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Abstract
Evolving smart grid (SG) services for demand side applications, markets, and various stakeholders are well addressed leaning on Information and Communication Technologies (ICTs). Yet, this technological leap induced high complexity in the grid, due to various power-ICT interdependencies. Managing this complexity has been very challenging over the last decade as prototyping and tools to faithfully replicate SG dynamics and all involved interactions with ICTs are this far out-of-reach. Advanced attempts considered co-simulation of both power and ICT infrastructures using domain-specific software, resulting in a relatively good description but an additional outlay of synchronization and handling different time scales. For SG studies that require low level of details and adopt a systemic view, like resilience evaluation, modeling is better suited to shed the light on paramount features. Smart grid modeling is generally electric system oriented by wide dominance of power flow analysis, associated with very few considerations of ICTs. Availability of telecommunication points-of-interest is considered in this work to capture the interdependence between power and ICT domains of the distribution grid. The integrated modeling inherently omits extra inter-domain synchronization overhead. Different telecommunication settings are therefore compared for fault localization, isolation, and service restoration (FLISR) function. An application of the joint modeling is successfully illustrated in case of resilience-based power service restoration under extreme event failure scenarios.

Keywords: Cyber-Physical Systems, Smart Grids, Power Flow, Telecommunication, Resilience

1. Introduction

Nearly all modern power grid components have cyber and physical characteristics, which result in an overall cyber-physical system (Arghandeh et al. 2016; Yu and Xue 2016). In particular, substations, transformers and intelligent electronic devices (IEDs) manage physical quantities (power, voltage, current), while being able to produce and process information. Similarly, control centers, intervention warehouses and field crews involve physical processes within the framework of a relatively intensive exchange and processing of information. The centralized and distributed constituents of the electrical system are connected via a telecommunication network, which is itself a cyber-physical system (CPS) coupled to the electrical network (Wu, Kao, and Tseng 2011). Smart grids have a wide range of applications that use various communication technologies. The FLISR function in the distribution grid is chosen to investigate the power-telecom coupling during crisis management situations, where localizing and isolating faults then restoring power supply to customers is critical (Liu, Qin, and Yu 2020). The FLISR function intervenes when damages are identified as permanent after initial reclosing cycles involved in protection mechanisms. Fault detectors (FDs) and remote-controlled switches (RCSs) are the main enablers of the remote service restoration (Heidari Kapourchali, Sepehry, and Aravinthan 2018), as the FDs transmit all suitable fault-related measurements to the control center, and the RCSs are used as decision levers to execute the commands issued by the control center. RCSs can in some cases open automatically as a response for a fault, which is typically the case at the upstream of feeders where RCSs are called circuit breakers (CBs) because their opening shuts off the whole feeder. Manual switches are nonetheless more present in power lines and require field intervention crews to operate them on-site (Chen et al. 2019).

Placement of RCSs (Fang and Sansavini 2017) and distribution service restoration problems are extensively studied in the literature (Zidan et al. 2017; Carvalho, Ferreira, and da Silva 2005; Abiri-Jahromi et al. 2012). We extend these studies here to integrate the impact of ICTs. Thereby, the main contributions of this work sum up to:

- Include the automatic response in the grid service restoration model
- Consider the ICT availability
- Study the deployment of new RCSs based on the state of the telecom points and related characteristics of coverage, battery storage, and redundancy of access.

The remaining of the paper is structured as follows: Section 2 presents the system model for the interdependent power-ICT system. Section 3 describes the optimization problem formulation. Simulations and results are shown in Section 4, and conclusion is given in Section 5.

2. System Model

The medium-voltage (MV) distribution level of the power grid is considered in this work. The distribution grid is represented as a graph, where edges are the power lines, and nodes comprise the high-voltage to medium-voltage (HV/MV) substations and the MV buses. A hierarchical graph captures the telecom domain of the grid, with edges representing communication links, while the control center is the top-level node, access points at the intermediate level, and connected grid assets (HV/MV substations, circuit breakers, RCSs) at the lowest level. FDs are considered perfect in this study as the focus is on the impact of ICTs and RCSs.

Interdependencies between the two domains are captured by considering ICT points as loads from the perspective of the electrical system, whilst electrical substations and switches are customers from the ICT perspective. Figure 1 summarizes the interactions between various components of the same domain or different domains, with three main actions: power supply, telecom service, and repair/manual switching.

Since RCSs can be operated both remotely and manually, they are more advantageous, and their proportion in the network is mostly determined by cost-benefit analyses due to increased expenses. The problem can be partitioned into four phases:

- **Pre-event phase (Anticipative new-RCS deployment):** In this phase, a new resilience-based deployment of RCSs is considered to determine proactively the manual switches to upgrade with the remote connection functionality, and which technology to use for that.

