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Abstract: Large-scale power distribution networks rely on the wide-area control (WAC) function to conduct daily grid operations. Grid control is even more critical during extreme events as the WAC function is required to orchestrate the response to contingencies and enhance the power system resilience through failure localization, isolation, and service restoration. Both power and telecommunication domains are involved in control applications, giving rise to multiple cyber-physical interdependencies. This paper proposes a resilience-based optimization of the distribution service restoration (DSR) by coordinating strategies of crew dispatch and manual/remote switches operation. The telecommunication service and underlying infrastructure are identified as main enablers of the co-optimization as all considered resilience strategies communicate with the control center that collects crisis management information. Therefore, the availability of telecom points in terms of power supply is examined in this work. Failure propagation in the coupled power-telecom network is highlighted, and differences in failure propagation between overhead and underground power lines are explored. The proposed approach is formulated as a mixed-integer linear programming (MILP) model, evaluated under a multi-feeder interdependent power-telecom test network. Results show that combined scheduling of resilience strategies as well as prioritization of power supply to telecom points-of-interest, yield an enhanced recovery strategy.

Keywords: Wide Area Control, Resilience, Distribution Service Restoration, Extreme Event, MILP.

NOMENCLATURE

Sets

N	All power nodes (HV/MV SS, MV buses)
SS	HV/MV Substations
Fx, W	Fixed, Wireless Telecom operator access points
RR	Utility-owned radio relays
$n(j)$	Neighbor nodes of node j
$n_M(l)$	Neighbor manual lines of line l
$L,\ SW$	All power lines, switches in lines
L^M	Manually switchable lines
F	Failures of power lines
DP	Depots
RC, MC	Repair crews, manual switching crews

Parameters

M	Large number
r_{ij}, x_{ij}	Resistance, Reactance of line (i,j)
P^{max}	Total active power demand
Q^{max}	Total reactive power demand
f_{ij}	1 if failure in line (i,j), 0 otherwise
f_i	1 if failure at telecom access point i, 0 otherwise
Res^l	Demand of repair resources from faulted line l
Res^{dp}	Repair resources available at depot dp
RT_l, MT_l	Repair, manual switching time of damage l, $RT_l \geq 1$
TT_{lm}	Travel time between l and m (depot or failed line) Manual switching/isolation time of line l
p_i^{disc}	Active battery discharge power of node i
s_i	Binary parameter. 1 if i is HV/MV SS, 0 otherwise
p_i^d, q_i^d	Active, Reactive power demand of node i

Variables

$sw_{ij,t}$	1 if switch at $l=(i,j)$ is closed at t, 0 otherwise
$p_{ij,t}, q_{ij,t}$	Active, Reactive power flow of line (i,j) at time t
$p_{i,t}^{sd}, q_{i,t}^{sd}$	Loss of active/Reactive load at node i at time t
$v_{i,t}$	Voltage magnitude at node i
$d_{ij,t}$	1 if power flows from i to j at t, 0 otherwise
$a_{ij,t}$	1 if line $l=(i,j)$ is available at time t, 0 otherwise
$a_{i,t}^e, y_{i,t}^e$	1 if bus i is available, energized at time t, 0 otherwise
$rr_{i,t}^c$	1 if telecom service (TS) from utility-owned radio relay i is available at t, 0 otherwise
$ss_{i,t}^c$	1 if TS of HV/MV SS i is available at t, 0 otherwise
$T_{i,t}^c$	1 if communication service from the telecom operator access point i is available at t, 0 otherwise
$T_{i,t}^e$	1 if electricity supply for the telecom operator access point i is available at t, 0 otherwise
E_i^{max}	Maximum energy storage of the battery of node i
$E_{i,t}$	Energy storage of the battery at node i at t
$b_{i,t}$	1 if the battery of node i is not empty at t, 0 otherwise
$rc_{l,t}^{dp,k}$, $mc_{l,t}^{dp,k}$	1 if line l is being repaired by repair crew, manual switching crew k of depot dp at time t, 0 otherwise

1. INTRODUCTION

Generalized deployment of wide-area measurement systems (WAMS) boosted WAC applications of monitoring, oscillation damping, voltage control, wide-area protection, and disturbance localization, isolation and mitigation

