringmicrogrids m_1 and m_2, $w_l \in \mathbb{R}^+$ is linearly proportional to the amount of power loss flowing from m_1 to m_2 (we address the detailed loss model later in this section). In the rest of the paper, we consider (M, L, w) as a weighted graph of diameter[1] 2^n (for some integer n) where $w_l > 1$ for every $l \in L$. The mentioned conditions on the graph diameter and its weight function don't reduce the generality of our model because any weighted connected graph can be converted to (M, L, w) by linearly scaling its weight function.

Let $\bar{\mathcal{S}}$ denote the microgrid sequence $\bar{\mathcal{S}} = (\mathcal{S}_0, \mathcal{S}_1, \ldots, \mathcal{S}_n)$, where $\mathcal{S}_n = \{M\}$, and for every i less than n, $\mathcal{S}_i$ is a 2^i-partition,[2] and for every $i = 0, 1, \ldots, n-1$, if microgrid set $\mathcal{M}$ belongs to $\mathcal{S}_i$, there exists some set $\mathcal{M}' \in \mathcal{S}_{i+1}$ such that $\mathcal{M} \subseteq \mathcal{M}'$. Microgrid set $\mathcal{S}_i$ is called the i^{th} member of sequence $\bar{\mathcal{S}}$. Microgrid v is called α-padded in $\bar{\mathcal{S}}$ $(0 < \alpha < 1)$ if for every i, the i^{th} microgrid partition $\mathcal{S}_i$ contains a subset of microgrids $\mathcal{S}$ such that $\mathcal{S}$ completely covers ball[3] $B_G(v, \alpha \cdot 2^i)$; in other

[1] Diameter of a graph is defined as the maximum distance between any pair of nodes in the graph.

[2] 2^i-partition of a weighted graph is defined as a partition of its vertex set into a number of subsets like $\mathcal{S}$ such that there exist no pair of nodes in $\mathcal{S}$ with distance of more than 2^i from each other.

[3] Set $B_G(v, r) \in V$ is called a ball of center $v \in V$ of radius r if $u \in B_G(v, r)$ iff $d_G(u, v) \leq r$.

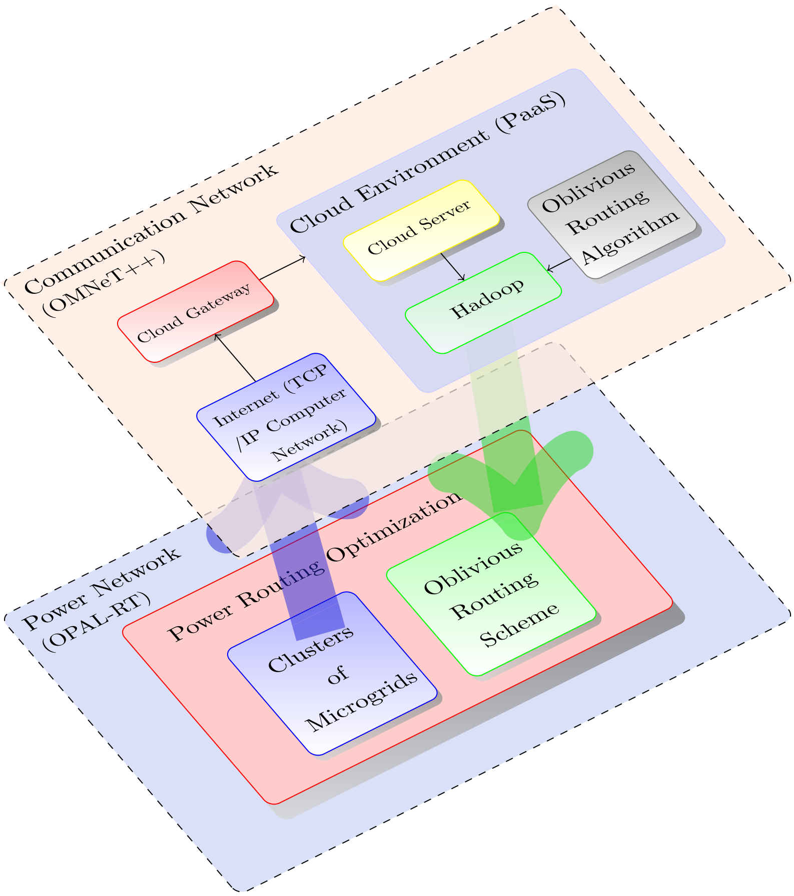

FIGURE 2. The schematic view of microgrids and their corresponding cloud system for communication.

words, for every level i, there exists some $\mathcal{S} \in \mathcal{S}_i$ such that $B_G(v, \alpha \cdot 2^i) \subseteq \mathcal{S}$ [55].

