Proactive Resilience Enhancement for Flexible Distribution Networks Containing Data Centers with Multiple Fault Phases Coupling

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NOMENCLATURE

Sets

Ω_L	Set of lines.
Ω_L^T	Set of tie lines (SOP candidate lines).
Ω_N	Set of nodes.
Ω_N^{DG}	Set of distributed generator (DG) nodes.
Ω_N^{IDC}	Set of data center (IDC) nodes.
Ω_N^{SS}	Set of substation nodes.

Parameters

β_i^{CE}	Constant power consumption of the cooling equipment at data center node i.
β_i^{RP}	Fixed power consumption of IT equipment at data center node i.
λ_i^{TL}, λ_i^{SL}	The proportion of temporal/spatial transferable workload in the total workload at IDC node i.
μ	Average service rate of servers in data center.
ω_i	The importance level of load at node i.
c^{RCS}, c^{SOP}	Annual deployment cost of RCS/SOP.
c^{TL}, c^{SL}	Demand response cost of temporal/spatial workload management.
c^{Voll}	Value of lost load (VOLL), representing the cost of unmet demand.
D_b	Delay tolerance time of delay-sensitive workload.
$F_{ij,c}^L$	Indicator of line ij failure in scenario c, which takes the value 1 if a fault occurs and 0 if the line is normal.
k_i^{PCS}	Cost of power consumption of IT equipment with each activated server.
k_i^{PUE}	Power usage effectiveness (PUE) coefficient for the data center at IDC node i, reflecting the efficiency of power use.
T_{DD}, T_{RI}, T_{SR}	Duration of the degradation phase, remote isolation phase, service restoration phase.
V_i^0	Value of lost load (VOLL), representing the cost of unmet demand.

Variables

C_I	Total investment cost for deploying smart switches (RCS and SOP).
C_O	Operational cost of DC-DR.
C_R	Total expected cost of load loss across all fault scenarios and management phases.
$P_{i,PD}$, $Q_{i,PD}$	Active/reactive power injection at node i during the pre-disaster stage, including substation, DG, SOP, and load components.
$P_{ij,PD}$, $Q_{ij,PD}$	Active/reactive power flow on line ij during the pre-disaster stage, based on the linearized DistFlow model.
$U_{i,PD}$	The square of voltage magnitude at node i during the pre-disaster stage.
$P_{i,PD}^{SS}$, $Q_{i,PD}^{SS}$	Active/reactive power injected by the substation at node i during the pre-disaster stage.
$P_{i,PD}^{DG}$, $Q_{i,PD}^{DG}$	Active/reactive power generated by the distributed generator (DG) at node i during the pre-disaster stage.
$P_{i,PH,c}$, $Q_{i,PH,c}$	Active/reactive power injection at node i during phase PH of fault scenario c.
$U_{i,PH,c}$	The square of voltage magnitude at node i during phase PH of fault scenario c.
$\Delta P_{i,PH,c}^{LS}$, $\Delta Q_{i,PH,c}^{LS}$	Load shedding of active/reactive power at node i during phase PH of fault scenario c.
$z_{ij,PD}$	Binary variable indicating the status of line ij during the pre-disaster stage (1 if connected, 0 if disconnected).
$z_{ij,DD,c}$	Binary variable indicating the status of line ij during the degradation phase (DD) at fault scenario c.
$z_{ij,RI,c}$	Binary variable indicating the status of line ij during the remote isolation phase (RI).
$z_{ij,SR,c}$	Binary variable indicating the status of line ij during the service restoration phase (SR).
$f_{i,PH,c}$	Binary variable indicating whether node i is in the fault area during phase PH of fault scenario c.
$\alpha_{i,PH,c}$	Binary variable indicating whether load at node i is picked up during phase PH of fault scenario c.
x_{ij}^{RCS}	Binary variable indicating the deployment of a remote-controlled switch (RCS) on line ij.
x_{ij}^{SOP}	Binary variable indicating the deployment of a soft-open point (SOP) on line ij.
S_i	Number of active servers at data center node i, related to workload processing.
$h_{ij,PD}^p$,$h_{ij,PD}^n$	Non-negative continuous auxiliary variables.