U.PORTO
FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

Methodology Description

Master Dissertation

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Algorithm:

1. Acquisition of the distribution network's model and characterization of the Distribution Grid Area (DGA):
   - Feeders' topology;
   - Line parameters (length, resistance, reactance, susceptance, maximum current allowed and maximum transmitted power capability);
   - Normally Open Points (NOP) connections;
   - Load data (installed power, power factor and load factor at the secondary substations);
   - Reliability data (failure and repair rates);

2. Division of the network in reliability zones (MV feeders delimited by NOP);

3. Assessment of the network's reconfiguration strategy for service restoration, through a power flow study and a short circuit analysis validation.

   a. The Power Flow (PF) study aims to validate the normal operation of the network in the several reconfigured modes, assessing the last delivery point possible to supply from a NOP connection, ensuring the preservation of the operational limits: $\mathbf{V^{min} \leq V \leq V^{max}}$[1]; $\mathbf{P^{min} \leq P \leq P^{max}}$;

   b. The Short Circuit (SC) analysis aims to ensure that the short circuit current in the several reconfigured modes are compatible with the short circuit power levels of the backup power sources: $\boldsymbol{I_{sc\_cable}^{max} \geq I_{sc}^{max} = \frac{c \times U_{MT}}{\sqrt{3} \times Z_{Th}}}$, ***c=1,1 (MT <35kV)***;

4. Calculation of the zones' reliability indices (over a pattern of faults for each feeder set based in the network's failure rate per kilometer):

$$\boldsymbol{ENS_i^j}$$
$$\boldsymbol{SAIFI_i^j}$$
$$\boldsymbol{SAIDI_i^j}$$

[1] ΔV=10% (±0,1 pu), *EN50160*

$$MAIFI_i^j$$

5. ***i=1*** (iteration);

6. Assessment of the zone where the deployment of the new recloser will produce the greater improvement in the technical Quality of Service (QoS):

    c. ***j=1*** (search zone);

    d. Assess the recloser's deployment in zone ***j***, dividing the load i.e. *n* reclosers deployed divide the zone's load in *n+1* equal parts;

        i. **If the number of reclosers deployed > max series reclosers[2]:**

        ***j*++;**

        ii. **Else:**

        The reclosers' locations are given by the points that divide the zone's load in n_j+2 parts:

$$\frac{\sum \boldsymbol{Load_j}}{(\boldsymbol{n_j}+\mathbf{2})}$$

$$\boldsymbol{n_j} = \textbf{reclosers already deployed in the section } \boldsymbol{j};$$

    e. Calculation of the reliability indices of the zone ***j*** with the new recloser installed (same pattern of faults):

$$ENS_i^j$$
$$SAIFI_i^j$$
$$SAIDI_i^j$$
$$MAIFI_i^j$$

    f. Calculation of the economic benefit associated to the reliability improvement relatively to the previous situation i.e. with the n_j reclosers in the network:

$$\Delta(ENS^j) = \left(ENS_{i-1}^j - ENS_i^j\right) \times V_{ENS}$$
$$\Delta(SAIFI^j) = \left(SAIFI_{i-1}^j - SAIFI_i^j\right) \times x^j \times FC_n$$
$$\Delta(SAIDI^j) = \frac{\left(SAIDI_{i-1}^j - SAIDI_i^j\right) \times x^j}{60} \times PC_n \times KC_n$$

[2] $t^n \leq \ldots \leq t^1 \leq t^{substation} \leq 1\ s$

$$V_{ENS} = value\ of\ 1\ kVAh\ of\ energy\ not\ supplied\ \left[\frac{€}{kVAh}\right]$$
$$x^j = total\ number\ of\ secondary\ substation\ in\ the\ feeder\ j$$
$$FC_n = value\ of\ 1\ interruption\ event\ (year\ n)\left[\frac{€}{interruption}\right]$$
$$PC_n = average\ contracted\ power\ (year\ n)\ [kVAh]$$
$$KC_n = value\ of\ 1\ hour\ of\ interruption\ of\ 1\ kVA\ of\ power\ (year\ n)\left[\frac{€}{kVAh}\right]$$

g. ***j*++;**

h. Assessment of the zone where the new recloser's deployment brings the higher economic benefit:

$$Max\{\Delta(ENS^j) + \Delta(SAIFI^j) + \Delta(SAIDI^j)\}, \forall\ j$$

i. n_j++;

