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# Optimal simultaneous day-ahead scheduling and hourly reconfiguration of distribution systems considering responsive loads

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ABSTRACT

This paper develops an optimal simultaneous hourly reconfiguration and day-ahead scheduling framework in smart distribution systems considering the operation of the protection devices. The objective function of the model is defined as the minimization of system's costs in terms of the costs associated with the purchased power from the wholesale market as well as the distributed generation (DG) owners, cost of switching actions, power losses cost and the cost for implementation of demand response (DR) programs. Moreover, a novel switching index along with the maximum number of switching actions based on the switch ages and critical branches in the network is presented. Due to the nonlinearity and non-convexity nature of the problem, the proposed optimization problem is then solved using a metaheuristic approach based on particle swarm optimization (PSO). As the result of the optimization process, the optimal set-points of DGs and responsive loads together with the optimal radial configuration of the distribution system for each hour of the scheduling time horizon are determined. To investigate the effect of DR programs and hourly reconfiguration on the load profile of the system, different price-based DR actions combined with interruptible load programs are also considered. Moreover, to demonstrate the satisfactory performance of the proposed model, the IEEE 33-bus distribution test system is thoroughly interrogated.

## 1. Introduction

The application of smart meters, improved communication capabilities, real time information and simulation systems, sophisticated automation technologies, and advanced control systems is envisaged to alter the current distribution systems into smart grids. The provided infrastructure of Smart Distribution Systems (SDSs) leads to accommodate high penetration levels of active components including Distributed Generations (DGs), Responsive Loads (RLs), and Remotely Controlled Switches (RCSs). The participation of these components along with the reconfigurable topologies of SDSs will pose more complex challenges in optimal day-ahead scheduling of SDSs [1]. To this end, the purpose of this study is to present a Distribution Management System (DMS) for day-ahead scheduling of existing active components.

Widespread implementation of RCSs in SDSs has now realized the hourly reconfiguration [2,3] as a practical solution. Beforehand, the reconfiguration of distribution system has been thoroughly assessed in long-term fashions (seasonal, annual) [4,5] considering different operational objectives, namely, total power losses reduction [6], voltage profile enhancement [7], and reliability improvement [8]. Distribution system reconfiguration is a process to identify the best radial topology for a distribution system by managing the close or open status of sectionalizing and tie switches in order to optimize an objective function. In [9], a bi-level approach for optimal day-ahead scheduling of DGs in an active distribution system has been proposed. In the first phase, the amounts of purchased power from the wholesale market and the state of DGs are specified, and in the second phase, real-time scheduling coordinated with hourly reconfiguration of the distribution system is proposed. In [10], a simultaneous reconfiguration and DG allocation method in a distribution system is proposed. The Genetic Algorithm (GA) has also been utilized to obtain the optimal configuration of the distribution feeders with the objective of minimizing the total losses. Likewise, Souza, et al. [11] solved combinatorial reconfiguration problem of distribution systems using artificial immune algorithm considering variable electrical demand.

Considering practical issues of operation and guaranteeing the acceptable lifetime for RCSs, the maximum daily allowable switching actions as a constraint and switching cost as an objective function should be taken into account in the hourly reconfiguration problem of SDSs, which have not been considered in [9–11]. In [12], a fuzzy-based

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## Nomenclature

### Indices and sets

| | |
|---|---|
| $t$ | Index of hour ($t = 1, 2, ..., T$). |
| $i, j$ | Index of bus ($i, j = 1, 2, ..., N_{bus}$). |
| $n$ | Index of number of devices at each bus ($n = 1, 2, ..., N_{device}$). |
| $m$ | Index of DGs ($m = 1, 2, ..., M$). |
| $br$ | Index of branches ($br = 1, 2, ..., N_{br}$). |
| $p$ | Index of particles ($p = 1, 2, ..., N_p$). |
| $k$ | Index of iterations. |

