Provisional Microgrids

Amin Khodaei, *Senior Member, IEEE*

***Abstract*— A new class of microgrids, called provisional microgrids, is introduced in this paper. Provisional microgrids hold similar characteristics as microgrids, however, do not possess the islanding capability and are dependent on one or more electrically connected microgrids for islanding purposes. Removing the islanding requirements and relying on the available unused capacity of existing microgrids, characterizes provisional microgrids as enablers of rapidly deploying variable generation renewable energy resources in distribution networks and further preventing underutilization of capital-intensive distributed energy resources (DERs) in microgrids. Provisional microgrids are defined and an uncertainty-constrained optimal scheduling model is developed which considers prevailing uncertainties associated with loads, non-dispatchable generation, and market price forecasts, as well as islanding incidents and the available unused capacity from coupled microgrids. The optimal scheduling problem is decomposed using Benders decomposition and solved via the robust optimization method. Numerical simulations study a test provisional microgrid for exploring its economic, reliability, and environmental merits.**

***Index Terms*— Provisional microgrid, optimal scheduling, islanded operation, distributed energy resource, uncertainty, robust optimization.**

NOMENCLATURE

Indices:

ch	Superscript for energy storage system charging mode
d	Index for loads
dch	Superscript for energy storage system discharging mode
i	Index for DERs
t	Index for time
$\wedge$	Index for calculated variables

Sets:

D	Set of adjustable loads
G	Set of dispatchable units
P	Set of primal variables
S	Set of energy storage systems
U	Set of uncertain parameters

Parameters:

c_0	No-load cost
c	Marginal cost of dispatchable units
DR	Ramp down rate
DT	Minimum down time
E	Load total required energy
K_d	Inconvenience penalty factor
LS	Load curtailment in islanded operation
MC	Minimum charging time
MD	Minimum discharging time
MU	Minimum operating time
U	Outage state of main grid line/Islanding state (0 when islanded, 1 otherwise)
UR	Ramp up rate
UT	Minimum up time
α, β	Specified start and end times of adjustable loads
ρ_{CM}	Coupled microgrid generation price
ρ_M	Market price

Variables:

C	Energy storage available (stored) energy
D	Load demand
I	Commitment state of dispatchable unit (1 when committed, 0 otherwise)
P	DER output power
P_{CM}	Coupled microgrid power
P_M	Main grid power
Q	Operation cost
SD	Shut down cost
SL_1, SL_2	Slack variables
SU	Startup cost
T^{ch}	Number of successive charging hours
T^{dch}	Number of successive discharging hours
T^{on}	Number of successive ON hours
T^{off}	Number of successive OFF hours
τ	Time period
u	Energy storage discharging state (1 when discharging, 0 otherwise)
v	Energy storage charging state (1 when charging, 0 otherwise)
w	Power mismatch
z	Adjustable load state (1 when operating, 0 otherwise)
λ, μ, π	Dual variables
Δ_d	Deviation in adjustable load operating time interval
Λ	Reflected operation cost in the master problem

A. Khodaei is with the Department of Electrical and Computer Engineering, University of Denver, Denver, CO 80210 USA (email: amin.khodaei@du.edu).

I. INTRODUCTION

THE MICROGRID, as defined by the U.S. Department of Energy, is "a group of interconnected loads and distributed energy resources (DERs) with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or island modes" [1]. DERs consist of distributed generators and energy storage which could be installed at electricity consumers' premises to provide a local supply of loads. Based on this definition, DER deployments must have three distinct characteristics to be considered as a microgrid: the electrical boundaries are clearly defined; a master controller is present to control and operate available resources as a single controllable entity; and the installed generation capacity exceeds the peak load for enabling islanded operation. Considering these characteristics, microgrids could be identified as small-scale power systems with ability of self-supply and islanding, which could generate, distribute, and regulate the flow of electricity to local consumers.

Islanding is the most salient feature of microgrids. The microgrid islanding capability enables the microgrid to be disconnected from the main grid in case of upstream disturbances or voltage fluctuations [2]-[6]. Islanded operation of microgrids provides significant social cost savings and load point reliability enhancements during major outages, which would justify the islanding design as part of microgrid planning decisions. This feature, however, may result in some drawbacks which are being identified as more microgrids are installed worldwide. First, islanded operation requires that the microgrid installed generation capacity exceeds critical local loads. The microgrid master controller cannot rely on generation of non-dispatchable units for this purpose. These units which primarily include renewable energy resources, such as solar and wind, produce a variable generation which cannot be controlled and there is always a possibility that the forecasted generation is not materialized. This issue is also fairly applicable to energy storage as islanded operation may occur when the energy storage is fully discharged. Therefore, microgrid developers commonly deploy a high percentage of dispatchable energy resources, primarily in the form of gas-fired plants, and reduce the capacity of renewable resources to ensure a reliable and seamless islanding at all times. This issue is further boosted by the relatively higher capital cost of renewable energy resources compared to gas-fired plants. The second issue is the underutilization of the installed dispatchable capacity. The main grid power benefits from economies of scale in generation, and even by accounting for transmission and distribution costs and the associated losses, it is normally less expensive than the generation price of local dispatchable units. Local dispatchable units may be more economical than the main grid power when the transmission network is congested and the real-time market price is high. This case, however, mainly occurs in peak hours. The rather small number of peak hours compared to the times that the transmission network is not congested advocates that the microgrid would rely more on the main grid power rather than the locally generated power for supplying local loads. This issue would significantly impact microgrid economic benefits, increase the anticipated return on investment, and negatively impact the deployment of this technology. The third issue, which is more critical for community microgrids in urban settings, is the placement of dispatchable units. Some DERs would require a small space for installation, such as solar panels which could be installed at consumers' rooftops. On the contrary, installation of dispatchable units in a neighborhood is not easy and space, considering the necessary right of way, is not always freely available.