7. Checking the stopping criterion:

j. Cost-benefit analysis, including all reclosers deployed:

$$Max\{\sum Benefits - \sum Costs\};$$

i. If Net Present Value decreases more than once in the last three iterations (*i-1*➔*i; i-2*➔*i-1; i-3*➔*i-2*):

STOP iterative process;

Sensitivity Analysis:

- *Technical sensitivity analysis (evaluation of the influence of technical aspects in the optimal solution definition: load factor and restoration/repair rates)*
- *Economic sensitivity analysis (evaluation of the influence of economic aspects in the optimal solution definition: recloser's acquisition and installation cost and recloser's lifetime period)*

ii. Else:

***i*++;**

Assumptions and Simplifications:

- All faults considered are represented by three-phase faults, regardless their true nature;
- Is not assumed the possibility of the occurrence of multiple faults in the network;
- Is not assumed the fault possibility of the protection systems;
- Is assumed that all NOP can be remotely operated;

Formulas:

Reliability Indices:

$$\lambda - failure\ rate\ [failures/year]$$
$$\mu - repair\ rate\ [hours]$$

$$m - mean\ time\ to\ failure: \frac{1}{\lambda}$$
$$r - mean\ time\ to\ repair: \frac{1}{\mu}$$

$$U - unavailability: \frac{\lambda}{\lambda + \mu} = \frac{r}{m + r} = \frac{\sum[down\ time]}{\sum[down\ time] + \sum[up\ time]}$$
$$A - availability: \frac{\mu}{\lambda + \mu} = \frac{m}{m + r} = \frac{\sum[up\ time]}{\sum[down\ time] + \sum[up\ time]}$$

System Average Interruption Frequency Index (SAIFI): indicates how often the average secondary substation experiences a sustained interruption over a predefined period of time.

$$SAIFI^{MT} = \frac{Total\ number\ of\ secondary\ substations\ interruptions}{Total\ number\ of\ secondary\ substations\ served} = \frac{\sum_{i=1}^{x}(FI_i)}{x}\ [interruptions/ss]$$

FI_i – number of interruption events at the secondary substation i;

x – total number of secondary substations;

Momentary Average Interruption Frequency Index (MAIFI): indicates how often the average secondary substation experiences a momentary interruption (less than 3 minutes in duration) over a predefined period of time.

$$MAIFI^{MT} = \frac{Total\ number\ of\ secondary\ substations\ momentary\ interruptions}{Total\ number\ of\ secondary\ substations\ served} = \frac{\sum_{i=1}^{x}(BI_i)}{x}\ [interruptions/ss]$$

BI_i – number of momentary interruption (between *1s* and *3 min* of duration, *page 34859* of the document [1]) events at the secondary substation i;

x – total number of secondary substations;

System Average Interruption Duration Index (SAIDI): indicates the total duration of interruption for the average secondary substation during a predefined period of time. It is commonly measured in minutes or hours of interruption.

$$SAIDI^{MT} = \frac{\textbf{Total secondary substations minutes of interruption}}{\textbf{Total number of secondary substations served}} = \frac{\sum_{i=1}^{x}\sum_{j=1}^{y}(DI_{ji})}{x}\,[\textbf{minutes/ss}]$$

DI_{ji} – duration of the interruption event j at the secondary substation i [minutes];

x – total number of secondary substations;

y – total number of interruptions at the secondary substation i;

Energy Not Supplied (ENS): indicates the total energy not supplied by the system due to interruption events, based on the formula presented at the *page 225* of the document [2].

$$ENS = \sum_{i=1}^{x}\sum_{j=1}^{y}(ID_{ji} \times L_i \times lf)\ [MWh]$$

ID_{ji} – duration of the interruption event j at the secondary substation i [hours];

L_i – average load of the secondary substation i [MW];

lf – load factor in the feeder where the secondary substation i is connected;

