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Electrical hubs: An effective way to integrate non-dispatchable renewable energy sources with minimum impact to the grid

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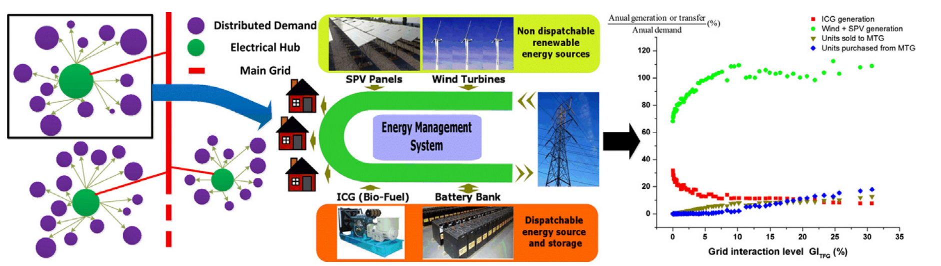
HIGHLIGHTS

- A novel method introduced to optimize Electrical Hubs.
- Novel dispatch based on fuzzy control and finite state machines.
- Evaluating sensitivity of three performance indices for system autonomy.
- Multi objective optimization considering system autonomy-cost.
- Electrical Hubs can cover above 60% of the demand using wind and Solar PV.

GRAPHICAL ABSTRACT



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ABSTRACT

A paradigm change in energy system design tools, energy market, and energy policy is required to attain the target levels in renewable energy integration and in minimizing pollutant emissions in power generation. Integrating non-dispatchable renewable energy sources such as solar and wind energy is vital in this context. Distributed generation has been identified as a promising method to integrate Solar PV (SPV) and wind energy into grid in recent literature. Distributed generation using grid-tied electrical hubs, which consist of Internal Combustion Generator (ICG), non-dispatchable energy sources (i.e., wind turbines and SPV panels) and energy storage for providing the electricity demand in Sri Lanka is considered in this study. A novel dispatch strategy is introduced to address the limitations in the existing methods in optimizing grid-integrated electrical hubs considering real time pricing of the electricity grid and curtailments in grid integration. Multi-objective optimization is conducted for the system design considering grid integration level and Levelized Energy Cost (LEC) as objective functions to evaluate the potential of electrical hubs to integrate SPV and wind energy. The sensitivity of grid curtailments, energy market, price of wind turbines and SPV panels on Pareto front is evaluated subsequently. Results from the Pareto analysis demonstrate the potential of electrical hubs to cover more than 60% of the annual electricity demand from SPV and wind energy considering stringent grid curtailments. Such a share from SPV and wind energy is quite significant when compared to direct grid integration of non-dispatchable renewable energy technologies.

1. Introduction

Integrating renewable energy technologies into the electricity grid is gradually getting popular due to rapid depletion of fossil fuel resources and global concerns on greenhouse gases emissions

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Nomenclature

Sets:
$t \in T$ set of all hours in the year
$F \in \mathcal{F}$ set of objective functions
$N \in \Gamma$ set of decision space variables related to system design
$d \in \mathcal{D}$ set of decision space variables related to control system (D: $W \cup L$)
$w \in W$ set of decision space variable related to fuzzy controller ($W \subset D$)
$l \in L$ set of all decision space variables related to secondary level controller ($L \subset D$)
$s \in S$ set of system components

Decision space variable
N^{SPV} number of SPV Panels
$N^{TY\text{-}SPV}$ type of SPV Panel
N^{W} number of wind turbines
$N^{TY\text{-}W}$ type of wind turbine
N^{Bat} number of battery banks
k type of ICG
w_{ij} weight matrix for fuzzy rules
Lim_{BC} limit cost for battery charge
Lim_{BD} limit cost for battery discharge
Lim_{GTB} limit cost for battery charge from grid
Lim_{BTG} limit cost for battery discharge to grid
SOC_{min} minimum state of charge
$SOC_{Min,G}$ minimum state of charge when discharging to grid
SOC_{Set} maximum state of charged to be reached when charging from grid

