Supplementary Material of "An Evolutionary Optimization-Learning Hybrid Algorithm for Energy Resource Management"

Rui Qi, *Student Member, IEEE,* Ya-Hui Jia, *Member, IEEE,* Wei-Neng Chen, *Senior Member, IEEE,* Ying Bi, *Member, IEEE,* Yi Mei, *Senior Member, IEEE*

I. The mathematical model of risk-based energy resource management

Risk-based energy resource management (ERM) is modeled as a mixed-integer nonlinear programming model, using a multi-period optimization approach [1], [2]. The mathematical model for risk-based ERM is represented by the following notations and formulas, as detailed in [3].

Indexs:

s	Index of scenario.
t	Index of period.

Sets:

Ω_{DG}	Set of distributed generation (DG) units.
Ω_{DG}^{d}	Subset of dispatchable DG units. (nonrenewable energy generation units).
Ω_{DG}^{nd}	Subset of non-dispatchable DG units (renewable energy generation units).

Parameters:

N_s	Total number of scenarios.
N_t	Total number of periods.
N_i	Total number of DG units.
N_k	Total number of demand response (DR) units.
N_o	Total number of external supplier (EXT) units.
N_v	Total number of electric vehicles (EVs) units.
N_e	Total number of energy storage systems (ESSs) units.
N_m	Total number of electricity markets (EM) units.
N_r	Total number of non-supplied demand (NSD) units.
ρ_s	Scenario probability.
α	Confidence level.
ξ	Penalty coefficient.
$C_{i,t}^{DG}$	Cost of the ith DG unit generation at t (m.u./MWh).
$C_{k,t}^{DR}$	Cost of the kth DR unit generation at t (m.u./MWh).
$C_{o,t}^{EXT}$	Cost of the oth EXT unit generation at t (m.u./MWh).
$C_{i,t}^{EAP}$	Cost of the ith non-dispatchable DG unit excess available power (EAP) at t (m.u./MWh).
$C_{r,t}^{NSD}$	Cost of the rth NSD unit at t (m.u./MWh).
$C_{e,t}^{ESS}$	Cost of the eth ESS unit discharge at t (m.u./MWh).
$C_{v,t}^{EV}$	Cost of the vth EV unit discharge at t (m.u./MWh).
$C_{m,s,t}^{EM}$	Price of the mth electricity market at period t in scenario s (m.u./MWh).
$UB_{d,s,t}$	Upper bound active power generation of the dth unit at period t in scenario s (MW).
$LB_{d,s,t}$	Lower bound active power generation of the dth unit at period t in scenario s (MW).
$P_{k,s,t}^{Load}$	Forecasted active power of the kth load at period t in scenario s (MW).
$P_{i,s,t}^{nd}$	Active power generation of the ith non-dispatchable DG unit at period t in scenario s (MW).
$LB_{i,t}^{DG_d}$	Minimum active power of the ith dispatchable DG unit at period t (MW).
$UB_{i,t}^{DG_d}$	Maximum active power of the ith dispatchable DG unit at period t (MW).
$LB_{o,t}^{EXT}$	Minimum active power of the ith EXT unit at period t (MW).
$UB_{o,t}^{EXT}$	Maximum active power of the ith EXT unit at period t (MW).
$LB_{e,t}^{ESS}$	Minimum active discharging power of the eth ESSs at period t (MW).
$UB_{e,t}^{ESS}$	Maximum active charging power of the eth ESSs at period t (MW).
$\eta_{e}^{ESS_c}$	Charging efficiency of the eth ESS.
$\eta_{e}^{ESS_d}$	Discharging efficiency of the eth ESS.
$E_{e,s,t}^{ESS}$	Stored energy in the eth ESS at period t (MWh).
$E_{e}^{ESS_{min}}$	Minimum stored energy in the eth ESS (MWh).
$E_{e}^{ESS_{max}}$	Maximum stored energy in the eth ESS (MWh).
$LB_{v,t}^{EV}$	Minimum active discharging power of the vth EV at period t (MW).
$UB_{v,t}^{EV}$	Maximum active charging power of the vth EV at period t (MW).
$\eta_{e}^{EV_c}$	Charging efficiency of the eth EV.
$\eta_{e}^{EV_d}$	Discharging efficiency of the eth EV.

