Ad-hoc Self-Organized Microgrid for Rural Electrification and Post-Disaster Response

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***Abstract*—This paper presents the concept for an ad-hoc self-organized microgrid based on moveable and renewable energy sources and fully distributed coordination between intelligent power routing nodes. The primary goal of the proposed architecture is to build an adaptive, scalable, and reliable system to support energy provisioning with limited infrastructural planning. Our vision focuses on two use-case scenarios: promote electrification and energy sharing in isolated rural areas, and support emergency response crews in disaster relief situations. Both scenarios rely on the deployment of an autonomous microgrid based on movable generators and renewable sources which will dynamically reconfigure itself and adapt to changes with minimal user intervention.**

***Keywords*-Smart Grid, Self-Organization, Ad-hoc Network**

I. INTRODUCTION

Smart Grids envision the creation of an Energy Internet, a rich ecosystem built upon protocols and standards enabling interoperability between different providers and servicing users worldwide [1], [2]. Research on the topic has focused both on enhancing existing systems, for example through smart metering devices, as well as on alternative architectures for power production and distribution. In this vision, alongside with *traditional* grids, which typically refer to national or regional scale power delivery systems, other concepts that concentrate on small scale distributed production have been defined [3], [4]. An example are microgrids [5], which can operate autonomously from the main grid and allow for more efficient usage and distribution of energy, because storage and consumption is in the vicinity of the generation facility [6].

A significant push for the deployment of innovative approaches to power distribution has been given by the widespread interest for distributed generation (DG) through renewable energy sources, such as photovoltaic, wind, or tidal generators [7]. These power sources are characterized by transient availability, and require intelligent control mechanisms to enable seamless operation alongside with the existing grid [8]. DG sources can thus solve the problem of on-demand provisioning, because additional sources can be rapidly activated to support ancillary services and balance production and consumption [9]. However, interconnecting DG sources and integrating them with the main grid introduces a number of challenges [8], because careful coordination between power sources is required to ensure reliable operation [10]. Thus the aforementioned increase in peak power capacity, flexibility, and reliability comes at the expenses of higher integration, production and management complexity and costs [4].

Despite these issues, microgrids and distributed generation have determined a shift from a passive distribution model, where energy is produced at centralized sites and routed toward passive consumers, to an active model, which includes multiple autonomous distributed generation sources that can produce and offer energy in a global energy market [11]. Therefore, the topics of microgrids and bidirectional distribution networks have spurred research and investigation forward, tackling a number of different axes: protection and fault detection, communication technologies, and automated control systems [12].

Although many challenges still lie ahead on the road toward sustainable and reliable systems, we can try to look ahead even further, and envision the development of ad-hoc microgrids that could provide adaptive, scalable, and reliable power distribution with limited infrastructural planning. This view draws inspiration from the evolution observed in computer networks and the similarities between the information networks and power networks, which are both evolving from centralized designs toward fully decentralized models, in order to increase robustness, scalability, and reliability. In this regard, when a communication infrastructure is not available or not desirable, ad-hoc networking models have emerged.

In this paper we propose to apply a similar concept to the realm of power networks, by detailing the concept of an ad-hoc self-organized microgrid. More specifically we consider the development of an isolated microgrid system composed of a multitude of dispersed components (referred to as *smart nodes*) that can be deployed with limited infrastructural planning, and can operate in a fully distributed manner without centralized monitoring and control. Each component of the grid is thus responsible for locally managing connectivity with other nodes and provide energy routing facilities between power sources and loads. Relying only on local sensing and peer-to-peer interaction, nodes need to engage themselves to coordinate and support efficient and reliable power distribution, by taking into account both the physical limitations of the system (i.e. current drawn from sources, phase synchronization,. . .), as well as user requirements (i.e. load priorities, usage schedule,. . .). To deal with this management complexity, we propose to employ self-organized mechanisms to monitor and control the system. Moreover, because of the promising results exhibited in other fields, we plan to concentrate on bio-inspired methodologies.