(Chakrabortty and Khargonekar, 2013). In case of extreme events, the WAC contributes to the DSR by maintaining essential system functions and coordinating the recovery process. Resilience-based optimization gained interest in recent years at distribution grid level, where operators seek fastest DSR strategies with minimal costs. (Arif *et al.*, 2018) proposed co-optimization resilience strategies of repair crew dispatch, distributed generators (DGs) placement, and switches-enabled reconfiguration. A MILP is formulated based on LinDistFlow model (Baran and Wu, 1989) and solved with the aim to maximize served load and minimize restoration time. Similarly, (Lei *et al.*, 2019) constructed a MILP to co-optimize equivalent resilience strategies, while proposing a novel vertex-wise formulation of the crew routing problem, breaking with the widely adopted edge-wise formulation derived from the well-known travel salesman problem (TSP) (Miller, Tucker and Zemlin, 1960). The co-optimization approach is applied to interdependent electric and natural gas systems (Lin *et al.*, 2019) to improve the combined restoration of both infrastructures. At this point, despite explicitly involving WAC during the DSR through remote switches manipulation, these works do not investigate the impact of WAC impairment, or unavailability of information and communication technologies (ICTs) that convey miscellaneous data and act as virtual hands for decision-making entities in the power system. The growing dependency on ICTs renders grid applications, especially WAC, very sensitive to data quality, interoperability, and security (Zhu, Chenine and Nordstrom, 2011). The grid is challenged by emerging coupling effects between the ICT and energy domains, which can be captured by extending the relatively mature modeling of power flow to include information flow as proposed in (Xin *et al.*, 2017). The resulting integrated model is highly non-linear due to dominantly event-driven communications. In line with this, (Huang *et al.*, 2019) developed a cyber-constrained power flow model to evaluate and enhance power system resilience. The model is once again highly non-linear, and authors proposed an exact bi-level linear programming reformulation to solve the problem.
To the best knowledge of the authors, only (Ye, Chen and Wu, 2021) investigates the state of telecommunication service (TS) in an integrated distribution system restoration framework, by considering the cooperation and coordination of the repair crews, the distribution system and emergency communication. The present work addresses the identified literature gap of not considering the state of ICT service during DSR optimization. Contributions of this work are:

- Demonstrate the need for TS awareness during DSR
- Quantify the benefit of co-optimizing reconfiguration and crew dispatch
- Present a more realistic model for modern smart distribution grids

The remaining of the paper presents in Section 2 the optimization model formulation. Simulations and numerical results are provided in Section 3, and the conclusion is drawn in Section 4.

2. MODEL FORMULATION

The primary response to damages on the network is not considered in this work, where we assume that all possible automatic protection and remote reconfigurations were made within some minutes after event occurrence (Liu, Qin and Yu, 2020). The resultant remote reconfiguration of the power distribution network (PDN) and received diagnoses, based on information from either field components (electrical sensors, drones, and connected smart devices) or inspection crews, are feeded to the model as a record of identified damages, an estimation of repair time, and an indication of damaged sites accessibility. Scenarios of events in the current work consist of damages in power lines, complemented with possible direct damage on a telecom access point due to the event or an indirect failure caused by shortage in the power supply.
Switches of different types exist in the network. They can be at two states: open or closed. A binary variable is used to model this behavior. Human intervention in the field is necessary to operate manual switches but optional for remote controllable switches (RCSs) that can be toggled from the control center via communication links. RCSs are most of the time fully controlled by the control center (CC) but can in some cases open automatically. This feature is generally implemented at the head of feeders as a safety measure for power ingress nodes, and sometimes across long-distance feeders to enable better initial isolation.
For the power domain, a graph theoretic approach is adopted representing power substations (HV/MV SS and MV buses) as nodes and lines as edges. The same approach is applied to the cyber domain as telecom points are considered as nodes, and communication links as edges. The interdependence between the two domains is captured by telecom points being loads from the grid perspective, while power substations and switches are clients from the telecom perspective (Figure 1).

2.1. Zone separation and PDN topology constraints

During the process of service restoration, three zones can be sorted out: 1) Damage zone: part of the network affected by the propagation of the damage; 2) Unserved zone: part of the network, at first included in the damage zone, but eventually

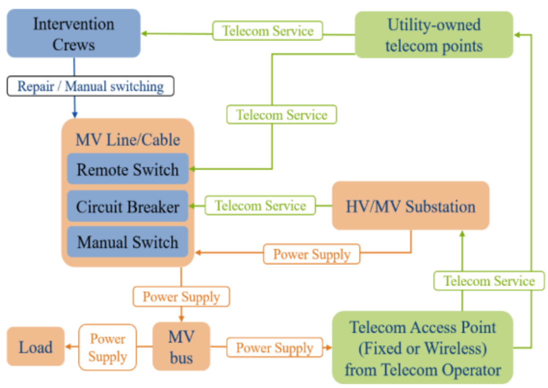

Figure 1. Summarized interactions in the proposed model

isolated using manual switches when operated by intervention crews, then wait for restoration 3) Served zone: segments of the PDN that are energized and safe from damages.

