Role of Distributed Energy Storage Systems in the Quest for Carbon-free Electric Distribution Systems

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***Abstract*—This paper presents an extensive analysis in relation to transforming electric distribution networks in order to accommodate large quantities of variable renewable energy sources (vRESs). For this purpose, a multi-stage and stochastic mixed integer linear programming (S-MILP) model is employed. The algebraic model developed optimally allocates energy storage systems (ESSs) along with an optimal dynamic distribution network switching. For the analysis, a standard IEEE 119-bus distribution network system was used as a case study. Test results reveal that the joint optimization of ESSs and network reconfiguration markedly increase flexibility in existing systems, leading to an increase in the levels of renewables integration and utilization. Moreover, the analysis of the results shows the prospect of such systems in going fully "carbon-free", i.e. with vRES power entirely meeting system demand. Generally, the current work demonstrates that a more effective integration and utilization of large-scale vRESs is possible when existing systems are equipped with enabling technologies that are already commercially available.**

***Keywords*—Distributed generation, energy storage systems, network switching, renewable energy sources, stochastic mixed integer linear programming.**

I. Nomenclature

A. Sets/Indices

$g/\Omega^g/\Omega^{DG}$	Index/set of DGs
$i,j/\Omega^i$	Index/set of nodes
k/Ω^k	Index/set of branches
s/Ω^s	Index/set of scenarios
t/Ω^t	Index/set of planning years
w/Ω^w	Index/set of operational snapshots
$\varsigma/\Omega^\varsigma$	Index/set of substations

B. Parameters

b, g	Susceptance, conductance of branch (Ω^{-1})
ER	Emission rates (tCO_2e/MWh)
IC	Investment cost (M€)
LT	Lifetime (years)
MC_{es}, MC_{tr}	Cost of maintenance of ESS/transformer (M€/annum)
MC_g^N, MC_g^E	Cost of maintenance of new and existing DGs (M€/ annum)
MC_k^N, MC_k^E	Cost of maintenance of new and existing line (M€/annum)
MP, MQ	Disjunctive parameters
OC	Unit cost of energy production (€/MWh)
pf	Power factor
R, X	Resistance and reactance of a line (Ω)
λ^{CO_2e}	Carbon price (€/tCO_2 equivalent)
λ^ς	Import electricity price (€/MWh)
ρ_s, π_w	Scenario probability and snapshot weight
υ^P, υ^Q	Penalties for load shed (€/MW, €/MVAr)
η_{ch}, η_{dch}	Storage efficiency (%)
μ_{es}	Scaling factor (%)

C. Variables

δ_i^P, δ_i^q	Load shed at node *i* (MW, MVAr)
ΔV	Voltage deviation (kV)
PD^i, QD^i	Active/reactive load at node *i* (MW, MVAr)
PG_g^E, QG_g^E	Active/reactive power supplied by existing DGs (MW, MVAr)
PG_g^N, QG_g^N	Active and reactive power supplied by new DGs (MW, MVAr)
$P_\varsigma^{SS}, Q_\varsigma^{SS}$	Imported power (MW, MVAr)
PL, QL	Feeder power losses (MW, MVAr)
E	Reservoir level of ESS (MWh)
I	Discharging/charging indicator variable
P^{dch}, P^{ch}	Discharged/charged power (MW)
u	Utilization variable
x	Investment variable

D. Functions

EC_t^{SS}	Expected cost of imported energy (M€)
$ENSC_t$	Expected cost of load shed (M€)
$EmiC_t^{DG}$	Expected cost of emissions by DGs (M€)
$EmiC_t^N, EmiC_t^E$	Expected cost of emissions by new and existing DGs, respectively (M€)
$EmiC_t^{SS}$	Expected cost of emissions as a result of imported power (M€)

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$InvC_t^{DNS}, MntC_t^{DNS}$	Investment/maintenance cost of DNS components (M€)
$InvC_t^{DG}, MntC_t^{DG}, EC_t^{DG}$	Investment/maintenance/expected energy cost of DGs, respectively (M€)
$InvC_t^{LN}, MntC_t^{LN}$	Investment/maintenance cost of lines (M€)
$InvC_t^{ES}, MntC_t^{ES}$	Investment/maintenance cost of ESS (M€)

II. Introduction

It is well-known fact that renewable energy sources (RESs) have immense potential to address multifaceted challenges of current world. These problems are largely related to the energy generation from clean sources, access to electricity at affordable prices to all, with high degree of reliability in order to respond to the growing trend of demand, the need to increase energy security, spur economic growth, among others. Moreover, the reduction of polluting gas emissions from current energy generation sources, in agreement with the political and governmental guidelines [1], [2], is of a paramount importance.