With the goal of addressing the economic and reliability needs of electricity consumers with less critical and sensitive loads, procuring distribution network flexibility offered by existing microgrids, and ensuring a rapid and widespread deployment of renewable energy resources in distribution networks, this paper proposes the novel concept of provisional microgrids. The concept of provisional microgrids is built upon current studies on microgrids to make sure that similar benefits will be offered while the deployment of small-scale renewable energy resources is boosted.

Early studies on microgrids can be found in [7]-[9], which further followed by studies on various aspects of microgrids with focus on economics, operation and control, role of power electronics, protection, and communication [10]-[12]. Microgrids introduce unique opportunities in power system operation and planning such as improved reliability by introducing self-healing at the local distribution network and lowering the possibility of load shedding, higher power quality by managing local loads, reduction in carbon emission by the diversification of energy sources, offering energy efficiency by responding to real-time market prices, and reducing the total system expansion planning cost by deferring investments on new generation and transmission facilities [13]-[21]. A discussion on existing microgrid optimal scheduling methods can be found in [5]. The optimal operation, comprising economic, reliability, and environmental merits of provisional microgrids, will be studied in this paper while other advantages will be investigated in follow-on research.

The rest of the paper is organized as follows. Provisional microgrids are defined and discussed in detail in Section II. The optimal scheduling problem is outlined in Section III and formulated in Section IV. Section V presents numerical simulations of a test system. Discussion on the features of the proposed model and concluding remarks are provided in Sections VI and VII, respectively.

II. PROVISIONAL MICROGRIDS

Definition: Provisional microgrids are similar to microgrids as their electrical boundaries are clearly defined and a master controller controls and operates available resources. Unlike microgrids, however, provisional microgrids do not have the ability to be islanded on their own. Provisional microgrids, as the name suggests, are dependent on one or more electrically connected microgrids, called coupled microgrids henceforth, for switching to an islanded mode. Provisional microgrids could utilize a high percentage of renewable energy resources without concerning about islanding requirements. When islanding is needed, the provisional microgrid would be disconnected from the main grid distribution network and rely on its own generation, as well as generation of the coupled microgrid, to supply local loads. Provisional microgrids could be considered as viable solutions to a more rapid deployment of variable generation renewable energy resources in distribution networks and further prevent underutilization of capital-intensive DERs in microgrids.

Rationale: The idea behind deployment of provisional microgrids is that by removing the islanding requirement there would be no need to deploy a high percentage of dispatchable units, hence any generation mix could be deployed. Therefore, a high percentage of variable generation resources without concerning about islanding requirements could be installed. This deployment, however, is contingent upon low criticality and sensitivity of local loads. By deploying variable generation resources it would be guaranteed that the installed capacity would not be underutilized as the generation of these resources will be used once it is produced regardless of the main grid price. Moreover, connection to the coupled microgrid would provide the required flexibility to coordinate variable generation if needed, and also the unused capacity of the coupled microgrid would be used in islanding incidents to ensure supply of local loads. To compare, the primary application of microgrids is to improve reliability for local customers and manage the ever increasing penetration of DERs, while the primary application of provisional microgrids is to boost deployment of variable generation renewable energy resources in distribution networks by leveraging the available flexibility offered by already installed microgrids and provide economic and reliability benefits for local customers.

The idea of the provisional microgrid is different from interconnected microgrids. Interconnected microgrids, also known as microgrid clusters or super-microgrids, include two or more microgrids which are electrically connected and could exchange power among themselves in order to manage loads, reduce losses, and reduce energy purchase from the main grid [22]. In this setting, each microgrid could be individually disconnected from the main grid distribution network, as well as from other microgrids, to operate in the islanded mode. The provisional microgrid, however, does not have the capability to be islanded by its own.

Operation: The core operational actions of provisional microgrids are depicted in Fig. 1 and defined as follows:

- Provisional microgrids generate energy by coordinating available resources and interact with the main grid and the coupled microgrid for power transfer to supply local loads in normal (i.e., grid-connected) operation.
- Provisional microgrids disconnect from the main grid distribution network and transfer power with the coupled microgrid for supplying local loads in islanded operation.

It is assumed that the connection between the provisional microgrid and the coupled microgrid will be maintained during islanding. This connection will ensure mutual benefits for both coupled microgrid and provisional microgrid, since the coupled microgrid would benefit by selling its unused capacity to the provisional microgrid, and the provisional microgrid would purchase power in the islanded mode for increasing its reliability. The provisional microgrid would further rely on the coupled microgrid for frequency regulation and voltage control in case dispatchable unit deployment is limited in the provisional microgrid. Significant economic and reliability benefits stemmed from the power transfer are momentous drivers in maintaining the connection between the provisional microgrid and the coupled microgrid in islanded modes. It is further assumed that the provisional microgrid and the coupled microgrid would operate simultaneously in the islanded mode in response to main grid failures and/or voltage fluctuations.

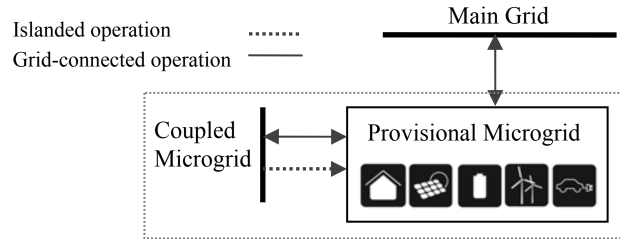

Fig. 1 Core actions of the provisional microgrid

Provisional microgrids could deploy any selected DER generation mix to supply loads and maximize economic and reliability benefits without the requirement of fully supplying loads. In most of the operating hours, the power transfer with the main grid and the coupled microgrid helps supply local loads. In minor and infrequent islanding hours, the power transfer with the coupled microgrid combined with the adjustable load and energy storage schedules enables supplying local loads. The coupled microgrid is designed to completely supply its critical local loads at peak hours. Therefore, the coupled microgrid would normally have unused capacity in both grid-connected and islanded modes. The coupled microgrid excess generation, beyond its load, would help the provisional microgrid to supply local loads during islanded operation. If sufficient generation is not available to fully supply loads, the provisional microgrid will curtail some of its load to guarantee load-supply balance. The possibility of load curtailment must be considered in the provisional microgrid design process as the cost of reliability.