The considered application scenarios envision support for isolated rural areas electrification using renewable sources, and disaster relief activities, by providing emergency response crews with the ability to quickly deploy an ad-hoc microgrid built upon moveable sources. Our goals depend on the development of support technologies to monitor and route energy in situations where infrastructural planning is limited or impossible, and where the topology and composition of the distribution network can dynamically change due to user requirements or equipment failures.

The rest of this paper is organized as follows: in Section II we discuss the application scenarios considered; in Section III we detail our model for an ad-hoc self-organized microgrid, whereas in Section IV we describe the current prototype for the provisioning protocol; Section V presents some related research work. Finally, Section VI provides conclusions and discusses future works.

II. APPLICATION SCENARIOS

Electrification of isolated rural areas plays an important role in the development of local businesses and helping people afford a better quality of life. In less developed countries, several regions have very limited or no access to the main grid and must rely on local energy production based on distributed sources souch as photovoltaic or wind power. The price of these installations does however limit their diffusion, and only a small percentage of individuals can actually afford one. In this situation, a viable solution would rely sharing the energy produced at different sites, which in turn depends on simplified energy distribution and consumption-based metering. Even in developed countries several mountain villages exist that depend solely on photovoltaic. In these areas, assuming that the overall offer exceeds the average demand, an energy sharing network would enable individuals to easily make use of solar power produced by other individuals.

Another scenario considers a post-disaster situation, where energy provisioning is essential for emergency operations and population recovery. In contrast to normal smart grid deployments, which have long-term objectives, emergency relief operations are basically short-term reactions to unplanned events [13]. Disaster relief operations are required to rapidly act rapidly in difficult environments and are typically faced with unexpected conditions where detailed infrastructure planning is not possible and conditions can rapidly change. In this regard, renewable sources and movable generators play an important role in providing electricity in the affected areas, especially if the main grid fails. Our vision is to support emergency response crews by providing them with the ability to deploy a small but reliable power distribution grid that can be dynamically adapted according to situational requirements quickly. This scenario clearly introduces a number of challenges, whose solution relies both on fundamental research as well as on engineering and technical expertise.

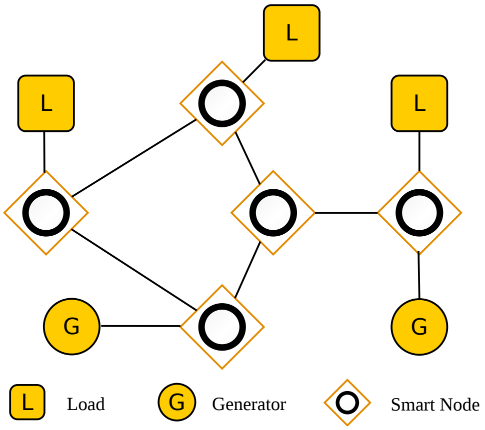

Figure 1. Example of an ad-hoc microgrid

In response to these challenges, as shown in Figure 1, we envision an unstructured power network composed of distributed generation devices, smart routing nodes, and loads. This network can be progressively expanded by emergency crews by deploying additional nodes, power cables, generators, and loads. The management software running on each node ensures continuous monitoring of the distribution network and the transmission paths, without user intervention. In normal conditions, the system proactively analyzes the network for potential problems and determines failback solutions. Should a link between two nodes fail, the system reacts by setting up alternative transmission paths. Similarly, if additional generators are available, automatic reconfiguration takes place to optimally balance the load between available sources. Conversely, when loads are attached to the system, provisioning policies ensure that additional transmission paths are activated, if necessary, to route energy from generators.

III. AD-HOC MICROGRID MODEL

There is a substantial similarity between the evolution of information networks (i.e Internet), observed since the birth of the World Wide Web, and the recent advancements in power networks. Computer networks and applications have evolved from centralized toward fully decentralized designs, thanks to the increased *intelligence* available in modern devices. In the last decade we observed a similar evolutionary trend in power distribution: on the one hand, both governments and the industry have put a considerable effort toward the deployment of intelligent devices (smart meters) capable of controlling consumption locally and promote a more efficient power usage. On the other hand, by means of distributed generation sources, the system has become more reliable and less dependent on a small number of providers. As with the Internet and the information shared by millions of users, consumers now take an active role, because energy can be produced anywhere and routed back to the main grid for the benefit of many. This similarity implies that many of the challenges faced by distributed computing, such as management and coordination of dispersed resources, are now faced by power grids. Therefore, it can be argued that solutions developed in the framework of computer networks are worth investigating.