Unserved and served zones are both safe from failures.

We focus in this paper on overhead lines as the underground case can be handled by a simplification of the overhead case.

$$a^e_{i,t} + sw_{ij,t} - 1 \leq a^e_{j,t}, \quad \forall (i,j) \in L, \forall t \qquad (1.a)$$

$$a^e_{j,t} + sw_{ij,t} - 1 \leq a^e_{i,t}, \quad \forall (i,j) \in L, \forall t \qquad (1.b)$$

Constraints $(1.a)$ and $(1.b)$ ensure that damage zones are not connected to served zones or reconnected to unserved zones This is guaranteed by requiring open lines between safe and damage zones. Connection between safe (served and unserved) zones is possible.

At the distribution level, radiality should be ensured at normal operation and always verified.

$$d_{ij,t} + d_{ji,t} \leq sw_{ij,t}, \forall (i,j) \in L, \forall t \qquad (2.a)$$

$$sw_{ij,t} - \left(2 - a^e_{i,t} - a^e_{j,t}\right) \leq d_{ij,t} + d_{ji,t}, \forall (i,j) \in L, \forall t \quad (2.b)$$

$$d_{ij,t} + d_{ji,t} - \left(2 - a^e_{i,t} - a^e_{j,t}\right) \leq sw_{ij,t}, \forall (i,j) \in L, \forall t \quad (2.c)$$

$$a^e_{i,t} + a^e_{j,t} - 1 \leq sw_{ij,t}, \forall (i,j) \in L^M, \forall t \qquad (3)$$

$$\sum_{i \in n(j)} d_{ij,t} \leq 1 - s_j, \forall i,j \in N, \forall t \qquad (4)$$

$$y^e_{j,t} = \sum_{i \in n(j)} d_{ij,t}, \forall j \in N, \forall t \qquad (5.a)$$

$$y^e_{i,t} \leq a^e_{i,t} \quad \forall i \in N, \forall t \qquad (5.b)$$

$$a^e_{i,t} \leq a^e_{i,t-1} + a_{ij,t}, \forall (i,j) \in F, \forall t \qquad (6)$$

$$sw_{ij,t-1} \leq sw_{ij,t}, \forall (i,j) \in L^M \backslash L^{F \times M} \qquad (7.a)$$

$$a_{ij,t-1} \leq a_{ij,t}, \forall (i,j) \in L \qquad (7.b)$$

$$a^e_{i,t-1} \leq a^e_{i,t} \quad \forall i \in N, \forall t \qquad (7.c)$$

$$y^e_{i,t-1} \leq y^e_{i,t} \quad \forall i \in N, \forall t \qquad (7.d)$$

Constraints $(2.a)$, $(2.b)$, and $(2.c)$ impose that when a line (i,j) is in a safe zone $\left(a^e_{i,t} = 1 \text{ and } a^e_{j,t} = 1\right)$, power will flow unidirectionally in any closed line. However, in a damage zone, power does not flow in closed lines. (3) states that manual lines are closed after repair or isolation from damage zones and will not be used as tie-switches. Constraint (4) prohibits power from flowing into HV/MV substations while indicating that power arrives to any bus from a single direction. Constraint $(5.a)$ says that a load can be energized if power flows into the corresponding bus, and from $(5.b)$ only available buses (not in damage zone) can supply power to their loads. In (6), individual buses need to wait for the availability of the linked line to become also available. Constraints $(7.a)$, $(7.b)$, $(7.c)$, and $(7.d)$ indicate respectively that: manual lines not directly adjacent to damages are not opened, lines are being repaired during all the time horizon, buses are recovered, and loads are restored to the network.