III. UNCERTAINTY-CONSTRAINED OPTIMAL SCHEDULING MODEL OUTLINE

Fig. 2 depicts the flowchart of the proposed optimal scheduling model. The problem is decomposed into a master problem and two subproblems. The master problem determines the optimal schedule of available dispatchable DERs as well as adjustable loads. The obtained binary solution will be used in subproblem 1, i.e., islanded operation, to examine power mismatches when islanded. If mismatches are not zero, i.e., sufficient generation is not available to supply local loads, the islanding cut is generated and added to the master problem for revising the current schedule. The islanding cut is represented in the form of an inequality constraint which provides a lower estimate of the total mismatch in the subproblem as a function of scheduling variables in the master problem. The islanding-capable schedule, which is obtained in an iterative manner between the master problem and subproblem 1, will be used in subproblem 2, i.e., grid-connected operation, to determine the optimal dispatch of local DERs and also interactions with the main grid and the coupled microgrid. If the solution does not satisfy a predefined optimality criterion, the optimality cut is formed and sent back to the master problem for revising the current schedule. The optimality cut is represented in the form of an inequality constraint which provides a lower estimate of the total operation cost as a function of scheduling variables in the master problem. The iterative procedure will continue until the final schedule, which meets both islanding and optimality criteria, is obtained.

The optimal scheduling problem is subject to several uncertainties. Uncertainty refers to the fact that some factors, having a major influence on scheduling decisions, are not under control of the microgrid master controller and/or cannot be predicted with certainty. Based on this definition, forecasts associated with fixed loads, market prices, non-dispatchable generation, and islanding incidents are considered as prevailing uncertainties in the scheduling process. Moreover, the information associated with the coupled microgrid is uncertain which includes the available unused capacity in grid-connected and islanded operation, and the generation price. Uncertain parameters are modeled using uncertainty intervals which represent lower and upper bounds of deviations from nominal (i.e., forecasted) values. A robust optimization approach is adopted for capturing uncertainties. The robust optimization finds out the worst case solution of subproblems as uncertain parameters vary within their associated uncertainty intervals. The robust optimization ensures that the obtained solution is robust against all realization of uncertain parameters [23]-[26].

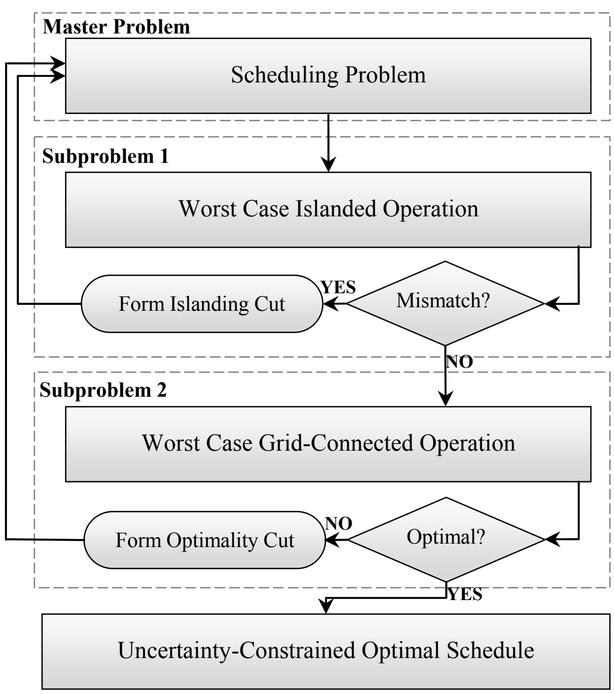

Fig. 2 Flowchart of the proposed optimal scheduling model

The proposed problem is solved for a 24-h scheduling horizon, i.e., a day-ahead schedule will be obtained. Any other scheduling horizon can be selected based on the master controller's discretion without loss of generality in the proposed model. Selection of a 24-h scheduling horizon, however, would enable microgrid master controller to benefit from day-ahead market price forecasts provided by the utility company and also keep track of the energy storage daily charging/discharging cycles. The considered time period is one hour, where schedules are obtained based on hourly operation and also the islanding duration is considered as an integer multiple of one hour. Shorter time periods could be employed to more accurately capture rapid changes in load and non-dispatchable generation as well as shorter islanding durations. The selection of a proper time period for scheduling represents a tradeoff between the solution accuracy and the computation time. Shorter time periods would analyze more data and provide more accurate solutions while increasing computation requirements.

IV. Uncertainty-Constrained Optimal Scheduling Problem Formulation

A. Component Modeling

Dispatchable units, energy storage, and adjustable loads are scheduled by the microgrid master controller. A mixed-integer programming representation of these components is required as a primary step to model microgrid scheduling problem. The component models can be found in [5], however, are briefly presented here for further use in the problem formulation. Non-dispatchable generations as well as fixed loads are obtained based on forecasts, hence treated as constants in the problem formulation.