### Parameters

| | |
|---|---|
| $\rho_{i,t}^{th}$ | Price threshold. |
| $P_i^{IL,\max}$ | Maximum curtailable power of bus $i$ (MW). |
| $T_i^{IL,\max}$ | Maximum daily allowable curtailable hours of bus $i$. |
| $P_{i,n}^{sh,av}$ | Average power of shiftable load $n$ at bus $i$ in hour $t$ (MW). |
| $\alpha_i$ | System inertia constant of air conditioner. |
| $R_i$ | Thermal resistance of air conditioner. |
| $C_i$ | Thermal capacitance of air conditioner. |
| $\eta_i$ | Efficiency factor of air conditioner. |
| $r_{br}$ | Resistance of branch $br$. |
| $K_q^{DG}$ | Reactive power pricing coefficient of DGs. |
| $K_q^{IL}$ | Reactive power pricing coefficient of IL |
| $\rho^{loss}$ | Price for power losses ($/MWh). |
| $\rho^{SW}$ | Price of each switching action ($). |
| $\rho_{m,t}^{DG}$ | Contracted price between DG $m$ and the DSO at time $t$ ($/MWh). |
| $\rho_t^{WM}$ | Day-ahead wholesale market electricity price at time $t$ ($/MWh). |
| $\rho_t^{IL}$ | Payments to ILs at time $t$ ($/MWh). |
| $N_{br,max}^{SW}$ | Maximum allowable number of switching actions. |
| $C_{1,2}$ | The learning coefficients. |
| $r_{1,2}$ | Random numbers selected between 0 and 1. |
| $W^k$ | Inertia weight factor in iteration $k$. |
| $\mathrm{I}_{br,t}^{p}$ | Pickup current of protection devices |
| $Iter_{\max}$ | Maximum allowable number of iterations. |
| $N_{\max}$ | The possible maximum number of switching operations |
| $\mathrm{MCT}_m$ | Maximum clearing time of the main fuse (s). |
| $\mathrm{MMT}_b$ | Minimum melting time of the backup fuse (s). |
| $\mathrm{P}_{i,n,t}^{adac}$ | Power of $n^{th}$ air conditioner at bus $i$ in time $t$ (MW). |
| $Iter_k$ | Number of iterations. |
| $P_{i,n,t}^{sh}$ | Power of shiftable load $n$ at bus $i$ in hour $t$ (MW). |
| $P_{i,t}^{IL}$ | Curtailed power of bus $i$ at hour $t$ (kW). |
| $P_{i,n,t}^{adil}$ | Power of $n^{th}$ illumination load of bus $i$ at time $t$ (MW). |
| $C_t^{loss}$ | Cost of power losses at time $t$ ($). |
| $C_t^{SW}$ | Cost of switching actions for RCSs at time $t$ ($). |
| $C_t^{DG}$ | Cost of purchasing power from DGs at time $t$ ($). |
| $C_t^{WM}$ | Cost of exchanging power with wholesale market at time $t$ ($). |
| $C_t^{DR}$ | Cost of participating IL in DR at time $t$ ($). |
| $T_{i,n,t}^{set,max}$ | Adjusted temperature set point of $n^{th}$ air conditioner of bus $i$ at time $t$ (°C). |
| $T_{i,n,t}^{set,base}$ | Base temperature set point of $n^{th}$ air conditioner of bus $i$ at time $t$ (°C). |
| $P_{i,n,t}^{adil,base}$ | Base power of $n^{th}$ illumination load of bus $i$ at time $t$ (MW). |
| $P_{i,n,t}^{adil,\min}$ | Adjusted power of $n^{th}$ illumination load of bus $i$ at time $t$ (MW). |
| $T_i^{in,\min}/T_i^{in,\max}$ | Minimum/ maximum indoor temperature of bus $i$ (°C). |
| $T_{i,t}^{out}$ | Outdoor temperature at time $t$ (°C). |
| $CD_{i,n}$ | Cycle duration of shiftable load $n$. |
| $Z_{i,n,t}^{sh,on}$ | Total operated hours of shiftable load $n$ at bus $i$. |
| $t_{op}$ | Operation time of the relay (s). |
| $T_m$ | Marginal coordination time of relay and fuses (s). |

