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Optimal autonomous microgrid operation: A holistic view

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HIGHLIGHTS

- An integrated framework for economical and stable microgrid operation is proposed.
- Consumer side load scheduling is accounted for while performing unit commitment.
- A real-time power balancing module for safe & reliable operation under uncertainty.
- Priority driven load shedding to avoid complete blackout.
- Fault tolerance against a DG unit failure.

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ABSTRACT

The prospects of incorporating a consumer side load-scheduling algorithm that works in conjunction with the unit commitment problem, which in turn coordinates with real-time load balancer, are discussed in this paper. An integrated framework for an autonomous microgrid with objectives of increasing stability, reliability and economy is proposed. From the microgrid operators' point of view, the load side scheduling helps reduce the stress on the system especially during peak hours thereby ensuring system stability and security. From the consumers' point of view, the dynamic electricity prices within a day, which are a reflection of this time varying stress on the system, encourage them to endorse such a scheme and reduce their bills incurred. The unit commitment problem is run a day in advance to determine generator outputs for the following day. Owing to unpredictable weather conditions, running unit commitment problem in advance does not guarantee planned real-time generation in the microgrid scenario. Such variability in forecasted generation must be handled in any microgrid, while accounting for load demand uncertainties. To address this issue a load side energy management system and power balance scheme is proposed in this paper. The objective is to ascertain uninterrupted power to critical loads while managing other non-critical loads based on their priorities.

1. Introduction

The power networks around the world are undergoing a transformation [1]. The transformation, from traditional passive distribution networks to active distribution networks with distributed energy resource (DER) penetration, is also encouraged as this augments the conventional generation sources. Another aspect of the transformation in progress is related to development, planning and management of sustainable energy systems [2,3], which rely heavily on non-conventional DERs. Generation augmentation through DERs improves overall power quality and reliability [4] and reach of power supply to remote areas [5]. Also the physical proximity of the generation sources to the load helps circumvent wasteful transmission losses. Since power is generated at low voltage, it is possible to connect a DER separately to the utility distribution network or they may be interconnected to form a microgrid (MG). MGs are usually designed to supply loads for small communities or industries. Some of the key challenges for MG operator are: (i) Economical operation of the distributed generation (DG) units, (ii) satisfactory operation of renewable energy (RE) sources and (iii) stability and control of the MG. A lot of research has been focused on addressing these concerns either in isolation or in a combined manner.

Most work focused on the MG economy rely on optimization [6,7], for example, they minimize the operational cost or maximize generation and hence export to the grid. Some stochastic optimization techniques are also employed to account for stochastic variations in the load demand. Multi-objective optimization has also been successfully applied to consider economy of operation as well as minimization of environmental impact [8,9]. Incorporating forecasting modules for load demand and RE generation (REG)

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Nomenclature

Offline optimization

A_g	conventional generator incidence matrix
A_{gr}	REG incidence matrix
A_l	load incidence matrix
CG	total number of conventional generators
$d(sl, j)$	start up status of load *sl*. It is 1 if load *sl* is connected at time *j* and 0 otherwise
$fl_{\max}(line)$	maximum power transfer capability of a line (kW)
i	indices of conventional DG unit
j	time index from 1 to *t*
$K(j)$	cost of power unit during interval *j*
l	indices of load
$line$	indices of line
L	total load aggregates
$MUT(i)$	minimum up time of *i*th DG unit (h)
$MDT(i)$	minimum down time of *i*th DG unit (h)
$MUT_r(r)$	minimum up time of *i*th REG unit (h)
$MDT_r(r)$	minimum down time of *i*th REG unit (h)
n	indices of bus
N	total number of buses
$P_{const}(sl)$	power requirement of schedulable load *sl*
$E(sl)$	energy requirement of schedulable load *sl*
$P_{inj}(n, j)$	power injected at bus *n* at instant *j*
$P_{\max}(i)$	maximum power generation of *i*th DG unit (kW)
$P_{\min}(i)$	minimum power generation of *i*th DG unit (kW)
$P_{r,\max}(r)$	maximum power generation of *r*th REG unit (kW)
$P_{r,\min}(r)$	minimum power generation of *r*th REG unit (kW)
r	indices of REG sources
R	Total number of REG sources
$R_d(i)$	ramp down constraint of *i*th DG unit (kW/h)
$R_{r,d}(r)$	ramp down constraint of *r*th REG unit (kW/h)
$R_u(i)$	ramp up constraint of *i*th DG unit (kW/h)
$R_{r,u}(r)$	ramp up constraint of *r*th REG unit (kW/h)
SL	total number of schedulable loads
sl	indices of schedulable loads
$S_{up}(i)$	start up cost of conventional generator (*i*)
$S_{dn}(i)$	shutdown cost of conventional generator (*i*)
t	time frame for which optimization is run
$T(sl)$	time needed to finish task(*sl*) or load(*sl*)
$T_d(sl)$	latest time limits exerted on task *sl*
$T_e(sl)$	earliest time limits exerted on task *sl*
$T_{on}(i, j)$	up time of *i*th DG unit at time index *j* (h)
$T_{off}(i, j)$	down time of *i*th DG unit at time index *j* (h)
$T_{r,on}(r, j)$	up time of *r*th REG unit at time index *j* (h)
$T_{r,off}(r, j)$	down time of *r*th REG unit at time index *j* (h)
$u(i, j)$	commitment status of *i*th conventional generator at time index *j*
$u_r(r, j)$	commitment status of *r*th REG unit at time index *j*
V	voltage at each bus
$X(n, k)$	reactance of line connecting bus *n* and bus *k* (Ω)
$R(n, k)$	resistance of line connecting bus *n* and bus *k* (Ω)
$x(sl, j)$	status of schedulable load *sl* at time instant *j*
x	reactance/km of line (Ω/km)
r	resistance/km of line (Ω/km)
$\delta(n)$	voltage angle at bus *n*
μ, ϕ, λ	the coefficients of the quadratic cost function of each DG set

