Sensitivity Analysis in Switches Automation Based on Active Reconfiguration to Improve System Reliability Considering Renewables and Storage

Cláudio Santos
FEUP,
Porto,
Portugal
cmmps95@gmail.com

Sérgio F. Santos
C-MAST/UBI,
Covilha,
Portugal
sdfsantos@gmail.com

Desta Z. Fitiwi
ESRI,
Dublin,
Ireland
desta.fitiwi@esri.ie

Marco R. M. Cruz
C-MAST/UBI,
Covilha,
Portugal
marco.r.m.cruz@gmail.com

João P. S. Catalão
INESC TEC and FEUP, Porto,
C-MAST/UBI, Covilha, and
INESC-ID/IST-UL, Lisbon,
Portugal
catalao@fe.up.pt

***Abstract*—Distributed Smart Systems (DSS) should operate and restore discontinued service to consumers. In order to the system gain theses ability it is necessary to replace the manual switches for remotely controlled switches, improving the system restoration capability having in view the Smart Grids implementation. This paper aims to develop a new model, determining the minimal set of switches to replace in order to automate the system, along with a senility analysis on the position of the new switches, whether it should be placed in the same place as the manual switch or in a new location. The optimization of the system is made considering the renewable energy sources (RES) integration in the grid and energy storage systems (ESS), simultaneously, in order to improve the system reliability. The computational tool is tested using the IEEE 119 Bus test system, where different types of loads are considered, residential, commercial and industrial.**

Keywords—Distribution Automation, Distributed Smart Systems, Reliability, Self-healing, Smart Grid, Service Restauration.

I. NOMENCLATURE

A. Sets/Indices

es/Ω^{es}	Index/set of energy storage
g/Ω^{g}	Index/set of generators
h/Ω^{h}	Index/set of hours
l/Ω^{l}	Index/set of lines
$n,m/\Omega^{n}$	Index/set of buses
s/Ω^{s}	Index/set of scenarios
ss/Ω^{ss}	Index/set of energy purchased
$\varsigma/\Omega^{\varsigma}$	Index/set of substations
Ω^{1}/Ω^{0}	Set of normally closed/opened lines
Ω^{D}	Set of demand buses

B. Parameters

$d_{n,h}$	Fictitious nodal demand
$E^{min}_{es,n,s,h}, E^{max}_{es,n,s,h}$	Energy storage limits (MWh)
$ER^{DG}_{g}, ER^{ss}_{\varsigma}$	Emission rates of DGs and energy purchased, respectively (tCO_2e/MWh)
d_l, b_l, S^{max}_{l}	Conductance, susceptance and flow limit of line l, respectively ($\Omega^{-1}, \Omega^{-1}, MVA$)
n_{DG}	Number of candidate nodes for installation of distributed generation
OC_g	Cost of unit energy production (€$/MWh$)
pf_g, pf_{ss}	Power factor of DGs and substation
$p^{DG,min}_{g,n}, p^{DG,max}_{g,n}$	Power generation limits (MW)
$p^{ch,max}_{es,n}, p^{dch,,max}_{es,n}$	Charging/discharging upper limit (MW)
$PD^{n}_{s,h}, QD^{n}_{s,n}$	Demand at node n ($MW, MVAr$)
R_l, X_l	Resistance and reactance of line l (Ω, Ω)
SW_l	Cost of line switching (€$/switch$)
V_{nom}	Nominal voltage (kV)
$\eta^{ch}_{es}, \eta^{dch}_{es}$	Charging/discharging efficiency
λ^{CO_2}	Cost of emissions (tCO_2e)
λ^{es}	Variable cost of storage system (€$/MWh$)
μ_{es}	Scaling factor (%)
$v^{p}_{s,h}, v^{Q}_{s,h}$	Unserved power penalty (€$/MWh$) (€$/MVAr$)
ρ_{es}	Probability of scenarios

C. Variables

$E_{es,n,s,h}$	Reservoir level of ESS (MWh)
$f_{l.h}$	Fictitious current flows through line l
$g^{SS}_{n,h}$	Fictitious current injections at substation nodes
$I^{ch}_{es,n,s,h}, I^{dch}_{es,n,s,h}$	Charging/discharging binary variables
$P^{DG}_{g,n,s,h}, Q^{DG}_{g,n,s,h}$	DG power ($MW, MVAr$)
$P^{ch}_{es,n,s,h}, P^{dch}_{es,n,s,h}$	Charged/discharged power (MW)

J.P.S. Catalão acknowledges the support by FEDER funds through COMPETE 2020 and by Portuguese funds through FCT, under Projects SAICT-PAC/0004/2015 - POCI-01-0145-FEDER-016434, POCI-01-0145-FEDER-006961, UID/EEA/50014/2013, UID/CEC/50021/2013, UID/EMS/00151/2013, 02/SAICT/2017 - POCI-01-0145-FEDER-029803, and also funding from the EU 7th Framework Programme FP7/2007-2013 under GA no. 309048. D.Z. Fitiwi acknowledges support by a research grant from the Science Foundation Ireland (SFI) under the SFI Strategic Partnership Programme Grant number SFI/15/SPP/E3125. The opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Science Foundation Ireland.

