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RESEARCH ARTICLE

Cooperative Operational Planning of Interruptible Load Contracts for Enhancing Performance Reliability of Multi-Microgrid Power Distribution Systems

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ABSTRACT This paper evaluates the benefits of cooperative utilization of available flexibility for enhancing the performance reliability of Multi-Microgrid (MMG) distribution systems in emergency situations. Interruptible Load Contracts (ILCs) with voluntary load points, with the goal to reduce the penalty cost of unexpected power interruptions during fault events, are considered as the source of flexibility. In this paper, the business as usual where Microgrid Operators (MGOs) independently plan ILCs for emergency operations is compared with cooperative planning of ILCs shared among multiple MGOs. To do so, a mathematical optimization model is developed to optimally allocate ILCs to each MG considering the presence of other MGs in the MMG distribution system. Decision variables include the optimal location and size of ILCs in each MG for a given incentive rate that motivates customers' enrollment. The model considers grid topological configuration, capacity, and voltage level as the main technical constraints. The model is formulated as a Mixed Integer Linear Programming (MILP) problem whose solution can be simply achieved via off-the-shelf software packages. Simulation results demonstrate the effectiveness of cooperative planning of ILCs in reducing the overall penalty costs of unexpected outages by 10% to 15% compared to the independent planning approaches, depending on the network characteristics.

INDEX TERMS Multi-microgrid distribution system, cooperative planning, operational planning, emergency operation, flexibility, demand response, interruptible load contracts.

ABBREVIATION

IL	Interruptible Load.
ILC	IL Contract.
DR	Demand Response.
EDRP	Emergency DR Program.
MG	MicroGrid.
MMG	Multi-MG.
MGO	MG Operator.
ECOST	Emergency Cost.
DSM	Demand Side Management.
DG	Distributed Generator.
MILP	Mixed-Integer Linear Programming.
VOLL	Value of Lost Load.
EENS	Expected Energy Not Supplied.
ROR	Rate of Return.
N.O.	Normally Open.

NOMENCLATURE

A. SETS AND INDICES

mg	Index of microgrids.
b	Index of buses.
h	Index of time periods (hours).
l	Index of lines.
i	Index of faults.
ss	Index of time intervals from occurrence of a given fault to its clearance (switching or isolation).

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kk	Index of piecewise intervals of linearization of parabola curve.
L_b^s, L_b^r	Set of lines with power flowing into and out of bus b.
b_s, b_r	Set of sending and receiving buses of line l.
B_{mg}	Set of buses within the microgrid mg.
B_{up}	Set of buses connected to PPC point (upstream network).
$L_{Maneuver}$	Set of maneuver lines.

B. PARAMETERS

λ_i, $r_{i,ss}$	Failure rate of event i and repair or outage time of event i at interval ss.
$\lambda_h^{Sell,Load}$	Electricity delivery rate at hour h.
$PD_{h,b}$, $QD_{h,b}$	Active and reactive power demand of load b at hour h.
$VOLL_b^{NC}$, $VOLL_b^{C}$	Value of lost load of non-contracted and contracted loads at bus b.
$\rho_{b,kk}$	Discount rate of electricity price for IL at bus b and interval kk.
g_l, b_l	Real and imaginary parts of the Y-bus matrix related to line l.
$SFL_l^{\max}$	Power flow limit of line l.
$V^{\min}$, $V^{\max}$	Minimum and maximum allowable limits of voltage at load points.
$IL_b^{\min}$	Minimum allowable demand can be contracted as interruptible load.
$ILs_{kk}^{\max}$	Maximum length of interval kk.
$LN_i^{Allowable}$	Maximum allowable number of maneuver operations in event i.
M	Big M (large value compared with other parameters or variables).

C. VARIABLES

$PD_{h,b,i,ss}^{Cur,NC}$, $QD_{h,b,i,ss}^{Cur,NC}$	Active and reactive power curtailment of non-contracted load b at hour h in event i and interval ss.
$PD_{h,b,i,ss}^{Cur,C}$, $QD_{h,b,i,ss}^{Cur,C}$	Active and reactive power curtailment of contracted load b at hour h in event i and interval ss.
$P_{h,u,i,ss}^{Up}$, $Q_{h,u,i,ss}^{Up}$	Active and reactive power transaction with upstream network at hour h in event i and interval ss.
$PFL_{h,l,i,ss}^{s}$, $QFL_{h,l,i,ss}^{s}$	Active and reactive power sent from line l at hour h in event i and interval ss.
$PFL_{h,l,i,ss}^{r}$, $QFL_{h,l,i,ss}^{r}$	Active and reactive power received from line l at hour h in event i and interval ss.
$V_{h,b,i,ss}$	Voltage magnitude of bus b at hour h in event i and interval ss.
$\delta_{h,b,i,ss}$	Voltage angle of bus b at hour h in event i and interval ss.
$LS_{l,i}$	Binary variable representing participation of line l in event i.
$LS_{l,i}^{Change}$	Binary variable representing participation of Maneuver line l in event i.
z_b	Binary variable representing participation of load point b in ILC.
$ILs_{b,kk}$	Interruptible load of bus b in interval kk.
IL_b	Interruptible load of bus b.
$EENS_{mg}$	Expected Energy Not Served in each MG.

I. INTRODUCTION

A. PROBLEM DESCRIPTION

Power distribution systems are increasingly susceptible to interruptions primarily due to inevitable and uncertain failures of outdated system components, which introduce a critical challenge from the system reliability perspective [1]. Most influential faults predominantly manifest in radial distribution feeders, where alternative paths are non-existent [2]. These incidents result in significant, unforeseen load curtailments, thereby imposing substantial high penalty costs on system operators [3]. Nevertheless, thanks to the smart grid technologies, the operators can utilize ILs as an incentive-based EDRP to reduce the penalty cost of service interruptions. These ILs are similar to insurance contracts, which provide the operators with the opportunity to leverage them during emergency situations [4], [5], [6].

ILCs oblige enrolling customers to cut a portion of their consumption during emergency conditions. In return, the customers receive financial incentives, such as extra payments or discounted electricity rates [7], [8]. This situation can be interpreted as the conflicting costs of interruption penalties and ILCs' incentives. Therefore, in the overall view of the problem, the operator needs to optimize ILCs, in a cost-benefit trade-off problem, in which the total cost for compensation payment to ILCs as well as for possible load shedding is minimized [9]. This optimization can become more challenging in power distribution systems encompassing multiple independent MGs [10], [11]. In such cases, the behavior exhibited by MGOs and the extent of their interactions play a pivotal role in shaping the ILCs—as a valuable flexibility resource—and thus, the ECOST reduction [12]. A collaborative operation wherein MGs facilitate sharing of their ILCs with adjacent MGs, results in significant cost savings. Furthermore, the increasing demand for flexibility services coupled with rising costs associated with flexibility procurement, as highlighted in [13], may further encourage MGOs to pursue better utilization of the available

ILCs during fault events, particularly when the financial advantages of such participation are accurately quantified.

B. LITERATURE REVIEW

In recent years, research has been dedicated to investigate the influence of customer's flexibility in the emergency operation of power distribution systems, with a particular emphasis on features of an MMG structure. In the early stages, [14] and [15] examined the operational benefits of load management to underscore the importance of DSM. In [14], the incorporation of ILs into DSM leads to a reduction in the system cost by reducing the spinning reserve of a composite system. Rabiee et al. [15] use ILs as an ancillary service for voltage support when power system encounters voltage instability. They introduce a control framework aimed at ensuring a desired loading margin, utilizing DSM along with other resources as a potent control mechanism. A cost-benefit analysis of ILCs has been conducted in [16] where a model is presented to minimize the total compensation cost, capturing the benefits of the company and the customers as the optimization constraints. Likewise, a model for optimal DR implementation is proposed in [17], formulated to minimize the total cost of the EDRP, while considering network operational limits on power flow and nodal voltages.

