GA-BASED APPROACH FOR INSPECTION PRIORITIZATION IN ELECTRIC POWER DISTRIBUTION NETWORKS

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ABSTRACT

The increasing need of ensuring appropriate levels of reliability, profitability and consumer satisfaction drives utilities to develop strategies to identify aging assets through scheduled inspections. Nevertheless, as total inspection capability is limited by available budget number of maintenance teams, a strategy to allocate teams into "the most critical" segments of the grids is desirable. Nowadays, inspection scheduling is still performed based on personal experience and on automated spreadsheets. This paper proposes a GA-based approach to assess grids' parameters, define metazones (i.e., grid segments among protection devices) and prioritize those that further enhance power quality features. Results demonstrate that the prioritized metazones are feasible for real-life application in a comprehensive fashion.

INTRODUCTION

Inspection of assets is a common practice in electric power distribution industry worldwide. By identifying assets and areas with great risk of causing grid failures, utilities may plan preventive maintenance actions. Such actions guarantee high levels of system reliability and ensure not only customer satisfaction, but also high profitability by meeting regulatory goals for power quality indexes and avoiding payments of customers refunding [1]. However, as distribution networks may span up to tens of thousands of kilometers, it becomes unfeasible to inspect them all due to budget limitations.

Nowadays, planning engineers often select portions of the grid for inspection based on personal experience and on automated spreadsheets. Such processes may be inaccurate and time-consuming. Many works have addressed inspection strategies for a wide variety of applications and contexts [2]. The present work proposes a GA-based approach for assessment of grid segments and prioritization for inspection. In contrast to existing approaches, the proposed methodology combines heuristic rules (i.e., personal experience and benchmarks) to a systematic approach based on merit indexes that, in short, considers load density, power flow results, and outages – henceforth referred to as physical, operational and contingency attributes – assisting planning engineers to identify the most critical network segments and yield an optimal inspection planning to the corresponding service area. A planning tool suitable for the needs of a Brazilian utility was implemented. Results are shown for a case study that utilizes real data from eight feeders, allowing to quantitatively assess zones with higher probability of failures.

METHODOLOGY

Input Data

The assessment utilizes data from several corporate systems such as GIS (for grid topology), OMS (for power outage records) and SCADA measurements at each feeder`s main breaker. External spreadsheets with maintenance schedule and inspection history are also used for pre-filtering of areas with mandatory inspection and areas in which no inspection should be performed in the current inspection cycle.

Metazones

The grid model is split into several **metazones**, which are herein defined as a set of network segments and equipment between protection devices. If traditional zones (segments between any circuit-opening device) are used, there would too many short sections to be prioritized, as shown in Figure 1, where four metazones for the primary feeder of a distribution network, each being composed by a few zones.

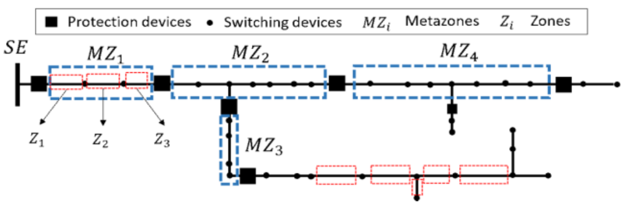

Figure 1 - Metazones illustration

A practical method used by the power utility included in this study to assess the need of inspection throughout a metazone is to pre-filter them into: **non-prioritized metazones**, which is the set of metazones where the last inspection has been dated prior to one year or are expected to undergo maintenance; **to be prioritized metazones**, which on the other hand, comprises the interval of one to three years; and, at last, m**andatory metazones**, which include the where the last inspection occurred after three years.

In the process of defining which metazones are going to be chosen for the next inspection cycle, the non-prioritized must be excluded from the prioritization, due to recent last inspection. Also, mandatory ones must also be excluded but beforehand included for inspection, due to outdated last inspection. To be prioritized metazones, however, include those that compete for a position in the next inspection cycle. By combining the aforementioned data, each metazone to be prioritized can be quantitatively assigned a set of attributes, divided into three groups, namely: physical, operational and contingency.