978-1-5386-5186-5/18/$31.00 ©2018 IEEE

$P^{SS}_{\varsigma,s,h}, Q^{SS}_{\varsigma,s,h}$	Imported power from grid $(MW, MVAr)$
$P^{NS}_{n,s,h}, Q^{NS}_{n,s,h}$	Unserved power $(MW, MVAr)$
$P_{l,s,h}, Q_{l,s,h}$	Power flow through a line l $(MW, MVAr)$
$PL_{l,s,h}, QL_{l,s,h}$	Power losses in each feeder $(MW, MVAr)$
$\chi_{l,h}$	Binary switching variable of line l
$\Delta V_{n,s,h}, \Delta V_{m,s,h}$	Voltage deviation magnitude (kV)
$\theta_{l,s,h}$	Voltage angles between two nodes line l

A. Functions

$EC^{DG}, EC^{ES}, EC^{SS}$	Expected cost of energy produced by DGs, supplied by the ESS and imported (€)
$EmiC^{DG}, EmiC^{SS}$	Expected emission costs of power produced by DGs and imported from the grid (€)
$ENCS$	Expected cost for unserved energy (€)
SWC	Cost of line switching (€)

II. INTRODUCTION

B. Motivation, Aims, and Background

In today's power systems ensuring the continuity of service is one of the major concerns because of the main changes that are expected in the near future of these networks. The interruption in power grids is unavoidable due to a wide variety of reasons, such as system components maintenance, grid expansion, improving protection devices, therefore maintaining continued service provision is a major concern [1]. Also, the regulations on continuity of service have evolved to improve customer satisfaction and to improve the energy quality available for residential, commercial and industrial activities. In this sense, it is necessary to proceed with the development of technological solutions in order to improve the service and system restoration. One of the ways is through the optimal positioning of automated switches in distribution lines (Fig. 1), developing technological resources in order to improve the network operation and restoration conditions. Remote control of switches is one of the possible approaches to achieving network improvement and responding to the problem in remote parts of the network.

Therefore, the future of the electrical system is one of the topics on the agenda where the great majority of roads indicate that the future of the electric grid is the smartification of the grid in order to make it "intelligent" giving rise to smart grids. Smart grids will have the ability to perform operations in an automated manner, operating with great reliability and with low operating and maintenance costs. In [2] can be found some projects and research in the area of the smart grid. Within the smart grid there is the concept of system automation, where distribution system automation o plays an important role in the operations and system restoration, achieved through the implementation of remotely controlled switches and new communication technologies [3].

The vast majority of works in the literature focus only on the distribution system reconfiguration, mainly with the aim of minimizing the energy losses or helping to integrate more RES into the system [4]–[6].

In [4] Tahboub *et al.* present a new formulation for the distribution system reconfiguration with the aim of reducing energy losses in one year considering several distributed generation profiles. Haghighat and Zeng present in [5] an operation strategy using distribution system reconfiguration considering the uncertainty of the load and renewable generation with the objective of minimizing losses. In [6] Capitanescu et al. present a work that assesses the potential of network reconfiguration to improve the integration capacity of DGs in an active network management scheme.

Also, there is a set that through the system reconfiguration aims to improve the system reliability [7], [8]. Chen et al. in [7] present a method to evaluate the reliability index's, the total distribution system delivery capacity considering the reconfiguration of the network and daily load curves. In [8] it is presented a work on reconfiguration of the system in operation formulated as a multi-objective problem, where it is intended to minimize the losses and several reliability indexes.

Therefore, there is a very limited set of works focuses on the automation of switches. In this works the great majority focuses on the total automation of the switches which is unthinkable for the distribution system operation (DSO) due the cost of updating the switches from manual to automated, being few works that make this distinction or account for this fact [9]–[11].

Chen *et al.* present in [9] an algorithm to perform the placement of switches on the system lines with the goal to automate the distribution system. In [10] it is made also the placement of remotely controlled switches to improve the restoration capacity of the distribution system. In [11] it is presented a new methodology to carry out distribution system reconfiguration (DSR) in an automated way incorporating DGs in the system operation. Only automated switches are considered in the analysis of this work.

In this work is presented a different approach from the previous works, since this work has two objectives, perform dynamic reconfiguration in the system operation and improve the system restore capacity after a failure. Therefore, the system is dynamically reconfigured considering that all switches are automated in the first phase.

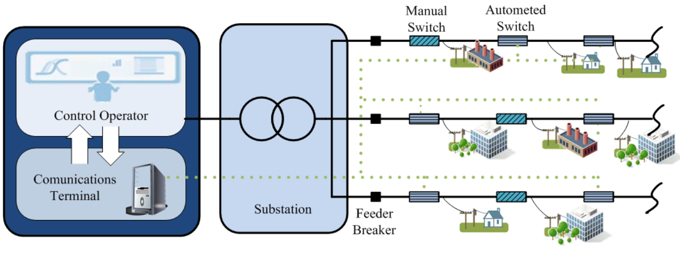

Fig. 1. Switch automation framework.

In a second phase, a sensitivity analysis is made based on the hourly reconfiguration topologies, in order to identify the minimum set of switches that must be upgraded from manuals to automatic, in order to improve system operation performance and restore capability after a failure. The sensitivity matrix will also allow identifying which switches will need the most maintenance.