Recently, MGs have attracted significant research interests, mainly due to their ability to improve the reliability and resilience of the power distribution systems [2], [10], [18], [19], [20], [21], [22]. Reference [2] indicates that a reliable operation of MMG distribution systems is achievable via utilizing an appropriate coordinated scheme. According to the scheme, a faulty distribution grid is divided into smaller MGs, and different operation modes are considered as an outage management strategy within each of the MGs. In the meantime, some of the MGs use ILs as peak shaving tools during normal operation or consider them as curtailable demands in the case of unintended events (i.e. emergency conditions) [18]. Lakuraj et al. [19] establish a risk-constrained stochastic framework, which can optimally schedule a dependent MG in both normal and emergency situations. The dependent MG is introduced as a group of MGs with additional interconnection points consisting of storage, DGs and DRs to guarantee a resilient and economic operation of the main MG. The suggested optimal energy management strategy is formulated as an MILP, utilizing linearized AC power flow constraints to improve computational efficiency. Yao et al. [20] examine operation modes of an MMG distribution system, including the single MG island operation as well as the MMG island and grid-connected operations. In this work, MGs are solely assumed as lumped energy source/demand and inner networks of MGs are neglected. In [21], the performance of a particular MMG distribution system in the presence of a number of MGs operated with mutual interconnection, but without connection to the main grid, is evaluated. To model such a decision-making framework for competing MGs, a bi-level optimization approach is developed in which MGs' interaction problem is modeled in the upper level and the MGs' inner problem is formulated in the lower level. By linearizing the nonlinear terms, the model was transformed into a MILP problem considering the objective functions of all MGs. Reference [22] claims that determining the most efficient boundaries of MGs under contingencies and optimal formation of these flexible MGs is one main challenge for electric utilities from reliability and economics points of view. It is also claimed that by doing so and taking the advantage of EDRP, the supply and demand balance will be kept in MGs.

In the later aforementioned works, although the undertaken tasks are directly associated with the network structure and its related constraints, MGs are generally assumed as a set of lumped energy resources/demands, and the inner network of MGs or even distribution grid configuration are neglected [20], [21], [22]. The primary reason for excluding the network in the investigations stems from the fact that its incorporation renders the problem non-convex which is challenging to address owing to the nonlinearities in power flow equations [23]. For instance, in [9], the nonlinear optimization problem is solved by decomposing the problem into a series of linear optimization problems, which are solved in a sequential manner, resulting in a computationally expensive, sub-optimal solution. To overcome the complexity, [19] and [24], [25] present MILP models. In [24], the long-term cost-benefit problem of distribution system automation is formulated in a MILP form that can be effectively solved by commercially available solvers, such as CPLEX. Moreover, in [25], the proposed MILP model of the simultaneous implementation of ILC in the EDRP and unit commitment program, ensures obtaining the globally-optimal solution. These studies indicate the application and importance of applying linearization approaches in more complex and time-consuming procedures, e.g. emergency operations and EDR implementations.

C. MOTIVATION

The benefits of ILs as an EDRP were highlighted in the previous research; however, the implementation of the developed approaches on enhancing the flexibility of an MMG distribution system during emergency operations is overlooked. On the other hand, previous literature has not analyzed the optimal size and location of pre-contract ILs in each MG to alleviate the consequences of an emergency situation. Moreover, the interaction possibility between MGs in this particular problem has not been assessed yet. Analyzing the benefits of IL sharing gives MGOs an explicit insight regarding its benefits and advantages. In addition, most of the proposed methods in the literature have nonlinear optimization characteristics, which make it hard to find the globally-optimal solution of the problem at a reasonable computational time.

D. MAIN CONTRIBUTIONS

In this paper, a comprehensive framework is developed to optimally allocate ILCs in MMG distribution systems based on customers' compensation value. In this model, the objective is to minimize the MGOs' ECOST, while the operational constraints are fully satisfied. The ECOST of each MG consists of two contrary variables namely the penalty cost of load curtailment and the compensation cost of ILs. The penalty cost can be simply calculated by well-known methods such as considering the VOLL parameter of each load point. However, the second term has not been yet thoroughly investigated and a method is proposed to model the compensation cost for ILs in this study. It is noteworthy that the cooperative operational planning of ILCs is also analyzed to illustrate its monetary benefits for MGs. Furthermore, the linearization of the problem is provided to enable finding the globally-optimal solution. Finally, a sensitivity analysis is conducted to assess the impacts of important parameters on ILCs, such as network reliability and incentives payments. Main contributions of this study can be highlighted as follows:

- Proposing a novel model for optimal allocation of ILCs in distribution systems or MGs
- Developing a framework for cooperative operational planning of ILCs in an MMG distribution system
- Evaluating the advantages of MGs' interactions
- Proposing an approach to modelling costumer's willingness in EDRP
- Incorporating grid constraints to enhance the comprehensiveness of the proposed model
- Linearization of the proposed model into a MILP formulation, ensuring existence of an optimal solution

E. PAPER ORGANIZATION

The rest of the paper is arranged as follows. Section II provides the detailed statement of ILC in an MMG structured power distribution system and the formulation of the problem. Section III presents the numerical studies including those of illustrative and standard case studies as well as sensitivity analysis. Finally, Section IV concludes the paper.

II. PROBLEM STATEMENT AND FORMULATION

A. PROBLEM STATEMENT

In emergency operating conditions, such as branch outages, it may be unavoidable for MGOs to shed some of their loads. Hence, each operator strives to minimize the effect of outages while observing system security concerns such as voltage, current and power flow constraints to maintain within their acceptable limits. Utilization of available maneuver switches and adjusting tap changers at the substation can serve as primary strategies for MGOs in managing such challenges.

If any violation is observed, load curtailment becomes inescapable. In load shedding process (Fig. 1), if the operator of the interrupted MG has already signed ILC(s) with its load points, curtailing demand power from ILs is the first option. Doing so, the high interruption costs due to significant VOLL associated with critical or uninterruptible loads can be avoided. By observing any violation again, each MGO may ask other MGOs to share some of their ILs, especially those that can support the system operation. If violations persist, other loads within the interrupted MG may be requested to cut the required portion of their consumption temporarily to address the issue.

It is obvious that MGOs are sufficiently incentivized to make contract with their own load points by providing financial incentives (e.g., extra payments or discounted electricity rates) seeking advantages such as enhanced reliability metrics and avoidance of substantial penalty expenses. In the meantime, MGOs may express willingness to share their ILs in whole or in part with other MGs, if it is beneficial. Evaluating this shared benefit is one main goal of this study.

Figure 1 illustrates a flowchart detailing the fault management process, elucidated in the preceding paragraphs. In response to a disrupting event, pertinent MG(s) initiates the fault management procedure, trying to supply load points to the maximum extent, while following the technical and operational constraints of the power grid. If maneuvers and other available measures do not mitigate potential violations, IL(s) of the involved MG(s) or other MG(s) is used to overcome the violations. The utilization of the other MGs' IL(s) depends on the interaction level between the MGs. If any violation is still observed, curtailment of uninterruptible loads in the affected MG(s) becomes necessary.