Physical Attributes

Physical attributes are related to load density. They consider the number and total consumption of customers, and the total primary feeder length within each metazone. The evaluation function of the physical attributes (f_i^{Phy}) of each metazone is given by

$$\mathrm{f}_{\mathrm{i}}^{\mathrm{Phy}} = \frac{kWh_i^{total} \times Ncons_i^{1.5}}{\mathrm{L}_{\mathrm{i}}^{\mathrm{MV_{total}}}} \tag{1}$$

where kWh_i^{total} is the total energy consumption; $Ncons_i$ is the total number of consumers; and $\mathrm{L}_{\mathrm{i}}^{\mathrm{MV_{total}}}$ is the total primary feeder (i.e., MV network) length. These attributes were designed from figures of merit such as the consumer-energy, represented by the product $kWh_i^{total} \times Ncons_i$, and the linear density of consumer-energy, obtained by the calculation of $\frac{kWh_i^{total} \times Ncons_i}{L_i^{MV total}}$. The factor 1.5 is intentionally used to give greater value to the number of consumers at the expense of the total energy consumption.

Operational Attributes

Operational attributes are related to static power flow simulation. SCADA measurements at each feeder`s main breaker is filtered, and a daily 1-hour-averaged demand profile is calculated. The profile is further considered in a load allocation algorithm. The attributes are calculated considering the power flow at the resulting profile`s peak demand hour. They consider the primary network length of segments with operation violations such as overloading and voltages out of regulatory limits. The evaluation function of the operational attributes of each metazone (f_i^{Op}) is given by

$$f_i^{Op} = K^V \times f_i^V + K^I \times f_i^I \tag{2}$$

where K^V and K^{I} are weighting parameters in the interval $[0,1]$ for voltage and line's current. Also, for each metazone i, f_i^V and f_i^I are defined as

$$f_i^V = \left(K^{V_{prec}} \times L_i^{V_{prec}} + K^{V_{crit}} \times L_i^{V_{crit}}\right) \times f_i^{Phy} \tag{3}$$

$$f_i^I = \left(K^{I_{prec}} \times L_i^{I_{prec}} + K^{I_{crit}} \times L_i^{I_{crit}}\right) \times f_i^{Phy} \tag{4}$$

where $K^{V_{prec}}$, $K^{V_{crit}}$, $K^{I_{prec}}$ and $K^{I_{crit}}$ are weighting parameters in the interval $[0,1]$ for precarious and critical voltage and current levels, according to Brazilian regulation [3]; $L_i^{V_{prec}}$, $L_i^{V_{crit}}$, $L_i^{I_{prec}}$ and $L_i^{I_{crit}}$ are the MV line length affected with precarious and critical voltage and current levels. It is worth mentioning that $f_i^{Op} = 0$ for all metazones with no violations. As f_i^V and f_i^I values might significantly differ, they are normalized to the maximum value found amongst all metazones before being multiplied by their respective weighting factors.

Contingency Attributes

Contingency attributes are related to power outages and system failures within a metazone. They consider the calculation of Customers Interrupted (CI), Customers Interrupted times Hours of Interruption (CIH), Energy Not Supplied (ENS) and Number of Interruptions (NI). The evaluation function of the contingency attributes of each metazone (f_i^{Con}) is given by

$$f_i^{Con} = K^{CI} \times CI_i + K^{CIH} \times CHI_i + K^{ENS} \times ENS_i + K^{NI} \times NI_i \tag{5}$$

where K^{CI}, K^{CIH}, K^{ENS} and K^{NI} are weighting parameters in the interval $[0,1]$ for CI, CIH, ENS and NI. Likewise the operational attributes their values are also normalized.

Problem Formulation

The problem is formulated as an optimization problem to maximize physical, operational and contingency attributes considering that utility's total inspection capability is limited. Mathematically it is represented as shown in (6), wherein I is the set of all metazones i after pre-filtering stage (i.e., only **to be prioritized metazones**); x_i is a binary variable to represent which metazones are selected for inspection ($x_i = 1$) or not ($x_i = 0$); f_i is the evaluation function of each metazone; and K_{pen} is a binary parameter to penalize the objective function if an obtained solution surpass teams' inspection capability.

$$max\ \mathrm{K_{pen}} \times \left(\sum_{\mathrm{i} \in \boldsymbol{I}} (\mathrm{x_i} . \mathrm{f_i})\right) \tag{6}$$

The aforementioned f_i represents a function to quantify and rank a priority order for inspections, and it can be expressed as in (7). The latter considers K^{Phy}, K^{Op} and

K^{Con} as physical, operational and contingency weighting parameters in the interval [0,1], while $K^{Phy} + K^{Op} + K^{Con} = 1$; and K_i^{Others} as an ascending linear function that increases f_i up to 20% through time as long as a metazone is operating without inspection in the interval of one to three years, as modeled in (8).