2.2. Power flow constraints

The operation of the PDN can be described in terms of power flow from substations to aggregated loads connected at the MV buses. The LinDistFlow model (Baran and Wu, 1989) is used as described below for the active power ($\forall (i,j) \in L, \forall t$)

$$\sum_{k:(j,k) \in L} p_{jk,t} + p^d_j = \sum_{i:(i,j) \in L} p_{ij,t} + p^{sd}_{j,t}, \forall j \in N \qquad (8)$$

$$v_{i,t} - v_{j,t} - 2\left(r_{ij} p_{ij,t} + x_{ij} q_{ij,t}\right) \leq \left(1 - d_{ij,t}\right) M \qquad (9)$$

$$v_{i,t} - v_{j,t} - 2\left(r_{ij} p_{ij,t} + x_{ij} q_{ij,t}\right) \geq -\left(1 - d_{ij,t}\right) M \qquad (10)$$

$$0 \leq p_{ij,t} \leq S^{max} d_{ij,t}, \forall (i,j) \in L, \forall t \qquad (11)$$

$$v^{min}_i \leq v_{i,t} \leq v^{max}_i, \forall i \in N, \forall t \qquad (12)$$

$$\left(1 - y^e_{i,t}\right) p^d_i \leq p^{sd}_{i,t} \leq p^d_i, \quad \forall i \in N, \forall t \qquad (13)$$

Constraint (8) is the power balance equation. (9) and (10) represent the node voltages difference in terms of power and impedance quantities. (11) limits the capacity of closed lines. (12) bounds the bus voltages. (13) sets the limits for the active shed power.

2.3. Telecom constraints

Telecom or ICTs used in distribution grids can be managed by the distribution system operator (DSO) itself or subcontracted to telecom operators. Figure 1 shows captured interactions between DSO or utility-owned ICT infrastructure and telecom operator services in the case of WAC. Besides RCSs and substations, which are electric components with communication capabilities, other components are involved:

- Utility-owned Radio Relays (RRs): Assumed to not fail due to the event given a large battery storage. Each RR has a primary fixed (wired) and a secondary wireless link. Serves RCSs and intervention crews
- Telecom operator fixed access points (FAP): The FAP serves the DSO assets as a primary link (HV/MV SS, RR).
- Telecom operator wireless access points (WAP): The WAP Serves DSO assets as a secondary link (HV/MV SS, RR).

FAPs and WAPs Can fail due to an event and rely on batteries to keep operation. In that case, HV/MV SS and RR will not necessarily fail, but will operate in a degraded (blind!) mode. Constraint (14) indicates that the TS is available at a RR when one of its serving FAP or WAPs is operating. A given RR can be served by just one FAP, but with one or more WAPs. Likewise, (15) describes the availability of the telecom service to substations. $(16.a)$ and $(16.b)$ emphasize that the TS is at disposal only when power supply is guaranteed. More precisely, from $(17.a)$ and $(17.b)$ power is drawn from either the grid or the battery storage. (18) sets the bounds for the batteries, quantified here as the number of time steps before depletion. A simple piecewise-linear discharge model is taken in (19). (20) checks whether the battery is empty.

$$\frac{1}{M}\left(T^c_{k,t} + \sum_{j:(j,i) \in W \times RR} T^c_{j,t}\right) \leq rr^c_{i,t}$$

$$\leq T^c_{k,t} + \sum_{j:(j,i) \in W \times RR} T^c_{j,t}, \forall (k,i) \in Fx \times RR, \forall t \quad (14)$$

$$\frac{1}{M}\left(T^c_{k,t} + \sum_{j:(j,i) \in W \times SS} T^c_{j,t}\right) \leq ss^c_{i,t}$$

$$\leq T^c_{k,t} + \sum_{j:(j,i) \in W \times SS} T^c_{j,t}, \forall (k,i) \in Fx \times SS, \forall t \quad (15)$$

$$T^c_{i,t} \leq T^e_{i,t}, \forall i \in W \cup Fx, \forall t \qquad (16)$$

$$\frac{1}{M}(1-f_i)(E_{i,t}+y_{i,t}^e) \le T_{i,t}^e \le M(1-f_i)(E_{i,t}+y_{i,t}^e),$$
$$\forall\, i \in W \cup Fx, \forall t \quad (17)$$

$$0 \le E_{i,t} \le E_i^{max}, \forall i \in W \cup Fx, \forall t \quad (18)$$

$$E_{i,t} = E_{i,t-1} - p_i^{disc}(1-y_{i,t-1}^e)b_{i,t-1}, \forall i \in W \cup Fx, \forall t \quad (19)$$

$$\frac{E_{i,t}}{M} \le b_{i,t} \le E_{i,t}, \forall i \in W \cup Fx, \forall t \quad (20)$$