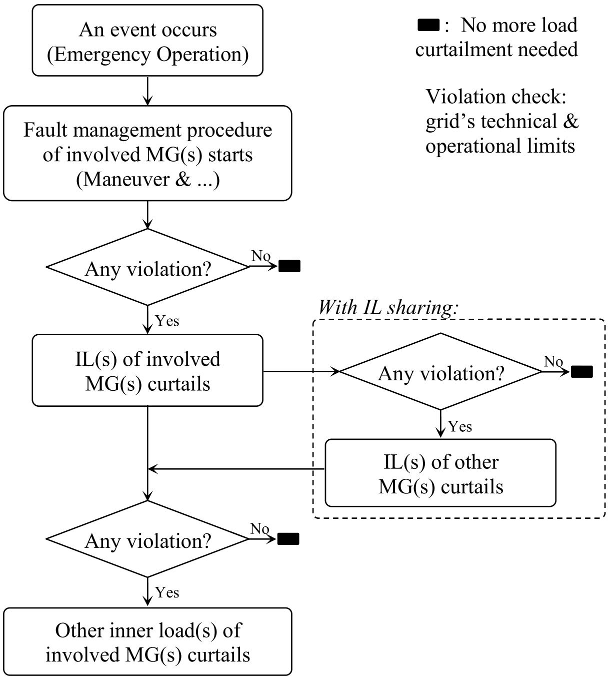

FIGURE 1. Flowchart of fault management procedure (IL and non-IL curtailment in MGs) during emergency operating conditions.

Based on the flowchart, the need for load curtailment (including contracted and non-contracted loads) in each event scenario is analyzed and determined. It is then possible to derive the objective function and formulate the optimization problem subject to a set of constraints.

B. OBJECTIVE FUNCTION

The objective of the proposed model is to minimize the annual ECOST of MGOs, which can be calculated as follows:

$$\min(\sum_{mg}\left\{Cost_{mg}^{Reliability}+Cost_{mg}^{ILs}\right\}) \tag{1}$$

where the first term in the equation signifies the curtailment costs associated with both non-contracted and contracted loads, while the second term pertains to the compensation cost of ILs, as defined in (2) and (3), respectively.

$$\begin{aligned} &Cost_{mg}^{Reliability}\\ &=\frac{1}{24}\sum_{h}\sum_{b\in B_{mg}}\sum_{i}\sum_{ss}\\ &\ldots\left\{\lambda_i.r_{i,ss}.\left[VOLL_b^{NC}.PD_{h,b,i,ss}^{Cur,NC}+VOLL_b^{C}.PD_{h,b,i,ss}^{Cur,C}\right]\right\} \end{aligned} \tag{2}$$

$$\begin{aligned} &Cost_{mg}^{ILs}\\ &=365\sum_{h}\sum_{b\in B_{mg}}\sum_{kk}\rho_{b,kk}.\lambda_h^{Sell,Load}.ILs_{b,kk} \end{aligned} \tag{3}$$

Regarding (2), it is worth mentioning that the curtailment cost of ILs is often presumed to be negligible. Nonetheless, depending on the type of contract, ILs may also receive additional forms of compensation, albeit modest, in case of interruption. The second part of this equation addresses this specific issue, where the penalty cost of ILs' outage is considered. It is important to highlight that VOLL of ILs is comparatively lower than that of the non-contracted loads.

C. CONSTRAINTS

The problem is subject to several constraints outlined in (4)-(17), elaborated in subsequent subsections.

1) POWER BALANCE EQUATIONS

The nodal active and reactive power balance equations are presented in (4) and (5). These equations are modified to include active and reactive power load curtailments.

$$\begin{aligned} &PD_{h,b}-PD_{h,b,i,ss}^{Cur,NC}-PD_{h,b,i,ss}^{Cur,C}\\ &=\sum_{u\in B_{up}}P_{h,u,i,ss}^{Up}-\sum_{l\in L_b^s}PFL_{h,l,i,ss}^{s}-\sum_{l\in L_b^r}PFL_{h,l,i,ss}^{r} \end{aligned} \tag{4}$$

$$\begin{aligned} &QD_{h,b}-QD_{h,b,i,ss}^{Cur,NC}-QD_{h,b,i,ss}^{Cur,C}\\ &=\sum_{u\in B_{up}}Q_{h,u,i,ss}^{Up}-\sum_{l\in L_b^s}QFL_{h,l,i,ss}^{s}-\sum_{l\in L_b^r}QFL_{h,l,i,ss}^{r} \end{aligned} \tag{5}$$

2) POWER FLOW EQUATIONS OF LINES

In order to keep linearity of the model, active and reactive line flows are formulated by linear expressions as follows. As can be seen, the below power flow equations are linear in terms of bus voltage angles and square of the bus voltage magnitudes. It should be noted that the accuracy of the above linear expressions has been justified in [26].

$$\begin{aligned} &\left|PFL_{h,l,i,ss}^{s}-\left[\begin{array}{l}-\frac{1}{2}g_l.\left(V_{h,b_s,i,ss}^2-V_{h,b_r,i,ss}^2\right)\\ +b_l.\left(\delta_{h,b_s,i,ss}-\delta_{h,b_r,i,ss}\right)\end{array}\right]\right|\\ &\le(1-LS_{l,i}).M \end{aligned} \tag{6}$$

$$\begin{aligned} &\left|PFL_{h,l,i,ss}^{r}-\left[\begin{array}{l}\frac{1}{2}g_l.\left(V_{h,b_r,i,ss}^2-V_{h,b_s,i,ss}^2\right)\\ -b_l.\left(\delta_{h,b_r,i,ss}-\delta_{h,b_s,i,ss}\right)\end{array}\right]\right|\\ &\le(1-LS_{l,i}).M \end{aligned} \tag{7}$$

$$\begin{aligned} &\left|QFL_{h,l,i,ss}^{s}-\left[\begin{array}{l}\frac{1}{2}b_l.\left(V_{h,b_s,i,ss}^2-V_{h,b_r,i,ss}^2\right)\\ +g_l.\left(\delta_{h,b_s,i,ss}-\delta_{h,b_r,i,ss}\right)\end{array}\right]\right|\\ &\le(1-LS_{l,i}).M \end{aligned} \tag{8}$$

$$\begin{aligned} &\left|QFL_{h,l,i,ss}^{r}-\left[\begin{array}{l}-\frac{1}{2}b_l.\left(V_{h,b_r,i,ss}^2-V_{h,b_s,i,ss}^2\right)\\ -g_l.\left(\delta_{h,b_r,i,ss}-\delta_{h,b_s,i,ss}\right)\end{array}\right]\right|\\ &\le(1-LS_{l,i}).M \end{aligned} \tag{9}$$

It is noteworthy that these equations also incorporate the participation of any N.O. maneuver line in the emergency operational framework of MGOs, while maintaining linearity of the formulation. When a line's binary variable ($LS_{l,i}$) is set to 1, the right-hand sides of equations for that specific line are considered zero, thus, the left-hand sides (power flow equations) are directly included in the calculations. Conversely, setting the $LS_{l,i}$ variable of line l to 0 assigns a significantly large value to the right-hand side of the power flow equations, causing the left-hand side of the equation to be disregarded. Consequently, in such conditions, the equations corresponding to the specific maneuver line are effectively excluded from the problem-solving process.

3) POWER FLOW LIMITS OF LINES

The power flowing in each line is capped with its thermal capacity in (10). This non-linear equation is linearized using polygon-based linearization method shown in Fig. 2 [27].

$$PFL_{h,l,i,ss}^2+QFL_{h,l,i,ss}^2\le\left(SFL_l^{\max}\right)^2.LS_{l,i} \tag{10}$$

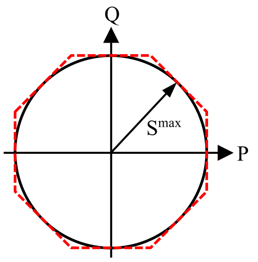

FIGURE 2. Polygon approximation of power flow limits of lines.