Distributed computing has even taken a further step with mobile ad-hoc networks, which enable users to create autonomous communities with little communication infrastructure, namely through self-organizing wireless communication. Each node within an ad-hoc network is responsible for managing connectivity with other nodes, and must provide local routing facilities in a dynamic environment. In this regard, we aim at applying a similar concept to power networks, namely by considering autonomous microgrids as our field of application. These microgrids must be able to route energy from producers to consumers in an efficient way and in absence of a fixed infrastructure and with little user-intervention, while providing fault-tolerant, self-adjusting and self-healing mechanisms. In this sense, we propose an architecture for an ad-hoc microgrid, the details of which will be discussed in the following.

A. System Architecture

The concept for an ad-hoc microgrid is based on a fully distributed design, namely an acyclic power transmission network composed of different devices such as generators, batteries, smart routing nodes, and consumer devices; in this sense, we concentrate on islanded (or isolated) operation (i.e. disconnected from the main grid). Critical to the operation of the microgrid are smart nodes, which are interconnected computing devices capable of routing power from producers to consumers in an efficient way. Accordingly, each smart node is connected to other sibling nodes by means of power and data connections, which are used to deliver electricity and information across the network without centralized control. Nodes exchange collected information about the status of the network (its topology, measured voltages, and currents) and coordinate their operations to enable efficient and reliable energy routing. The logical structure of the management middleware is composed of three layers: a power switching layer, a communication and monitoring layer (comprised of two modules), and a control layer. Each node is responsible for locally managing concerns from all layers. A schematic overview of the logical components of the system is depicted in Figure 2.

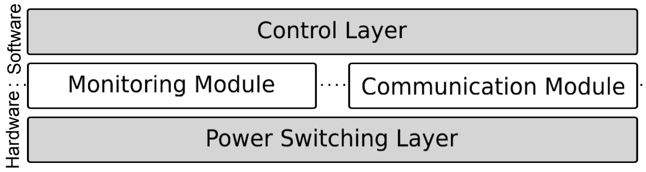

Figure 2. Middleware architecture

Power Switching Layer At the lowest level, the power switching layer is concerned with directing power from a production or storage device toward consumers. This layer does not execute the logic of the routing schema, but only provides the hardware capability to switch power from and to connected sibling nodes by means of relay switches.

Monitoring Module The monitoring module is responsible for collecting local data on each node, such as the identity of sibling nodes, voltage, and current across all connections, and passing it to the control layer. Voltage and current are measured by hardware, while the identity of sibling nodes is obtained by means of a basic signaling protocol that runs on a point-to-point wired data link between nodes, which also enables nodes to detect failures of both nodes and lines. Nodes can measure the impedance of both active and inactive transmission lines: in the latter case, a measurement current is achieved with the help of a storage battery on each node.

Communication Module Exchange of information between nodes, for example to activate new power routing paths, is supported by the communication module, which implements IP communication over a wired or wireless link. The details of this module are not enforced in our model, as we rely on existing solutions developed for ad-hoc mobile networks and pervasive systems instead. Nonetheless, in the current implementation an ad-hoc wireless network is employed, with PLC (Power Line Communication) planned for future versions. It is important to note that data transmission should not depend on the topology and the routing schema of the power network; in particular, two sibling nodes should be able to exchange data even if no current flows through the corresponding power line.

Control Layer Coordination between nodes and decisions concerning power routing and recovery from failures is performed by the control layer. Because of its fully distributed design, this layer implements decentralized algorithms that depend on both local data obtained by the monitoring module, as well as with the interaction with sibling nodes achieved through the communication module. Each node is managed by a small computer that drives the switching layer to activate new power routing paths, plans recovery actions, and proactively searches for alternative routing schemes.