C. Contributions

The main contributions of this paper are the following:

- Develop an improved stochastic mixed integer linear programing (SMILP) operation model considering de presence of DGs-based renewables, ESS and dynamic reconfiguration;
- Create a methodology on the system sensitivity analysis to identify the minimum set of switches to be updated from manual to automatic based on dynamic reconfiguration.
- Identify whether the automate switches will be placed, if only in places were manual switches exist or also in places.
- Identify switches that require more maintenance due to dynamic reconfiguration.

III. MATHEMATICAL FORMULATION

A. Objective Function

The objective of the current work is to minimize the sum of the most relevant cost terms (1); namely, the costs related to network reconfiguration (switching), operation, emissions and load shed.

$$MinTC = SWC + TEC + TENSC + TEmiC \tag{1}$$

The switching cost term (2) is incurred when a change of status in a given line occurs, that is, when it goes from 0 (open) to 1 (closed) or vice versa.

$$SWC = \sum_{l\in\Omega^l}\sum_{h\in\Omega^h} SW_l * (y_{l,h}^{+} + y_{l,h}^{-}) \tag{2}$$

The emission cost (3) is given by the sum of costs of power produced by DGs, discharged from ESS and imported from upstream grid.

$$\begin{aligned} TEC = &\sum_{s\in\Omega^s}\rho_s\sum_{h\in\Omega^h}\sum_{g\in\Omega^g} OC_g P_{g,n,s,h}^{DG} \\ &+ \sum_{s\in\Omega^s}\rho_s\sum_{h\in\Omega^h}\sum_{es\in\Omega^{es}} \lambda^{es} P_{es,n,s,h}^{dch} \\ &+ \sum_{s\in\Omega^s}\rho_s\sum_{h\in\Omega^h}\sum_{\varsigma\in\Omega^\varsigma} \lambda_h^{\varsigma} P_{\varsigma,n,s,h}^{SS} \end{aligned} \tag{3}$$

The cost of load shedding, given by *TENSC*, is formulated as follows:

$$TENSC = \sum_{s\in\Omega^s}\rho_s\sum_{h\in\Omega^h}(v_{s,h}^{P} P_{n,s,h}^{NS} + v_{s,h}^{Q} Q_{n,s,h}^{NS}) \tag{4}$$

Finally, equation (5) refers to the total cost of emissions as a result of power either supplied by DGs or imported from upstream.

$$\begin{aligned} TEmiC = &\sum_{s\in\Omega^s}\rho_s\sum_{h\in\Omega^h}\sum_{g\in\Omega^g}\sum_{n\in\Omega^n} \lambda^{CO_2} ER_g^{DG} P_{g,n,s,h}^{DG} \\ &+ \sum_{s\in\Omega^s}\rho_s\sum_{h\in\Omega^h}\sum_{\varsigma\in\Omega^\varsigma}\sum_{n\in\Omega^n} \lambda^{CO_2} ER_\varsigma^{SS} P_{\varsigma,s,h}^{SS} \end{aligned} \tag{5}$$

A. Constraints

The sum of all incoming flows to a node should be equal to the sum of all outgoing flows, which is given by the *Kirchhoff's Law*. This is applied to both active (6) and reactive (7) power flows, and must be respected at all times:

$$\begin{aligned} &\sum_{g\in\Omega^g} P_{g,n,s,h}^{DG} + \sum_{es\in\Omega^{es}}\left(P_{es,n,s,h}^{dch} - P_{es,n,s,h}^{ch}\right) + P_{\varsigma,s,h}^{SS} \\ &+ P_{n,s,h}^{NS} + \sum_{in,l\in\Omega^l} P_{l,s,h} - \sum_{out,l\in\Omega^l} P_{l,s,h} = PD_{s,h}^{n} \\ &+ \sum_{in,l\in\Omega^l}\frac{1}{2}PL_{l,s,h} + \sum_{out,l\in\Omega^l}\frac{1}{2}PL_{l,s,h}\,;\ \forall\varsigma\in i \end{aligned} \tag{6}$$

$$\begin{aligned} &\sum_{g\in\Omega^g} Q_{g,n,s,h}^{DG} + Q_{c,n,s,h}^{c} + Q_{\varsigma,s,h}^{SS} + Q_{n,s,h}^{NS} \\ &+ \sum_{in,l\in\Omega^l} Q_{l,s,h} - \sum_{out,l\in\Omega^l} Q_{l,s,h} = QD_{s,h}^{n} \\ &+ \sum_{in,l\in\Omega^l}\frac{1}{2}QL_{l,s,h} + \sum_{out,l\in\Omega^l}\frac{1}{2}QL_{l,s,h}\ \forall\varsigma\in i \end{aligned} \tag{7}$$

Equations (8) and (9) present the linearized AC power flows through each feeder, which are governed by the *Kirchhoff's Voltage Law.* Note that $\theta_{l,s,h}$ refers to the angle difference $\theta_{n,s,h} - \theta_{m,s,h}$ where n and m are bus indices corresponding to the same line l.