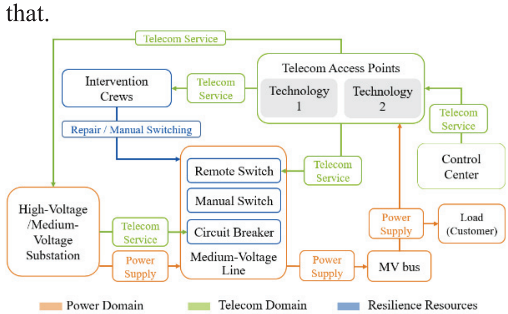

Figure 1. Interactions in the proposed model

• **Automatic isolation:** Scenarios of damages include in the current work faults in power lines and telecom points (TPs). The first response of the distribution grid is the automatic opening of circuit breakers of affected feeders to protect HV/MV substations. In underground networks, LV/MV substations are directly placed on the mainstream, and RCSs are commonly integrated into the substations. Overhead networks contain more derivations, and RCSs are placed on the lines.

• **Remote isolation:** The initial affected zone isolated by automatic devices is wide and can be reduced using RCSs. In this phase, RCSs are opened wherever they allow to isolate some nodes from faulted zones.

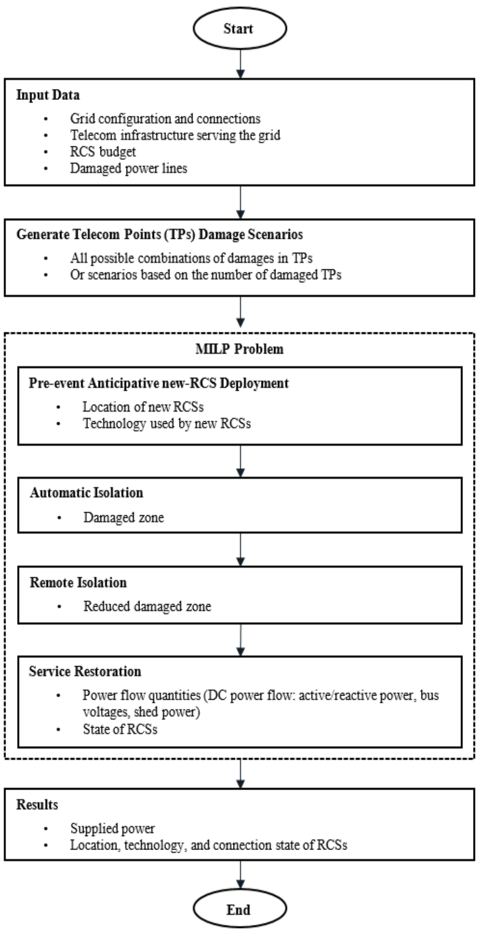

Fig. 2. Flowchart of the proposed approach

• **Fast service restoration:** Also called fast reconfiguration. At this point, some loads can be restored. An evaluation of the power flow conditions is conducted, and decisions on the state of switches are made. The output of this last phase of the fast reconfiguration stage will be taken by the operator during the deployment of latent restoration resources (e.g. repair crews, mobile distributed generators), which are not considered here.

The proposed model takes as input the electric-telecom configuration of the smart grid, as well as the available budget (B) expressed by the number of possible manual-to-remote upgrades. The scenario of damaged electrical segments is also assumed known. This is motivated by the fact that the distribution system operator (DSO) has a relatively good knowledge of the network vulnerability zones, and techniques out of the scope of this work are applied to estimate the impact on electrical lines. For the possible damages in TPs, the DSO has less insight as the TPs are usually managed by a telecom operator. To cope with this, scenario of damages in TPs are considered.

3. Optimization Formulation

The introduced four phases in Section 2 are assembled in Figure 2, alongside initial data and scenario settings, to construct the flowchart of the proposed approach.

3.1. Zone separation and topology

For the FLISR function, three zones can be distinguished: 1) Damage zone: affected by the propagation of the damage; 2) Unserved zone: initially affected by the damage but could be isolated using automatic and remote switches; 3) Served zone: completely safe zone, isolated from damages and supplied by power. Unserved and served zones are both safe from the failures.

We focus on the case of overhead lines as damages propagate wider under this scheme, and the model can be simplified to describe the underground case.

Associated constraints guarantee that damage zones are not connected to served zones or reconnected to unserved zones at any time step. In addition, radiality should be ensured at normal operation and remain verified in subsequent periods.

3.2. Power flow

The operation of the distribution grid can be described in terms of power flow from HV/MV substations to aggregated loads connected at the MV buses. The LinDistFlow model (Baran and Wu 1989).