4) BUS VOLTAGE MAGNITUDE LIMITS

These limits ensure acceptable voltage magnitudes at all buses across the system, and are characterized as follows:

$$\left(V^{\min}\right)^2\le V_{h,b,i,ss}^2\le\left(V^{\max}\right)^2 \tag{11}$$

5) ILC FORMULATION AND LIMITS

The power available for contracting at each bus must not exceed the minimum demand power. Additionally, load points with demands less than a specified amount are neglected from the ILC program. This limit is defined as follows:

$$z_b.IL_b^{\min} \leq IL_b \leq PD_{h,b} \tag{12}$$

On the other hand, the decrease in consumers' willingness to join high-value contracts is modelled as incremental requested cost by a parabola curve shown in Fig. 3. To maintain linearity of the model, a piecewise linearization of the customers' behavior is used.

$$IL_b = \sum_{kk} ILs_{b,kk} \tag{13}$$

$$0 \leq ILs_{b,kk} \leq z_b.PD_{h,b}.ILs_{kk}^{\max} \tag{14}$$

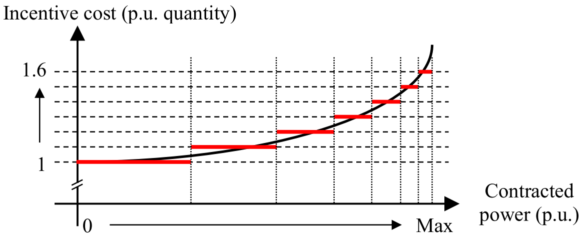

FIGURE 3. The cost curve of the contract with ILs.

6) MAXIMUM CONTRACTED AND NON-CONTRACTED LOAD SHEDDING

Equation (15) enforces that power curtailment from contracted loads at each node is less than the total contracted power at the same node. Equation (16) ensures that the total curtailed power is less than normal consumption of the load:

$$PD_{h,b,i,ss}^{Cur,C} \leq IL_b \tag{15}$$

$$PD_{h,b,i,ss}^{Cur,NC} + PD_{h,b,i,ss}^{Cur,C} \leq PD_{h,b} \tag{16}$$

7) MAXIMUM MANEUVER OPERATION

Considering the limited number of maneuver teams, performing maneuver operations is limited as modeled in (17).

$$\sum_{l\in L_{Maneuver}} LS_{l,i}^{Change} \leq LN_i^{Allowable} \tag{17}$$

8) RELIABILITY INDICES

Quantitative evaluation of the system performance reliability indices provides a better understanding of the grid situation in confronting with power outages. Therefore, the EENS metric of system reliability is emphasized in this study.

$$EENS_{mg}^{NC} = \frac{1}{24}\sum_{h}\sum_{b\in B_{mg}}\sum_{i}\sum_{ss}\lambda_i.r_{i,ss}.PD_{h,b,i,ss}^{Cur,NC} \tag{18}$$

$$EENS_{mg}^{C} = \frac{1}{24}\sum_{h}\sum_{b\in B_{mg}}\sum_{i}\sum_{ss}\lambda_i.r_{i,ss}.PD_{h,b,i,ss}^{Cur,C} \tag{19}$$

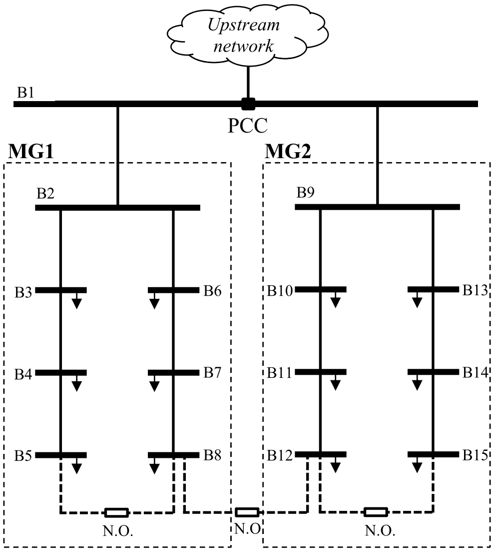

FIGURE 4. Illustrative distribution network with 2 identical MGs.

Using the above formulation, the solution procedure of the ILC problem in an MMG distribution system is executed mathematically, where the objective function is the minimization of total ECOST of MGOs subjected to all operational and technical constraints, including MGs' transaction agreements, line capacity, and voltage violations. In this model, the decision variables are z and IL parameters at each bus of each MG, where, as explained in nomenclature, z and IL represent the selection of IL location and relevant contracted power, respectively. According to the linearized formulation, the proposed model is a MILP problem that can be efficiently solved in GAMS software environment via CPLEX solver (efficient in solving MILP problems) [25].

It should be noted that the main goal of this study is to showcase the profit potential of ILs shared between MGs (improving system flexibility in emergency operating conditions), as well as achieving optimal allocation of these ILs within any MG, based on MGOs' collaboration level. This goal will be thoroughly analyzed and discussed in the subsequent section, supported by illustrative and standard case studies. Additionally, various sensitivity analyses with a focus on the participation of MGs in ILs sharing are included, and the advantage of the cooperative agreements is determined.

III. NUMERICAL STUDIES AND DISCUSSION

To assess the effectiveness of the proposed ILC allocation model in an MMG distribution system and quantify the benefits of IL sharing within this structure, a comprehensive analysis is presented in this section. Initially, an illustrative case study comprising two MGs is examined to demonstrate its applicability. Subsequently, the ILC allocation model is further tested on IEEE 33-bus test system. The problem instances are solved on a PC with 12th Gen Intel(R) Core-i7 CPU clocking at 3.61 GHz and 16-GB of RAM.

A. ILLUSTRATIVE CASE STUDY

An illustrative power distribution network consisting of 2 similar MGs is studied. The single-line diagram of this network can be found in Fig. 4. Each MG is equipped with 6 uniform load points. MGOs have the flexibility to join a contract with all or some of these consumers, known as ILs, according to their individual objectives. MGOs can offer incentives, such as discounts on electricity bills (for contracted amount of power demand), seeking permission for power curtailment during outage scenarios. Moreover, these MGs can mutually share their own ILs with each other. This contribution can bring mutual benefits, by significantly enhancing the control capabilities of the MGs during fault events, ultimately resulting in a reduction in outage costs.

Some of the main parameters or assumptions underlying the studied system are outlined below:

- Fault events include only branch outages with failure rate of 0.75 f/yr.
- A typical per unit 24-hour load profile, with load factor of 0.7 and the valley of 0.3 p.u. at hour 4 (shown in Fig. 5), is used to be multiplied with the original nodal peak load in [28] to obtain the typical hourly load profiles. Peak load of each costumer is assumed to be 1.667 MW.
- The electricity delivery rate is assumed to be 150 \$/MWh at peak hours, and the VOLL of non-contracted loads is assumed to be 50 times of the offered electricity price [16], whereas the VOLL of contracted loads is neglected, in return for the given 20% discount in their electricity price, during 4 months of the year.
- Predominant uncertainties such as loads and prices are considered by multiple operating scenarios. These scenarios are developed based on 5% and 15% standard deviations for load consumption and electricity price –from their forecasted values, respectively.
- Only large customers with peak consumption greater than 100 kW are allowed to participate in ILCs. The maximum and minimum contracts for the participating customers are assumed to be 30% of their peak load and 50 kW, respectively.
- Customers have the option not to be included in ILC program of MGOs; however, they are required to notify their absence in advance.
- In MGs, lower and upper limits of voltages are considered to be 0.9 p.u. and 1.1 p.u., respectively. Thermal constraints of power lines are also considered in the network modelling.
- The switching and repair times of the fault management procedure are estimated to be approximately 1 and 8 hours, respectively.
- Due to maneuver's team's limitations, a maximum of 2 maneuver operations are enforced.