$$P_i^{\min} I_{it} \le P_{it} \le P_i^{\max} I_{it} \qquad \forall i \in \mathrm{G}, \forall t \qquad (1)$$

$$P_{it} - P_{i(t-1)} \le UR_i \qquad \forall i \in \mathrm{G}, \forall t \qquad (2)$$

$$P_{i(t-1)} - P_{it} \le DR_i \qquad \forall i \in \mathrm{G}, \forall t \qquad (3)$$

$$T_i^{\mathrm{on}} \ge UT_i (I_{it} - I_{i(t-1)}) \qquad \forall i \in \mathrm{G}, \forall t \qquad (4)$$

$$T_i^{\mathrm{off}} \ge DT_i (I_{i(t-1)} - I_{it}) \qquad \forall i \in \mathrm{G}, \forall t \qquad (5)$$

$$P_{it} \le P_{it}^{\mathrm{dch,max}} u_{it} - P_{it}^{\mathrm{ch,min}} v_{it} \qquad \forall i \in \mathrm{S}, \forall t \qquad (6)$$

$$P_{it} \ge P_{it}^{\mathrm{dch,min}} u_{it} - P_{it}^{\mathrm{ch,max}} v_{it} \qquad \forall i \in \mathrm{S}, \forall t \qquad (7)$$

$$C_{it} = C_{i(t-1)} - P_{it} u_{it} \tau / \eta_i - P_{it} v_{it} \tau \qquad \forall i \in \mathrm{S}, \forall t \qquad (8)$$

$$C_i^{\min} \le C_{it} \le C_i^{\max} \qquad \forall i \in \mathrm{S}, \forall t \qquad (9)$$

$$T_i^{\mathrm{ch}} \ge MC_i (u_{it} - u_{i(t-1)}) \qquad \forall i \in \mathrm{S}, \forall t \qquad (10)$$

$$T_i^{\mathrm{dch}} \ge MD_i (v_{it} - v_{i(t-1)}) \qquad \forall i \in \mathrm{S}, \forall t \qquad (11)$$

$$u_{it} + v_{it} \le 1 \qquad \forall i \in \mathrm{S}, \forall t \qquad (12)$$

$$D_{dt}^{\min} z_{dt} \le D_{dt} \le D_{dt}^{\max} z_{dt} \qquad \forall d \in \mathrm{D}, \forall t \qquad (13)$$

$$\sum_{t \in [\alpha_d, \beta_d]} D_{dt} = E_d \qquad \forall d \in \mathrm{D} \qquad (14)$$

$$T_d^{\mathrm{on}} \ge MU_d (z_{dt} - z_{d(t-1)}) \qquad \forall i \in \mathrm{D}, \forall t \qquad (15)$$

The dispatchable unit generation is subject to minimum and maximum generation capacity limits (1), ramp up and ramp down rate limits (2)-(3) and minimum up and down time limits (4)-(5). A dispatchable unit can be further subject to fuel and emission limits based on the unit type.

The energy storage power is subject to charging and discharging minimum and maximum limits depending on its mode (6)-(7). The energy storage charging power is considered as negative, so the associated limits are denoted with a minus sign. Energy storage available energy is calculated based on the amount of charged/discharged power and efficiency (8) and restricted with capacity limits (9). Hourly studies are performed where the time period is considered to be 1 hour, i.e., τ =1 h. The available energy at t=1 is calculated based on the available energy at the last hour of the previous scheduling horizon. The energy storage is subject to minimum charging and minimum discharging time limits, respectively (10) and (11), which are the minimum number of consecutive hours that the energy storage should maintain charging/discharging once it changes its operational mode. It is further ensured that the energy storage is operated at one of the charging and discharging modes at every hour (12).

Adjustable loads are subject to minimum and maximum rated powers (13). Each load consumes required energy to complete an operating cycle in the time intervals specified by consumers (14). α_d and β_d respectively represent the start and end operating times of an adjustable load. Certain loads may be subject to minimum operating time which is the number of consecutive hours that a load should consume power once it is switched on (15). The proposed formulation is applicable to adjustable loads that could be curtailed (i.e., curtailable loads) or deferred (i.e., shiftable loads).

B. Problem Formulation

Master Problem: Scheduling

The master problem is proposed as follows:

$$\min \sum_t \sum_{i \in G} [c_{i0} I_{it} + SU_i + SD_i] + \sum_{d \in D} K_d \Delta_d + \Lambda \tag{16}$$

Subject to (4)-(5), (10)-(12), and (15).

The master problem objective (16) comprises three terms associated with dispatchable units, adjustable loads, and the grid-connected operation cost. The no-load, startup, and shut down costs of dispatchable units are calculated in the master problem since all are dependent only on binary commitment variables. The operation costs of the energy storage and adjustable loads are zero. The inconvenience encountered by consumers to revise their adjustable load operating time interval is considered in the second term in the objective, where $\Delta_d = (\beta_d^{\text{new}} - \alpha_d^{\text{new}}) - (\beta_d - \alpha_d)$ is the total change in the operating time interval. The inconvenience cost is represented as a penalty term times the total change in the operating time interval. This term prioritizes adjustable loads based on their criticality to be operated at the specified time interval. The last term in (16) is the grid-connected operation cost which is calculated in subproblem 2 and reflected in the master problem via optimality cuts.

The proposed master problem formulation includes only binary scheduling variables associated with dispatchable units, energy storage, and adjustable loads. Clearly, this problem will result in an all zero solution in the first iteration. This solution, however, will be revised in subsequent iterations as islanding and optimality cuts are generated in subproblems and added to the master problem for governing the master problem solution.

Subproblem 1: Islanded Operation

The objective of the islanded operation problem is to minimize power mismatches when islanded (17).

$$\max_{U} \min_{P} \; w = \sum_t (SL_{1,t} + SL_{2,t}) \tag{17}$$

Subject to (1)-(3), (6)-(9), (13)-(14), and

$$\sum_i P_{it} + P_{M,t} + P_{CM,t} + SL_{1,t} - SL_{2,t} = \sum_d D_{dt} \quad \forall t \tag{18}$$

$$-P_M^{\max} U_t \le P_{M,t} \le P_M^{\max} U_t \qquad \forall t \tag{19}$$

$$P_{CM,t}^{\min} \le P_{CM,t} \le P_{CM,t}^{\max} \qquad \forall t \tag{20}$$

The power balance equation (18) ensures that the sum of power generated by DERs, power from the main grid, and power from the coupled microgrid matches the hourly load. The energy storage power can be positive (discharging), negative (charging) or zero (idle). The main grid power can be positive (import), negative (export) or zero. The coupled microgrid power can be positive (import), negative (export) or zero. Slack variables, which are both nonnegative, characterize virtual generation and load in the provisional microgrid and represent the mismatch between the available generation and the load. The provisional microgrid power transfer with the main grid is limited by the flow limit of the associated connecting line (19). The provisional microgrid power transfer with the coupled microgrid is limited by the coupled microgrid available unused capacity limits (20). The binary outage state U_t is included in the main grid power transfer constraint to model islanded operation. When the binary outage state is set to zero the main grid power will be zero, hence the provisional microgrid is enforced to operate in the islanded mode. The power transfer with the coupled microgrid, however, could always be nonzero. Islanding is considered as an uncertain parameter in this problem, thus the worst case solution associated with islanding incidents will be obtained. The number of islanding hours, moreover, will be restricted by a limit on uncertainty option as $\sum_t U_t \le U^{\max}$, where $U^{\max}$ is the maximum number of islanding hours in the scheduling horizon.