$$f_i = \left(K^{Phy} \times f_i^{Phy} + K^{Op} \times f_i^{Op} + K^{Con} \times f_i^{Con}\right) \times K_i^{Others} \quad (7)$$

$$K_i^{Others} = \begin{cases} (t-1) \times 0.1 + 1, & if\ 1 \le t \le 3; \\ 0, & otherwise. \end{cases} \quad (8)$$

It is of utmost importance ensuring the normalization of f_i^{Phy}, f_i^{Op} and f_i^{Con} in order to avoid discrepancies that neglect the effects of one or another attribute. The presented K_{pen} represents a parameter to penalize the objective function ($K_{pen} = 0$) if a solution surpass utility's total inspection capability (Cap_{total}), and it is modeled as shown in (9). Ultimately, the total inspection capability (Cap_{total}), which is represented by (10), considers the product of the number of teams available (N_{teams}), the inspection capacity of a team in km/day (Cap_{team}) and the inspection cycle in days (T).

$$K_{pen} = \begin{cases} 1, & if \sum_{i \in \boldsymbol{I} | \boldsymbol{x_i} = \boldsymbol{1}} L_i^{MV_{total}} \le Cap_{total}; \\ 0, & otherwise. \end{cases} \quad (9)$$

$$Cap_{total} = N_{teams} \times Cap_{team} \times T \quad (10)$$

As the objective of the inspections is to help utilities to reduce grid failures at their networks and minimize customer outages, which are directly measured by the contingency parameters, they should have a greater weighting factor when compared to the others. Physical attributes must assume sufficiently high values as well, due to its feature of aiming at areas with high load density. On the other hand, as operational attributes are obtained from power flow and it is common that utilities lack of reliable information for this kind of data, it is suggested to consider relatively low operational attribute values in order to avoid poor outcomes as a result of inaccurate inputs.

Genetic Algorithm

The prioritization proposed is based on a Genetic Algorithm (GA) with a binary formulation and aims to determine the set of metazones that leads to a maximized sum of ranks. Each chromosome has the size of the number of metazones N_{mz} to be prioritized and each gene corresponds to a specific metazone and can assume a binary value, representing if the respective metazone should be prioritized or not, as shown in Figure 2. Further details regarding GAs may be found in [4].

MZ_1	…	MZ_i	…	$MZ_{N_{mz}}$
1	…	0	…	1

Figure 2 - Binary GA Chromosome

The genesis process is defined with an 80% probability of a specific gene being initialized as 0 because during experimental simulations it has been verified that in several cases the initial contained a significant number of chromosomes whose total length of metazones exceeded the total inspection capacity. In these cases, the GA generally was not able to evolve and converge to a final generation whose best evaluated chromosome satisfied this constraint. The general steps performed by the GA are summarized below:

1: Genesis;
2: Define the number of generations as stop criteria;
3: **while** (stop criteria is not met) **do**
4: Evaluate fitness functions (4) for each chromosome;
5: Elitism, mutation and crossover;
6: **end while**
7: All x_i variables for the best evaluated chromosome are found as final solution.

Inspection Types

The existence of different inspection types, with different number of teams and capacity is dealt by grouping metazones to be prioritized depending on the region where each metazone is located, i.e., if it is in urban or rural areas since inspection capacity per team may significantly differ between those regions, and on its relative position in the feeder, which means if it is in feeder's main trunk or not since thermal inspection is usually performed in this particular segment, whereas visual inspection is performed throughout the entire MV network. The tool developed can automatically split the metazones in their groups according to a specific methodology adopted by the utility involved in this study. Once each inspection type is assigned a set of metazones to be prioritized and inspection capacity, the GA is executed for each group independently. Since visual and urban inspection type prioritization deals with the highest number of metazones compared to the other types, the case study presented in this paper considers only this inspection type without loss of generality and for the sake of simplicity.

CASE STUDY: 8 BRAZILIAN MV NETWORKS

The proposed GA is tested using a real 88/13.8 kV Brazilian distribution substation comprised by 8 MV feeders. Their topology is illustrated in Figure 3.

Table 1 shows the main physical and contingency attributes of each feeder. Available 10-minute SCADA measurements from January to September 2017 have been considered for the calculation of the daily 1-hour averaged demand profile. As these characteristics have been assessed by the first time, contingency attributes have been calculated by all OMS outages data available which has been recorded from January 2013 to June 2018. However, as the inspection planning is often run in a yearly basis, the next executions should consider only the data pertaining to the last planning cycle. In fact, this applies not only to OMS but also to all SCADA and GIS data as well.