$E^{EV}_{v,s,t}$ Stored energy in the vth EV at period t in scenario s (MW).
$E^{EV_{min}}_{v}$ Minimum stored energy in the vth EV (MWh).
$E^{EV_{max}}_{v}$ Maximum stored energy in the vth EV (MWh).
$UB^{DR}_{k,t}$ Maximum active load reduction power in the kth DR at period t (MW).
$LB^{EM}_{e,t}$ Maximum active power sell from the eth EM at period t (MW).
$UB^{EM}_{e,t}$ Maximum active power buy from the eth EM at period t (MW).

Variables:

f^{Co}_{s} Operational cost in scenario s (m.u.).
f^{In}_{s} Operational income in scenario s (m.u.).
f^{Pe}_{s} Penalty for bound violation in scenario s (m.u.).
f_{s} Net operational cost in scenario s (m.u.).
f^{Ex} Expected cost (m.u.).
$P^{DG_d}_{i,t}$ Active power generation of the ith dispatchable DG unit at period t in scenario s (MW).
$P^{DG_{nd}}_{i,s,t}$ Active power generation of the ith non-dispatchable DG unit at period t in scenario s (MW).
$P^{DR}_{k,t}$ Active power generation of the kth DR unit at period t (MW).
$P^{EXT}_{o,t}$ Active power generation of the kth EXT unit at period t (MW).
$P^{EV}_{v,t}$ Active power generation of the vth EV unit at period t (MW).
$P^{EAP}_{i,s,t}$ Active power generation of the ith EAP unit at period t in scenario s (MW).
$P^{NSD}_{r,s,t}$ Active power generation of the rth NSD unit at period t in scenario s (MW).
$P^{ESS}_{e,t}$ Active power generation of the eth ESS unit at period t (MW).
$ESS^{cost}_{e,t}$ Discharging cost of the eth ESS unit at period t (m.u.).
$EV^{cost}_{v,t}$ Discharging cost of the vth ESS unit at period t (m.u.).
$P^{EM}_{m,t}$ Active power traded in the mth EM unit at period t (MW).
$P_{d,s,t}$ Active power generation of the dth unit at period t in scenario s (MW).
$E^{ESS}_{e,s,t}$ Stored energy in the eth ESS at period t in scenario s (MWh)
$E^{EV}_{e,s,t}$ Stored energy in the eth EV at period t in scenario s (MWh)
$x^{DG}_{i,t}$ Binary variable of the ith DG unit in period t.
$x^{EXT}_{o,t}$ Binary variable of the oth EXT unit in period t.

Model

$$\min F = f^{Ex} + \beta \cdot CVaR_{\alpha}(\Gamma) \tag{1}$$

s.t.

$$f_s = f^{Co}_s - f^{In}_s + f^{Pe}_s \tag{2}$$

$$\Gamma = \bigcup_{s=1}^{N_s} f_s \tag{3}$$

$$f^{Ex} = \sum_{s=1}^{N_s} (\rho_s \cdot f_s) \tag{4}$$

$$VaR_{\alpha}(\Gamma) = \sigma(\Gamma) \cdot \textit{z-score}(\alpha) \tag{5}$$

$$\varphi_s = \begin{cases} f_s - f^{Ex} - VaR_{\alpha}(\Gamma) & ,if\ f_s \geq f^{Ex} + VaR_{\alpha}(\Gamma) \\ 0 & ,otherwise \end{cases} \tag{6}$$

$$CVaR_{\alpha}(\Gamma) = VaR_{\alpha}(\Gamma) + \frac{1}{1-\alpha} \sum_{s=1}^{N_s} \rho_s \cdot \varphi_s \tag{7}$$