If the objective is not zero, i.e., sufficient generation is not available to supply local loads, the islanding cut is formed and added to the master problem for revising the current schedule. The islanding cut is defined as

$$\begin{aligned} &\hat{w} + \sum_t \sum_{i \in G} \lambda_{it} (I_{it} - \hat{I}_{it}) + \sum_t \sum_{i \in S} \mu_{it}^{\text{dch}} (u_{it} - \hat{u}_{it}) \\ &+ \sum_t \sum_{i \in S} \mu_{it}^{\text{ch}} (v_{it} - \hat{v}_{it}) + \sum_t \sum_{i \in D} \pi_{dt} (z_{dt} - \hat{z}_{dt}) \le 0 \end{aligned} \tag{21}$$

where λ_{it}, μ_{it}^{dch}, μ_{it}^{ch}, π_{dt} are dual variables associated with dispatchable unit commitment states, energy storage discharging state, energy storage charging state, and adjustable load scheduling state, respectively. It is probable that after a certain number of iterations and revising the master problem solution a feasible islanding is not achieved and the power mismatch still persists. The microgrid master control will, therefore, curtail loads. This action is considered as the last resort since it causes a significant inconvenience for microgrid consumers. The microgrid master controller will simply curtail the load, equal to the power mismatch between the available generation and the load, to achieve a feasible islanding. Once curtailed, the obtained feasible schedule will be sent to the grid-connected operation problem.

Subproblem 2: Grid-Connected Operation

The objective of the grid-connected operation problem is to minimize the microgrid total operation cost (22).

$$\max_{U}\min_{P} \quad Q=\sum_{t}\sum_{i\in G} c_i P_{it} + \sum_{t}\rho_{M,t}P_{M,t} + \sum_{t}\rho_{CM,t}P_{CM,t} \tag{22}$$

Subject to (1)-(3), (6)-(9), (13)-(14), and

$$\sum_{i} P_{it} + P_{M,t} + P_{CM,t} = \sum_{d} D_{dt} - LS_t \qquad \forall t \tag{23}$$

$$-P_M^{\max} \le P_{M,t} \le P_M^{\max} \qquad \forall t \tag{24}$$

$$P_{CM,t}^{\min} \le P_{CM,t} \le P_{CM,t}^{\max} \qquad \forall t \tag{25}$$

The first term in the objective is the operation cost of dispatchable units in the provisional microgrid, which includes generation cost over the entire scheduling horizon. The no-load, startup, and shut down costs are excluded as these costs are already considered in the master problem objective. The generation cost is approximated by a single-step linear model. The second term is the cost of power transfer from the main grid based on the market price at the point of common coupling. When the provisional microgrid excess power is sold back to the main grid $P_{M,t}$ would be negative, so this term would represent a benefit rather than a cost. The last term is the cost of power transfer from the coupled microgrid. When the provisional microgrid excess power is sold back to the coupled microgrid $P_{CM,t}$ would be negative, so this term would represent a benefit rather than a cost. The power balance equation (23) ensures that the sum of power generated by DERs, power from the main grid, and power from the coupled microgrid matches the revised load, i.e., the provisional microgrid hourly load minus the load curtailment calculated in islanded operation. The provisional microgrid power transfer with the main grid is limited by the flow limits of the associated connecting line (24). The provisional microgrid power transfer with the coupled microgrid is limited by the coupled microgrid available unused capacity limits (25). Since the provisional microgrid is grid-connected, the binary outage state is not considered in (24).

The solution optimality is examined by comparing an upper bound (obtained from the grid-connected operation problem) and a lower bound (which is the solution of the master problem). The proximity of two bounds ensures solution optimality, otherwise the optimality cut (26) is generated and added to the master problem for revising the current schedule.

$$\begin{aligned}\Lambda \ge \hat{Q} &+ \sum_{t}\sum_{i\in G}\lambda_{it}(I_{it}-\hat{I}_{it}) + \sum_{t}\sum_{i\in S}\mu_{it}^{\text{dch}}(u_{it}-\hat{u}_{it}) \\ &+ \sum_{t}\sum_{i\in S}\mu_{it}^{\text{ch}}(v_{it}-\hat{v}_{it}) + \sum_{t}\sum_{i\in D}\pi_{dt}(z_{dt}-\hat{z}_{dt})\end{aligned} \tag{26}$$

where λ_{it}, μ_{it}^{dch}, μ_{it}^{ch}, π_{dt} are dual variables associated with dispatchable unit commitment states, energy storage discharging state, energy storage charging state, and adjustable load state, respectively. $\hat{Q}$ is the calculated objective value of the grid-connected operation problem.

Using robust optimization, the worst case solution of subproblems will be achieved where the objectives are represented in the form of max-min optimization. Objectives are minimized over primal variables and maximized over uncertain parameters. To solve complex max-min optimization subproblems, the dual problem of the inner minimization problem is found in each subproblem and combined with the associated maximization problem. The problem is accordingly solved for the set of dual variables and uncertain parameters [25]-[26]. The employed robust optimization captures uncertainties in load, non-dispatchable generation, market prices and islanding, as well as available unused capacity and price of the coupled microgrid. The level of uncertainty related to each uncertain parameter could be further adjusted by adding a limit on uncertainty option [27].