(19) contains a non-linear quadratic component. As the involved variables are integers, this can be easily linearized

$$z_{i,t} = (1-y_{i,t}^e)b_{i,t}, \forall i \in N_T, \forall t$$

$$E_{i,t} = E_{i,t-1} - p_i^{disc} z_{i,t-1}, \forall i \in N_T, \forall t \quad (19.a)$$

$$z_{i,t} \le (1-y_{i,t}^e), \forall i \in N_T, \forall t \quad (19.b)$$

$$z_{i,t} \le b_{i,t}, \forall i \in N_T, \forall t \quad (19.c)$$

$$(1-y_{i,t}^e) + b_{i,t} - 1 \le z_{i,t}, \forall i \in N_T, \forall t \quad (19.d)$$

Constraints $(19.a)-(19.d)$ replace constraint (19). An equivalent procedure is conducted for (28) and (29) later.

2.4. Routing and scheduling constraints

Early collected data from field devices and diagnosis crews help to estimate important quantities (such as the repair time) and ultimately provide an intervention timeline. In practice, instructions about the paths towards damage sites are also specified. This combines into handling a routing and scheduling problem. Most available literature adapts through generalization the formulation of the traveling salesman problem (TSP) to tackle specific problems. The TSP defines routing variables on paths between each city pairs. This is less convenient when considering the distribution service restoration problem where tasks are to be conducted at damage sites. In such a problem, depots and damage sites are nodes connected with road paths seen as edges, and the aim is to find the sequence of locations each crew visited while minimizing the overall restoration time. This node-centered approach (unlike the TSP edge-centered approach) bypasses the issues of transportation−grid coupling and their different timescales. We adopt in this work the formulation proposed and demonstrated in (Lei *et al.*, 2019) where routing variables have a time subscript to utterly characterize the node visited by each crew at any given time. We define then variables $rc_{l,t}^{dp,k}$/ $mc_{l,t}^{dp,k}$ as repair/manual switching crew k, from depot dp, being at site l (damage site or depot), at time step t. We use variable $c_{l,t}^{dp,k}$ when the same constraint applies to both. the notation using the cross sign between different sets is used in this paper to represent indexed sets, where only meaningful elements are evaluated. In other words, $DP \times RC \times F^{dp} \times F^{dp}$ does not contain all possible four-dimensional (dp,k,l,m) combinations formed by the four sets,but includes only the valid (l,m) pairs assigned to crew, which is associated to depot dp. For example, in case of two depots 1 and 2 each having one repair crew k, forming the pairs (dp,rc): $(1,1),(2,1)$. Let us say that damages m and l were assigned to depot 1, and damages r and s to depot 2. Valid combinations would be $(1,1,l,m)$ and $(2,1,r,s)$ and an example of a non-valid combination is $(1,1,r,s)$.

$$\sum_{\tau=0}^{\min(TT_{l,m}^{rc},T-t)} \left(c_{l,t+\tau}^{dp,k} + c_{m,t}^{dp,k} - 1\right) \le 0,$$
$$\forall (dp,k,l,m) \in DP \times C \times F^{dp} \times F^{dp}, \forall l \ne m, \forall t \quad (21)$$

$$\sum_{\tau=t}^{T} \sum_{\forall (dp,k,l) \in DP\times MC\times F} mc_{l,\tau}^{dp,k}$$
$$\le M\left(1 - \sum_{\forall (dp,k,l) \in DP\times RC\times F} rc_{l,\tau}^{dp,k}\right), \forall l \in F, \forall t \quad (22)$$

$$\sum_{\tau=t}^{T} \sum_{\forall (dp,k',l) \in DP\times RC\times F\,;\,k'\ne k} c_{l,\tau}^{dp,k'} \le M\left(1 - c_{l,t}^{dp,k}\right),$$
$$\forall (dp,k,l) \in DP \times RC \times F, \forall t \quad (23)$$

$$\sum_{\tau=t+\sum_{\forall m\in n_M(l)} MT_m}^{T} mc_{l,\tau}^{dp,k} \le M\left(1 - mc_{l,t}^{dp,k}\right),$$
$$\forall (dp,k,l) \in DP \times MC \times F, \forall t \quad (24)$$

$$\sum_{\tau=t}^{T} \sum_{\forall (dp,k,l) \in DP\times MC\times F} mc_{l,\tau}^{dp,k} \le \sum_{\forall m\in n_M(l)} MT_m,$$
$$\forall l \in F, \forall t \quad (25)$$

$$\sum_{\forall (dp,k,l) \in DP\times RC\times F} rc_{l,t}^{dp,k} + \sum_{\forall (dp,k,l) \in DP\times MC\times F} mc_{l,t}^{dp,k} + a_{l,t} \le 1$$
$$\forall l \in F, \forall t \quad (26)$$

$$\sum_{\forall l\in F} a_{l,T} Res^l \le Res^{dp}, \forall (dp,l) \in DP \times F \quad (27)$$