In addition, when considering whether to share ILs, two main scenarios can be envisioned. In the first scenario, each MGO uses its ILs individually, whereas, in the second scenario, interrupted MG can incorporate other MGs' ILs into its control tools during the fault management procedure.

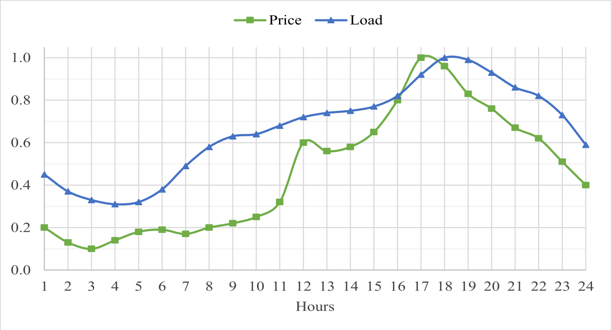

FIGURE 5. Per unit hourly price and load consumption profile.

B. RESULTS OF THE ILLUSTRATIVE CASE STUDY

1) BASE CASE SCENARIO

In the absence of any contract with load points in the base case scenario, the ECOST and EENS of each MG is equivalent to 160.53 k\$/yr and 31.57 MWh/yr, respectively. Figure 6 illustrates a scheme showing how each fault affects the EENS at each MG (shown in MG1) and highlights the impact of individual load points on the EENS (shown in MG2). Note that, since the MGs depicted in Fig. 6 are identical, the values referred in MG1 are likewise true for MG2. For example, the outage of the branch between B2 and B3 yields the same reliability index as the one between B9 and B13. Similarly, the reliability index of the existing load point at B3 is equal to that of the load point B13.

In Fig. 6, as observed in MG1, it is evident that the impact of faults in the upstream branches of the feeders is more significant due to the radial structure of the MG. Moreover, faults occurring in the left feeder of MG1 have a greater impact compared to those in the right feeder as the latter is connected to maneuver points from both sides, whereas the left feeder is only connected from one side. Consequently, maneuver operations can alleviate a larger portion of outages affecting the existing load points in the right feeder. From the perspective of load point reliability metrics, it can be observed that the load points positioned near the end of the feeder experience less interruption, thanks to their strategic proximity to maneuver points. Other load points, even though encountering fewer power outages, are faced with a more challenging situation since they lack the flexibility to receive power from alternative routes (i.e., through maneuver operations).

The above example provides valuable insights into identifying network weaknesses such that the use of ILCs could be justified to address these vulnerabilities. For instance, when the load points in the left feeder of the MG1 experience more outages, at the first glance, it is anticipated that the MGO should make more contracts with these load points to reduce the penalties resulting from power interruptions. Another example is about load points B3 and B6 which experience the longest interruption. Therefore, it is expected that the MGO

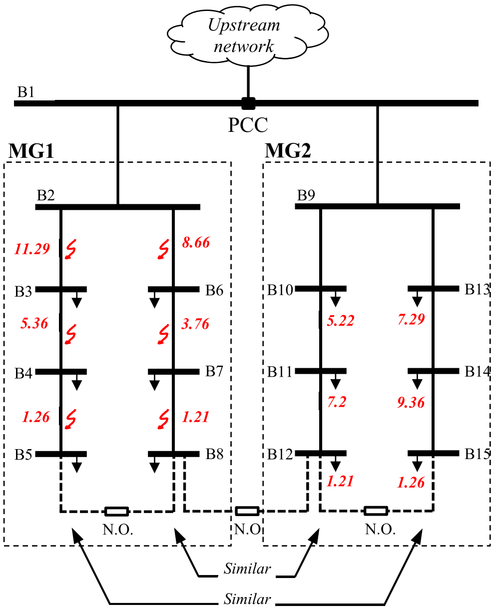

FIGURE 6. Share of each branch outage and load point in the overall EENS index (MWh/yr) of MGs: Base Case Scenario.

establishes more contracts with these load points to improve MG's reliability and minimize the interruptions costs.

It is worth noting that the presence of border maneuver point –middle N.O. switch– in this case study has greatly enhanced the efficiency of emergency operations in MGs. Neglecting this control tool would result in ECOST and EENS indices for each MG amounting to 203.3 k$/yr and 41.98 MWh/yr, respectively, reflecting an approximately 30% increase compared to the original base case scenario. This simple comparison underscores the substantial positive impact that cooperative operation of MGOs may have a significant impact on improving their operational efficiency. It is expected that sharing ILs between MGs would also create a similar improvement in these performance reliability indices. In the two upcoming subsections, this potential has been extensively explored.

2) SCENARIO 1; NO IL SHARING

In the first scenario, it is assumed that each MG independently and separately enters into individual contracts for ILs and decides to utilize them exclusively during its respective interruptions, without sharing them with other MGs. Under this assumption, each MG aims to sign a contract with a portion of its load points individually, in order to optimally establish a compromise between contract costs (i.e., incentives) and the reduction in penalties imposed from uncontracted load shedding (i.e., reliability costs).

The optimal amount of contracts for ILs to achieve this objective is shown in Fig. 7. As can be seen, the size and location of these ILs differ from what was previously anticipated. While conventional wisdom favored prioritizing contracts with load points exhibiting high EENS and interruption costs, the latest findings indicate that the optimal approach is to contract with those load points that are strategically located near maneuvering points (N.O. switches) or in the middle of the feeders. Accordingly, the MGO can derive maximum benefits from such resources when facing various failure events.

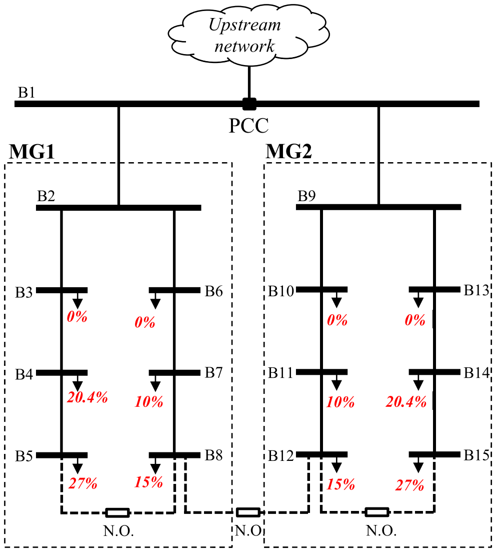

FIGURE 7. ILs allocation in illustrative case study: Scenario 1.

To gain a deeper comprehension of the findings, multiple events are further analyzed. Considering the case where MGO1 engages in a contract with the existing load point at B3, this IL would prove beneficial solely in the event of a fault occurrence in branch B2-B3 (branch between B2 and B3), causing an interruption in the aforementioned load point. Otherwise, the IL would serve no purpose in handling other failures. This is while the IL in B5 can be used in all failure events to directly address failures on the branches within the left feeder of MG1 (B2-B3, B3-B4 and B4-B5) and the those of the right feeder (B2-B6, B6-B7 and B7-B8) by closing the N.O. switch. By employing this approach, the MGO can promptly activate this IL during any fault scenario, which results in reducing load shedding of uncontracted demands and averted high penalties. By signing the contracts with ILs as pointed in Fig. 7, it can be observed that the ECOST of MG1 decreases from 160.53 k$/yr to 140.73 k$/yr, and the EENS index plummets from 31.57 MWh/yr to 16.85 MWh/yr. In essence, leveraging ILs empowers MGOs to decrease ECOST and EENS of MGs by around 12% and 47%, respectively.

