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

Cláudio Santos
FEUP, Porto, Portugal
cmsps95@gmail.com

Sérgio F. Santos
C-MAST/UBI, Covilhã, Portugal
dsf-santos@gmail.com

Destá Z. Fitiwi
ESRI, Dublin, Ireland
desta.fitwi@esri.ie

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

João P. S. Catalão
INESC TEC and FEUP, Porto, Portugal
joao.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 Restoration.

I. NOMENCLATURE

A. Sets/Indices

\( \Xi^{es} \) Index/set of energy storage
\( g/\Omega \) Index/set of generators
\( h/\Omega \) Index/set of hours
\( l/\Omega \) Index/set of lines
\( n, m/\Xi^{a} \) Index/set of buses
\( s/\Omega^{r} \) Index/set of scenarios
\( ss/\Omega^{ss} \) Index/set of energy purchased
\( z/\Omega^{s} \) Index/set of substations
\( \Omega^{1}/\Omega^{b} \) Set of normally closed/opened lines
\( \Omega^{b} \) Set of demand buses

B. Parameters

\( d_{n,h} \) Fictitious nodal demand

Energy storage limits (MWh)
Emission rates of DGs and energy purchased, respectively (tCO₂/€/MWh)
Conductance, susceptance and flow limit of line \( l \), respectively (Ω⁻¹, Ω⁻¹, MVA)
Number of candidate nodes for installation of distributed generation
Cost of unit energy production (€/MWh)
Power factor of DGs and substation
Power generation limits (MW)
Charging/discharging upper limit (MW)
Demand at node \( n \) (MW, MVAr)
Resistance and reactance of line \( l \) (Ω, Ω)
Cost of line switching (€/switch)
Nominal voltage (kV)
Charging/discharging efficiency
Cost of emissions (tCO₂e)
Variable cost of storage system (€/MWh)
Scaling factor (%)
Unserved power penalty (€/MWh) (€/MVAr)
Probability of scenarios

Reservoir level of ESS (MWh)
Fictitious current flows through line \( l \)
Fictitious current injections at substation nodes
Charging/discharging binary variables
DG power (MW, MVAr)
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 SAI-UTL/IN-L/0040/2015 - POCI-01-0145-FEDER-016434, POCI-01-0145-FEDER-006961, UID/EIA/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
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 plays an important role in the operations and system restoration, achieved through the implementation of remotely controlled switches and new communication technologies [3].
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 the 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.

\[ MinTC = SWC + TEC + TENS + TEMIC \]  

(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.

\[ SWC = \sum_{i \in E} \sum_{j \in E} SW_{ij} \ast (y_{ij}^0 + y_{ij}^1) \]  

(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.

\[ TEC = \sum_{i \in E} \sum_{j \in E} \sum_{g \in G} \sum_{h \in H} OCP_{g,n,s,h} p_{g,n,s,h}^D + \sum_{i \in E} \sum_{j \in E} \sum_{h \in H} \lambda_{g}^p p_{g,n,s,h}^{dch} + \sum_{i \in E} \sum_{j \in E} \sum_{h \in H} \lambda_{g}^q p_{g,n,s,h}^{NS} \]  

(3)

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

\[ TENS = \sum_{i \in E} \sum_{j \in E} \sum_{h \in H} (y_{i,j}^p p_{i,j}^{NS} + v_{i,j}^Q Q_{i,j}^{NS}) \]  

(4)

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

\[ TEMIC = \sum_{i \in E} \sum_{j \in E} \sum_{h \in H} \sum_{s \in S} \lambda_{g}^C ER_{g}^{D} p_{g,n,s,h}^{D} + \sum_{i \in E} \sum_{j \in E} \sum_{h \in H} \sum_{s \in S} \lambda_{g}^C ER_{g}^{SS} p_{g,n,s,h}^{SS} \]  

(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.

\[ \sum_{i \in E} p_{g,n,s,h}^{D} + \sum_{j \in E} p_{j,n,s,h}^{D} = 0 \]  