B. Addressing Complexity

Self-organization refers to systems that are able to maintain a functional structure in an autonomous way [14]. More precisely, self-organized systems do not depend on a omniescent centralized entity that governs their actions, but exploit emergent behaviors of simple fully decentralized components. Furthermore self-organized systems typically show a significant degree of adaptiveness that helps improving their robustness and reliability. Hence the internal organization of the system is not static but continuously adjusted toward optimal configurations. Self-organizing systems are thus ideal candidates to overcome the complexity bottleneck that can easily arise in dynamic systems, and can help establish reliable, efficient and scalable distributed solutions. Among the known self-organized methodologies, swarm intelligence [15] and bio-inspired systems have been successfully adopted for solving distributed systems problems. Swarm intelligence is a field of artificial intelligence that mimics the behavior of swarms of insects in order to solve computationally intensive optimization problems. Of all swarm-based techniques, Ant Colony Optimization (ACO) [16] represents a natural choice for graph and network related problems, because ant algorithms are of simple logic and inherently distributed, do not require neither central control nor direct communication between agents. The foraging behavior of ants has been exploited for implementing adaptive routing algorithms, as shown in [17], [18]. Hence, the principles of the ant colony paradigm are ideal candidates to simplify the implementation of distributed self-organized management and control mechanisms for an ad-hoc microgrid.

IV. SMART NODE IMPLEMENTATION

In contrast to other existing approaches for microgrid control and management, we consider an always evolving system with dynamically changing constraints. The control middleware must take into account both the physical limitations of each component, such as the maximum current that can be provided by a generator, and user defined constraints, such as load priorities. This section details the central element of the control system, namely the provisioning protocol.

A. Fully Distributed Provisioning Protocol

To ensure robust, reliable, and scalable operation energy provisioning is achieved by means of a fully distributed protocol executed on smart nodes, which are also responsible for managing locally connected loads, generators, and transmission lines. If malfunctions are experienced by one or more nodes, the remaining nodes should be minimally affected (provided that alternative power routing path are available).

1) Provisioning Phases: The protocol can be initiated by any node requiring power to drive associated loads. The design follows a *check-then-act* sequence, where requests result in a pre-allocation of the resources that must be confirmed in order for the routing schema to be applied to the power transmission network. The idea of the algorithm is to mimic the operation of a travel agency, which can put airline tickets on hold for some period of time with the possibility of confirming or canceling them. In the following the different phases of the provisioning mechanism are presented.

REQUEST Smart nodes broadcast request messages in order to discover appropriate generation sites and transmission paths to power connected loads. We assume that nodes know the current required by attached loads, either by asking the user or by interrogating devices themselves (smart devices). Request messages are forwarded, in a point-to-point fashion and for a limited number of hops (i.e. traversed smart nodes), through the communication layer. Forbidden paths can be also be defined, for example to avoid loops: in this case messages are simply routed to alternate nodes.

OFFER Upon reception of a request message, a node connected to a generator replies to the requesting node directly with its availability by means of an offer message. Furthermore can hold (pre-allocate) the necessary amount of energy for the requesting node. If the requesting node had already submitted other simultaneous requests for other loads the pre-allocation can be simply increased. Because the topology of the communication network matches the power network, paths traveled by request messages reflect the considered transmission path. If a pre-allocated offer is not confirmed within a time limit it is simply canceled, and all reserved resources are released. The requesting node waits for incoming offers and evaluates them based on different criteria, such as the maximum amount of current that can be provided by the generator or the transmission cost (distance and impedance). If no offers are received by the requesting node, the latter issues another request for a reduced amount of power: in this case multiple offers would be necessary to fulfill load requirements.

HOLD The best offer is evaluated by the requesting node, which then issues an hold message to all nodes on the chosen transmission path. During this phase the requesting node also tries to avoid paths that would generate loops in the transmission line because they could result in monitoring and control issues. In this regard, held and confirmed paths are bound to the identifier of the connected generators. Upon reception of an hold message, if the activation of a link results in a connection with an already bound generator (because of a concurrent request from another node), the pre-allocation is continued on the existing path. Conversely, if a node on the path to be pre-allocated does not respond, the pre-allocation fails.

CONFIRM When a path has been successfully verified, the requesting node issues a confirm message to effectively enable energy routing. The requesting node as well as each node on the transmission path activate the corresponding relay switches on the power switching layer (if necessary). Furthermore, they engage to continuously monitor the current flow and signal possible problems to the requesting node.