Constraint (21) enforces any repair or manual switching crew to be present at a maximum of one node (damage site or depot) at any given time. Moreover, moving between two nodes is restricted with the travel time $(TT_{l,m}^{rc}, TT_{l,m}^{mc})$. (22) indicates that no Isolation crew can visit an incident after a previous visit from a repair crew to that incident. In (23), if a crew visits a damage, no other crew with the same function visits that incident in subsequent periods. (24) sets isolation crews to intervene in contiguous periods, and (25) forces isolation crews to be at an incident for the isolation duration only. According to (26), at any time step, the damage is in one of the following states: not visited yet, under isolation, under repair, or resolved. (27) limits the number of incidents in depot.

2.5. Interdependence constraints

Power and telecom domains of the smart PDN are interdependent as the telecom points require power supply from the grid, and RCSs as well as intervention crews need the telecom service to exchange information and commands with the control center. Constraints (16), stated before for convenience, show one side of this relationship, and the following constraints illustrate the other side.

$$sw_{ij,t-1} \le sw_{ij,t} \le sw_{ij,t-1} + ss_{k,t}^c a_{i,t}^e,$$
$$\forall\, (k,(i,j)) \in L^{SS\times CB}, \forall t \quad (28)$$

$$sw_{ij,t-1} - rr_{k,t}^c(2 - a_{i,t}^e - a_{j,t}^e) \le sw_{ij,t}$$
$$\le sw_{ij,t-1} + rr_{k,t}^c a_{i,t}^e, \forall\, (k,(i,j)) \in L^{RR\times SW}, \forall t \quad (29)$$

$$a_{l,t} \le rr_{k,t}^c, \forall\, (k,l) \in L^{RR\times F}, \forall t \quad (30)$$

(28) indicates that circuit breakers can be operated only when the telecom service from substations is up, and (29) implies the same condition for other RCSs for which communications transit by the RR. A given line is available for reconnection if the communication link is available (30).

$$a_{l,t} \leq \frac{\sum_{\tau=0}^{t}\left(\sum_{\forall(dp,k)\in DP\times RC} rc_{l,\tau}^{dp,k} + \sum_{\forall(dp,k)\in DP\times MC} mc_{l,\tau}^{dp,k}\right)}{RT_l + 2\sum_{\forall m\in n_M(l)} MT_m} \quad \forall l \in F, \forall t \qquad (31)$$

$$sw_{m,t} \leq a_{l,t} + 2 - \varepsilon - \frac{1 + \sum_{\tau=h}^{t-1}\left(\sum_{\forall(dp,k)\in DP\times RC} rc_{l,\tau}^{dp,k} + \sum_{\forall(dp,k)\in DP\times MC} mc_{l,\tau}^{dp,k}\right)}{1 + \sum_{\forall m\in n_M(l)} MT_m}, \quad \forall l \in F, \forall t \qquad (32.a)$$

$$sw_{m,t-1} - \varepsilon - \frac{1 + \sum_{\tau=h}^{t-1}\left(\sum_{\forall(dp,k)\in DP\times RC} rc_{l,\tau}^{dp,k} + \sum_{\forall(dp,k)\in DP\times MC} mc_{l,\tau}^{dp,k}\right)}{1 + \sum_{\forall m\in n_M(l)} MT_m} \leq sw_{m,t}, \forall l \in F, \forall t \qquad (32.b)$$

With $h = \max\left(0, t - 1 - \sum_{\forall m\in n(l)} MT_m\right)$.

A second major type of interdependence resides between resilience strategies of intervention crews and reconfiguration. A line is not operable unless repair is finished (31). Also, opening manual switches directly adjacent to damages achieves best isolation. This is done according to $(32.a)$ and $(32.b)$ after isolation and repair crews spent required time to finish their tasks.