Finally, we define an Overlay Routing Tree (ORT) T based on the microgrid sequence $\bar{\mathcal{S}}$ in the following way: T is an n-level tree where its i^{th} level nodes are the members of $\mathcal{S}_i$ (for every $i = 0, 1, \ldots, n$) and any i^{th}-level tree node $\mathcal{S} \in \mathcal{S}_i$ is connected to its parent $\mathcal{S}' \in \mathcal{S}_{i+1}$ in upper-level $(i+1)$ if and only if $\mathcal{S} \subseteq \mathcal{S}'$. Later in this section, we describe the role of ORT on how each microgrid participates in the process of power routing in the proposed system.

B. THE PROPOSED OBLIVIOUS ROUTING ALGORITHM

Fig. 3 illustrates the details of our proposed oblivious routing method. In the first step, the power routing problem is formulated as an MCFP with some oblivious elements including the objective function and source/sink nodes. Then, an oblivious routing scheme is constructed in the form of a set of overlay spanning trees on the graph representing the network of microgrids. In this step, we show how Algorithm 1 constructs the oblivious routing scheme (mentioned in [55]). In the third step, we restrict the solution space of the problem by ruling out the routing solutions which utilize the paths other than those specified by the previously constructed routing scheme. In the last step, we utilize the optimization toolbox of MATLAB in order to solve the MCFP specified in the first step and restricted in the third one.

1) FORMAL SPECIFICATION OF POWER ROUTING PROBLEM

Optimal power routing for cluster of microgrids $M = \{m_1, m_2, \ldots, m_n\}$ is the problem of specifying the generation level of microgrids to satisfy their load demands while minimizing the generation cost. Note that we don't consider the apparent power $S_{m_1m_2}$ of a line between two neighboringmicorgrids m_1 and m_2 as the optimization parameters; instead, we only consider the power flow magnitude $f_{m_1m_2} = \mathcal{R}\{S_{m_1m_2}\}$ in the connecting lines between microgrids. In addition, we consider the following model for the power loss in each line connecting microgrids m_1 and m_2 [70]:

$$\text{loss}_{m_1m_2} = w_{m_1m_2} f_{m_1m_2} + c_{m_1m_2};$$

where $w_{m_1m_2}(c_{m_1m_2})$ denote the resistance (constant loss) of the line connecting m_1 and m_2 (see Fig. 4 for illustration).

The problem of optimizing power routing for clusters of microgrids can be formally modeled in the following way:

$$min_{f_{...}} \left\{ \sum_{m \in M} C_m(-\sum_{r \neq m} f_{r,m}) \right\} \tag{1}$$