Recently, in many countries, especially in Europe, favorable policies and ambitious targets have been set forth to scale up the integration of RESs, and gradually phase out conventional energy production regimes. As a result, the scale of RES development (both distributed and centralized) has been showing steady growth in many power systems. The integration of renewable energy sources into different areas of activity is expected to accelerate due to the Paris climate agreement by states to reduce greenhouse gas emissions and mitigate the adverse consequences of climate change [3]. Given the wide-range abundance of RESs, their share in the final energy consumption is expected to dramatically increase in the medium- to long-run [4], [5]. Despite their wide-range benefits, the integration of RESs comes with several challenges [7]. The greatest challenge of all comes from the nature of renewables, i.e. the variability and unpredictability (uncertainty) of power produced by such resources. If integrated massively in power systems (particularly, at distribution levels), these energy resources can complicate operation, planning and control of such systems. In addition to the challenges, there are also others, mainly technical challenges such as violation of technical limits of lines, increased losses, and congestion among others.

These challenges are particularly problematic at the distribution level because the room for maneuver in terms of reliability, stability and system quality is very small. Because of all these issues, system regulators and operators generally limit the amount of RES that can be integrated into the system (in a range of 20-25%), which is a major problem in the much needed development of RES. One may then ponder over the question of whether commercially available technologies address the technical challenges of integrating intermittent power sources, make it possible to increase their penetration level to 100%, and hence accelerate the transition to carbon-free distribution network systems. Therefore, the integration of RES in the distribution system has a set of negative consequences that can be mitigated or even overcome, by integrating a set of existing concepts and technologies that can be used together with renewable energy sources. One of the technologies is energy storage systems (ESSs), which are presented as a way to increase renewable integration in the network, thus minimizing the side effects of renewable integration [8], [9], [10].

Storage systems even out the imbalances between the intermittent power generations and demand that may frequently arise in systems accommodating large-scale RESs. This is accomplished by storing energy in periods of low electricity demand or high RES power production, and releasing the stored energy in periods of higher electricity demand. The use of this technology brings several benefits for the network, both from technical and economic perspectives, in terms of cost reduction and improvement in terms of power quality, stability and system reliability. Also, the use of distribution system reconfiguration [11], [12] raises the network flexibility as a whole, increasing the capability to accommodate a larger quantity of renewables.

Given the problem presented above, this work focuses on an extensive analysis of integrating large quantities of renewable sources in the distribution system (solar and wind in particular). For this purpose, a dynamic stochastic optimization model is presented, which is of a mixed integer linear programming (MILP) nature. The model presented takes into account the optimal integration of renewables, simultaneously with energy storage systems and dynamic reconfiguration of the network. The stochastic MILP model is based on a linearized AC network model that precisely represents the physical characteristics of the AC system under consideration. The objective of the resulting optimization model is to maximize the deployment of RESs while respecting the technical limits of the distribution system. Along with the RES allocation, the model also jointly finds the optimal allocation of ESSs and reconfiguration of the network, aiming to efficiently exploit available resources, mainly RESs.

III. Formulation

As previously mentioned, in this work, a multi-stage and stochastic MILP optimization model is presented. The objective of the model is to minimize the total system costs (1). The optimization model is based on the assumption of a perpetual planning horizon [13] with the intention of balancing the several costs inside and outside the planning horizon. Further information can be found in [14].

A. Objective Function

The objective function is presented in (1). Five different types of cost are considered in this work. One of the cost type is the investment ($TInvC$) that reproduces the total investment price considering a continuous planning horizon (2). The types of investment considered are investment in DGs ($InvC_t^{DG}$), distribution network components (DNS), $InvC_t^{DNS}$, such as lines and transformers, and ESSs, $InvC_t^{ES}$. Another cost type is maintenance denoted as TMC (total maintenance cost) that quantifies the maintenance costs of new and existing components ($MntC_t^{DG}$, $MntC_t^{DNS}$, $MntC_t^{ES}$) in each level and after the planning horizon in (3). The cost of the energy generated in the system, TEC, is presented in (4) and consists of the costs of generation from the DGs, ESSs and the energy that come from the upstream network (EC_t^{DG}, EC_t^{ES}, EC_t^{SS}) in and outside the planning horizon. The last two in (1) are the costs of the energy not supplied $TENSC$ and emissions $TEmiC$ in the system.