The proposed uncertainty-constrained optimal scheduling model is proposed for a single provisional microgrid and will be solved by its respective master controller. The coupled microgrid revenue from the optimal scheduling problem will be equal to the cost of power transfer from the coupled microgrid, as represented in the last term of (22), and will be calculated for both grid-connected and islanded modes.

V. Numerical Simulations

A provisional microgrid with three non-dispatchable units, one energy storage, and five adjustable loads is used to analyze the proposed optimal scheduling model and investigate the provisional microgrid economic operation. The problem is implemented on a 2.4-GHz personal computer using CPLEX 11.0 [28]. The characteristics of adjustable loads are given in Table I. The forecasted values for hourly fixed load, aggregated non-dispatchable generation, and market prices over the 24-h scheduling horizon are respectively given in Tables II, III and IV, with respective forecast errors of ±10%, ±20%, and ±20%. The capacity of the energy storage is 10 MWh with min-max charging/discharging power of 0.4-2 MW, respectively. A minimum charging/discharging time of 5 hours is considered for the energy storage, i.e., the minimum number of consecutive hours that the energy storage must maintain its current operational state once the operational mode is changed. The main grid power transfer limit is 10 MW.

The proposed case studies focus on the coupled microgrid available unused capacity to investigate the behavior of the provisional microgrid and calculate costs and benefits. It is assumed that the provisional microgrid requirements for power import during islanded operation are taken into account in the design process, i.e., the coupled microgrid could provide the provisional microgrid with sufficient generation for ensuring seamless islanding. The coupled microgrid maximum hourly unused capacity is assumed to be 4 MW. The amount of available unused capacity, however, is uncertain which will be considered in the provisional microgrid scheduling problem.

TABLE I
CHARACTERISTICS OF ADJUSTABLE LOADS
(S: SHIFTABLE, C: CURTAILABLE)

Load	Type	Min.-Max. Capacity (MW)	Required Energy (MWh)	Initial Start-End Time (h)	Min Up Time (h)
L1	S	0 - 0.4	1.6	11 – 15	1
L2	S	0 – 0.4	1.6	15 – 19	1
L3	S	0.02 – 0.8	2.4	16 – 18	1
L4	S	0.02 – 0.8	2.4	14 – 22	1
L5	C	1.8 - 2	47	1 – 24	24

TABLE II
MICROGRID HOURLY FIXED LOAD

Time (h)	1	2	3	4	5	6
Load (MW)	1.86	1.82	1.81	1.92	1.88	1.88
Time (h)	7	8	9	10	11	12
Load (MW)	2.16	2.33	2.39	2.51	2.58	2.59
Time (h)	13	14	15	16	17	18
Load (MW)	2.97	3.26	3.28	3.35	3.44	3.44
Time (h)	19	20	21	22	23	24
Load (MW)	3.32	3.31	2.99	2.78	2.10	2.02

TABLE III
AGGREGATED GENERATION OF NON-DISPATCHABLE UNITS

Time (h)	1	2	3	4	5	6
Power (MW)	0	0	0	0	2.52	3.20
Time (h)	7	8	9	10	11	12
Power (MW)	2.48	2.84	2.72	2.40	2.48	4.44
Time (h)	13	14	15	16	17	18
Power (MW)	4.84	6.27	4.93	5.12	4.21	3.28
Time (h)	19	20	21	22	23	24
Power (MW)	2.84	3.68	2.29	2.40	0	0

TABLE IV
HOURLY MARKET PRICE

Time (h)	1	2	3	4	5	6
Price ($/MWh)	15.03	10.97	13.51	15.36	18.51	21.80
Time (h)	7	8	9	10	11	12
Price ($/MWh)	17.30	22.83	21.84	27.09	37.06	68.95
Time (h)	13	14	15	16	17	18
Price ($/MWh)	65.79	66.57	65.44	79.79	115.5	110.3
Time (h)	19	20	21	22	23	24
Price ($/MWh)	96.05	90.53	77.38	70.95	59.42	56.68

Case 1: Base case with load, non-dispatchable generation, and market price uncertainties

The uncertainty in the power transfer with the coupled microgrid is overlooked, i.e., the provisional microgrid can import/export power from/to the coupled microgrid up to 4 MW at each scheduling hour in grid-connected and islanded modes. The worst case islanding occurs at hour 4 when the provisional microgrid does not have any local generation. The provisional microgrid is disconnected from the main grid at this hour but is still connected to the coupled microgrid. A power transfer of 3.92 MW from the coupled microgrid ensures seamless islanding where the load is fully supplied. The imported power supplies the fixed load, considering 10% uncertainty, and the curtailable load L5. The provisional microgrid total operation cost is $3066.50. Power transfers with the main grid and the coupled microgrid are depicted in Fig. 3 which respectively result in power purchase costs of $1088.53 and $1977.97. This figure exhibits that the provisional microgrid would consider the coupled microgrid as an alternative to purchase power when the main grid power is more expensive. Also in hours 12-14 when the provisional microgrid generation exceeds its load, the excess generation is sold back to the main grid to increase economic benefits and reduce the operation cost. The charging/discharging schedule of the energy storage is adjusted based on the islanding hour, in which the energy storage charging is started at hour 5 to reduce the required power to be purchased from the coupled microgrid in islanded operation. The obtained results demonstrate how uncertainties, which are considered in subproblems, would impact the scheduling decisions in the master problem. Considering only provisional microgrid economics, the energy storage must be charged at hours 1-5, however, this schedule is revised in subsequent iterations as the worst case islanding solution is identified in the islanded operation problem.