(6)

\[ \sum_{i \in E} Q_{g,n,s,h}^{D} + \sum_{j \in E} Q_{j,n,s,h}^{D} = 0 \]  

(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 \( \theta_{i,j} \) 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 \( l \).

\[ P_{i,j,h} = (V_{n,s} \Delta V_{n,s,h} - V_{m,s,h}) b_{l,h} \leq M_{\theta} (1 - \chi_{l,h}) \]  

(8)

\[ Q_{i,j,h} = (V_{n,s} \Delta V_{n,s,h} - V_{m,s,h}) b_{l,h} \leq M_{\theta} (1 - \chi_{l,h}) \]  

(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.

\[ P_{i,j,h} + Q_{i,j,h} \leq X_{i,j} (S_{i,j}^{max})^2 \]  

(10)

\[ PL_{i,j,h} = R_{i,j} (P_{i,j,h}^2 + Q_{i,j,h}^2) / V_{n,s}^2 \]  

(11)

\[ QL_{i,j,h} = X_{i,j} (P_{i,j,h}^2 + Q_{i,j,h}^2) / V_{n,s}^2 \]  

(12)

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

\[ 0 \leq P_{i,j,h}^{ch} = \frac{v_{i,j}}{i_{i,j}} p_{i,j}^{ch,\max} \]  

(13)

\[ 0 \leq p_{i,j,h}^{dch} = \frac{v_{i,j}}{i_{i,j}} p_{i,j}^{dch,\max} \]  

(14)

\[ \chi_{i,j} + \chi_{i,j} \leq 1 \]  

(15)
The radial operation of the considered system is guaranteed by including the constraints in (25) through (31). Constraints (27) through (31) ensure radiality in the presence of DGs, and simultaneously avoid islanding.

\[
E_{es,n,s,h} = E_{es,n,s,h-1} + \eta_{es} p_{es}^{dis} - \frac{p_{dis}^{dis}}{\eta_{es}} \tag{16}
\]

\[
E_{es,n,h}^{min} \leq E_{es,n,s,h} \leq E_{es,n} \tag{17}
\]

\[
E_{es,n,s,h0} = \mu_{es} E_{es,n}^{max}, E_{es,n,s,h24} = \mu_{es} E_{es,n} \tag{18}
\]

The limits on the amount of power charged and discharged are given by (13) and (14), respectively. Inequality (21) limits the DGs ability to inject or consume reactive power.

\[
P_{DG,n,s,h}^{min} \leq P_{DG,n,s,h} \leq P_{DG,n,s,h}^{max} \tag{19}
\]

\[
Q_{DG,n,s,h}^{min} \leq Q_{DG,n,s,h} \leq Q_{DG,n,s,h}^{max} \tag{20}
\]

\[
0 \leq \sum_{i \in \Omega_\ell} f_{i,h} + \sum_{i \in \Omega_\ell} f_{i,h} \leq n_{DG}; l \in n \tag{30}
\]

\[
0 \leq g_{n,h}^{SS} \leq n_{DG}, \forall n \in \Omega^c; l \in n \tag{31}
\]

**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.
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, 0.4MW, 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 it can profile 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. From this table can be highlight the cost of power not served, 0.4MW, as shown in Fig. 2, due to the integration of smart grid enabling technologies.

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, 0.4MW, 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 it can profile 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 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 [linee23, linee26, linee34, linee39, linee42, linee53, linee61, linee74, linee76, linee82, linee85, linee95], that it is beneficial to put an automated switch. From this set the lines, [linee42, linee53, linee74, linee85 e, linee90] are part of the priority set to be automated.
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.

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.

TABLE III - SET OF LINES TO AUTOMATE

<table>
<thead>
<tr>
<th>Set of Lines to Automate</th>
</tr>
</thead>
<tbody>
<tr>
<td>{line42, line53, line74, line85, line90, line118, line119}</td>
</tr>
<tr>
<td>line121, line122, line126, line127, line130</td>
</tr>
</tbody>
</table>

REFERENCES