$$Minimize\ TC = TInvC + TMC + TEC + TENSC + TEmiC \tag{1}$$

$$TInvC = \underbrace{\sum_{t\epsilon\Omega^t} (1+r)^{-t} (InvC_t^{DG} + InvC_t^{DNS} + InvC_t^{ES})/r}_{NPV\ of\ investment\ cost} \tag{2}$$

$$TMC = \underbrace{\sum_{t\epsilon\Omega^t}(1+r)^{-t}\ (MntC_t^{DG}+MntC_t^{DNS}+MntC_t^{ES})}_{NPV\ of\ maintenance\ costs} + \underbrace{(1+r)^{-T}(MntC_T^{DG}+MntC_T^{DNS}+MntC_T^{ES})/r}_{NPV\ maintenance\ costs\ incured\ after\ stage\ T} \quad (3)$$

$$TEC = \underbrace{\sum_{t\epsilon\Omega^t}(1+r)^{-t}\ (EC_t^{DG}+EC_t^{SS}+EC_t^{ES})}_{NPV\ of\ operation\ costs} + \underbrace{(1+r)^{-T}(EC_T^{DG}+EC_T^{SS}+EC_T^{ES})/r}_{NPV\ operation\ costs\ incured\ after\ stage\ T} \quad (4)$$

$$TENSC = \underbrace{\sum_{t\epsilon\Omega^t}(1+r)^{-t}\ ENSC_t}_{NPV\ of\ unserved\ power\ costs} + \underbrace{(1+r)^{-T}ENSC_T/r}_{NPV\ unserved\ power\ costs\ incured\ after\ stage\ T} \quad (5)$$

$$TEmiC = \underbrace{\sum_{t\epsilon\Omega^t}(1+r)^{-t}\ (EmiC_t^{DG}+EmiC_t^{SS})}_{NPV\ emission\ costs} + \underbrace{(1+r)^{-T}(EmiC_T^{DG}+EmiC_T^{SS})/r}_{NPV\ emission\ costs\ incured\ after\ stage\ T} \quad (6)$$

Equations (7)—(9) represent the investment costs of DGs $IC_{g,i}$, feeders IC_k , transformers IC_{tr} and energy storage system IC_{es}, respectively. All investments take into account the capital recovery factor $\frac{r(1+r)^{LT}}{(1+r)^{LT}-1}$. And, through (7) - (10), it is ensured that the investment in a given component is only considered once in the optimization process.

$$InvC_t^{DG} = \sum_{g\epsilon\Omega^g}\sum_{i\epsilon\Omega^i}\frac{r(1+r)^{LT_g}}{(1+r)^{LT_g}-1}IC_{g,i}\big(x_{g,i,t} - x_{g,i,t-1}\big)\ ;where\ x_{g,i,0}=0 \quad (7)$$

$$InvC_t^{DNS} = \sum_{k\epsilon\Omega^\ell}\frac{r(1+r)^{LT_k}}{(1+r)^{LT_k}-1}IC_k(x_{k,t}-x_{k,t-1}) + \sum_{ss\epsilon\Omega^{ss}}\sum_{tr\epsilon\Omega^{tr}}\frac{i(1+i)^{LT_{tr}}}{(1+i)^{LT_{tr}}-1}IC_{tr}\big(x_{tr,ss,t} - x_{tr,ss,t-1}\big)\ ;\ where\ x_{tr,ss,0}=0 \quad (8)$$

$$InvC_t^{ES} = \sum_{es\epsilon\Omega^{es}}\sum_{i\epsilon\Omega^i}\frac{r(1+r)^{LT_{ess}}}{(1+r)^{LT_{es}}-1}IC_{es}\big(x_{es,i,t} - x_{es,i,t-1}\big)\ ;where\ x_{es,i,0}=0 \quad (9)$$

Maintenance costs are calculated using the expressions in (10) - (12). Likewise, (12) is related to the maintenance costs of energy storage at each stage.

