Meshed Operation of Distribution Network Systems: Enabling Increased Utilization of Variable RES Power

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***Abstract*—Electrical distribution systems are facing new challenges mainly due to the growing penetration of distributed generation of mainly intermittent nature such as wind and solar PV. As a result, these systems need to undergo massive transformations in terms of operational scheme. In other words, new operational strategies, which increase the flexibility of distribution systems, have to be put in place. This is highly required if distribution systems are to support large quantities of variable RES power. One plausible strategy worth considering relates to the meshed operation of such systems. The main topic of this paper revolves around the prospects of operating distribution grids in a meshed manner. The benefits are quantified in terms of added flexibility to the system, and vRES utilization levels. A mixed integer linear programming model is employed to perform the required analysis, and a 119-bus distribution system is used for this purpose. The analysis of the results generally shows the strong viability of the new operation strategy in terms of adding flexibility and scaling up the utilization level of variable RES power in the considered system. This strategy can be considered as a viable flexibility option that enables further integration of intermittent power sources.**

Keywords—Distribution System, Meshed Scheme, Mixed Integer Linear Programing, Stochastic Programming, Variable Renewable Energies.

I. NOMENCLATURE

A. Sets/Indices

i/Ω^i	Index/set of buses
$g/\Omega^g/\Omega^{DG}$	Index/set of generators/vRES
k/Ω^k	Index/set of branches
$hh, h/\Omega^h$	Index/set of hourly snapshots
s/Ω^s	Index/set of scenarios
$\varsigma/\Omega^\varsigma$	Index/set of substations

B. Parameters

ER_g, ER_ς^{SS}	Emission rates of vRES, and energy purchased, respectively (tCO$_2$e/MWh)
g_k, b_k, S_k^{max}	Conductance, susceptance and flow limit of branch k (Ω, Ω, MVA)
MP_k, MQ_k	Big-M parameters associated to active and reactive power flows through branch k
$OC_{g,i,s,h}$	Operation cost of unit energy production by vRES (€/MWh)
N_i, N_ς	Number of buses and substations, respectively
V_{nom}	Nominal voltage (kV)
Z_{ij}, R_k, X_k	Impedances of branch *i-j* (Ω)
$\lambda_{s,h}^{CO_2e}$	Price of emissions (€/tons of CO$_2$ equivalent)
$\lambda_{s,h}^{\varsigma}$	Price of electricity purchased upstream (€/MWh)
ρ_s, π_w	Probability of hourly scenario *s* and weight (in hours) of hourly snapshot group h
$\upsilon_{s,h}^P,\ \upsilon_{s,h}^Q$	Penalty for active and reactive unserved power, respectively (€/MW, €/MVAr)

C. Variables

$PD_{s,h}^i, QD_{s,h}^i$	Active and reactive power demand at node *i* (MW, MVAr)
$P_{g,i,s,h}, Q_{g,i,s,h}$	Active and reactive power produced by vRESs (MW)
$P_{\varsigma,s,h}^{SS}, Q_{\varsigma,s,h}^{SS}$	Active and reactive power imported from grid (MW)
P_k, Q_k, θ_k	Active and reactive power flows, and voltage angle difference of link k (MW, MVAr, radians)
PL_k, QL_k	Active and reactive power losses (MW, MVAr)
$PL_{\varsigma,s,h}, QL_{\varsigma,s,h}$	Active and reactive power losses at substation ς (MW, MVAr)
$P_{i,s,h}^{NS}$	Unserved power at node *i* (MW)
$Q_{i,s,h}^{NS}$	Unserved power at node *i* (MW)
V_i, V_j	Voltage magnitudes at nodes *i* and *j* (kV)
$u_{k,h}$	Utilization variables of existing lines
θ_i, θ_j	Voltage angles at node *i* and *j* (radians)
$\lambda_{s,h'}$	Real-time price of electricity (€/MWh)

D. Functions

EC_h^{SS}	Expected cost of imported energy (€/h)
EC_h^{vRES}	Expected cost of energy from vRESs (€/h)
$ENSC_h$	Expected cost of unserved power (€/h)
$EmiC_h^{vRES}$	Expected emission cost of vRESs (€/h)
$EmiC_h^{SS}$	Expected emission cost of purchased power (€/h)