$$f^{Co}_s = \sum_{t=1}^{N_t} \begin{bmatrix} \sum_{i\in\Omega^d_{DG}} P^{DG_d}_{i,t} \cdot C^{DG}_{i,t} + \sum_{i\in\Omega^{nd}_{DG}} P^{DG_{nd}}_{i,s,t} \cdot C^{DG}_{i,t} + \\ \sum_{k=1}^{N_k} P^{DR}_{k,t} \cdot C^{DR}_{k,t} + \sum_{o=1}^{N_o} P^{EXT}_{o,t} \cdot C^{EXT}_{o,t} + \\ \sum_{e=1}^{N_e} ESS^{cost}_{e,t} + \sum_{v=1}^{N_v} EV^{cost}_{v,s,t} + \\ \sum_{i\in\Omega^{nd}_{DG}} P^{EAP}_{i,s,t} \cdot C^{EAP}_{i,t} + \sum_{r=1}^{N_r} P^{NSD}_{r,s,t} \cdot C^{NSD}_{r,t} \end{bmatrix}, \forall s \tag{8}$$

$$ESS^{cost}_{e,t} = \begin{cases} \sum_{e=1}^{N_e} P^{ESS}_{e,t} \cdot C^{ESS}_{e,t} & ,if P^{ESS}_{e,t} \leq 0 \\ 0 & ,otherwise \end{cases} \tag{9}$$

$$EV^{cost}_{v,t} = \begin{cases} \sum_{v=1}^{N_v} P^{EV}_{v,t} \cdot C^{EV}_{v,t} & ,if P^{EV}_{v,t} \leq 0 \\ 0 & ,otherwise \end{cases} \tag{10}$$

$$f^{In}_s = \sum_{t=1}^{N_t} \sum_{m=1}^{N_m} P^{EM}_{m,s,t} \cdot C^{EM}_{m,s,t}, \forall s \tag{11}$$

$$f^{Pe}_s = \xi \cdot \sum_{t=1}^{N_t} \sum_{d=1}^{N_D} \begin{pmatrix} \max(0, P_{d,s,t} - UB_{d,s,t}) + \\ \max(0, LB_{d,s,t} - P_{d,s,t}) \end{pmatrix}, \forall s \tag{12}$$

$$N_D = N_i + N_k + N_o + N_v + N_e + N_m + N_r \tag{13}$$

$$LB^{DG_d}_{i,t} \cdot x^{DG}_{i,t} \leq P^{DG_d}_{i,t} \leq UB^{DG_d}_{i,t} \cdot x^{DG}_{i,t}, \forall i \in \Omega^d_{DG}, t \tag{14}$$

$$P^{DG_{nd}}_{i,s,t} = P^{nd}_{i,s,t} \cdot x^{DG}_{i,t}, \forall i \in \Omega^{nd}_{DG}, t, s \tag{15}$$

$$LB^{EXT}_{o,t} \cdot x^{EXT}_{o,t} \leq P^{EXT}_{o,t} \leq UB^{EXT}_{o,t} \cdot x^{EXT}_{o,t}, \forall o, t \tag{16}$$

$$-LB_{e,t}^{ESS} \leq P_{e,t}^{ESS} \leq UB_{e,t}^{ESS}, \forall e, t \tag{17}$$

$$E_{e,s,t}^{ESS} = E_{e,s,t-1}^{ESS} + \eta_e^{ESS_c} \cdot P_{e,t}^{ESS} - \frac{1}{\eta_e^{ESS_d}} \cdot P_{e,t}^{ESS}, \forall e, t, s \tag{18}$$