The number of metazones (N_{mz}) are 89 in the urban area, consisting a total line length of 115.51 kilometers.

Table 1 - Feeder characteristics

	Feeder							
Attribute	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
L^{MV} [km]	60	48	16	31	52	40	85	9
kWh_{avg}^{daily}[MWh]	875	792	1497	566	1570	2426	236	807
N_{cons}	7586	6863	4856	5819	8155	5309	3690	1038
N_{mz}	21	15	17	15	16	16	11	8
NI	2545	1637	647	206	1474	1197	2044	231

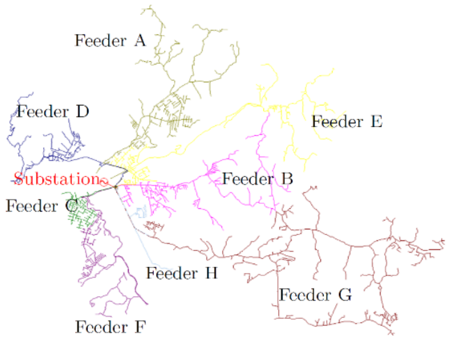

Figure 3 – Real MV networks from the Southeast of Brazil

Metazones Attributes Calculation

For tuning the metazones attributes, $k^{Phy} = 0.4$; $k^{Op} = 0.1$ and $k^{Con} = 0.5$ have been used. As discussed in section Problem Formulation, low and high weighting factors are considered to the operational and contingency attributes, respectively. Regarding the weighting factors of the contingency attributes, it was taken: $k^{CI} = k^{CHI} = 0.15$; $k^{ENS} = 0.2$; and $k^{NI} = k^{V} = k^{I} = 0.5$. At last, for the operational attributes, the same value has been considered for thermal and voltage violations, $k^{V_{prec}} = k^{I_{prec}} = 0.25$. However, it has been assumed that the criticality of the violations in the critical range is three times higher than the ones in the precarious range, therefore $k^{V_{crit}} = k^{I_{crit}} = 0.75$.

RESULTS

Metazones Evaluation

Table 2 lists the top-ranked metazones with the evaluation function of all attributes group normalized to 1000. One can see that there is not a single metazone with the highest value of all functions. For instance, the metazone with highest f presents the highest f^{Phy} while its f^{Op} is negligible compared to other metazones.

Table 2 - Five Top-Ranked Metazones

ID	Feeder	$L^{MV}[km]$	f^{Phy}	f^{Con}	f^{Op}	f
1	C	4.1	1000	274.0	0.0	537.0
2	A	14.2	0.63	1000	0.67	500.0
3	F	8.7	615.0	237.2	1000	464.6
4	A	4.7	575.4	134.5	0.0	297.4
5	E	22.7	56.1	541.2	0.0	293.0

The effect of the high weight given to the operation attributes group by observing the evaluation function of the 2nd best ranked metazone. Even though the values of f_2^{Phy} and f_2^{Op} are low compared to the others, it presents the highest f^{Con}. Thus, it is reasonable to classify MZ_2 with an extension of 14.2km as more critical than MZ_4 with only 4.71km and a much higher energy density. In other words, according to the factors selected, it is more reasonable to "spend" 14.2km of inspection capability in MZ_2 than three times less in MZ_4.

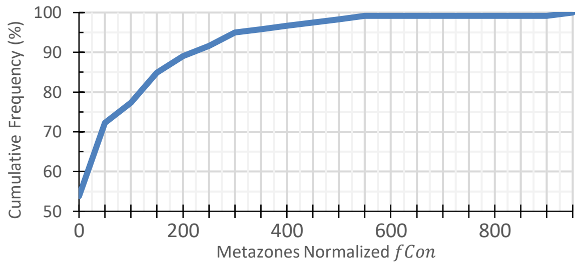

Figure 4 - Cumulative Frequency for Normalized f^{Con}

Figure 4 shows the cumulative frequency distribution of f^{Con} and that few metazones concentrate the highest values. Over time, f^{Con} distribution should become more uniform since it is expected that inspections on those metazones which clearly have reliabilty issues will lead to preventive maintenance operations that ultimately will reduce the number of outages and consequently f^{Con} in the next planning cycles, especially if the main reason for those outages are infrastructure-related. However, it is also expected that there always will be some outlier metazones in terms of f^{Con} due to power outages caused by natural phenomena with unpredictable severity. Once the uniformity of f^{Con} is reached, the high weighting factor K^{Con} will become less relevant and the decision about which metazone should be prioritized will become more dependent on the other attributes group.