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II. INTRODUCTION

A. Motivation and Aims

Electrical distribution systems need to adapt to a new reality different from that for which they were first built [1]–[4]. These systems need to undergo massive transformations in terms of operational schemes. In other words, new operational strategies, which increase the flexibility of distribution systems, have to be put in place. Furthermore, given the increasing penetration of distributed generations (DGs), in particular, variable Renewable Energy Sources (vRESs), the design and operation of the entire electric distribution system must be rethought. All this is highly required if distribution systems are to support large quantities of variable RES power. Hence, apart from the traditionally radial configuration and operation strategies, new structural topologies must be studied and analyzed. One of the most promising solutions for enabling large-scale RESs is smart grid [5]–[9]. The transformation of current distribution systems to smart grids is expected to bring a lot of other benefits. However, this transformation may be tremendously expensive, and may not be accomplished in short term prospects. Many distribution networks are meshed by design but operated radially because of some technical limitations such as the set-up of system-wide protection which works well in radial networks [10]–[13]. The normally open loops and tie-lines in traditional distribution systems are often used in the event of contingencies, mainly for reliability reasons i.e. to minimize/avoid load shedding during abnormal conditions (fault).

Another plausible strategy worth considering is related to the meshed operation of such systems. This is a new paradigm of operating distribution systems which apparently goes against the conventionally known radial operation scheme. Obviously, there are reasons why distribution grids cannot be operated in a meshed manner (just like the transmission grids). Fault clearance and system protection are among the vast reasons. However, current technological advances can adequately address these and other limitations. Fast deloopers can, for example, be used to transform meshed distribution grids into radial structures in the event of fault situations so that conventional protection devices can act. The introduction of new technologies such as fault current limiters (FCLs) can make meshed operation possible [14].

Hence, operating distribution grids in a meshed way, rather than radially, may become a norm in the near future. Hence, the main topic of this paper revolves around the prospects of operating distribution grids in a meshed manner. The benefits are quantified in terms of added flexibility to the system, and vRES utilization levels. A mixed integer linear programming model is employed to perform the required analysis, and a 119-bus distribution system is used.

B. Literature Review

When increasing DG penetration in distribution systems, limitations on bus voltages, current flows, voltage oscillations, protection schemes, voltage regulation and control equipment are factors that must be taken into consideration [15]. The placement of DGs within distribution systems can cause changes in some current directions in the branches, which can impact the voltage regulation, due to the fact stated earlier since distribution network systems are normally designed for unidirectional power flows. Generally, operating distribution systems in a meshed scheme can result in a multitude of benefits (e.g. in terms of accommodating more vRES power that is relevant to address global and local concerns).

Distribution systems, implementing meshed operation schemes, can in principle accommodate an increased amount of vRES power. However, this possibility has rarely been explored in the literature with few exceptions. In [16], a comparative analysis of meshed operation and network reinforcement is presented. Authors in [17] have developed a model to estimate the maximum allowable DG penetration based on two steady-state factors, the bus voltage and line current operating limits. They have concluded that meshed operation can be a promising technology to accommodate higher penetration levels of DGs. In [18], authors have established a Voltage Sensitivity Index for optimal DG placement in meshed distribution network for assessing the impact of DG on the system performance.

However, unlike in this paper, majority of these previous works focus on the integration of conventional power sources in distribution networks. In [19], authors present a comparison of optimal power flows that are obtained in radial and meshed distribution systems with integration of DGs and compensating devices. In [20], authors try to assess the prospect of a meshed operation scheme of distribution systems consisting of a resistor, inductor and a capacitor (RLC) elements. In [21], a time sequence load-flow method is developed to make a steady-state investigation of a meshed distribution system operation with the integration of DGs. However, none of the above references focus on the analysis of operating a meshed distribution system to increase the utilization of vRESs.

With the advent of new technologies, this paper argues that distribution systems can be operated in a meshed manner under normal situations and automatically switched to radial configurations in the event of fault. This way, the benefits of meshed operation can be reaped fully, which include reduced losses, improved voltage profiles and better management of variable RESs in distribution networks. Practically, all this does not require huge investments in distribution network systems. The approach makes use of existing switches (loops and tie lines).

C. Contributions and Paper Organization

Large-scale integration of variable RESs especially creates a different set of challenges that need to be addressed by analyzing different operation strategies. This is the main focus of our paper, subjected to extensive analysis. More specifically, mechanisms that enable meshed operation of distribution networks are discussed. Suitable mathematical formulations are in full development to assure that a distribution system can be stochastic managed with large-scale penetration of vRESs. The analysis is accomplished in terms of optimal topology, losses, voltage profiles, costs and others operation variables within the distribution network system. In order to do so, it is developed, in this paper, a stochastic mixed integer linear program to achieve optimal operation under heavy integration of vRES with a meshed operation scheme. Extensive analysis is made concerning the flexibility provided by meshed topology and its impact on the utilization and penetration of vRESs. This work is organized as follows. In Section III, the mathematical model used in this work is described. Section IV provides discussions of the numerical results obtained by carrying out a number of case studies. The last section concludes the paper.