$$\begin{aligned} &\big|P_{l,s,h} - (V_{nom}\left(\Delta V_{n,s,h} - \Delta V_{m,s,h}\right)g_k \\ &- V_{nom}^2 b_k \theta_{l,s,h}\big| \le MP_l(1-\chi_{l,h}) \end{aligned} \tag{8}$$

$$\begin{aligned} &\big|Q_{l,s,h} - (-V_{nom}\left(\Delta V_{n,s,h} - \Delta V_{m,s,h}\right)b_k \\ &- V_{nom}^2 g_k \theta_{l,s,h}\big| \le MQ_l(1-\chi_{l,h}) \end{aligned} \tag{9}$$

The maximum amount of flow that can pass through a line is given by inequality (10). Equations (11) and (12) represent active and reactive power losses in a given line.

$$P_{l,s,h}^2 + Q_{l,s,h}^2 \le \chi_{l,h}(S_l^{max})^2 \tag{10}$$

$$PL_{l,s,h} = R_l\left(P_{l,s,h}^2 + Q_{l,s,h}^2\right)/\,V_{nom}^2 \tag{11}$$

$$QL_{l,s,h} = X_l\left(P_{l,s,h}^2 + Q_{l,s,h}^2\right)/\,V_{nom}^2 \tag{12}$$

ESS is modeled by the expressions (13)--(18).

$$0 \le P_{es,n,s,h}^{ch} \le I_{es,n,s,h}^{ch} P_{es,n,h}^{ch,max} \tag{13}$$

$$0 \le P_{es,n,s,h}^{dch} \le I_{es,n,s,h}^{dch} P_{es,n,h}^{ch,max} \tag{14}$$

$$I_{es,n,s,h}^{ch} + I_{es,n,s,h}^{ch} \le 1 \tag{15}$$

$$E_{es,n,s,h} = E_{es,n,s,h-1} + \eta_{es}^{ch} P_{es,n,s,h}^{cg} - \frac{P_{es,n,s,h}^{dch}}{\eta_{es}^{dch}} \quad (16)$$

$$E_{es,n}^{min} \leq E_{es,n,s,h} \leq E_{es,n}^{max} \quad (17)$$

$$E_{es,n,s,h0} = \mu_{es} E_{es,n}^{max};\ E_{es,n,s,h24} = \mu_{es} E_{es,n}^{max} \quad (18)$$

The limits on the amount of power charged and discharged are given by (13) and (14), respectively, while (15) guarantees that charging and discharging processes do not simultaneously happen at any given time.

The state of charge is modelled as presented in (16). Inequality (17) ensures that the storage level is always within a permissible range. Finally, (18) sets the initial storage level, and ensures the storage is left with the same amount at the end of the operational period.

The active and reactive power limits of DGs are given by (19) and (20), respectively. Inequality (21) limits the DGs ability to inject or consume reactive power.

$$P_{g,n,s,h}^{DG,min} \leq P_{g,n,s,h}^{DG} \leq P_{g,n,s,h}^{DG,max} \quad (19)$$

$$Q_{g,n,s,h}^{DG,min} \leq Q_{g,n,s,h}^{DG} \leq Q_{g,n,s,h}^{DG,max} \quad (20)$$

$$-\tan\left(cos^{-1}(pf_g)\right) P_{g,n,s,h}^{DG} \leq Q_{g,n,s,h}^{DG} \leq tan\left(cos^{-1}(pf_g)\right) P_{g,n,s,h}^{DG} \quad (21)$$

The active and reactive power limits at the substations are given by (22) and (23), due to stability reasons.

$$P_{\varsigma,s,h}^{SS,min} \leq P_{\varsigma,s,h}^{SS} \leq P_{\varsigma,s,h}^{SS,max} \quad (22)$$

$$Q_{\varsigma,s,h}^{SS,min} \leq Q_{\varsigma,s,h}^{SS} \leq Q_{\varsigma,s,h}^{SS,max} \quad (23)$$

The reactive power that is withdrawn from the substation is subject to the bounds presented in inequality (24).

$$-\tan\big(cos^{-1}(pf_{ss})\big) P_{\varsigma,s,h}^{SS} \leq Q_{\varsigma,s,h}^{SS} \leq tan\big(cos^{-1}(pf_{ss})\big) P_{\varsigma,s,h}^{SS} \quad (24)$$

The radial operation of the considered system is guaranteed by including the constraints in (25) through (31). Constraints (27)—(31) ensure radiality in the presence of DGs, and simultaneously avoid islanding.