$$MntC_t^{DG} = \sum_{g\epsilon\Omega^g}\sum_{i\epsilon\Omega^i}MC_g^N\,x_{g,i,t} + \sum_{g\epsilon\Omega^g}\sum_{i\epsilon\Omega^i}MC_g^E\,u_{g,i,t} \quad (10)$$

$$MntC_t^{DNS} = \sum_{k\epsilon\Omega^{e\ell}}MC_k^E\,u_{k,t} + \sum_{k\epsilon\Omega^{n\ell}}MC_k^N x_{k,t} + \sum_{tr\epsilon\Omega^{E\_tr}}MC_{tr}^E\,u_{tr,ss,t} + \sum_{tr\epsilon\Omega^{N}tr}MC_k^N x_{tr,ss,t} \quad (11)$$

$$MntC_t^{ES} = \sum_{c\epsilon\Omega^c}\sum_{i\epsilon\Omega^i}MC_{es}x_{es,i,t} \quad (12)$$

The costs associated with supplied energy (from DG, ESS and imports) are given by (13)—(15), respectively.

$$EC_t^{DG} = \sum_{s\epsilon\Omega^s}\rho_s\sum_{w\epsilon\Omega^w}\pi_w\sum_{g\epsilon\Omega^g}\sum_{i\epsilon\Omega^i}(OC_{g,i,s,w,t}^N P_{g,i,s,w,t}^N + OC_{g,i,s,w,t}^E\,P_{g,i,s,w,t}^E) \quad (13)$$

$$EC_t^{ES} = \sum_{s\epsilon\Omega^s}\rho_s\sum_{w\epsilon\Omega^w}\pi_w\sum_{es\epsilon\Omega^{es}}\lambda_{s,w,t}^{es}P_{es,i,s,w,t}^{dch} \quad (14)$$

$$EC_t^{SS} = \sum_{s\epsilon\Omega^s}\rho_s\sum_{w\epsilon\Omega^w}\pi_w\sum_{\varsigma\epsilon\Omega^\varsigma}\lambda_{s,w,t}^{\varsigma}P_{\varsigma,s,w,t}^{SS} \quad (15)$$

The cost of energy not supplied is expressed as in (16). Notice that different penalty factors are used for involuntary active and reactive power curtailments.

$$ENSC_t = \sum_{s\epsilon\Omega^s}\rho_s\sum_{w\epsilon\Omega^w}\pi_w\sum_{i\epsilon\Omega^i}\big(\upsilon_{s,w,t}^P\delta_{i,w,s,t}^Q + \upsilon_{s,w,t}^q\delta_{i,w,s,t}^Q\big) \quad (16)$$

Equations (17)—(19) include the expected costs of emissions as a result of power generation by new and existing DGs. Emission cost is given by (20).

$$EmiC_t^{DG} = EmiC_t^N + EmiC_t^E \quad (17)$$

$$EmiC_t^N = \sum_{s\epsilon\Omega^s}\rho_s\sum_{w\epsilon\Omega^w}\pi_w\sum_{g\epsilon\Omega^g}\sum_{i\epsilon\Omega^i}\lambda_{s,w,t}^{CO_2e}ER_g^N P_{g,i,s,w,t}^N \quad (18)$$

$$EmiC_t^E = \sum_{s\epsilon\Omega^s}\rho_s\sum_{w\epsilon\Omega^w}\pi_w\sum_{g\epsilon\Omega^g}\sum_{i\epsilon\Omega^i}\lambda_{s,w,t}^{CO_2e}ER_g^E P_{g,i,s,w,t}^E \quad (19)$$

$$EmiC_t^{SS} = \sum_{s\epsilon\Omega^s}\rho_s\sum_{w\epsilon\Omega^w}\pi_w\sum_{\varsigma\epsilon\Omega^\varsigma}\sum_{i\epsilon\Omega^i}\lambda_{s,w,t}^{CO_2e}ER_\varsigma^{SS}P_{\varsigma,s,w,t}^{SS} \quad (20)$$

B. Constraints

At each node in the system, Kirchhoff's current law should be respected. These power balances are:

$$\sum_{g\epsilon\Omega^{DG}}P_{g,i,s,w,t}^{DG} + \sum_{es\epsilon\Omega^{es}}\big(P_{es,i,s,w,t}^{dch} - P_{es,i,s,w,t}^{ch}\big) + P_{\varsigma,s,w,t}^{SS} + \sum_{in,k\epsilon i}P_{k,s,w,t} - \sum_{out,k\epsilon i}P_{k,s,w,t} + \delta_{i,w,s,t}^P = \sum_{in,k\epsilon i}0.5PL_{k,s,w,t} + \sum_{out,k\epsilon i}0.5PL_{k,s,w,t} + PD_{s,w,t}^i\ ;\ \forall\varsigma,\forall\varsigma\epsilon i \quad (21a)$$