III. MATHEMATICAL FORMULATION

In this section, it is described the stochastic mixed integer linear programing that was developed in this work. The model is responsible for carrying out analysis of optimal operation of a meshed distribution system featuring large-scale vRES.

The meshed operation should increase the utilization of vRES without affecting negatively the operation of the system. A linearized AC power flow model is used. It grants the accuracy of the model and have less computational requirements.

A. Objective Function

Minimization of some cost terms is employed in this model. The objective is therefore to minimize the sum of suitable cost terms. These costs are associated to the costs of operating the system, with unserved power and emissions coming from importing power from upstream and with operating vRESs.

$$Minimize\ TOC = TEC + TENSC + TEmiC \tag{1}$$

Equation (1) minimizes *TOC*, which is related to the expected total operation costs in the system. In (1) the first term TEC represents the expected costs by producing power from renewable technologies (wind and solar in this case) and purchasing energy from upstream grid.

The two terms are calculated as:

$$EC^{vRES} = \sum_{s\in\Omega^s} \rho_s \sum_{h\in\Omega^h} \sum_{g\in\Omega^g} OC_g P^{vRES}_{g,i,s,h} \tag{2}$$

$$EC^{SS} = \sum_{s\in\Omega^s} \rho_s \sum_{h\in\Omega^h} \sum_{\varsigma\in\Omega^\varsigma} \lambda^\varsigma_h P^{SS}_{\varsigma,s,h} \tag{3}$$

Referring to the second term *TENSC* in (1), it computes the cost of energy not supplied. It is given by the sum of costs related to unserved active and reactive power. The terms $\upsilon^P_{s,h}$ and $\upsilon^Q_{s,h}$ are defined as penalty parameters. These must be big enough to avoid undesirably high unserved power.

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

The last term $TEmiC$ refers to the expected emissions cost in the system. It is resultant of vRESs generation power and importing energy through the substation.

$$TEmiC = EmiC^{vRES} + EmiC^{SS} \tag{5}$$

The terms in (5) are determined as follows:

$$EmiC^{vRES} = \sum_{s\in\Omega^s} \rho_s \sum_{h\in\Omega^h} \sum_{g\in\Omega^g} \sum_{n\in\Omega^n} \lambda^{CO_2} ER^{vRES}_g P^{vRES}_{g,i,s,h} \tag{6}$$

$$EmiC^{SS} = \sum_{s\in\Omega^s} \rho_s \sum_{h\in\Omega^h} \sum_{\varsigma\in\Omega^\varsigma} \sum_{n\in\Omega^n} \lambda^{CO_2} ER^{SS}_\varsigma P^{SS}_{\varsigma,s,h} \tag{7}$$

B. Constraints

Here are presented the constraints used. The first one is related to Kirchhoff's current law. This constraint describes that the sum of all incoming flows to a node must be equal to the sum of all outgoing flows of the node. This condition need to be respected all time to guarantee a safe operation of the system. Active and reactive power flows are governed by this rule.

$$\begin{aligned} \sum_{g\in\Omega^g} P^{vRES}_{g,i,s,h} + \sum_{es\in\Omega^{es}} + P^{SS}_{\varsigma,s,h} + P^{NS}_{i,s,h} + \sum_{in,l\in\Omega^l} P_{l,s,h} \\ - \sum_{out,l\in\Omega^l} P_{l,s,h} = PD^i_{s,h} + \sum_{in,l\in\Omega^l} \frac{1}{2} PL_{l,s,h} \\ + \sum_{out,l\in\Omega^l} \frac{1}{2} PL_{l,s,h}\ ; \forall\varsigma\epsilon\Omega^\varsigma;\ \forall\varsigma\epsilon i; l\epsilon i \end{aligned} \tag{8}$$

$$\begin{aligned} \sum_{g\in\Omega^g} Q^{vRES}_{g,i,s,h} + Q^{SS}_{\varsigma,s,h} + Q^{NS}_{i,s,h} + \sum_{in,l\in\Omega^l} Q_{l,s,h} \\ - \sum_{out,l\in\Omega^l} Q_{l,s,h} = QD^i_{s,h} \\ + \sum_{in,l\in\Omega^l} \frac{1}{2} QL_{l,s,h} \\ + \sum_{out,l\in\Omega^l} \frac{1}{2} QL_{l,s,h}\ ; \forall\varsigma\epsilon\Omega^\varsigma;\ \forall\varsigma\epsilon i; l\epsilon i \end{aligned} \tag{9}$$