$$\sum_{l \in \Omega^l} \chi_{l,h} = 1, \forall m \in \Omega^D; l \in n \quad (25)$$

$$\sum_{in, l \in \Omega^l} \chi_{l,h} - \sum_{out, l \in \Omega^l} \chi_{l,h} \leq 1, \forall m \notin \Omega^D; l \in n \quad (26)$$

$$\sum_{in, l \in \Omega^l} f_{l,h} - \sum_{out, l \in \Omega^l} f_{l,h} = g_{n,h}^{SS} - d_{n,h}, \forall n \in \Omega^\varsigma; l \in n \quad (27)$$

$$\sum_{in, l \in \Omega^l} f_{l,h} - \sum_{out, l \in \Omega^l} f_{l,h} = -1, \forall n \in \Omega^g; \forall n \in \Omega^D \quad (28)$$

$$\sum_{in, l \in \Omega^l} f_{l,h} - \sum_{out, l \in \Omega^l} f_{l,h} = 0, \forall n \notin \Omega^g; \forall n \notin \Omega^D \forall n \notin \Omega^\varsigma \quad (29)$$

$$0 \leq \sum_{in, l \in \Omega^l} f_{l,h} + \sum_{out, l \in \Omega^l} f_{l,h} \leq n_{DG}; l \in n \quad (30)$$

$$0 \leq g_{n,h}^{SS} \leq n_{DG}, \forall n \in \Omega^\varsigma; l \in n \quad (31)$$

IV. Numerical Results

The 119 bus test system from IEEE is used to test the proposed optimization model, Fig. 2, where can be seen the position and type of DGs in the system. Detailed data about this test system can be found in [12].

In this system, there are two types of DGs, solar and wind which have an installed capacity of 2 MW and 1 MW, respectively. The ESS have as installed capacity of 1 MW with both charging and discharging efficiencies assumed to be 90%. The total active and reactive loads of the system are 3.93 MW and 1.62 MVar, respectively. The operational period is assumed to 24 hours long. A possible hourly reconfiguration is considered. The voltage of the system is 10 kV, and the maximum voltage deviation allowed at each node is ± 5% of the nominal voltage value. The substation is considered as the reference node, where the voltage magnitude is set to the nominal voltage and the angle as 0. In addition, the power factor at the substation 0.95 is considered to be constant. Electricity prices follow the demand trend, ranging from 42 to 107 €/MWh. The lowest electricity price happens during the valley periods and the highest ones during peak consumption periods. The operation cost of ESS during charging and discharging is considered to be 5 €/MWh. The rate of emissions at the substation is assumed to be 0.4 tCO2e/MWh, and a carbon price of 7 €/tCO2 is considered in all simulations.

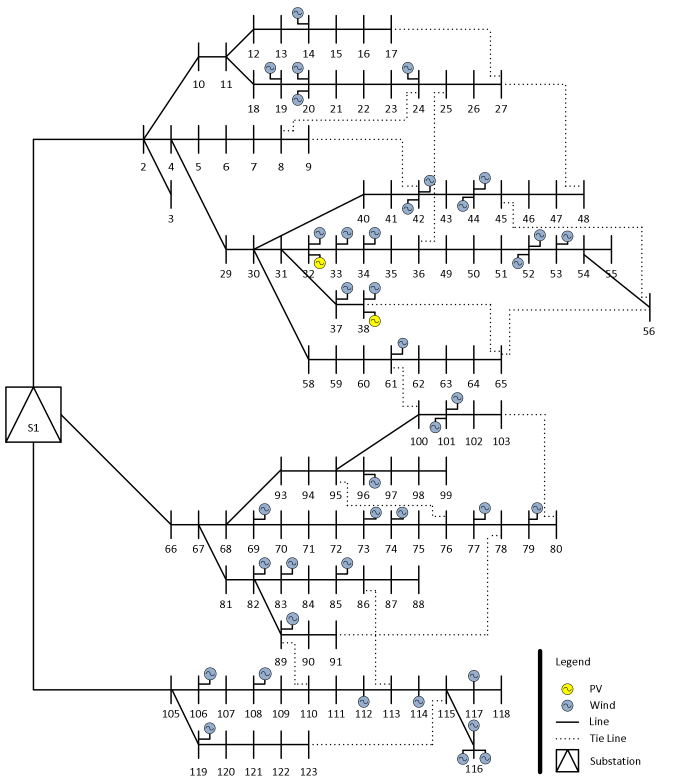

Fig. 2. 119 Bus test system.

A tariff of 40 €/MWh and 20 €/MWh are considered for remunerating the power productions from solar PV and wind farms. The cost of switching any line is considered to be 5 €/switching.

In this work the automation of switches was considered, based on the network dynamic reconfiguration considering the presence of renewable (wind and solar generation), as well as ESS. This reconfiguration was obtained from the perspective of optimizing the system operation, considering the economic requirements and technical restrictions of the system.

Thus, in Table I can see the total cost of system operating together with the cost terms that make up the objective function. From this table can be highlight the cost of power not served, 0MW, as shown in Fig. 2, due to the integration of smart grid enabling technologies. In this case, the presence of DGs combined with ESS, which allows a better balance of generation and demand, leading to all the energy being used while the reliability of the system is maintained.

Also in Table I is presented the total value of the energy losses, and in Fig. 3 its profile can be analyzed over the period of operation, which due to the dynamic reconfiguration together with the DGs and ESS, presents lower losses than the without these technologies being present, compared with the literature values [13].

Therefore, in the first phase of this work, system dynamic reconfiguration was done based on the mathematical formulation presented, where different reconfiguration for each hour was obtained. The reconfiguration results are presented in Table II, where the closed lines set and open lines set constituting the network topology.