$$\sum_{g\epsilon\Omega^{DG}}Q_{g,i,s,w,t}^{DG} + \delta_{i,w,s,t}^Q + Q_{\varsigma,s,w,t}^{SS} + \sum_{in,k\epsilon i}Q_{k,s,w,t} - \sum_{out,k\epsilon i}Q_{k,s,w,t} = \sum_{in,k\epsilon i}0.5QL_{k,s,w,t} + \sum_{out,k\epsilon i}0.5QL_{k,s,w,t} + QD_{s,w,t}^i\ ;\ \forall\varsigma,\forall\varsigma\epsilon i \quad (21b)$$

where $P_{g,i,s,w,t}^{DG} = P_{g,i,s,w,t}^E + P_{g,i,s,w,t}^N$ and $Q_{g,i,s,w,t}^{DG} = Q_{g,i,s,w,t}^E + Q_{g,i,s,w,t}^N$.

It should be noted that power losses in a branch are regarded as "virtual loads", distributed equally to the nodes belonging to the same branch:

$$PL_{k,s,w,t}\ =\ R_k\left(P_{k,s,w,t}^2\ +\ Q_{k,s,w,t}^2\right)/\ V_{nom}^2 \quad (22)$$

$$QL_{k,s,w,t}\ =\ X_k\left(P_{k,s,w,t}^2\ +\ Q_{k,s,w,t}^2\right)/\ V_{nom}^2 \quad (23)$$

In addition to the previous Kirchhoff's current law, the Kirchhoff's voltage law should also be respected. This is ensured by including the following constraints, which are some linearized forms of the familiar AC power flow equations:

$$\big|P_{k,s,w,t} - \big(V_{nom}\big(\Delta V_{i,s,w,t} - \Delta V_{j,s,w,t}\big)g_k - V_{nom}^2 b_k\theta_{k,s,w,t}\big)\big| \le MP_k(1-u_{k,t}) \quad (24)$$

$$\big|Q_{k,s,w,t} - \big(-V_{nom}\big(\Delta V_{i,s,w,t} - \Delta V_{j,s,w,t}\big)b_k - V_{nom}^2 g_k\theta_{k,s,w,t}\big)\big| \le MQ_k(1-u_{k,t}) \quad (25)$$

$$\Delta V^{min} \le \Delta V_{i,s,w,t}\ \le\ \Delta V^{max};\ \theta_{k,s,w,t} = \theta_{i,s,w,t} - \theta_{j,s,w,t}. \quad (26)$$

Equation (26) refers to the boundary conditions of voltage deviation at each node, and the voltage angle difference in a feeder. Furthermore, the power flowing through each line cannot exceed the thermal capacity which is given by:

$$P_{k,s,w,t}^2 + Q_{k,s,w,t}^2 \le u_{k,t}(S_k^{max})^2 \quad (27)$$

Notice that (22), (23) and (27) include the utilization variable of the branch $u_{k,h}$ (which is 1 if connected and 0 otherwise). Line losses are linearized using the first order of approximation, as shown in equations (21) and (23) [15]. Five linear segments are considered in this paper, according to [15].

The power flow and capacity limit constrains presented above are valid for existing lines. But it is straightforward to formulate the power flow equations for new lines. The only change needed to the above constraints is to replace the utilization variable $u_{k,t}$ by the investment variable $x_{k,t}$.

In this work, a generic ESS is whose model is given by the expressions in (28) - (34). Equations (28) and (29) ensure the amount of power charged or discharged does not surpass the technical limits of the ESS, respectively. Inequality (30) prevents the ESS from simultaneously charging and discharging at a given operational time w. The storage balance (state of charge) is given by (31). In (32), the maximum and minimum levels of energy stored at a given time w and the ESSs initial level (33) are given as a function of the maximum capacity. Throughout the planning horizon, the ESS's energy level at the end of the planning horizon must be equal to the initial level (34). The efficiency parameters η_{es}^{dch} and η_{es}^{ch} are assumed to be equal for the sake of simplicity.