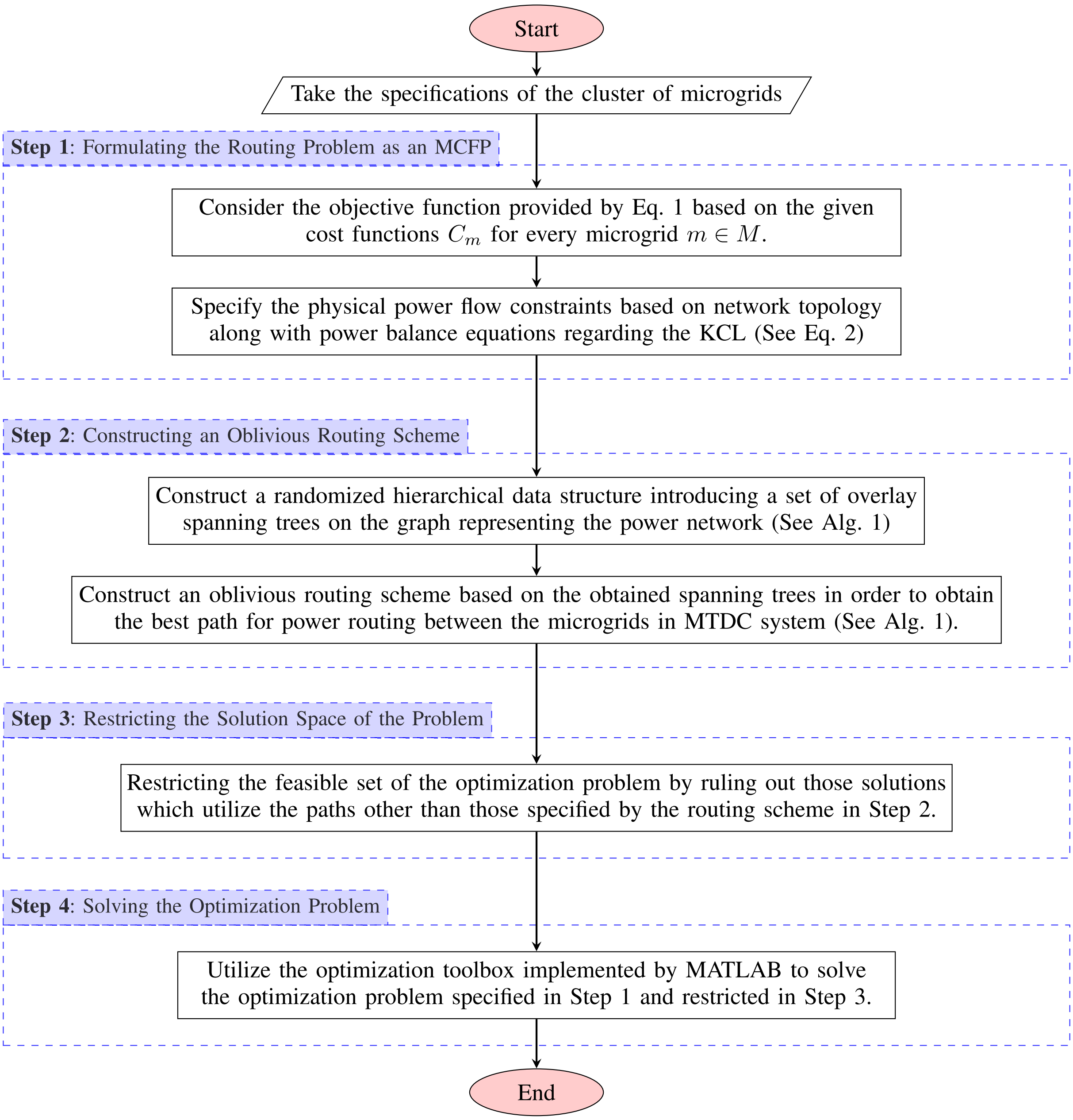

FIGURE 3. Flowchart of the proposed oblivious routing algorithm for optimal power routing problem for clusters of microgrids.

subject to

$$\begin{cases} (i) & -D_m \le \sum_{r \neq m} f_{r,m} \le S_m \\ (ii) & f_{m_1 m_2} + f_{m_1 m_2} + w_{m_1 m_2} f_{m_1 m_2} + c_{m_1 m_2} = 0 \\ & \forall \text{neighboringmicrogrids } m_1 \text{ and } m_2 \\ (iii) & f_{m_1 m_2} = 0, \text{ if } \{m_1 m_2\} \text{ are not neighbors} \\ (iv) & |f_{m_1 m_2}| \le \mathcal{L}_{m_1 m_2} \end{cases} \tag{2}$$

where C_m denotes the generation cost function for microgrid m, D_m and S_m denote the high-threshold demand and supply of microgrid m (respectively), and $\mathcal{L}_{m_1 m_2}$ represents the capacity of line connecting m_1 and m_2.

2) CONSTRUCTING OBLIVIOUS ROUTING SCHEME

Algorithm 1 gets the weighted graph $\mathcal{G} = (M, L, w)$ as its input and returns function $\mathbb{S} : M^2 \mapsto \mathcal{P}(L)$ which represents the oblivious routing scheme and specifies a path[5]

[4]Consider γ_l as the shortest path between the incident nodes of arbitrary edge $l \in p$ in graph G. The projection of tree path p on the graph is obtained by concatenating all of the shortest paths γ_ls back to back. In the case that the concatenation result is not a simple path and has crossed some nodes more than once, the projected path will be the shortest simple path corresponding to the concatenation result.

[5]In this paper, path of a graph is considered as a simple path and represented by a subset of edge set L such that there exist a permutation of edges in a path where the first edge is incident to the start node of the path, each two consecutive edges are incident to a common node, and the last edge is incident to the end node of the path.