In a second phase, a sensitivity analysis was performed to the dynamic reconfiguration of the system. Based on the analysis of Table II, the number of switches per line was analyzed. This analysis can be realized in Fig. 4, where it can be seen that not all lines undergo reconfiguration. From the totality of all lines, only 22% of them perform reconfiguration at least once in the time period considered, which means that 78% of lines do not need to be automated. However, the 22% of the lines still represent a major investment effort to automate the system. In this perspective, it is necessary to identify using one or several criteria which set of switches are essential to automate. As a result, the criterion of the average value was used, where for the lines that have a number of switches above the average are the possible candidates to constitute the set of switches to be automated. For the majority of cases, the set of lines belonging to the set of values above the average represent more than 50% of the total system switches. In this case, as shown in Fig. 5, this set of values represents 62% of the total switches.

Also, in the realization of this study it was considered that all lines can perform reconfiguration to evaluate if the automation of the switches would be in the same place where the manual switches are, or in other places of the network are positioned (since the manual switches are only present in the tie lines). Since the tie lines correspond to the lines belonging to the set of lines 118 to 132 it is possible to verify that there is a set of lines $\{ine23, line26, line34, line39, line42, line53, line61, line74, line76, line82, line85, line95\}$, that it is beneficial to put an automated switch. From this set the lines, $\{\mathrm{line42, line53, line74, line\ 85\ e, line90}\}$ are part of the priority set to be automated.

TABLE I – SYSTEM COSTS

Total Cost [€]	29912,27
Reconfiguration Cost [€]	1010
Energy Cost [€]	27901,72
Emission Cost [€]	1000,55
Power nor served [€]	0
P Losses [MW]	10,00
Q Losses [MVAr]	6,60

TABLE II – NETWORK RECONFIGURATION FOR EACH HOUR (WITHIN A 24 HOURS PERIOD)

Hour	Closed Lines	Open Lines
1	1-22; 24; 25; 27-33; 35-60; 62-81; 83-89; 91-94; 96-116; 118; 120; 123; 125; 126; 129; 131; 132;	23; 26; 34; 61; 82; 90; 95; 117; 119; 121; 122; 124; 127; 128; 130;
2	1-22; 24; 25; 27-33; 35-41; 43-60; 62-75; 77-81; 83; 84; 86-89; 91-94; 96-118; 120; 121; 123; 125; 126; 128-130; 132;	23; 26; 34; 42; 61; 76; 82; 85; 90; 95; 119; 122; 124; 127; 131;
3	1-22; 24; 25; 27-33; 35-60; 62-73; 75; 77-81; 83; 84; 86-89; 91-94; 96-118; 120; 123; 125-130; 132;	23; 26; 34; 61; 74; 76; 82; 85; 90; 95; 119; 121; 122; 124; 131;
4	1-22; 24; 25; 27-33; 35-52; 54-60; 62-73; 75; 77-81; 83; 84; 86-89; 91-94; 96-117; 119; 120; 122; 123; 125-130; 132;	23; 26; 34; 53; 61; 74; 76; 82; 85; 90; 95; 118; 121; 124; 131;
5	1-22; 24; 25; 27-33; 35-41; 43-52; 54-60; 62-73; 75; 77-81; 83-89; 91-94; 96-117; 119-123; 125-129; 132;	23; 26; 34; 42; 53; 61; 74; 76; 82; 90; 95; 118; 124; 130; 131;
6	1-22; 24; 25; 27-33; 35-52; 54-60; 62-73; 75; 77-81; 83-89; 91-94; 96-117; 119; 120; 122; 123; 125-129; 132;	23; 26; 34; 53; 61; 74; 76; 82; 90; 95; 118; 121; 124; 130; 131;
7	1-22; 24; 25; 27-33; 35-41; 43-60; 62-73; 75; 77-89; 91-94; 96-118; 120; 121; 123; 125-128; 132;	23; 26; 34; 42; 61; 74; 76; 90; 95; 119; 122; 124; 129-131;
8	1-22; 24; 25; 27-33; 35-52; 54-60; 62-81; 83; 84; 86-89; 91-94; 96-118; 120; 122; 123; 125; 126; 129; 130; 132;	23; 26; 34; 53; 61; 82; 85; 90; 95; 119; 121; 124; 127; 128; 131;
9	1-22; 24; 25; 27-33; 35-60; 62-81; 83; 84; 86-89; 91-94; 96-118; 120; 123; 125; 129; 130; 132;	23; 26; 34; 61; 82; 85; 90; 95; 119; 121; 122; 124; 126-128; 131;
10	1-22; 24; 25; 27-33; 35-38; 40-52; 54-60; 62-89; 91-94; 96-118; 120; 122; 123-126; 132;	23; 26; 34; 39; 53; 61; 90; 95; 119; 121; 127-130; 131;
11	1-22; 24; 25; 27-33; 35-38; 40-52; 54-60; 62-73; 75-117; 119; 120; 122-124; 126; 127; 132;	23; 26; 34; 39; 53; 61; 74; 118; 121; 125; 128-130; 131;
12	1-22; 24; 25; 27-33; 35-38; 40-60; 62-84; 86-89; 91-118; 120; 123; 124; 130; 132;	23; 26; 34; 39; 61; 85; 90; 119; 121; 122; 125; 116-129; 131;
13	1-22; 24; 25; 27-33; 35-52; 54-60; 62-89; 91-94; 96-118; 120; 122; 123; 125; 126; 132;	23; 26; 34; 53; 61; 90; 95; 119; 121; 124; 127; 128-130; 131;
14	1-22; 24; 25; 27-33; 35-60; 62-73; 75-81; 83;84; 86-117; 120; 123; 127; 129; 130; 132;	23; 34; 61; 74; 82; 85; 118; 119; 121; 122; 124-126; 131;
15	1-22; 24; 25; 27-33; 35-60; 62-73; 75-81; 83; 84; 86-116; 120; 123; 127; 129-132;	23; 34; 61; 74; 82; 85; 117-119; 124-126; 128;
16	1-22; 24; 25; 27-33; 35-38; 40-52; 54-60; 62-84; 86-117; 120; 122-124; 130; 132;	23; 34; 39; 53; 61; 85; 118; 119; 121; 125-129; 131;
17	1-22; 24; 25; 27-33; 35-52; 54-60; 62-73; 75-89; 91-94; 96-116; 119; 120; 122; 123; 125-127; 131; 132;	23; 26; 34; 53; 61; 74; 90; 95; 117; 118; 121; 124; 128-130;
18	1-22; 24; 25; 27-33; 35-52; 54-60; 62-73; 74-89; 91-94; 96-118; 120; 122; 123; 125; 126; 132;	23; 26; 34; 53; 61; 90; 95; 119; 121; 124; 127-131;
19	1-25; 27-33; 35-38; 40-52; 62-84; 86-117; 119; 122; 123; 124; 130; 132;	26; 34; 39; 53; 61; 85; 118; 120; 121; 125; 126-128; 129; 131;
20	1-25; 27-33; 35-38; 40-60; 62-73; 75-118; 123; 124; 127; 132;	26; 34; 39; 61; 74; 119-122; 125; 126; 128-130;131;
21	1-25; 27-38; 40-60; 62-73; 75-84; 86-117; 86-117; 119; 123; 124; 127; 130;	26; 39; 61; 74; 85; 118; 120-122; 125; 126; 128; 129; 131; 132;
22	1-22; 24-33; 35-38; 40-52; 54-60; 62-75; 77-81; 83; 84; 86-117; 120; 122-124; 128-130; 132;	23; 34; 39; 53; 61; 76; 82; 85; 118; 119; 121; 125-127; 131;
23	1-22; 24; 25; 27-33; 35-52; 54-60; 62-73; 75-81; 83; 84; 86-118; 120; 122; 123; 127; 129; 130; 132;	23; 26; 34; 53; 61; 74; 82; 85; 119; 121; 124-126; 131;
24	1-22; 24; 25; 27-33; 35-41; 43-52; 54-73; 75-81; 83; 84; 86-89; 91-94; 96-116; 118; 120-122; 125-127; 129-132;	23; 26; 34; 42; 53; 74; 82; 85; 90; 95; 117; 119; 123; 124; 128;