Table 1 presents a comprehensive breakdown of the results. In this specific scenario, the MGO engages in contracts with 4 out of 6 load points totaling 1.206 MW of the total 10 MW peak demand. These contracts incur an annual cost of k$ 51.11 (applied as a discount on their electricity bills), while decreasing the imposed interruption cost of MGO by 70.91 k$/yr. In simpler terms, this initiative led to an overall cost reduction of 19.8 k$/yr. In terms of reliability indices, a noteworthy observation pertains to the EENS of uncontracted loads (UC-EENS), whose interruption is subject to heavy penalties, facing a significant decrease of 47%. This reduction is due to the fact that most of the interruptions have been attributed to ILs.

TABLE 1. Comparison of MG's overall reliability indices in the illustrative case study: Base Case Scenario and Scenario 1.

Indices	Unit	Base case	Scenario 1	Change (%)
ECOST	*k$/yr*	160.53	140.73	-12
Reliability cost	*k$/yr*	160.53	89.62	-44
ILC cost	*k$/yr*	-	51.11	-
EENS	*MWh/yr*	31.57	34.34	9
UC-EENS*	*MWh/yr*	31.57	16.85	-47
C-EENS**	*MWh/yr*	-	17.49	-
ILC	*MW*	-	1.206	-
ILC	*p.u.*	-	0.1206	-
ILs	*Count*	-	4	-

* UC-EENS: EENS of uncontracted power consumption
** C-EENS: EENS of contracted power consumption (IL)

In other words, when incidents occur, priority has been given to shedding the consumption of ILs before addressing any further demand power. This approach results in an annual electricity interruption of 17.49 MWh for the ILs. Considering the average ILs' capacity of 1.206 MW, this annual electricity interruption translates to approximately 15 hours of interruptions per year (about 1 hour per month). This may not be deemed high relative to the significant discount granted on their electricity bills.

3) SCENARIO 2; WITH IL SHARING

In the first scenario, the ILC allocation in each MG was addressed, highlighting the impactful cost reductions achieved through the effective utilization of ILs. This work is done with the assumption that each MG contracts with ILs individually and will not share them with other MGs during disruptive events. Conversely, the endeavor in scenario 2 is to investigate the collaborative operational planning of ILCs, with a specific emphasis on how sharing of ILs can optimize the performance and flexibility of interconnected MGs.

By sharing ILs between MGs, it is observed that the ECOST of each MG has decreased by 13% compared with the previous scenario. The findings reveal that mutual sharing of ILs can be beneficial for the involved MGs. Detailed comparative analysis in Table 2 between scenarios 1 and 2 highlights a significant 28% reduction in reliability costs for the MGs thanks to the effective sharing of ILs resources, with securing slightly more contract (only 17% more ILs required).

Figure 8 illustrates the location and size of ILs in this scenario. Upon careful analysis of the results, it is evident that the number and amount of ILCs have increased at some load points while decreasing at others. This increase is primarily attributed to the load points on the right feeder of MG1, allowing MG2 to also benefit from these ILs through the border maneuver point, whenever required.

Figure 9 presents the key findings from the investigated analyses. As depicted, scenario 2 yields the greatest ECOST reduction in emergency operations, which is the main goal of MGOs in this research work. Specifically, under scenario 2, the ECOST reduction amounts to around k$ 38 per year compared to the base case scenario.

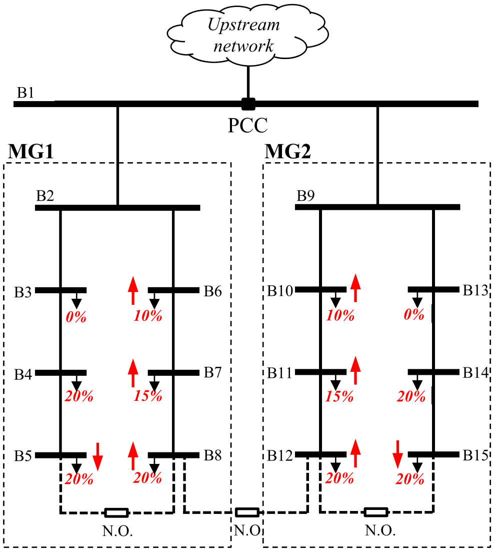

FIGURE 8. ILs allocation in illustrative case study in Scenario 2 by comparing the amount of ILCs with Scenario 1.

TABLE 2. Comparison of MG's overall reliability indices in illustrative case study: Scenarios 1 and 2.

Indices	Unit	Scenario 1	Scenario 2	Change (%)
ECOST	*k$/yr*	140.73	122.79	-13
Reliability cost	*k$/yr*	89.62	64.1	-28
ILC cost	*k$/yr*	51.11	58.69	15
EENS	*MWh/yr*	34.34	35.53	3
UC-EENS*	*MWh/yr*	16.85	12.56	-25
C-EENS**	*MWh/yr*	17.49	22.97	31
ILC	*MW*	1.206	1.415	17
ILC	*p.u.*	0.1206	0.1415	17
ILs	*Count*	4	5	25

* UC-EENS: EENS of uncontracted power consumption
** C-EENS: EENS of contracted power consumption (IL)

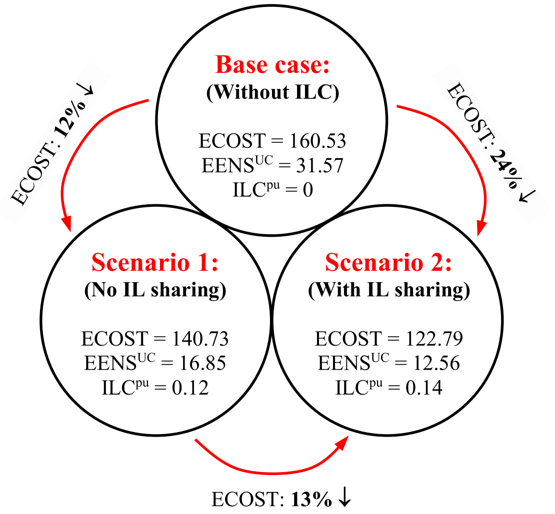

FIGURE 9. Comparison of MG's overall reliability indices in illustrative case study.

One main challenge in ILs' sharing ideology is the notable increase in the EENS of the contracted power by about 30%.

This escalation in EENS may consequently lead to an overall average interruption time increment of ILs compared with scenario 1. Therefore, load points may be reluctant to enter into such a contract. To delve deeper into this challenge, the EENS of each IL is examined in both studied scenarios. The results, as depicted in Fig. 10, demonstrate that by sharing ILs among MGs, the worst EENS value decreases from 7.13 MWh/yr to 6.29 MWh/yr. In fact, despite the C-EENS increase by 31%, the number of ILs has risen from 4 to 5, and the power involved in the contracts has also grown from 1.206 MW to 1.415 MW, indicating 25% and 17% increase, respectively. This increased expansion in contracts results in a wider coverage of interruptions by involving more ILs, without unduly burdening on any of the contracted load points. However, in situations where the increase in EENS of ILs is excessive, MGOs may offer higher incentive rates to compensate for any additional and unusual interruptions. This will be analyzed in the standard case study section, which will include extensive sensitivity analysis on the most effective and important parameters of the problem.

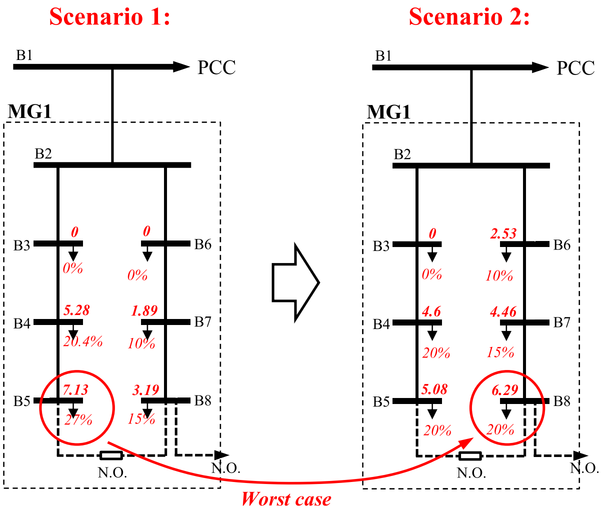

FIGURE 10. Comparison of nodal EENS index (MWh/yr) of each IL for MG1: Scenario 1 and Scenario 2.