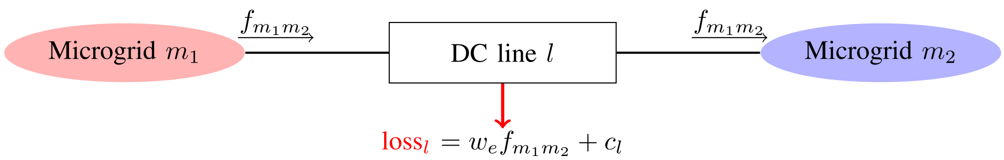

FIGURE 4. **Power loss model for DC line connecting two neighboringmicorgrids [47].**

Algorithm 1 SchemeConstructor [55]

// This algorithm constructs an oblivious routing scheme and returns it as function $\mathbb{S} : M^2 \mapsto \mathcal{P}(L)$.

1 **for** $k \leftarrow 1$ **to** $27 \log |L|$ **do**
2 $\quad \mathcal{S}^{(k)}_{0\cdots n-1} \leftarrow \emptyset$; $\mathcal{S}^{(k)}_{n} \leftarrow \{L\}$; $\pi \leftarrow$ random permutation on M; $r \leftarrow$ random number in $[1/2, 1)$;
3 $\quad$ **for each** $i \leftarrow n-1$ **to** 0 **do**
4 $\quad\quad$ **for each** $\mathcal{S} \in \mathcal{S}^{(k)}_{i+1}$ **do**
5 $\quad\quad\quad$ **for each** $x \in \mathcal{S}$ **do**
6 $\quad\quad\quad\quad$ $x.\text{set} \leftarrow \emptyset$; $x.\text{grid} \leftarrow \pi\Big(\min_j \{\pi(j) \in \mathcal{S} \cap B_{\mathcal{G}}(x, r \times 2^{i-1})\}\Big)$; $x.\text{selected} \leftarrow$ **true**;
7 $\quad\quad\quad$ **end**
8 $\quad\quad\quad$ **for each** $x \in \mathcal{S}$ **do**
9 $\quad\quad\quad\quad$ **for each** $y \in \mathcal{S}$ **and** $y.selected =$ **true** **and** $y.grid = x$ **do**
$\quad\quad\quad\quad\quad$ // Add y to x.set
10 $\quad\quad\quad\quad\quad$ $x.\text{set} \leftarrow x.\text{set} \cup \{y\}$;
11 $\quad\quad\quad\quad\quad$ $y.\text{selected} \leftarrow$ **false**;
12 $\quad\quad\quad\quad$ **end**
$\quad\quad\quad\quad$ // Add non-empty x.set to $\mathcal{S}_i$
13 $\quad\quad\quad\quad$ $\mathcal{S}^{(k)}_i \leftarrow \mathcal{S}^{(k)}_i \cup \{x.\text{set}\}$;
14 $\quad\quad\quad$ **end**
15 $\quad\quad$ **end**
16 $\quad$ **end**
17 $\quad$ $T^{(k)} \leftarrow$ the ORT corresponding to $\bar{\mathcal{S}}^{(k)}$;
18 **end**
19 **for each** *source* **in** M **and** *sink* **in** M **do**
20 $\quad$ **for** $i \leftarrow 1$ **to** $27 \log |L|$ **do**
21 $\quad\quad$ **if** *source and sink are* α*-padded by* $\bar{\mathcal{S}}^{(i)}$ **then**
22 $\quad\quad\quad$ $T \leftarrow T^{(i)}$; $p \leftarrow$ the only path between the leaves source and sink in tree T; **break**;
23 $\quad\quad$ **end**
24 $\quad$ **end**
25 $\quad$ $\mathbb{S}(source, sink) \leftarrow$ the projection[4]of p on graph $\mathcal{G}$;
26 **end**
27 **return** $\mathbb{S}$;

in graph $\mathcal{G}$ for every pair of source-sink microgrids. The algorithm starts with generating $27 \log |M|$ random microgrid sequences $\{\mathcal{S}^{(k)}_{0\ldots n-1}\}^{27 \log |M|}_{k=1}$ utilizing the lines 3-16 of Algorithm 1. The reason for generating multiple random microgrid sequences is to assure the existence of at-least one sequence $\bar{S}$ for every pair of mircrogids in M. In fact, Iyengar *et al.* in [55] proved that the probability of existing at-least one α-padding sequence among the $c \log |V|$ sequences generated by Algorithm 1 is more than $1 - e^{-\frac{(c-2)^2}{2c}}$ (for every $\alpha \leq 1/8$). By considering $c \geq 27$, the mentioned probability would be greater than $1 - 10^{-5}$ which provides a reasonable theoretical guarantee that Algorithm 1 will find at-least one α-padding sequence for every source-sink pair of microgrids.