$$0 \le P_{es,i,s,w,t}^{ch} \le I_{es,i,s,w,t}^{ch} x_{es,i,t} P_{es,i}^{ch,\max} \quad (28)$$

$$0 \le P_{es,i,s,w,t}^{dch} \le I_{es,i,s,w,t}^{ch} x_{es,i,t} P_{es,i}^{ch,max} \quad (29)$$

$$I_{es,i,s,w,t}^{ch} + I_{es,i,s,w,t}^{dch} \le 1 \quad (30)$$

$$E_{es,i,s,w,t} = E_{es,i,s,w-1,t} + \eta_{ch,es} P_{es,i,s,w,t}^{ch} - P_{es,i,s,w,t}^{dch} / \eta_{dch,es} \quad (31)$$

$$E_{es,i}^{min} x_{es,i,t} \le E_{es,i,s,w,t} \le x_{es,i,t} E_{es,i}^{max} \quad (32)$$

$$E_{es,i,s,w_0,T1} = \mu_{es} x_{es,i,T1} E_{es,i}^{max} \quad (33)$$

$$E_{es,i,s,w_1,t+1} = E_{es,i,s,W,t} \; ; \; E_{es,i,s,W,T} = E_{es,i,s,w_0,T1} \quad (34)$$

Hence, the nonlinear terms are transformed into a set of linear constraints. Further information regarding such a linearization approach can be found in [16]. Inequalities (35a) and (36a) represent active power generation limits (existing and new). The corresponding reactive power capability constraints are shown in (35b) and (35b).

$$P_{g,i,s,w,t}^{E,min} u_{g,i,t} \le P_{g,i,s,w,t}^{E} \le P_{g,i,s,w,t}^{E,max} u_{g,i,t} \quad (35a)$$

$$P_{g,i,s,w,t}^{N,min} x_{g,i,t} \le P_{g,i,s,w,t}^{N} \le P_{g,i,s,w,t}^{N,max} x_{g,i,t} \quad (36a)$$

$$-tan\left(cos^{-1}(pf_g)\right) P_{g,i,s,w,t}^{E} u_{g,i,t} \le Q_{g,i,s,w,t}^{E} \le tan\left(cos^{-1}(pf_g)\right) P_{g,i,s,w,t}^{E} u_{g,i,t} \quad (35b)$$

$$-tan\left(cos^{-1}(pf_g)\right) P_{g,i,s,w,t}^{E} x_{g,i,t} \le Q_{g,i,s,w,t}^{N} \le tan\left(cos^{-1}(pf_g)\right) P_{g,i,s,w,t}^{N} x_{g,i,t} \quad (36b)$$

In (37), several logical constraints are presented that are designed to ensure that a given investment cannot be undone once decided.

Radiality constraints, similar to the ones used in [14], [17], [18], are included here to ensure a radial operation of the considered system regardless of operational changes.

$$x_{k,t} \ge x_{k,t-1}; \;\; x_{g,i,t} \ge x_{g,i,t-1}; \;\; x_{es,i,t} \ge x_{es,i,t-1} \quad (37)$$

IV. CASE STUDY

A. Data and Assumptions

The IEEE 119-bus standard system is used to test the model presented earlier, and the system data can be found in [19]. According to [20], active power losses amount to 1298.09 kW, and bus 116 is the node with the lowest voltage in the system, which is 0.8783 per unit.

Other assumptions made are as follows. The planning horizon spans over 3 years, which is divided into yearly stages. The useful life of DGs and branches is assumed to be 25 years and that of ESSs is 15 years. An ESS with a nominal power of 1 MW and a storage capacity of 5 MWh is considered in the study. Interest rate is 7%. Investments in wind and/or solar PV power technologies are possible. For investments in wind and solar, two technology types with 0.5 and 1.0 MVA are considered. The installation costs and other associated data can be found in [21]. The maintenance costs considered for the lines are 450 € / km / year and that of DGs is assumed to be 2% of the investment costs. Investing in any feeder is assumed to cost 38700 €/km. All feeders are eligible for switching, if deemed necessary and economical.

A 5% voltage deviation is the maximum tolerable magnitude at any bus in the system. The reference bus is the first bus (i.e. node 1), and has its voltage magnitude and angle set to 1.0 per unit and 0 radians. Demand is assumed to expand by 5% annually. The prices considered for the emissions in the first, second and third stages are 25, 45 and 60 € / tCO2e respectively. A 0.4 tCO2e/MWh emission rate is arbitrarily assumed for the energy imported from the upstream. The penalty for unserved power (active and reactive alike) is 2000 €/MW or MVAr.

B. Discussion of Test Results

In order to carry out the required analysis, several cases are considered, here denoted as Case A, Case B and Case C.