2) Autonomous monitoring: In order to cope with unexpected failures, each node monitors confirmed paths by means of a self-organized mechanism, and periodically submits proactive queries aimed at discovering alternative or more convenient paths toward power sources. The monitoring solution mimics the foraging behavior of ants, by employing artificial pheromone trails to signal paths according to their quality. This mechanism, called stigmergy, enables simplified maintenance of existing path and resolution of newer optimal transmission paths in a fully distributed way according to different goals (cost functions).

More precisely, each path registered on a node is associated with a numeric value that represents the concentration of pheromone on the path. The pheromone value is progressively decreased to simulate evaporation. When the pheormone concentration falls below a certain threshold value the path is deactivated. However, as long as the path is working and is employed to route power from the generator, the smart node attached to the load generates mobile ant agents that reinforce the pheromone on the path to keep it alive.

A node can also issue proactive requests for alternative paths toward generators. Accordingly, if a better path is found (typically a path with lower impedance) the node can perform a switch-over, and let the previous path die by not reinforcing it anymore. Nodes can also store non-optimal discovered alternatives and, if needed, quickly initiate a hold-and-confirm process to achieve a seamless path transmission switchover in case of unexpected failures.

3) Evaluation: We present here a brief evaluation of the provisioning protocol by considering the example system depicted in Figure 1. The reported results have been obtained in a software simulator based on Gnucap (Gnu Circuit Analysis Package[1]), although real-world experiments on a hardware testbed are also planned in the near future. The considered setup consists of five smart nodes, three loads (lamps requiring $2.5A$), and two generators (providing at most $10A$ and $15A$, respectively). Figure 3 illustrates possible distribution flows determined by the protocol: the maximum amount of current produced or consumed by each component is indicated. Dotted segments represent inactive transmission lines that can be rearranged freely by the users depending on their needs. Conversely, solid segments, along with the amount of current passing through them, correspond to active lines.

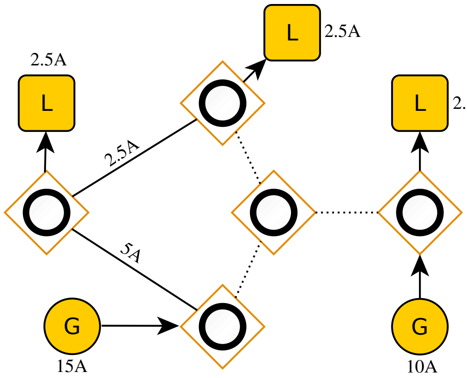

Figure 3. Routing determined by the provisioning protocol (1)

Energy produced by generators is routed correctly toward each load, and the shortest transmission paths are exploited. If a connection between two nodes fails or is removed, the protocol quickly resolves alternative routing paths, as shown in Figure 4, where one transmission line and one generator have been disconnected from the system. In the considered example we assume that the remaining generator is able to cope with the increased load, however the provisioning protocol might also deny routing energy toward a node if that results in a generator overload.

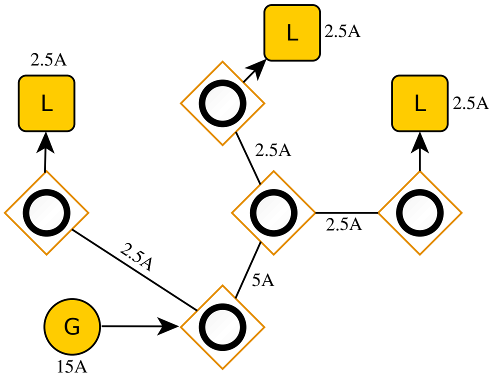

Figure 4. Routing determined by the provisioning protocol (2)

Despite the simplicity of this initial version of the algorithm, it achieves our goal for a fully distributed provisioning mechanism. Nonetheless, future developments will include support for dynamic reallocation, prioritized loads, on demand activation of power sources, and enhacements to the proactive discovery of alternative transmission paths based on bio-inspired mechanisms. Furthermore, the required interaction with the user when no provisioning solution can be found will also be investigated.