After creating $27 \log |V|$ random sequences and their corresponding ORTs (in line 17), Algorithm 1 runs its main loop in lines 19 to 24 for every pair of source-sink nodes. Assume T as the ORT corresponding to an α-padding sequence of microgrids. Tree T would have a pair of leaves (level-zero nodes) corresponding to the source and sink (as $\mathcal{G}$ is supposed to be a weighted graph of the weight function greater than one for every edge). Also, let p denote the only path in ORT connecting the mentioned leaves together. The routing scheme is computed in line 25 where the path between source and sink nodes $\mathbb{S}(source, sink)$ is obtained by projecting the overlay path p on graph $\mathcal{G}$.

3) RESTRICTING THE SOLUTION SPACE OF THE PROBLEM

In the third step, we restrict the feasible set of the optimization problem (defined by Eq. 1 and 2) by ruling out those solutions which utilize the paths (power lines) other than those specified by the routing scheme $\mathbb{S}$ (obtained by Alg. 1).

4) SOLVING THE PROBLEM ON A MULTI-TERMINAL DC TEST SYSTEM INCLUDING THE CLUSTER OF 14 MICROGRIDS

Fig. 1 depicts the topology of a designed 14-MTDC test network which is a sample of non-radial electric grids. Our simulation procedure on this test network is implementing the oblivious power routing algorithm presented in Alg. 1 for some given demand/supply values and compare the results with the output of MATPOWER[6] software for the same given input. This comparison has illustrated by three plots shown in Fig. 5. Also, the detailed values of the obtained resluts for the total cost (in USD) and loss (in MW) are specified in Table 1. Also, we applied our proposed routing scheme on an MTDC system with a large-scale non-radial topology inspired by the IEEE-118 bus standard test system [71]. To design the simulation platform, we modified the IEEE-118

[6]MATPOWER is a package of MATLAB®M-files for solving power flow and optimal power flow problems [70]. Source: http://www.pserc.cornell.edu/matpower/

TABLE 1. Comparison of the Proposed algorithm with MATPOWER on the designed 14-bus microgrid test system.

Cost (USD)			Loss per Generated Unit (%)			Loss (MW)		
Load	Proposed work	MATPOWER	Load	MATPOWER	Proposed work	Load	MATPOWER	Proposed work
$100MW$	3,073	2,936	$100MW$	3.92	3.76	$100MW$	3.92	3.76
$200MW$	4,210	4,278	$200MW$	4.77	4.72	$200MW$	9.54	9.44
$500MW$	10,332	10,823	$500MW$	5.10	5.16	$500MW$	25.5	25.80

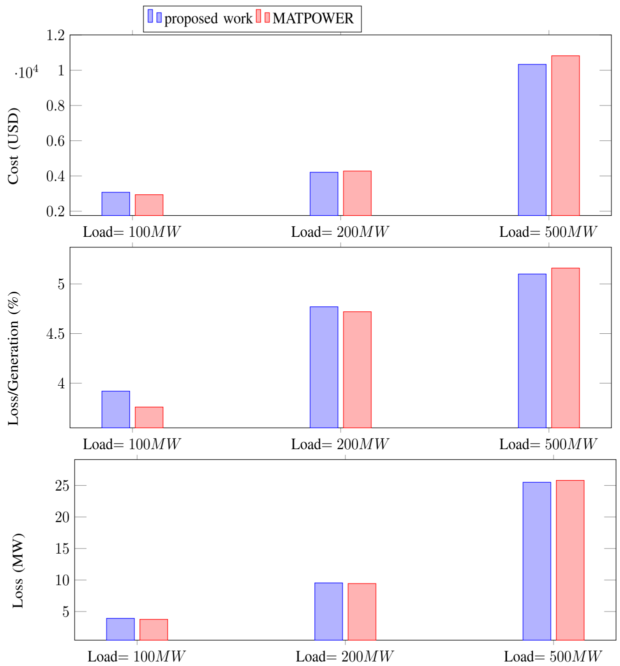

FIGURE 5. Comparison of the proposed algorithm with MATPOWER on the designed 14-bus microgrid test system.