### Variables

| | |
|---|---|
| $T_{i,t}^{adac}$ | Temperature adjustment of air conditioner in working mode at time $t$ (°C) |
| $T_{i,n,t}^{set}$ | Temperature set point of $n^{th}$ air conditioner at bus $i$ in time t (°C). |
| $T_{i,t}^{in}$ | Indoor temperature at time $t$ (°C). |
| $I_{i,n,t}^{sh}$ | Binary variable showing the status of shiftable load $n$ at bus $i$ in time $t$ (1: when the load is on). |
| $I_{i,t}^{IL}$ | Binary variable showing the status of IL of bus $i$ at time $t$ (1: the load is curtailed). |
| $\mathrm{I}_{i,n,t}^{adil}$ | Binary variable showing the status of illumination load $n$ of bus $i$ at time $t$ (1: when the hourly price is higher than price threshold). |
| $I_{i,n,t}^{adac}$ | Binary variable showing the status of air conditioner $n$ at bus $i$ in time $t$ (1: when the hourly price is higher than price threshold). |
| $I_{br,t}$ | Current of branch $br$ at time $t$ (kA). |
| $X_{br,t}$ | Binary variable showing the status of branch $br$ at time $t$ (1: when the related RCS is closed) |
| $P_{m,t}^{DG}$ | Output power of DG $m$ at time $t$ (MW). |
| $P_t^{WM,b}/P_t^{WM,s}$ | Day-ahead active power purchased/sold from/to wholesale market at time $t$ (MW). |
| $P_{i,n,t}^{IL}$ | The amount of curtailed active power of IL $n$ at bus $i$ in time $t$ (MW). |
| $Q_{i,n,t}^{IL}$ | The amount of curtailed reactive power amount of IL $n$ at bus $i$ in time $t$ (MW). |
| $P_{i,t}^{fix}$ | Active power of fixed load at bus $i$ in time $t$ (MW). |
| $Q_{i,t}^{fix}$ | Reactive power of fixed load at bus $i$ in time $t$ (MW). |
| $Y_{ij}/\theta_{ij}$ | Magnitude/phase of impedance between bus $i$ and $j$. |
| $V_{i,t}/\delta_{i,t}$ | Voltage magnitude/phase of bus $i$ at time $t$. |
| $S_t^{WM}$ | Amount of exchanged power between wholesale market and DSO at time $t$ (MW). |
| $X_p^k$ | Postion of particle $p$ in iteration $k$. |
| $V_p^k$ | Velocity of particle $p$ in the iteration $k$. |
| $Gbest^k$ | Global best in iteration $k$. |
| $Pbest_p^k$ | Personal best of particle $p$ in iteration $k$. |
| $F_{\max}/F_{\min}$ | Maximum/Minimum amount of objective function among all particles in the initial population. |
| $I_{br,t}^{F\min}$ | Minimum fault current |

parallel GA has been proposed for short-term reconfiguration of the 119-bus SDS where loss minimization, voltage profile improvement and the number of switching have been considered as objective functions. In [13], hybrid Particle Swarm Optimization (PSO) approach has been presented to solve the formulated Mixed Integer Non-Linear Programming (MINLP) problem. The target was to find the optimal day-ahead scheduling of controllable switches and all DGs in order to minimize the comprehensive cost function including the cost of power losses and switching cost in a distribution system. Jabbari, et al. [14] proposed a simultaneous probabilistic hourly reconfiguration and unit commitment model to achieve optimal set points of the DGs in the micro-grid. The objective function of the optimization problem including system loss cost, electricity cost of wholesale market, electricity cost of DGs, and switching cost was solved using PSO algorithm.

Authors of the aforementioned literature [12–14] have underlined the remarkable technical improvements and monetary savings of simultaneous short-term scheduling and hourly reconfiguration through RCSs. However, these research works have dismissed the participation