Online optimization

$E(k)$	battery energy state (kW h)
E_0	ideal battery energy level (kW h)
$E_{\max}$	maximum battery energy limits (kW h)
$E_{\min}$	minimum battery energy limits (kW h)
f	fraction of the adjustable load that is compromised
i	index of curtailable loads
k	time index
N	total number of curtailable loads
$P_{adj}(k)$	power requirement of the adjustable load at time index *k* (kW)
$P_{cur}(i, k)$	power requirement of *i*th curtailable load at time index *k* (kW)
$P_{bat\text{-}\max}$	maximum battery power flow limits (kW)
$P_{bat\text{-}\min}$	minimum battery power flow limits (kW)
$P_{bat}(k)$	battery power flow (kW)
P_{crit}	power requirement of critical load(kW)
P_{sink}	power dissipated in the sink (kW)
s	sampling time of the online algorithm (minutes)
$u(i, k)$	status (on or off) of *i*th curtailable load at time index *k*
α	penalty for compromising adjustable load
$\beta(i)$	penalty for compromising *i*th curtailable load
γ	penalty for using the power sink
δ	penalty for deviating from set battery energy level
kW	kilowatt
kW h	kilowatt-hour
kW/h	kilowatts per hour
h	hour of the day
Ω/km	ohms/km

has been shown to further aid the optimization capabilities [10]. Some hybrid optimization techniques have also been proposed to maximize the expected profit enjoyed by the DG owners [11]. Further adaptive approach for optimal integration of distributed generators has also been looked into [12].

Another challenging aspect of a MG operation is that of RE sources. Penetration of RE sources has added to the challenges of MG operation due to their uncertain and intermittent nature. For MGs having significant RE penetration, energy management systems are becoming essential. Various approaches have been proposed to address the uncertainties in the REG, e.g. direct load control [13,14], resource scheduling [15] and optimal expansion planning [16], etc.

Management of RE sources as well as stability and control of the MG go hand-in-hand. Various control strategies, ranging from fully decentralized to a hierarchical approach, have been proposed in the literature [17,18]. Direct load control, where portions of system load are under control of the operator, has also been investigated [19]. These approaches either consider controllable loads under direct control of the operator [14] or schedule some loads based on REG profile [20]. Some load scheduling approaches are also geared toward minimizing the generation cost as well as peak-to-average ratio of the load curve [21]. Spinning reserve and/or energy storage (ES) devices are commonly employed to enhance reliability of a MG [22,23]. It has also been shown that a stable operation can be achieved in spite of REG fluctuations [24]. However, use of ES devices necessitates dedicated battery management system for proper maintenance and enhanced battery life. Thus, along with power balance, battery management must also be taken care of. These various aspects of MG operation have been studied in the literature one at a time, i.e. in isolation. However there is a need for holistic view that ensures stability, reliability as well as economy of the MG, while adequately addressing uncertainties such as, generation of RE sources, load demand and consumer behavior.

In this paper, an integrated framework is proposed that not only ensures economical and stable MG operation but also gives their consumer a choice to minimize electricity bills. Such