$$\begin{bmatrix} \sum_{i \in \Omega_{DG}^{d}} P_{i,t}^{DG_d} + \sum_{o=1}^{N_o} P_{o,t}^{EXT} + \\ \sum_{i \in \Omega_{DG}^{nd}} (P_{i,s,t}^{DG_{nd}} - P_{i,s,t}^{EAP}) + \\ \sum_{k=1}^{N_k} (P_{k,t}^{DR} - P_{k,s,t}^{Load}) + \\ \sum_{e=1}^{N_e} P_{e,t}^{ESS} + \sum_{v=1}^{N_v} P_{v,t}^{EV} + \\ \sum_{r=1}^{N_r} P_{r,s,t}^{NSD} + \sum_{m=1}^{N_m} P_{m,t}^{EM} \end{bmatrix} = 0, \forall s \tag{19}$$

$$E_{e,t}^{ESS_{min}} \leq E_{e,s,t}^{ESS} \leq E_e^{ESS_{max}}, \forall e, t, s \tag{20}$$

$$-LB_{v,t}^{EV} \leq P_{v,t}^{EV} \leq UB_{v,t}^{EV}, \forall v, t \tag{21}$$

$$E_v^{EV_{min}} \leq E_{v,s,t}^{EV} \leq E_v^{EV_{max}}, \forall v, t, s \tag{22}$$

$$E_{v,s,t}^{EV} = E_{v,s,t-1}^{EV} + \eta_v^{EV_c} \cdot P_{v,t}^{EV} - \frac{1}{\eta_v^{EV_d}} \cdot P_{v,t}^{EV}, \forall v, t, s \tag{23}$$

$$P_{k,t}^{DR} \leq UB_{k,t}^{DR}, \forall k, t \tag{24}$$

$$-LB_{m,t}^{EM} \leq P_{m,t}^{EM} \leq UB_{m,t}^{EM}, \forall m, t \tag{25}$$

In the risk-based ERM formulation, the task is to determine the optimal values of N_i for DG, N_k for DR, N_o for EXT, N_v for EVs, N_e for ESS, N_m for EM, and N_r NSD in each period, with the aim of minimizing the evaluation metrics F in (1). This metric consists of two components: the expected operation costs f^{Ex} and $\beta \cdot CVaR_\alpha(\Gamma)$. For each scenario s, a cost-benefit analysis is executed. The difference between the operational costs f_s^{Co} and the income f_s^{In}, plus the penalty for bound violations f_s^{Pe} constitutes amended operation costs f_s. Then, the set Γ is constructed by (3). In (4), the expected operation cost f^{Ex} is calculated, taking into account the probability of various scenarios. In (5), VaR_α at a $\alpha = 95\%$ is calculated by the standard deviation of the amended operation costs $\sigma(\Gamma)$ and z-score obtained from MATLAB's *norminv()* function. (6) shows that if f_s exceeds $f^{Ex} + VaR_\alpha(\Gamma)$, φ indicates an extreme scenario (with a probability of $1-\alpha$); otherwise, $\varphi = 0$. In (7), $CVaR_\alpha$ is calculated by adding VaR_α and an extra penalty to the extreme scenarios.

The formulation incorporates several key constraints. The generation limits of dispatchable DG are captured by (14). (15) quantifies the non-dispatchable generation, encompassing resources such as wind and photovoltaic power, under varying scenarios. External supply resources are constrained by (16), while (17) shows discharge limits on energy storage systems. The battery balance constraint, which governs the remaining electricity level, is represented by (18). (19) showcases the active power balance constraint, ensuring the equilibrium between generation and demand. The storage system's battery capacity is restricted by (20), (21)-(22) delineates the battery balance and capacity limits for EVs. Demand response programs are accounted for through the maximum load reduction constraint in (24). Finally, (25) limits the amount of electricity that can be traded with the EM, ensuring that buy or sell adheres to specified bounds.

References

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[3] J. Almeida, J. Soares, F. Lezama, and Z. Vale, "Robust energy resource management incorporating risk analysis using conditional value-at-risk," *IEEE Access*, vol. 10, pp. 16 063–16 077, 2022.