2.6. Objective function

The standpoint of a DSO is adopted in this work as the main objective is supplied power, while the cost of resilience strategies is considered to settle cases where many restoration policies minimize to the same level non-supplied load (or equivalently maximize supplied load).

$$\min_{P,sw,d,a,y,rc,mc,b,z,T,E} \alpha \sum_{\forall t}\sum_{\forall i\in N} w_i p_{i,t}^{sd} + \gamma \sum_{\forall t}\sum_{\forall l\in F} C_l(1 - a_{l,t}) \qquad (33)$$

The objective function is given in (33) with P as a vector of all electrical quantities (*p, q, v*) and T representing all telecom-related variables. The remaining vectors assemble all variables with the corresponding name. C_l is the cost of repairing a damaged line l. Note that for the constants α and γ : $\alpha \gg \gamma$ as from the standpoint of a DSO during crisis management, restoring power to clients is of utter most importance and costs are only considered when equivalently performing strategies are compared. As adopted in most of the literature (Panteli *et al.*, 2017; Fang and Zio, 2019), the resilience of the system can be calculated based on the temporal evaluation of a performance measure, which we choose here as supplied load.

3. SIMULATION AND RESULTS

A case study is designed based on the layout of the IEEE 12-node test feeder to demonstrate the effectiveness of the proposed approach. Figure 2.a shows the buses served by each feeder, and the interconnections between feeders using tie-switches (or normally-open switches). We set: $\alpha = 10$, $\gamma = 0.01$, $C_l = 100$, and $Res^l = 1$ for all failed lines. The MILP is implemented in Pyomo (Hart *et al.*, 2017) and solved using CPLEX on a personal computer with Intel Core i7 Processor (1.8 GHz) and 8 GB RAM. A time step of 30 mn is used.

Nodes 1, 2, and 3 in Figure 2.a represent the HV/MV substations, while the remaining nodes are the MV buses, which not only supply power to electrical loads, but also energize telecom operator *Fx* and *W* access points. A scenario of 8 physical damages is considered, with 7 affected power lines and 1 telecom access point (Figure 2.a). Damages 23-24, 2-17, 20-21 are pre-assigned to DP1, and the remaining to DP2. The used (widely adopted) technique pre-allocates damages to depots based on their distances to the depots as (Lin *et al.*, 2019) Repair crews (RC) and manual switching crews (MC) are initially located at depots. DP1 is set to have 1 RC ($Res^1 = 1$) and 1 MC, whereas DP2 has 2 RCs ($Res^2 = 2$) and 1 MC. The travel time is proportional to the distance between a depot and a damage or between two damages, whilst MCs are twice faster than RCs. Without loss of generality, repair and operation of manual switches by crews are chosen for all lines to last 2 and 1 time steps respectively. The damage in the telecom access point is not repaired as the repair process is limited to grid assets, and this task should be handled by the telecom operator. Unlike utility-owned radio relays that are assumed to have power storage of one to two days, telecom operator access points have only limited battery storage, set for a duration of 1.5h (3 time steps). Remote switches and intervention crews get TS from the closest RR, and substations provide TS to circuit breakers. RRs and substations connect to the closest WAP and FAP.

A preliminary simulation is conducted to confirm the intuitive (and literature well-verified) statement that co-optimization achieves better performance than non-cooperative approaches. Considering perfect communications, we obtain a gain of 12% in total supplied load using the proposed co-optimization, compared to a case where we solve first an optimization problem for crew schedules, then take the result as an input to switch reconfiguration stage under power flow constraints (Arif *et al.*, 2018).

Next, to quantify the criticality of TS in smart distribution grids, a telecom agnostic case is constructed. The co-optimization is solved within 8 sec for telecom agnostic case (Case I), and 75 sec for telecom aware case (Case II). Figure 2.b depicts the evolution of supplied power during the event scenario. TS agnostic case satisfies 79% of the power demand during the simulation horizon compared to 71% in the more realistic TS aware case. Case I clearly dominates Case II between $t = 2$ and $t = 9$, meaning that the difference in total supplied power is experienced in a limited time window, towards the beginning of the event, which corresponds to the