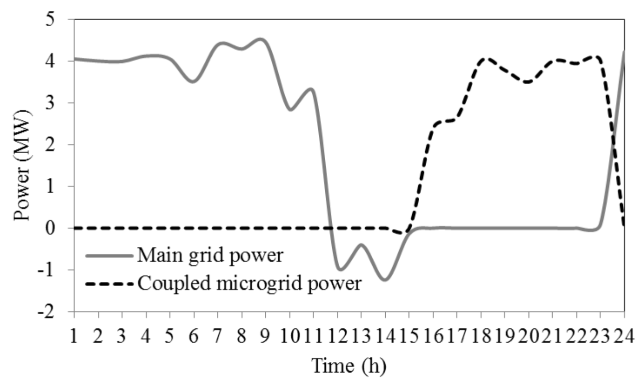

Fig. 3 Power transfers with the main grid and the coupled microgrid

Case 2: Considering uncertainty in the coupled microgrid available unused capacity

An uncertainty of 25% is considered in the coupled microgrid available unused capacity in islanded and grid-connected modes. The grid-connected schedule will differ from Case 1, where the available grid-connected power from the coupled microgrid in hours 16-23 is reduced to 3 MW. The microgrid would reschedule adjustable loads by shifting away from these hours as it is a more economical solution than purchasing relatively more expensive power from the main grid. The energy storage schedule is also changed as it is discharged in a longer period of time. The islanding, which has occurred at hour 4, results in 0.92 MW load curtailment. The total cost in this case is $3069.70 with a cost breakdown of $1188.91 power purchase from the main grid and $1880.79 power purchase from the coupled microgrid.

Comparing Cases 1 and 2, it can be concluded that the provisional microgrid could rely on the coupled microgrid grid-connected power for increasing economic benefits, and islanded power for islanding purposes. The installed generation capacity in the provisional microgrid is fully utilized without any concern regarding capacity underutilization. The cost paid for preventing underutilization is infrequent load curtailments during islanding incidents. It is noteworthy that the load curtailment is obtained considering the worst case solution under all uncertainties associated with loads, market prices, non-dispatchable generation, the coupled microgrid available unused capacity, and the time of the islanding. Thus, the obtained value represents the maximum possible load curtailment under considered assumptions and the actual value will be lower than this.

If loads are critical and require a zero load curtailment during islanding, the installed generation mix could be reinforced with dispatchable DERs. Two alternatives will be sought here to prevent the load curtailment in the islanded mode: a) using faster energy storage with a lower minimum charging/discharging time, and b) using a relatively small dispatchable unit.

Case 2-a: Employing fast charge/discharge energy storage

Using energy storage with a 2-h minimum charging/discharging time not only improves the provisional microgrid economic operation but also removes load curtailment in islanded operation. The total operation cost in this case is reduced to \$3003.00 and the load curtailment in islanded operation at hour 4 is reduced to zero. The energy storage is charged at hours 1-3 and discharged at hour 4 to provide the required power to supply local loads. The energy storage encounters three charging/discharging cycles in this case compared to only one cycle in Case 1. This study exhibits that the provisional microgrid could still rely on non-dispatchable units for grid-connected operation and benefit from fast charge/discharge energy storage to ensure seamless islanding.

Case 2-b: Addition of a 1 MW dispatchable unit

A 1 MW dispatchable unit is added to the provisional microgrid with a single step generation price of \$75/MWh. Addition of this unit will reduce the load curtailment to zero. Moreover, this unit will generate power at high price hours for reducing the power purchase from the main grid. The total operation cost is \$3047.70 including \$567.87 generation cost of the dispatchable unit. Although dispatchable unit is added to the provisional microgrid, a high percentage of the installed capacity would be non-dispatchable. Thus, the provisional microgrid would mainly rely on non-dispatchable generation and the energy storage for its economic and reliable operation.

These two cases suggest that provisional microgrids could represent a viable solution to economically supply local loads and achieve desired reliability targets while employing a high degree of non-dispatchable generation, primarily in the form of variable generation renewable energy resources. Moreover, the emission produced by the provisional microgrid is much lower than a microgrid with the same size which mainly relies on gas-fired plants. Therefore, the provisional microgrid could significantly support environmental objectives and be considered as a sustainable alternative to large-scale deployment of renewable energy resources.

VI. Discussions

Although significant social cost savings and load point reliability enhancements offered by islanding justify the islanding design as part of the microgrid planning decisions, the resultant increased investment cost, underutilization of dispatchable units, and under-deployment of renewable energy resources necessitates introduction of new classes of microgrids. Provisional microgrids are introduced in this paper to address these challenges. Specific features of provisional microgrids and the proposed optimal scheduling model are listed as follows:

- Avoiding capacity underutilization: Provisional microgrids reduce the need to build microgrids with high dispatchable generation capacity and the possibility of installed capacity underutilization. Non-dispatchable units present the majority of installed capacity in provisional microgrids which will generate power independent of market prices variations.
- Removing the need to enhance distribution network flexibility: Provisional microgrids will benefit from the available flexibility in distribution networks offered by existing microgrids. Thus, there would be no need for system operators to reinforce the distribution network flexibility by additional installations and system upgrades.
- Reduced tension on transmission and distribution networks: Provisional microgrids improve power system operational efficiency in integrating local DERs. Consequently, the tension on congested transmission and distribution networks will be reduced which will benefit system developers by deferring required system upgrades.
- Environmental impacts: Provisional microgrids address environmental concerns by enabling large and distributed penetration of emission-free variable generation renewable energy resources in distribution networks and reduce the need to employ large centralized coal and gas-fired plants.

VII. Conclusions

A new class of microgrids, called provisional microgrids, was proposed in this paper to address prevailing challenges in microgrid deployments associated with islanding requirements. An uncertainty-constrained optimal scheduling model was proposed to efficiently model the day-ahead operation of provisional microgrids considering prevailing operational uncertainties. The robust optimization was employed, where the original problem was decomposed into smaller and coordinated problems for uncertainty consideration. The proposed model was analyzed through numerical simulations, and it was shown that provisional microgrids offer economic benefits, ensure reliability, and prevent underutilization of deployed capital-intensive DERs.