V. RELATED WORK

The design of an ad-hoc self-organized microgrid spans over several research areas, such as autonomous control issues, self-healing mechanisms, and efficient power routing.

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[1] http://www.gnu.org/software/gnucap/

The published literature is abundant with studies, examples and solutions for each of these concerns. Accordingly, in this section we will present some of the projects that are closely related to the work presented in this paper. Our attention goes in particular to autonomous control, decentralized power routing algorithms, and self-organized operation.

Of particular interest is the work presented in [19], which evaluates the use of a microgrid to support emergency response and disaster relief. In the event of a natural disaster, microgrids could represent a significant resource that helps reducing the consequences of failures of the main electric power supply. The authors also detail a control scheme to coordinate the operation of generation units connected to the microgrid, and precisely highlight the need for self-adaptive decentralized collaborative control solutions. In [20] decentralized control is deemed critical for microgrids, because it enables survival should any component or generator fail. Decentralized control can be achieved through a peer-to-peer and plug-and-play operation model, and allows for robust and fault-tolerant operation. In this respect, the paper presents a microgrid concept where autonomous control is used to isolate the system from the main grid in order to overcome failure situations or other disturbances. In islanded operation, each source is then able to balance the power requirements using a power vs. frequency droop controller.

In relation to decentralized models, agent-oriented designs have been applied to simplify the development of distributed solutions. In [21] an agent-oriented system for a self-healing smart grid is presented. The authors praise agent technologies as a way to promote autonomous behaviors and distributed decision-making capabilities. Agents are responsible for monitoring the grid, cooperate, and intervene to prevent failure situations. Self-healing is implemented by means of protection schemes that dynamically route and reroute power to optimal paths depending on the current system state. In [22], agents are used to manage micro-storage units by implementing a market-based strategy. Distributed routing algorithms in an agent-based network are also discussed in [23], where the performance of different solutions is compared. The concepts of intelligent power routers, presented in [24] and [25], promote distributed coordination to increase the robustness and configurability of a distribution network. Conversely, in [26] the routing problem is related to price, and therefore an optimization problem for maximizing the total revenue (for both power suppliers and power customers) is derived and analyzed. Finally, an evolution toward self-managed and adaptive energy management solutions is advocated in [27], proving that the need for self-organization is not confined to microgrids but can be applied to the smart grid concept as a whole.

VI. CONCLUSIONS

In this paper we introduced the concept of an ad-hoc self-organized microgrid, detailing its architecture and discussing its initial implementation. The system relies on fully-distributed autonomous control, where intelligent power routing nodes communicate and collaborate with each other by exchanging locally collected information about the state of the network. The goal of the proposed solution is to build an adaptive, scalable, and reliable isolated microgrid, enabling fast deployment and efficient energy provisioning with limited infrastructural planning. The considered application scenarios envision simplified electrification of rural areas and support for emergency response crews in disaster relief situations. Both scenarios require coordinated control of multiple movable generators and renewable sources through self-organized mechanisms. In this regard, a basic fully distributed provisioning protocol was presented and evaluated in a sample scenario. The proposed scheme is based on messages exchanged between smart routing nodes; line activation decisions are taken without centralized supervision, and take into account both the load requirements as well as output limitations of the generators. Current research is focusing on the development of an open low-voltage hardware testbed platform that will enable an in depth evaluation and validation of a small-scale ad-hoc microgrid. This platform will also serve as research and teaching aid for exploring smart grid technologies and experiment with power monitoring and routing algorithms. Future work will include enhancements to the provisioning protocol to include dynamic reconfiguration and self-healing. Furthermore, we plan to implement additional swarm-intelligence based mechanisms to ensure adaptive and robust operation while limiting the complexity of the resulting management middleware. The initial evaluation of the provisioning protocol suggests the viability of our approach to achieve autonomous control, we do however recognize that a real-world deployment would require us to consider additional issues such as AC phase synchronization between different generators.

VII. ACKNOWLEDGMENTS

The author would like to thank Stefano Guatieri, Marco Sala, Giovanni Badaracco, and Giancarlo Corti for their valuable help and assistance.

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