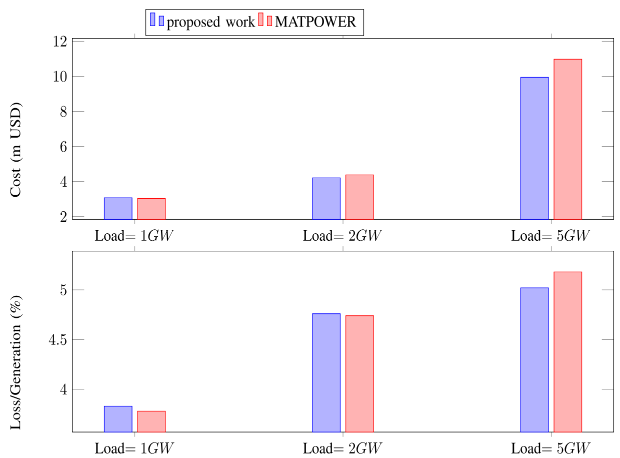

FIGURE 6. Comparison of the proposed algorithm with MATPOWER on the designed microgrid system based on IEEE-118 bus standard test system.

bus standard test system by replacing both the demand and generation buses with microgrids of random-valued (positive and negative) SOEs. The obtained results is compared with the output of MATPOWER software for the same given input. This comparison is illustrated by the two plots shown in Fig. 6.

IV. REAL-TIME DIGITAL POWER SYSTEM SIMULATOR

Communication interface is of instrumental importance in clusters of microgrids [62]. However, practical communication interfaces are characterized by inherent latencies and limited bandwidths [63]. This means that in realistic situations, we cannot expect that the control algorithms, which are normally designed in continuous time domain (or in the some cases, designed based on synchronized discrete time domain), behave as expected in the reality. While there has been tremendous amount of attention devoted to analytical investigation of the impacts of communication delays on modern power systems in the automatic control research community, derived methods are overly complicated and unapproachable in practical scenarios [64]. Therefore, real time simulation plays an indispensable role in analysis and design of future cyber-physical systems. OPAL-RT[7] eMEGASim is the cutting-edge simulator which integrates distributed processing software and hardware platforms for high speed and real-time simulation of electromagnetic transients [65]. Furthermore, it comprises fully customized I/O channels which allow seamless integration of physical hardware within the simulation loop or a third party software to emulate certain parts of the system. This latter functionality will be utilized in this paper to integrate OMNeT++, which emulates communication protocols.

Fig. 7 represents the general schematic overview of the proposed real time simulation (RTS) platform. According to this platform, the topology of each cluster can be modeled in OPAL-5600 system. Also, the communication network is simulated in OMNeT++ on a separate computing system. Each microgrid within the cluster is assigned to one of the Ethernet ports of the OPAL interface to emulate the input and output gates of each microgrid. All the Ethernet wires are connected to the OMNeT++ platform through the Ethernet hub.[8] OPAL-5600 communicates with the power simulation model utilizing an interface based on power hardware-in-the-loop (PHIL).[9]

[7]OPAL-RT is the world leader in the development of PC/FPGA Based Real-Time Digital Simulators, Hardware-In-the-Loop (HIL) testing equipment and Rapid Control Prototyping (RCP) systems. Their systems are utilized to design, test and optimize control and protection systems for power systems, power electronics, motor drives, automotive, railway, aircraft and industries, as well as R&D centers and universities.
Source: http://www.opal-rt.com/

[8]The IEEE 802.3 Ethernet communication protocol is followed in this schema.

[9]Power hardware-in-the-loop (PHIL) simulation is an extended version of hardware-in-the-loop (HIL) simulation where the simulation environment exchanges power with real hardware in a virtual fashion. However, the usual case in HIL simulation only involves the signal exchange rather than considering the power exchange [65].