Thus, the set of lines to be automated is presented in Table III and corresponds to 62% of the total of switches, as mentioned, allowing that from the hourly reconfigurations presented in Table II it is possible to realize 68% of the configurations, with the automation of these lines. Since the minimum set of switches to be updated corresponds to the most used switches, these will consequently be also the set of lines that will require higher maintenance.

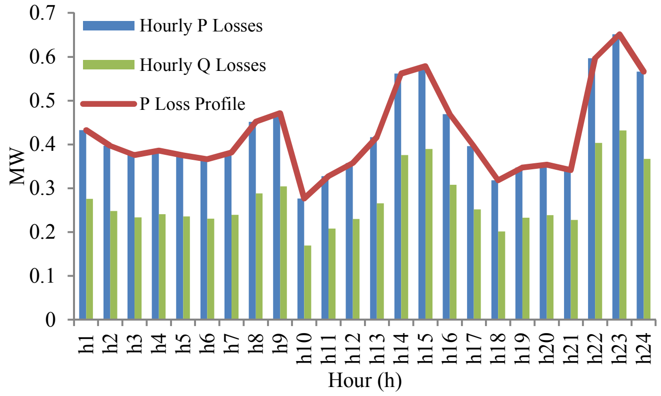

Fig. 3. Active and reactive hourly losses for the different time settings.

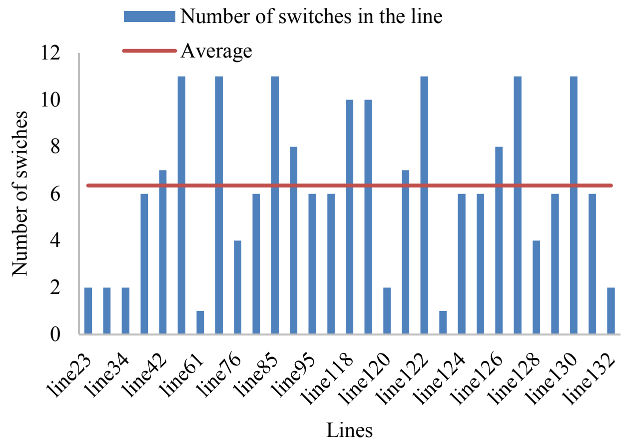

Fig. 4. Number of switches per line.