In this paper the concept of provisional microgrids was introduced and the optimal scheduling model was developed for demonstrating the merits of this new class of microgrids. A more extensive discussion of provisional microgrids, however, is needed which will be studied in follow-on work. Future studies, which will be built upon the provisional microgrid concept and short-term operation developed in this paper, include but are not limited to: optimal planning of provisional microgrids with the objective of economically justifying the provisional microgrid deployment, control studies for ensuring that frequency and voltages within the provisional microgrid could be efficiently controlled and maintained within limits during grid-connected and islanded modes, calculating the distribution network hosting capacity when integrating increased levels of non-dispatchable generation via provisional microgrids, and communication studies for ensuring that the information could be reliably exchanged between provisional microgrids and coupled microgrids.

References

[1] Microgrid Exchange Group, DOE Microgrid Workshop Report, August 2011 [Online]. Available: http://energy.gov/oe/downloads/microgrid-workshop-report-august-2011

[2] M. Shahidehpour, "Role of smart microgrid in a perfect power system," *IEEE Power and Energy Society Gen. Meeting*, 2010.

[3] A. Flueck, Z. Li, "Destination perfection," *IEEE Power and Energy Mag*., vol. 6, no. 6, pp 36-47, Nov./Dec. 2008.

[4] M. Shahidehpour and J. Clair, "A functional microgrid for enhancing reliability, sustainability, and energy efficiency," *Electricity Journal*, Oct. 2012.

[5] A. Khodaei, "Microgrid optimal scheduling with multi-period islanding constraints," *IEEE Trans. Power Syst.*, accepted for publication, 2014.

[6] S. Bahramirad, W. Reder, and A. Khodaei, "Reliability-constrained optimal sizing of energy storage system in a microgrid," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 2056-2062, Dec. 2012.

[7] C. Marnay, F. Rubio, and A. Siddiqui, "Shape of the microgrid," in IEEE Power Engineering Society Winter Meeting, vol. 1, 2001, pp. 150–153.

[8] A. Meliopoulos, "Challenges in simulation and design of μgrids," in IEEE Power Engineering Society Winter Meeting, vol. 1, 2002, pp. 309–314.

[9] R. Lasseter, "Microgrids," in IEEE Power Engineering Society Winter Meeting, vol. 1, 2002, pp. 305–308.

[10] S. Chowdhury, S.P. Chowdhury, P. Crossley, Microgrids and Active Distribution Networks., IET Renewable Energy Series, 2009.

[11] H. Jiayi, J. Chuanwen, and X. Rong, "A review on distributed energy resources and MicroGrid," *Renewable and Sustainable Energy Reviews*, vol. 12, no. 9, pp. 2472-2483, 2008.

[12] N. Hatziargyriou, Microgrids: Architectures and Control, Wiley, 2014.

[13] A. Khodaei, "Resiliency-oriented microgrid optimal scheduling," *IEEE Trans. Smart Grid*, Accepted for publication, 2014.

[14] B. Kroposki, R. Lasseter, T. Ise, S. Morozumi, S. Papathanassiou, and N. Hatziargyriou, "Making microgrids work," *IEEE Power and Energy Mag.* vol. 6, no. 3, May 2008.

[15] I. Bae and J. Kim, "Reliability evaluation of customers in a microgrid", *IEEE Trans. Power Syst.*, vol. 23, no. 3, Aug. 2008.

[16] S. Kennedy, M. Marden, "Reliability of islanded microgrids with stochastic generation and prioritized load," *IEEE Powertech, Bucharest*, Jun. 2009.

[17] N. Hatziargyriou, H. Asano, M.R. Iravani, and C. Marnay, "Microgrids: An overview of ongoing research, development and demonstration projects," *IEEE Power and Energy Mag.,* vol. 5, no. 4, Jul./Aug. 2007.

[18] F. Katiraei, M.R. Iravani, "Power management strategies for a microgrid with multiple distributed generation units," *IEEE Trans. Power Syst.,* vol. 21, no. 4, Nov. 2006.

[19] C. Hou X. Hu, D. Hui, "Hierarchical control techniques applied in micro-grid," *IEEE Conf. on Power Syst. Tech. (POWERCON)*, Hangzhou, Oct. 2010.

[20] A.G. Tsikalakis, N.D. Hatziargyriou, "Centralized control for optimizing microgrids" *IEEE Trans. Energy Conv*., vol. 23, no. 1, pp. 241-248 2008.

[21] A. Khodaei and M. Shahidehpour, "Microgrid-based co-optimization of generation and transmission planning in power systems," *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 1582-1590, May 2013.

[22] R. Lasseter, "Smart distribution: Coupled microgrids," Proceedings of the IEEE, vol. 99, no. 6, pp. 1074–1082, 2011.

[23] A. Ben-Tal, and A. Nemirovski. "Robust optimization–methodology and applications." Mathematical Programming 92.3 (2002): 453-480.

[24] H. G. Beyer, and B. Sendhoff. "Robust optimization–a comprehensive survey." Computer methods in applied mechanics and engineering 196.33 (2007): 3190-3218.

[25] A. Ben-Tal, L. El Ghaoui, and A. Nemirovski. Robust optimization. Princeton University Press, 2009.

[26] D. Bertsimas, D. B. Brown, and C. Caramanis. "Theory and applications of robust optimization." SIAM review 53.3 (2011): 464-501.

[27] A. Thiele, T. Terry, and M. Epelman, "Robust linear optimization with recourse," Rapport technique, pp: 4-37, 2009.

[28] ILOG CPLEX, ILOG CPLEX Homepage 2009 [Online]. Available: http://www.ilog.com

Amin Khodaei (SM'14) received the Ph.D. degree in electrical engineering from the Illinois Institute of Technology (IIT), Chicago, in 2010. He was a visiting faculty (2010–2012) in the Robert W. Galvin Center for Electricity Innovation at IIT. He joined the University of Denver, Denver, CO, in 2013 as an Assistant Professor. His research interests include power system operation, planning, computational economics, microgrids, and smart electricity grids.