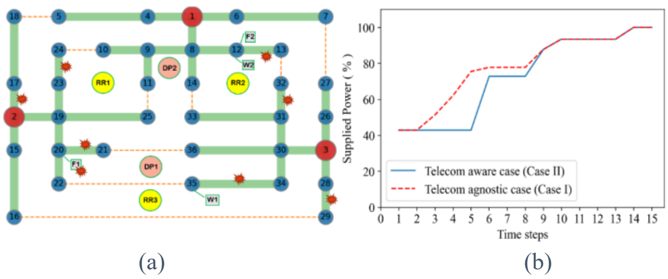

Fig 2. (a) Multi-feeder network (b) Evolution of supplied power

most critical period for contingency mitigation. Thus, Case I magnifies the restoration potential by not considering the availability of telecom points, and better insight can be taken from Case II as the telecom domain is modeled. Figures 3 and 4 display the timelines of all intervention crews in both cases. MC1 of DP2 (MC(2,1)) isolated buses 8 and 14 from damaged 12-13 by opening 8-12, but branches 8-14-33 could not be restored till $t = 6$ due to unavailability of the TS. Likewise, Line 20-21 was repaired by RC1 of DP1 (RC(1,1)) at $t = 4$ but could not be reconnected till $t = 6$ that corresponds to the completion of repair at 12-13 , which enabled the TS provided by W2 and F2. These two waived reconnections contributed considerably to the gap in supplied power between I and II. Damages 12-13 and 34-35 are visited by MC(2,1) and MC(1,1) respectively, many time periods before repair is conducted (Figure 3). Figure 2.b unveils the gain in terms of supplied power (curve of Case I) as loads connected to $8, 14, 31, 30,$ and 36 could be restored as soon as isolated from the propagating incidents. Hence, it is important to have fast moving crews, which can perform such operations and not always wait for heavily equipped repair crews to launch the restoration. Still, repair crews operate manual switches after finishing their task as they are already on site, in accordance with the control center instructions. Figures 3 and 4 depict the post-repair manual switching by retaining repair crews at the handled damage longer than the repair time, set here to 2 time steps. From Figure 4, the obtained solution prioritizes repair of line segments directly affecting the availability of TS. Lines 20-21 and 12-13 that supply power to telecom access points are repaired during first time steps. 12-13 contributes indeed to boost the restoration process, however, as F1 is damaged, the TS intended benefit from this repair could not be leveraged. This reveals the drawback of situational blindness about repair operations conducted by telecom operators. In better observable cases, the optimization is able to use knowledge about battery discharging of telecom access points, to delay sending MC(2,1) to 34-35, because in any case the possible profitable reconfigurations allowed by manual isolation cannot be carried till restoration of a portion of the TS at $t = 6$. This delay can allow to assign another task to the crew and avoid the cost of waiting at the site until the TS is restored.

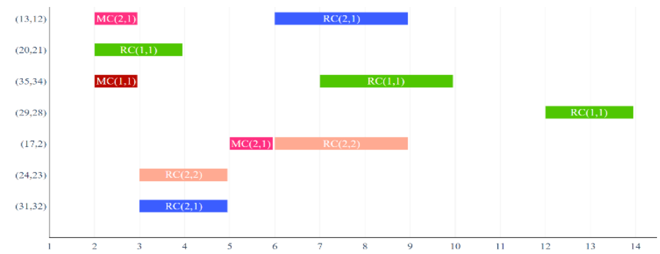

Figure 3. Schedule of intervention crews for Case I

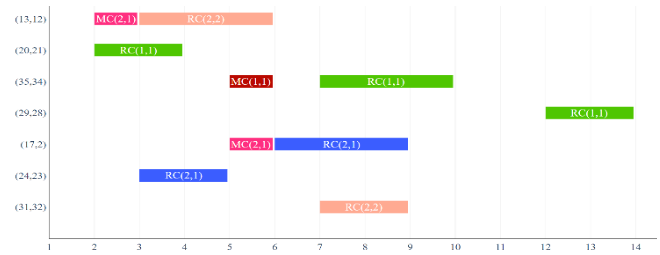

Figure 4. Schedule of intervention crews for Case II

4. CONCLUSION

This paper proposes a resilience-based optimization of intervention crews dispatch and manual/remote switches operation. The objective is to maximize the total supplied power during an outage scenario, while minimizing the intervention cost in case two strategies achieve the same performance. In addition to repair crews, fast moving isolation crews are introduced to allow highly flexible recovery. A more realistic model of the distribution grid is considered, where ICT points are supplied from electrical buses and have limited battery storage. RCSs and intervention crews get their TS from utility-owned RR and substations, which are served from the telecom operator access points.

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