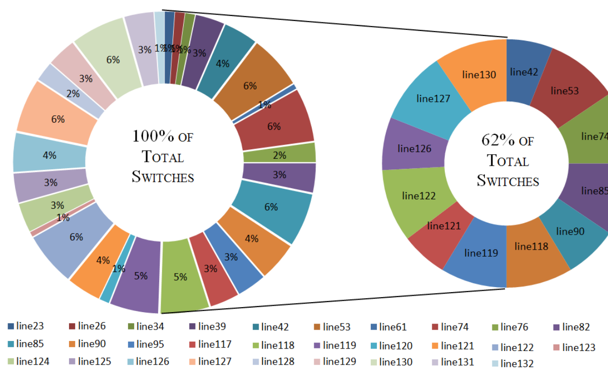

Fig. 5. Percentage of number of switches per line.

TABLE III – SET OF LINES TO AUTOMATE

Set of Lines to Automate
$\left\{\begin{matrix} line42, line53, line74, line85, line90, line118, line119, \\ line121, line122, line126, line127, line130 \end{matrix}\right\}$

V. Conclusions

In this study, an analysis on the dynamic reconfiguration used in conjunction with DGs and ESS as a way to operate the system with more reliability and integrate higher levels of RES was presented. To perform this analysis an improved stochastic MILP was used to obtain numerical results of operating the 119 bust test system assessing the impact on systems operation with the integration of DSR, DGs and ESS. The analysis of the case study showed that:

- From the dynamic reconfiguration analysis it was possible to identify jointly with one or several criteria which is the minimum set of switches that must be automated, so as not to lose the benefits of dynamic reconfiguration and increase the system reliability through faster system restoration due to automated switches.
- It was also possible to determine that the automated switch positioning is not always in the place where the manual switch is located, being possible through this analysis to identify the locations where it is beneficial to place them. Moreover, it was possible to identify the set of switches which will require more maintenance.

With this approach to automate the system it is possible to perform 68% of the dynamic reconfigurations obtained.

References

[1] C. Lueken, P. M. S. Carvalho, and J. Apt, "Distribution grid reconfiguration reduces power losses and helps integrate renewables," Energy Policy, vol. 48, pp. 260–273, Sep. 2012.

[2] R. E. Brown, "Impact of smart grid on distribution system design," in Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE, 2008, pp. 1–4.

[3] M. Sperandio et al., "Automation Planning of Loop Controlled Distribution Feeders," presented at the 2nd Int. Elect. Eng. Conf., 2007.

[4] A. M. Tahboub, V. R. Pandi, and H. H. Zeineldin, "Distribution System Reconfiguration for Annual Energy Loss Reduction Considering Variable Distributed Generation Profiles," IEEE Trans. Power Deliv., vol. 30, no. 4, pp. 1677–1685, Aug. 2015.

[5] H. Haghighat and B. Zeng, "Distribution System Reconfiguration Under Uncertain Load and Renewable Generation," IEEE Trans. Power Syst., vol. 31, no. 4, pp. 2666–2675, Jul. 2016.

[7] F. Capitanescu, L. F. Ochoa, H. Margossian, and N. D. Hatziargyriou, "Assessing the Potential of Network Reconfiguration to Improve Distributed Generation Hosting Capacity in Active Distribution Systems," IEEE Trans. Power Syst., vol. 30, pp. 346–356, Jan. 2015.

[8] K. Chen, W. Wu, B. Zhang, S. Djokic, and G. P. Harrison, "A Method to Evaluate Total Supply Capability of Distribution Systems Considering Network Reconfiguration and Daily Load Curves," IEEE Trans. Power Syst., vol. 31, no. 3, pp. 2096–2104, May 2016.

[9] N. G. Paterakis et al., "Multi-Objective Reconfiguration of Radial Distribution Systems Using Reliability Indices," IEEE Trans. Power Syst., vol. 31, no. 2, pp. 1048–1062, Mar. 2016.

[10] C. S. Chen, C. H. Lin, H. J. Chuang, C. S. Li, M. Y. Huang, and C. W. Huang, "Optimal Placement of Line Switches for Distribution Automation Systems Using Immune Algorithm," IEEE Trans. Power Syst., vol. 21, no. 3, pp. 1209–1217, Aug. 2006.

[11] Y. Xu, C.-C. Liu, K. P. Schneider, and D. T. Ton, "Placement of Remote-Controlled Switches to Enhance Distribution System Restoration Capability," IEEE Trans. Power Syst., vol. 31, no. 2, pp. 1139–1150, Mar. 2016.

[12] D. P. Bernardon, A. P. C. Mello, L. L. Pfitscher, L. N. Canha, A. R. Abaide, and A. A. B. Ferreira, "Real-time reconfiguration of distribution network with distributed generation," Electr. Power Syst. Res., vol. 107, pp. 59–67, Feb. 2014.

[13] D. Zhang, Z. Fu, and L. Zhang, "An improved TS algorithm for loss-minimum reconfiguration in large-scale distribution systems," Electr. Power Syst. Res., vol. 77, no. 5–6, pp. 685–694, Apr. 2007.