C. STANDARD CASE STUDY

The IEEE 33-bus distribution system, shown in Fig. 11, is used to examine the proposed ILC allocation model in an MMG distribution system. IEEE 33-bus test system is a 13.8 kV radial distribution network with 33 nodes, 3 laterals, and 5 N.O. tie-lines labelled from (1) to (5) [27]. To investigate the objectives of this study, this network is divided into 4 MGs, in a way that each lateral is located inside an MG, and the main path is treated as a single MG. It is important to note that the boundaries of the formed MGs are hypothetical and not mandatory. In fact, an MG can be defined as a single load point, a set of several load points, or even the entire network, and the problem-solving approach remains the same in all possible combinations.

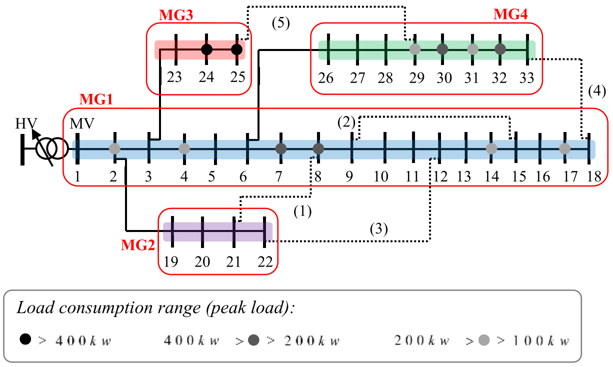

FIGURE 11. IEEE 33-bus distribution system separated to 4 MGs.

D. RESULTS OF THE STANDARD CASE STUDY

Figure 12 and Table 3 depict the optimal allocation of ILs within the IEEE 33-bus test system and presents the comparative results of implementing the proposed method, for the base case scenario, scenario 1, and scenario 2, respectively. In Fig. 12, the location of each ILC is indicated by red circles. In scenario 1, MGOs make contract with load points 7, 8, 14, 25, 30, and 32 by 30% of their peak demands, as well as load point 24 by 27% of its peak demand. In the scenario 2, load points 29 and 31 are included in this set, with the same amount of contract.

Considering the network shown in Fig. 12, the most important findings are summarized as follows:

- ➢ MGOs prefer to enter into contracts with large loads. By adopting this approach, a significant portion of power interruptions of these large loads can be covered, leading to a notable reduction in interruption penalty costs. Moreover, establishing contracts with major consumers helps MGOs to minimize the coordination challenges during fault incidents.
- ➢ Generally, ILCs are strategically established with load points located at the end of a radial path (in both scenarios) or in the adjacency of the maneuvering points (in scenario 2). This guarantees that the MGOs can efficiently utilize the ILCs' potential to cover power interruptions caused by inevitable events.
- ➢ In scenario 2, MGO4 contracts with load points 29 and 31 which have been added to the previous contracts. This implies that these load points are included in the contract framework for the IL interaction between MGs, due primarily to their strategic locations in strategic MG (MG4 plays a pivotal role in the network). Therefore, MG4 provides support to MGs 1 and 3 through maneuver points 4 and 5.

Table 3 clearly demonstrates that incorporation of ILs in the emergency operational framework of MGOs leads to a significant reduction in the ECOST and uncontracted EENS, presenting the positive impact on important reliability indices. With the careful examination of results, the following main conclusions can be interpreted:

- ➢ The ECOST of MGs is reduced by 10% and 17% through implementing the ILCs in scenario 1 and scenario 2, respectively. This comparison demonstrates the

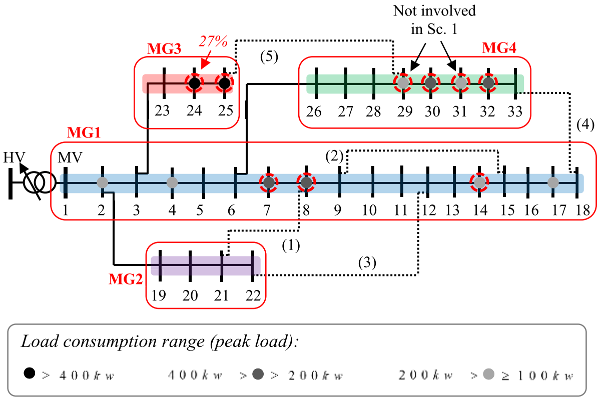

FIGURE 12. ILs allocation in IEEE 33-bus distribution system: Scenarios 1 and 2.

importance of collaboration among MGs where ECOST can be further reduced by 7%.

- The implementation of the proposed method leads to a noteworthy 25-30% reduction in the EENS of the uncontracted load points. This can be regarded as a promising opportunity for MGOs to enhance their systems performance reliability indices.
- ILs are given 20% discount rate in their consumption electricity price, which can be considered as a great opportunity to reduce their electricity cost, in expense of less than 5 times annual service interruptions which last approximately 34 hours totally (about 0.5 hours power interruption per event in average).

TABLE 3. Comparison of MG's overall reliability indices in the standard case study.

Indices	Unit	Base case	Scenario 1	Scenario 2
ECOST	*k$/yr*	255.48	229.61 *(10%↓)******	212.96 *(17%↓)******
Reliability cost	*k$/yr*	255.48	205.42	185.53
ILC cost	*k$/yr*	-	24.19	27.43
EENS	*MWh/yr*	60.34	61.87	63.08
UC-EENS*	*MWh/yr*	60.34	45.31 *(25%↓)******	42.52 *(30%↓)******
C-EENS**	*MWh/yr*	-	16.56	20.56
ILC	*MW*	-	0.531	0.602
ILC	*p.u.*	-	0.143	0.162
ILs	*Count*	-	7	9

* UC-EENS: EENS of uncontracted power consumption
** C-EENS: EENS of contracted power consumption (IL)
*** Reported changes are in comparison with the base case

E. SENSITIVITY ANALYSIS

Some of the input parameters assumed to be permanent in the above studies, could directly influence the ILCs in any MG as well as their sharing benefits among MGs in an MMG distribution network. In this section, sensitivity analyses will be performed on key parameters, such as failure rate of the grid events, ILs' incentives, and curtailment costs of ILs, to provide further insight into the effective role of ILCs.

1) FAILURE RATE OF NETWORK EVENTS

Figure 13 illustrates that implementing ILs in MGs with high failure rates can lead to further improvements in system reliability. Therefore, ILCs have better applicability for such MGs. Furthermore, when these ILs are shared among MGs, there is a marked increase in profitability. Conversely, if the ILs are not shared, their effectiveness in MGs with lower failure rates will significantly decrease. In such cases, the utility of ILCs is limited, and entering into a contract can be economically justified only when ILs are shared among MGs.