3.3. Power-Telecom interdependence

Telecom points require power supply from the grid to deliver the communication service needed by RCSs. Despite this dependence, TPs have batteries that delay the impact of initial failures, and make the points-of-interest in the ICT infrastructure indirectly dependent on the grid. Likewise, the power network could suffer the consequences of a blind operation if ICTs are down. The two-way coupling is thus captured through linear constraints in the proposed MILP.

The telecom access points in Figure 1 enable connection to the control center that centralizes grid operations. This connection is assumed available in this work as long as the access points are operating.

3.4. Objective function

The main objective considered is maximizing supplied power, while introducing a term related to TPs battery capacity and redundancy.

$$\max_{p,y,T,sw,a} \sum_{\forall SC} p_{sc} \left(\alpha * \sum_{\forall i \in N} p_{i,t}^{load} + \beta * \sum_{\forall k \in T} \sum_{\forall l \in L} a_{k,l} batt(k) \right) \quad (1)$$

With p_{sc} the probability of TPs damage scenario sc ; $p_{i,t}^{load}$ the supplied power to node i at phase t ; $a_{k,l}$ the indication if line l is connected to telecom point k ; $batt(k)$ the battery capacity of TP k ; y the connection state of loads; p the vector of electrical quantities (active/reactive power, node voltages) ; T the vector representing the state of TPs ; sw the state of the remote switches. $t \in \{0, 1, 2, 3\}$ indexes the different phases. Note that for convenience, the scenario specific subscript is omitted, as all variables are scenario specific.

The constants α and β allow to tune the tradeoff between restoring the maximum immediate load, and making best anticipative choices which will be advantageous for service restoration. The resilience of the system is calculated based on the temporal evaluation of the supplied load.

4. Simulation and Results

A case study of 36 power nodes is set based on the IEEE 12-node test feeder to demonstrate the effectiveness of the proposed approach. Capacitors, transformers, and regulators are simplified/ignored in compliance with the study objectives. A per-phase analysis is conducted in the constructed generic medium-size 20kV nominal voltage unbalanced distribution network of total 1305 kW demand. Figure 3 shows the buses served by each feeder, and the interconnections between feeders using tie-switches (dashed lines representing normally-open switches).

Each time step represents one phase in Figure 2. Nodes 1, 2, and 3 represent the HV/MV substations, and the blue nodes are the MV buses, which not only supply power to electrical loads, but also energize TPs of two wireless technologies: telecom operator-owned {T1, T2, T3, T4, and T5}, and utility-owned {R1 and R2}. Assets of technology T have coverage radius of 2.8 km and battery capacity of 3 hours, whereas for technology R the coverage radius is 3.5 km and battery capacity 5 hours. We can say that R has better coverage and battery storage, while T offers better options in terms of redundancy.

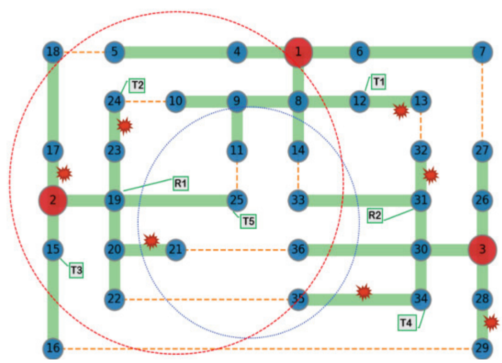

Fig. 3. Test case

Table 1. Percentage of supplied power at each phase with varying number of damages in telecom points; Budget B=3

Number of telecom damages	0	1	2	3	4	5	6	7
Pre-event phase	100%							
Automatic & Remote Isolation phases	29.5%							
Restoration Phase	50.96%	40.23%	33.77%	30.79%	29.91%	29.61%	29.5%	29.5%

Table 2 summarizes the initial type of switch in each power line. A line or a TP has a binary state, either damaged or safe. Then, a scenario of 7 physical damages in power lines is considered. All the possible 128 combinations of failures in TPs are inspected, constructing a scenario-based evaluation where each scenario is assigned with an equal probability of 1/128. This straightforward stochastic optimization attempts to cope with the uncertainty around damaged TPs. The propagation of damages in overhead and underground lines is well described in the compact MILP formulation.

Result 1.

As we consider a single fault scenario in electrical lines as shown in Figure 3, the damage scenarios are categorized based on the number of affected TPs (Table 1). Damages in TPs clearly affect the ability to restore power supply to customers. Table 1 also shows that if a given threshold of affected TPs is attained, no restoration would be possible even that some points are still available. In this case, the budget for new-RCS deployment was fixed to B=3, meaning only three manual switches could be upgraded to RCSs.

Result 2.

Table 2 illustrates that, when the number of damages is fixed to 3 and the budget (B) for new-RCS deployment is varied, the supplied power increases with increasing B from 0 to 5. However, when the budget is increased further, no gain is achieved in terms of supplied power. This suggests that beyond an optimal number of RCSs, restoration is no longer possible with RCSs, corroborating that most of the time only a limited recovery is carried out during fast reconfiguration.