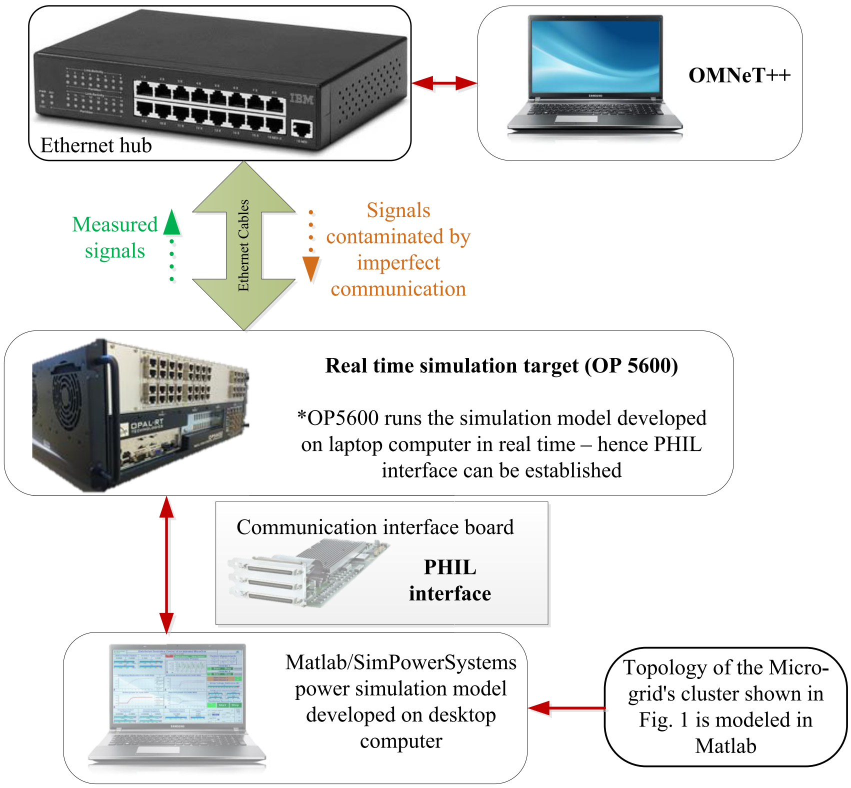

FIGURE 7. General structure of OPAL-RT implementation.

V. CLOUD-BASED INFORMATION NETWORK FOR MICROGRIDS COMMUNICATION

Consider that in a cloud system, serving as Platform as a Service (PaaS), the cloud server is located in the private cloud which has a connecting point (cloud gateway) to the Internet. The cloud server is equipped with a Hadoop framework in order to have high computational power needed for running the proposed routing algorithm. Every microgridis considered to be a cloud customer which is located in the public cloud and communicates with the cloud servers via the cloud gateway (See Fig. 8 for schematic view of the system). A two-way communication between microgrids and the gateway is done through a network of routers connected with pre-established TCP connections [72].

PaaS is a category of cloud computing services that provide a platform allowing customers to develop, run, and manage Web applications without the complexity of building and maintaining the infrastructure typically associated with developing and launching an app. PaaS can be delivered in two ways: as a public cloud service from a provider, where the consumer controls software deployment and configuration settings, and the provider provides the networks, servers, storage and other services to host the consumer's application; or as software installed in private data centers or public infrastructurex as a service and managed by internal IT departments.

In PaaS, the provider might give some control to the people to build applications on top of the platform. But any security below the application level such as host and network intrusion prevention will still be in the scope of the provider and the provider has to offer strong assurances that the data remains inaccessible between applications [73]. PaaS is intended to enable developers to build their own applications on top of the platform. As a result, it tends to be more extensible than Software as a Service (SaaS), at the expense of customer-ready features. This tradeoff extends to security features and capabilities. In fact, the built-in capabilities are not complete, but they are flexible enough for more security extension.

VI. OMNET++: AN EFFECTIVE MEANS FOR ENABLING MODERN COMMUNICATION

Combination of several simulator to realize a particular modeling objective is called co-simulation. Based on whether the simulations are real time or off-line, there may be a need to synchronize simulation time of the simulators involved in the simulation. In smart grid studies, this coordination of simulators represents a promising scientific contribution as it enables researchers to study a variety aspects of smart grid operation [74]. So many efforts have been done in co-simulation of the power grid and communication links. Most of the work highlight the integration of the different simulator types as the main issue. OMNeT++ itself is not a simulator of any communication network, but rather provides infrastructure and tools for writing simulations. One of the fundamental ingredients of this infrastructure is a modular architecture