Investment Costs:

$$CAPEX = C_{acquisition} + C_{installation}\ [€]$$

$$OPEX = C_{maintenance} = CAPEX \times i_{maintenance}\ [€]$$

$C_{acquisition}$ – cost of acquisition [€];

$$C_{acquisition} = n° \textit{ of reclosers} \times \textit{cost of } 1 \textit{ unit}\ [€]$$

$C_{installation}$ – cost of installation [€];

$$C_{installation} = n° \textit{ of reclosers} \times \textit{cost of installation of } 1 \textit{ unit}\ [€]$$

$C_{maintenance}$ – cost of maintenance [€];

$i_{maintenance}$ – maintenance rate [%];

Benefit with CENS reduction:

Cost of Energy Not Supplied (CENS): indicates the global cost of energy not supplied by the system due to interruption events.

$$\boldsymbol{CENS = ENS \times V_{ENS}}\ [€]$$

ENS – energy not supplied [kWh];

V_{ENS} – value of the ENS [€/kWh];

Benefit: $\boldsymbol{B_{CENS} = CENS_{i-1} - CENS_i}$ [€] **(cost reduction ➔ [i-1]-[i])**

Benefit with TC reduction:

Total Compensation (TC): indicates the total compensation to be paid due to individual patterns violation.

$$\boldsymbol{TC = NC + DC}\ [€]$$

NC – compensation due to number of interruptions pattern violation [€];

Where: $\boldsymbol{NC = (NI - NI_{pattern}) \times V_{CN}}$ [€]

NI – number of interruptions;

$NI_{pattern}$ – number of pattern interruptions;

V_{CN} – value of the compensation [€];

Where: $\boldsymbol{V_{CN} = V_{CN}^{2013} \times \left(1 + \frac{CPI}{100}\right)}$ [€]

CPI – consumer prices index variation [%] (Published by "Instituto Nacional de Estatística");

DC – compensation due to duration of interruptions pattern violation [€];

Where: $\boldsymbol{DC = (DI - DI_{pattern}) \times CP \times V_{CD}}$ [€]

DI – duration of interruptions [hours];

$DI_{pattern}$ – duration of interruptions pattern [hours];

CP – average contracted power [kWh];

V_{CD} – value of the compensation [€/kWh];

Where: $\boldsymbol{V_{CD}} = \boldsymbol{V_{CD}^{2013}} \times \left(\mathbf{1} + \frac{\boldsymbol{CPI}}{\mathbf{100}}\right)$ [€/$\boldsymbol{kWh}$]

CPI – consumer prices index variation [%] (Published by "Instituto Nacional de Estatística");

Benefit: $\boldsymbol{B_{TC} = TC_{i-1} - TC_i}$ **[€] (cost reduction ➔ [i-1]-[i])**

Benefit with IQS Penalties reduction or Rewards increase:

IQS: incentive to QoS improvement.

Penalty:

$$\boldsymbol{IQS = Max\{IQS_{min}; (ENS_{ref} + \Delta ENS - ENS) \times V_{ENS}\}} \text{ [€]}$$

Reward:

$$\boldsymbol{IQS = Min\{IQS_{max}; (ENS_{ref} - \Delta ENS - ENS) \times V_{ENS}\}} \text{ [€]}$$

$IQS_{min/max}$ – penalty maximum value / reward maximum value [€];

ΔENS – ENS tolerance range [kWh];

V_{ENS} – value of the compensation [€/kWh];

Benefit: $\boldsymbol{B_{IQS} = IQS_i - IQS_{i-1}}$ **[€] (profit increase ➔ [i]-[i-1])**

Global cost-benefit analysis:

$$\boldsymbol{Max\left\{\sum Benefits - \sum Costs\right\}}$$
$$\boldsymbol{= Max\{(B_{CENS} + B_{TC} + B_{IQS}) - (CAPEX + OPEX)\}} \text{ [€]}$$

References:

[1] *Regulamento 455/2013 - Regulamento da Qualidade de Serviço do Setor Elétrico*, 2013.

[2] R. Billinton and R. N. Allan, *Reliability Evaluation of Power Systems*: Plenum Press, 1996.