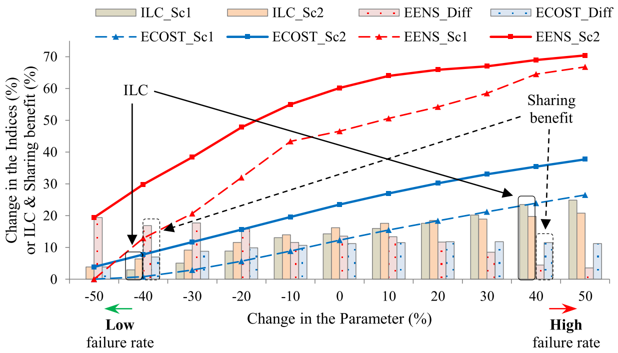

FIGURE 13. Impact of system reliability (failure rate) on ILCs and reduction of ECOST and EENS indices in Scenarios 1 and 2 in comparison with the base case scenario.

2) INCENTIVES PAID TO ILS

The level of incentives provided by MGOs to costumers is inversely proportional to the reduction in ECOST and EENS indices of MGs. Figure 14 indicates that MGOs capable of establishing incentive-based ILs programs with minimal incentives are poised to make significant advancements. Moreover, through comparing the EENS differences under varying incentive levels, it becomes evident that the influence of IL sharing in higher incentives is more pronounced.

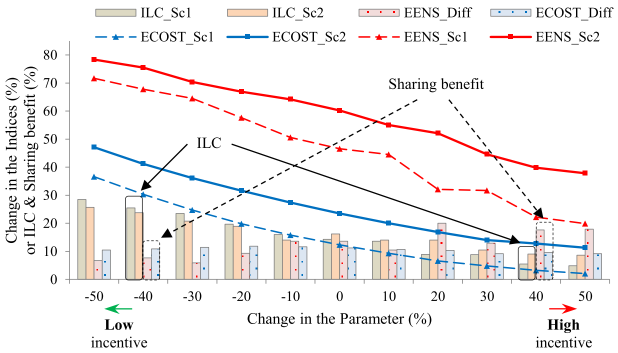

FIGURE 14. Impact of IL's incentive on ILCs and reduction of ECOST and EENS indices in Scenarios 1 and 2 in comparison with the base case scenario.

3) CURTAILMENT COSTS OF ILS

In IL contracts, it may be mutually agreed upon that in case of any load shedding occurrence, an extra compensation will be paid to shed ILs in addition to the prior incentives. If this cost escalates, fewer contracts will be included in the MGO's agenda, resulting in limited enhancements in emergency operation. However, it is worth noting that sharing the ILs between MGs sustains these contracts' beneficiary, in all analyzed ILs' VOLL amounts. Figure 15 depicts the results.

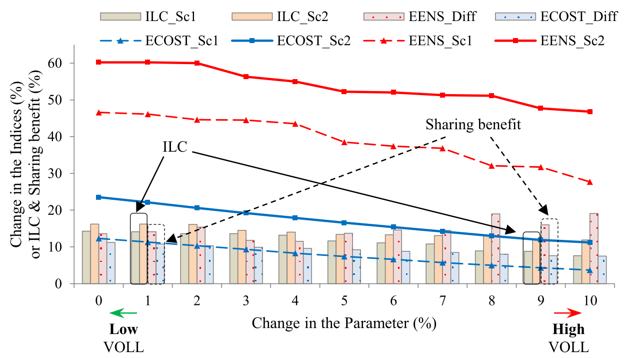

FIGURE 15. Impact of IL's curtailment cost on ILCs and reduction of ECOST and EENS indices in Scenarios 1 and 2 in comparison with the base case scenario.

4) SUBSTITUTING THE ILS WITH ENERGY STORAGE UNITS

ILs can be regarded as either negative consumption or positive generation during events, akin to energy storage systems. In scenario 2, a requirement of approximately 0.6 MW ILCs is observed (Table 3), correlating to an initial investment cost of M$ 3 that can yield returns of up to k$ 300 annually. Comparing this with the annual cost of ILCs around k$ 27, it is apparent that establishing ILCs proves to be more cost-effective. Nonetheless, energy storage applicability in normal operations should not be neglected, although it lies outside the scope of this study. However, emphasizing solely on emergency operations, the adoption of ILCs is strongly recommended.

In the fingertip calculations outlined above, the key assumptions include: an investment cost of 0.2 $/W for energy storage units [29], an assumed infinitive lifespan for these units, and an investor's required ROR set to 10%.

IV. CONCLUSION

A. SUMMARY AND CONCLUSION

This paper developed a model to find the profitability of ILs' sharing between MGs (improving system flexibility in emergency operating conditions), as well as finding the optimal location and size of these ILs from MGOs' perspective. Assuming that the financial incentives such as discount rates are already set up, MGOs will allocate ILCs and choose between the candidate customers based on compensation cost, lines capacity constraints, voltage limits, system topology, and reliability level. The results of the case studies show that the optimal implementation of ILCs can enable the customers to gain reasonable compensation cost, as well as bringing a considerable profit to the MGOs. Furthermore, cooperative planning of ILCs is analyzed and sharing benefit of these ILs indicated that this policy can further improve the system flexibility in emergency conditions. In addition, using the linearized equations, the proposed model is a MILP problem which can be effectively solved by commercially available software packages.

Here, some key findings of this research are highlighted:

- By employing ILCs as an emergency operational tool, it empowers MGOs to effectively alleviate the detrimental effects of unforeseen grid events, leading to a remarkable reduction of approximately 15% and 25% in ECOST and EENS, respectively.
- Cooperative planning and coordinated utilization of ILs hold the promise of maximizing the advantages of such contracts for all MGOs engaged in the initiative, potentially enhancing the benefits by up to 10%.
- Typically, ILCs are strategically positioned with load points placed at the end of a radial path or in close proximity to the maneuvering points. The latter case emphasizes the significance of mutual interactions among MGOs.
- MGs with poor reliability characteristics (high failure rate of network components) stand to gain greater advantages from the implementation of ILCs.
- In the MGs with high-priority loads (high VOLL), ILs can effectively prevent MGOs from incurring significant penalty costs due to power interruptions, thanks to the support of these voluntarily contracted loads.
- The provision of adequate incentives plays a pivotal role in enabling more ILCs, leading to enhanced profitability. It is imperative that these incentives are enticing enough to motivate customers to actively participate in contractual engagements. This can be sensitively analyzed by MGOs to find the optimum point in the contracts.

B. FUTURE WORKS

This paper demonstrates the benefits of utilizing ILs in the MGOs' operational framework (in emergency operating conditions), especially where MGOs agree to share their resources, to improve the overall system flexibility. However, some areas require further investigation, such as:

- Investigating the details of information, power and monetary interactions between interconnected MGOs in case of disruptive events.
- Investigating the feasibility analysis of ILs' sharing and determining a coordinator agenda for this purpose. Simply, the DSO, one of MGOs or an independent service provider can take this role.
- Investigating the obligatory level of IL sharing (when needed) and considering characteristics of MGO's in the emergency operating conditions.
- Exploring the economic value of ILCs when being planned in the presence of pre-installed energy storage or diesel generator units which may have been primarily installed for use in normal operations, but yet also capable of supporting emergency operations.
- Addressing the value sharing issues about IL sharing and developing an optimal market to encourage MGOs participation in such a cooperative planning, especially using coalitional game theory [30].

Continuing to work on these research directions, it is expected to discover new opportunities and challenges associated with potential benefit of the customer flexibility in alleviating the adverse effects of unforeseen power outages. MGOs can strategically regard EDRPs, particularly ILCs, as an insurance mechanism to mitigate the financial impact of probable events, while consumers perceive these initiatives as opportunities to receive discounted electricity rates, creating a mutually win-win scenario. Furthermore, resource sharing within MMG structured DNs presents additional collaborative opportunities that warrant comprehensive investigation of the associated practical challenges.

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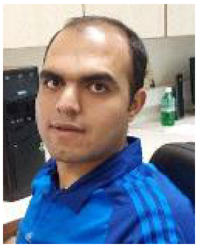

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