Other variables used in the model:
CRF capital recovery factor
DOD depth of discharge
FAC fixed annual cash-flow
FAC^{GI} cash flow for grid integration
ICC initial capital cost
θ_t^{SPV} SPV cell temperature
η_t^{PV} efficiency of SPV panels
F_t^{ICG} fuel consumption by ICG
G_t^{β} global tilted solar irradiation on SPV panel
LPS_t loss of power supply
$P_t^{Bat-Max}$ maximum power flow from the battery
P_t^{EG} units exported to the grid
P_t^{ELD} electricity demand of the micro grid at time step t
P_t^{ICG} power generation by ICG
P_t^{IG} units imported from the grid
P_t^{RE} power generated using renewables
P_t^{SPV} power generated from SPV panels
P_t^{W} power generated from wind turbines
x_t^k inputs to the fuzzy controller
y_t operating load factor of ICG
R^l lth implication rule for the fuzzy controller

Input Parameters for the model:
β tilt angel of SPV panels
$\eta_{W-losses}$ general power losses in wind turbine
AM air mass
A_{SPV} collector area of one SPV panel
ELD_t electricity load demand
GC_t^{EG} COE for selling electricity to MUG
GC_t^{IG} COE for purchasing electricity from MUG
P_R rated power of the turbine
v_{CI} cut-in wind speed of the turbine
v_{CO} cut-off wind speed of the turbine
v_R rated wind speed of the turbine
v_t wind speed at hub level of wind turbine

Objective functions used:
LEC levelized energy cost
GI_{EG} grid Integration level considering exports
GI_{IG} grid integration level considering imports
GI_{IEG} grid integration level considering both imports and exports

Constraints used:
EG_{Lim} maximal units sold to the grid
IG_{Lim} maximum units purchased from the grid
LOLP loss of load probability

Other acronyms used
ESP energy service provider
GI Grid Interactions
ICG internal combustion generator
SPV solar PV
SOC state of charge of battery bank
t time step
OM operation and maintenance cost
WRE waste of renewable energy
GC grid cost for electricity

and nuclear energy. Several countries have their own goals with different time lines in this regard. For example, Germany has a goal to cover 50% of the generation system using renewable energy by 2030 [1], while in Finland it is 38% by 2020 [2]. Switzerland is expected to phase-out nuclear energy by 2035 by increasing the energy efficiency and the share of renewable energy sources. In Sri Lanka, it is expected to increase the share of non-conventional renewables, such as SPV and wind energy, up to 20% by the end of 2020. Recent studies highlight that distributed generation using solar PV (SPV) and wind energy is promising to foster the renewable energy penetration in the market [3,4].

Energy systems fully driven using renewable energy sources is a dream that wider community of researchers try to make a reality [5–9]. Replacing dispatchable energy sources driven by fossil fuel through distributed SPV, wind and biomass/bio energy sources is the major challenge in this context. Mismatch in time of peak demand and generation due to stochastic nature of wind speed and solar radiation as well as of electricity demand makes the renewable energy integration process difficult [10,11]. Integration of dispatchable energy sources, energy storage and converting into hybrid renewable energy systems is a cost effective approach in increasing the reliability during the renewable energy integration process. Further, this helps to amalgamate energy sources with higher seasonal variation in energy potential [12,13] with less impact to the grid. More importantly, this is the starting point of minimizing the contribution of dispatchable energy sources based on fossil fuels, which makes existing energy systems more eco-friendly and sustainable [10,14]. However, optimum designing of such energy systems is a challenging task.

Several research groups have focused on optimizing grid-integrated hybrid energy systems. Fathima and Palanisamy [15] provides a detailed review of the major recent works on grid-integrated hybrid energy systems. Two different approaches can