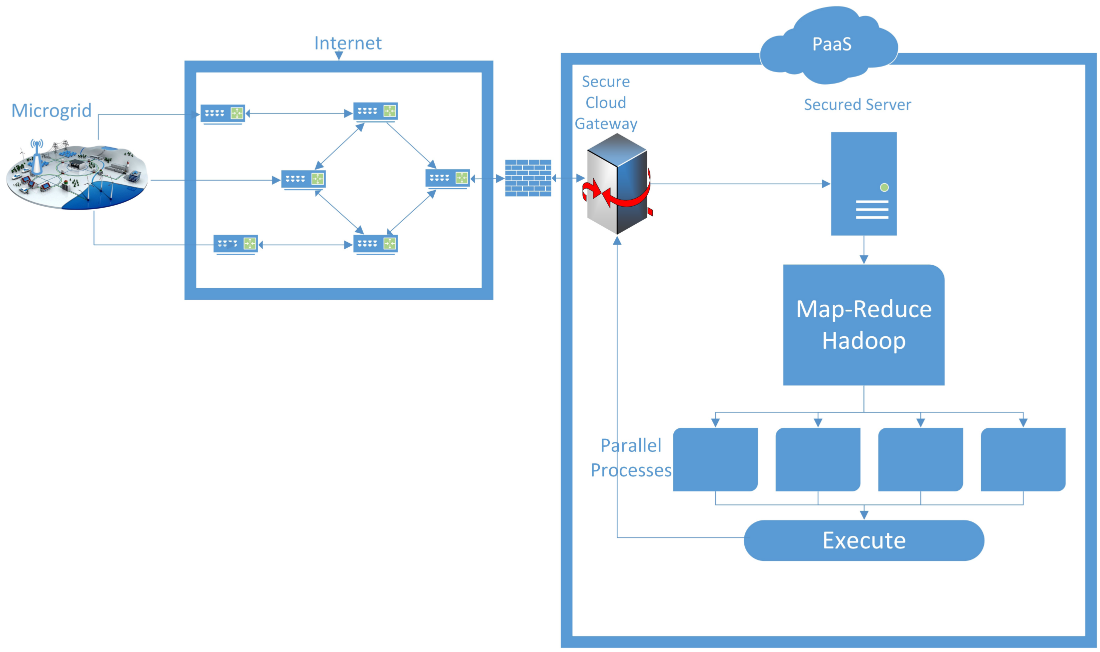

FIGURE 8. Schematic view of the cloud-based server for secure communication in clusters of microgrids.

for simulation models. These modules enables OMNeT++ to emulate several communication and networking protocols, such as IPv4, IPv6, TCP, UDP, and Ethernet.

One major component of the smart power grid is the communication protocol. Without a proper communication network, the element of intelligence loses its sensibleness in the power system. So far, many simulations have been done by researchers to investigate certain conceptual designs and intellectual ideas, however, they are mostly impractical due to negligence of the communication limitations in their system. In order to fulfill this limitation, OMNeT++ simulation tool is used in conjunction with the real-time simulator of smart grid, to model: 1) the wireless communication networks, 2) oblivious network protocol, 3) distributed hardware system, and 4) validating the hardware architecture.

In our proposed work, the clusters of microgrids are emulated in OPAL-RT and RTDS real-time simulation platforms. This is an essential task since the queuing networks and propagation delay impose a significant constraint in realization of the actual system. In fact, we need to deploy a network simulation platform in order to evaluate the performance of the two-way communication network connecting the clusters of microgrids to the cloud server. To this end, we propose OMNeT++ which is a discrete event simulator for modeling and performance evaluation of the communication network. The co-simulation of RTDS and OMNeT++ enables us to run the power system models concurrently with real-time network simulator. Therefore, the simulations can be done simultaneously and the results can be fed into the calling application automatically. The structure of the system simulation is shown in Fig. 1.

VII. SUMMARY AND CONCLUSION

This paper presents a framework for implementation, simulation, and evaluation of a novel power routing algorithm for clusters of microgrids. We utilized an oblivious routing algorithm which is an efficient tool for network optimization in large-scale real world systems. Oblivious routing design is most suited for the networks in which we have little/no knowledge regarding their current and future states. Therefore, it goes well in line with the microgrid concept, as they are largely independent entities by definition. In order to validate the effectiveness of the oblivious routing algorithm, the proposed algorithm was implemented on a cluster composed of 14 microgrids and compared the performance results with the output of MATPOWER for the same input specifications. In order to implement the oblivious network routing algorithm, we presented a cloud environment in the form of PaaS which is an economic and secure tool for computing the power routing scheme for clusters of microgrids. In order to simulate our novel routing algorithm in a large-scale and realistic system, we proposed to integrate RTDS in our framework for further implementation. Our comprehensive framework deployed a network simulator in order to evaluate the performance of the two-way communication network connecting the clusters of microgrids to the cloud server. To this end, we introduced OMNeT++ which is a discrete event simulator for modeling and performance evaluation of the communication network.

We plan to extend this work in the following three major directions:

- implementing an oblivious power routing algorithm on OPAL-RT and evaluating its performance in a real-time simulation environment;

- extending the cloud environment as an effective means for communication in the network of microgrids;
- deploying OMNeT++ which is a discrete event simulator for modeling the communication network and distributed systems that can be used for modeling and testing a wide-area communication protocols.

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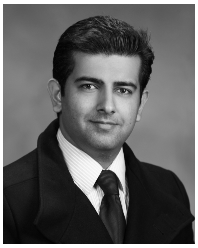

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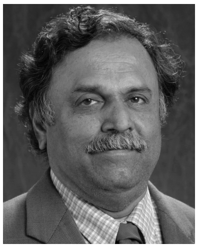

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