Case A represents the base case, where no investment is made. The other cases contemplate the optimal investment planning in DGs, ESSs and reconfiguration of the network in a coordinated way. The difference between Cases B and C is that, in Case B, the system is allowed to import power from the grid (if necessary); whereas, in Case C, the system is deliberately forced to operate in an island mode (i.e. with no imported power) throughout the planning horizon. It should be emphasized that the only supply sources in Case C are the intermittent power sources (specifically, wind and solar).

Table I compares the three cases in terms of the values corresponding to the most relevant system variables computed over the three-year planning horizon. One of the first conclusions that can be drawn from this table is the great variation of the values between the different cases, namely, the cost terms in the system, investment costs, maintenance, generation, energy not provided, emissions and losses. The results of Case B and C are also compared with that of Case A (the base case), where no investments are made and the network topology is fixed.

TABLE I. RESULTS OF RELEVANT VARIABLES FOR VARIOUS CASES

Optimization variables		Cases A	Cases B	Cases C
Cost terms (k€)	Investment	0	99368	143817
	Maintenance	189	56513	81707
	Energy + Emission	424715	48973	10706
	PNS	94441	0	629
	Losses	12515	1098	643
Total cost (k€)		531860	205952	237503
Energy share (%)	Wind	-	90	100
	Solar	-	0	0
	Imported	100	10	0
Installed size (p.u.)	Wind	-	40	58
	Solar	-	0	0
	ESS	-	17	24

TABLE II. OPTIMAL AGGREGATED SIZES OF DGS AND ESSS FOR DIFFERENT CASES AND IN EACH PLANNING STAGE

Year	Case B Wind	Case B Solar	Case B ESS	Case C Wind	Case C Solar	Case C ESS
1	36	0	15	54	0	23
2	1	0	2	1	0	1
3	3	0	0	3	0	0
Total	40	0	17	58	0	24

Comparing Case B with Case A, one can observe net reductions of costs and losses in more than 90% and 89.66%, respectively. It should be noted that only 10% of the energy demand comes from the substation, which shows the system immensely benefits from the coordinated investments in DGs and ESSs. Generally, the contribution of ESSs in terms of increasing system flexibility is dramatic as it is evident to see from the numerical results. Obviously, the added flexibility enables the system to support large-scale RES energy. In this particular study, RESs and ESSs in Case B jointly cover about 90% of the total energy consumption in the system. Normally, a network switching should also enhance the flexibility of the considered system, the end-result being a higher level of RES penetration and utilization. The use of distribution network reconfiguration does not seem to have a significant effect on the system, perhaps because of the optimal placement of the DGs in the system. Table I also shows some numerical results corresponding to Case C, which seem to reinforce the possibility of having a standalone system, featuring only RESs in tandem with strategically placed ESSs. In this case, all of the energy required to meet the demand comes from the renewable type DGs placed in the distribution system. The ESSs play a key role in countering the imbalances between generation and demand, and maintaining grid stability.

In Figure 1, the location and size of DGs and ESSs in the system corresponding to Case B are clearly shown. Over the planning horizon, the allocation outcomes of DGs and ESSs for Case B and Case C in the three stages can be seen in Table II. In this table, one can overserve that majority of investments take place in the first stage. This can happen due to two factors. One can be due to the absence of restrictions related to investment and logistics. The other and most plausible factor is that the NPV in the first stage is higher than in any other subsequent stage. It should be noted that the higher the factor is, the more relevant are the costs in the objective function, which justifies more investments in DGs and ESSs.

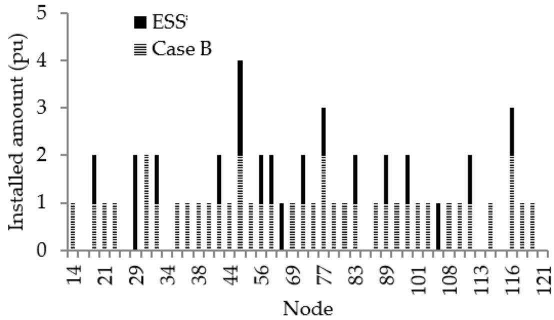

Figure 1. Optimal placement and size of DGs and ESSs.