Table 2. Supplied power considering new-RCS deployment with varying budget (B); Number of telecom damages = 3

	Initial setup (B=0)	B=1	B=2	B=3	B=4	B=5	B=6	B=13
Circuit Breakers	1-4, 16, 1-8, 2-15, 2-17, 2-19, 3-26, 3-28, 3-30							
Remote Controlled Switches (RCS)	22-35, 14-33, 15-16, 31-33, 10-24, 5-18, 21-36, 11-25, 26-27, 13-32, 7-27, 16-29, 9-11, 4-5	17-18 {R1}	8-12 {T1,T4}	19-23 {T2,T3, T4}	30-31 {T1,T5}, 30-34 {R2}, ~~19-23~~	19-23 {T2,T3, T4}	8-9 {T1,T3, T4}	All lines are RCS
Manual Switches	8-9, 20-22, 12-13, 20-21, 30-31, 6-7, 31-32, 19-23, 9-10, 30-34, 30-36, 23-24, 31-32, 17-18, 28-29, 8-12, 8-14, 34-35, 19-25	~~17-18~~	~~8-12~~	~~19-23~~	~~30-31, 30-34,~~ 19-23	~~19-23~~	~~8-9~~	
Supplied Power (%)	29.5	30.16	30.63	30.79	30.94	31.1	31.1	31.1

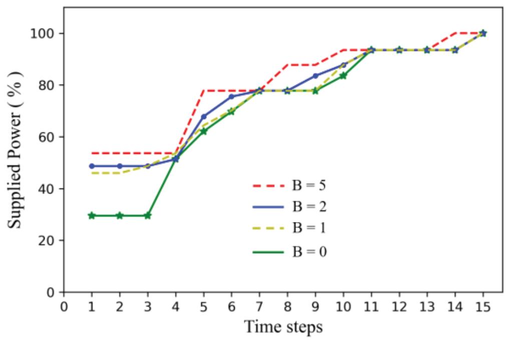

Figure 4. Evolution of restoration in terms of supplied power under different budgets

The supplied power values after fast restoration in Table 2 are close to the initial value, as the restored power is around 1% despite the spent budget. Still, a DSO would be willing to make this investment knowing that during a crisis the early actions target the critical load (hospitals, patients with high vital risks, government facilities, etc.), which represent a very small portion of the entire electrical load.

Result 3.

The newly equipped lines with RCS are shown in green (Table 2) for the different budgets. The present approach helps to establish a priority between the lines which should be upgraded. The telecom technology used is also specified, inside the curly brackets. By closely inspecting the setup of the network, the lines which can possibly be served by one T point and one R point (17-18, 30-34), tend to choose the R point as it has more resilience in terms of battery storage. At the same time, lines which are in the covered vicinity of one R point and multiple T points, choose rather the T technology for the offered redundancy of access.

Result 4.

Fast reconfiguration achieves a partial recovery as illustrated in tables 1 and 2. Yet, improving this first response can contribute to accelerate subsequent operations. Figure 4 shows the evolution of supplied power over time (Time steps in hours), in the case of assigning intervention crews to isolate faulted zones (by manoeuvres in manual switches) and repair damaged power lines. With identical crew resources for different budgets, the restoration is revealed to perform better, in terms of cumulative supplied power, as the budget is increased. Interestingly, the lower budget curves (B ∈ {0, 1, 2}) can ultimately catch up the high budget one (B = 5), suggesting that deploying more RCSs will not necessarily accelerate attaining an advanced level of recovery. However, the impact of fast reconfiguration on the overall restoration is not limited to the first hours. When fast reconfiguration is improved through RCSs deployment, the restoration process exhibits enhancement during the whole crisis management.

5. Conclusion

This work provides a resilience-based optimization for fast restoration using remote controlled switches. The objective is to maximize the total power delivered during a failure event, while identifying the optimal scheme (location, technology) for new RCSs. The uncertainty around damages in TPs is partially accounted for through scenario-based optimization. The improvement to the overall restoration brought by fast reconfiguration is quantified.

Results suggest that fast restoration is stopped even when some TPs are still available, and there exists a threshold beyond which increasing the RCS deployment budget brings no more benefit. The chosen technology for each upgrade is linked to battery storage and connection redundancy. The fast reconfiguration is shown to improve the entire restoration process, not just during primary phases, but even well later. Many extensions are under exploration for this work, such as the adjustment of probabilities on different scenarios of TP failures and the investigation of more than just one power line failure scenario. In addition, the impact of the power supply failure to telecom points is considered by including the capacity of batteries into the objective function, but other options can be tested.

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