GA Input Data

For this case study the initial population has been set with of 200 chromosomes. The number of generations has been set to 2000. And as for the evolution of the GA, a crossover rate of 75% and a mutation rate of 1% have been selected. The number of teams and inspection capacity per team selected have been 3 and 20 km/day, respectively. As the study considers a single substation, the total period of analysis has been selected as 1.5 days. Then, the total inspection capacity constraint is 90 km.

Prioritized Metazones

The GA has prioritized a total number of 70 out of 89 metazones, which leads to a total inspection length of 89.93 out of 115.5km. Note that this value is close to the total inspection capability of 90km. The maximum length of a non-prioritized metazone with a non-zero rank is 0.27km. Thus, the prioritization of any other metazone with a non-zero rank would exceed the inspection capacity. One of the excluded metazones has a zero rank and it is only 0.02km lengthy, which fits in the 0.07km remaining capacity. In these situations, the GA cannot distinguish a chromosome which includes this metazone since it brings no benefit towards the objective of maximizing the evaluation function. However, metazones with zero rank are exceptions. They usually appear because some sort of metazone bad formation due to either the formation rule or bad GIS data. Despite that, a simple check of the set of non-prioritized metazones could catch these metazones or they could just be left to be prioritized mandatorily after three years, at the pre-filtering stage.

Finally, Table 3 shows a few of the set of 89 metazones considered for inspection sorted from the largest to the smallest rank. As expected, the metazones with the highest ranks have been prioritized. As the rank of a metazone gets similar to another and as the GA evolves, it naturally tends to prioritize the metazones with lower length. This can be clearly seen for the metazone with id ranging from 54 to 63, because the metazones with highest length Mz_{55} and Mz_{61} have not been prioritized, which makes sense since there are several shorter metazones whose sum of their length have a similar value but lead to a higher objective function. For instance, by comparing Mz_{61} with the last four metazones the capacity utilized is 2.37km for both, whereas the total rank accrued to the objective function considering MZ_{61} would be only 23.35 while it is 44.33 in the later case.

Table 3 - Metazones Filtered for Urban Visual Inspection

ID	Feeder	L^{MV} [km]	f	Prioritized?
1	C	4.10	536.95	Yes
4	A	4.71	297.41	Yes
6	E	6.36	282.25	Yes
54	E	0.98	25.82	Yes
55	F	4.16	25.75	No
57	A	1.1	25.04	Yes
58	A	0.62	24.56	Yes
60	A	1.2	24.07	Yes
61	C	2.37	23.35	No
62	E	0.93	20.71	Yes
63	A	0.67	19.74	Yes
86	B	0.62	11.33	Yes
87	C	0.54	11.07	Yes
88	C	0.79	11.06	Yes
89	F	0.42	10.87	Yes

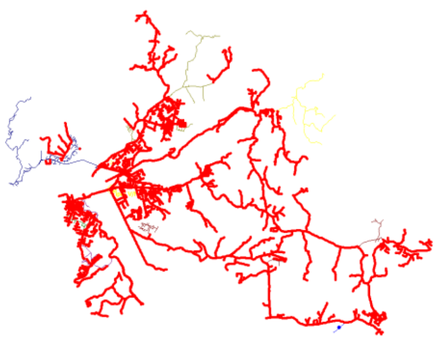

Figure 5 - Set of prioritized metazones (in red)

CONCLUSIONS

This work presents a GA-based approach to assist prioritization of inspections in a power utility's service area. Grid segments' time without inspection and the capacity of available teams to inspect the grid within a time period are considered. To accomplish that, grid segments named as metazones are defined and ranked based on physical, operational and contingency attributes. Heuristics are also used to facilitate a smooth transition from automated spreadsheets to implementation and application in real-life. The proposed approach is assessed in a 13.8 kV Brazilian distribution network.

The proposed methodology succeeded in selecting an effective set of metazones for a planning cycle. The results have shown it was possible to allocate teams with more than 99,9% of its utilization capacity. Furthermore, although metazones are ranked, it is inefficient to simply choose the higher ranks ones as it might reduce team's utilization. The use of an optimization method such as GA selected them efficiently as it takes into consideration the length of each metazone. Ultimately, we highlight the importance of well-integrated corporate systems such as GIS, OMS and SCADA systems for an effective prioritization of inspections.

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