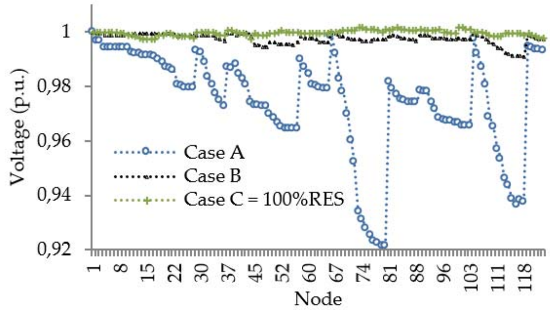

Figure 2. Average voltage profiles in the system for different cases.

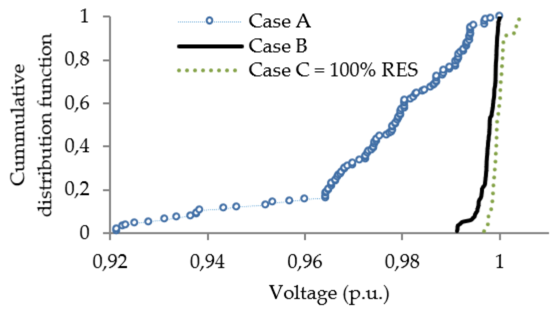

Figure 3. Cumulative distribution functions of average voltages.

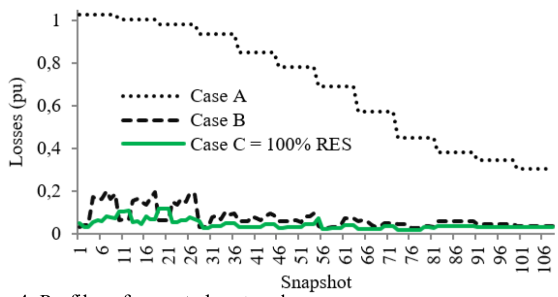

Figure 4. Profiles of expected system losses.

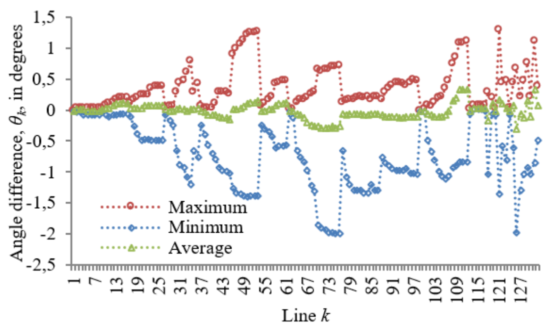

Figure 5. Profiles of expected voltage angle differences.

Figure 2 shows the average voltage profiles for the considered cases. Alternatively, these are represented in the form of cumulative distributions Figure 3.

The positive contribution of DGs and ESSs optimal placement combined in the voltage profile can be easily seen in Figures 3 and 5. (i.e. Cases B and C) which leads to more or less flat voltage profiles in the system. Such a coordination also results in a considerable reduction of network losses (> 89% on average), which can be inferred from Figure 4.

The stability of the considered system has also been analyzed. The profile of the voltage angle differences of the branches in the system can be taken as a good proxy for stability. In this case, 0.035 radians is the maximum absolute value recorded, $\max\{|\theta_{k,s,w,t}|\}$, which translates into approximately 2º. This value is well below the maximum stability limit, which is often in the order of 25º. Figure 5 clearly illustrates the average angle difference profile as well as the maximum and the minimum values recorded depending on the operational situations. It is interesting to observe in Figure 5 that all these values are significantly low, ensuring a stable operation of the entire system. This means, despite the high penetration of RESs, there is an increased stability margin in the considered system.

V. CONCLUSIONS

This paper has developed an optimization model that aims to jointly allocate variable type renewables and ESSs in electrical distribution network systems, along with dynamic network reconfiguration. The resulting model is of a mixed integer linear programming nature. The ultimate goal of this exercise is to maximize the integration and efficient usage of variable RESs, mainly wind and solar, while respecting a number of constraints in the system. This work also assessed the possibility of a standalone system, which has variable RESs as its main supply sources. The analysis is carried out on a standard test system. The analysis of the results has showed the immense benefits of jointly allocating ESSs and variable renewable DGs, particularly in terms of the increased level and the optimal exploitation of such energy sources. In addition, the voltage profile throughout the system is substantially improved, and the overall system stability is ensured despite the high penetration of variable energy resources. In general, increased flexibility of distribution network systems through reconfiguration and optimal deployment of ESSs make it possible for such systems to support a significant amount (even 100%) of such energy sources. In particular, strategically deployed ESSs have proved to be viable options for more efficient utilization of clean energy sources, and their contribution in terms of emission reduction is dramatic.

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