It can be noted in (8) that the incoming power flows into a node encompass active power injected by the renewables, inward active power flows associated with feeders and the imported energy from substation. On the other hand, outgoing power flows are associated to the demand in the node, losses (treated here as fictitious loads) and outward power flows of the feeders. It is applied the same principle to reactive power flow in (9).

Kirchhoff's voltage law constraint is also taken in consideration. This constraint rules the power flow in any feeder, by including linearized power flow equations considering two practical approaches. Primary states that the bus voltage magnitudes are probable to be close to the nominal value of voltage V_{nom}, that is only valid in distribution systems. Secondly is correlated with the voltage angle difference θ_k. Indeed, this difference is very small, which lead to the trigonometric approximations $\sin\theta_k \approx \theta_k$ and $\cos\theta_k \approx 1$. Assuming the two approaches, AC power flow equations are linearized and concerns with nonlinearities and non-convex functions of voltage magnitude and angles are resolved.

$$\begin{aligned} \left|P_{k,s,h} - \left(V_{nom}\left(\Delta V_{i,s,h} - \Delta V_{j,s,h}\right) g_k - V^2_{nom} b_k \theta_{k,s,h}\right)\right| \\ \leq MP_k(1 - u_{k,h}) \end{aligned} \tag{10}$$

$$\begin{aligned} \left|Q_{k,s,h} - \left(- V_{nom}\left(\Delta V_{i,s,h} - \Delta V_{j,s,h}\right) b_k - V^2_{nom} g_k \theta_{k,s,h}\right)\right| \\ \leq MQ_k(1 - u_{k,h}) \end{aligned} \tag{11}$$

$$\Delta V^{min} \leq \Delta V_{i,s,h} \leq \Delta V^{max}. \tag{12}$$

The power flow in each branch cannot be higher than the respective maximum transfer capacity, as in (13). And, the active and reactive power losses in each branch are given by (14) and (15)

$$P^2_{k,s,h} + Q^2_{k,s,h} \leq u_{k,h}(S^{max}_k)^2 \tag{13}$$

$$PL_{k,s,h} = R_k\left(P^2_{k,s,h} + Q^2_{k,s,h}\right) / V^2_{nom} \tag{14}$$

$$QL_{k,s,h} = X_k\left(P^2_{k,s,h} + Q^2_{k,s,h}\right) / V^2_{nom} \tag{15}$$

Equations (13)-(15) were linearized. For this it is used a piecewise linearization method, which is very employed in the literature.

The vRES generators also have limits of active and reactive power, so they are also considered.

$$P^{vRES,min}_{g,i,s,h} \leq P^{vRES}_{g,i,s,h} \leq P^{vRES,max}_{g,i,s,h} \tag{16}$$

$$\begin{aligned} -tan\left(cos^{-1}(pf_g)\right) P^{vRES}_{g,i,s,h} \leq Q^{vRES}_{g,i,s,h} \\ \leq tan\left(cos^{-1}(pf_g)\right) P^{vRES}_{g,i,s,h} \end{aligned} \tag{17}$$

Not only vRES have limitations on the reactive power but also substation is subjected to lower and upper bounds of reactive power due to stability reasons.

$$
\begin{aligned}
-\tan\left(cos^{-1}(pf_{ss})\right)\ P^{SS}_{\varsigma,s,h} \le Q^{SS}_{\varsigma,s,h} \\
\le \tan\left(cos^{-1}(pf_{ss})\right)\ P^{SS}_{\varsigma,s,h}
\end{aligned}
\tag{18}
$$

Note that the angle difference $\theta_{k,s,h}$ is well-defined as $\theta_{k,s,h} = \theta_{i,s,h} - \theta_{j,s,h}$. In this case, i and j correspond to same branch k.

IV. CASE STUDIES, RESULTS AND DISCUSSION

A. Data and Assumptions

The 119-bus distribution system is used to take out the simulations and analysis, Fig. 1. In order to put it as a meshed distribution system all lines are connected. Nominal voltage of the system is 11 kV with value of the demand being 22709.72 kW and 17041.068 kVAr. More relevant information can be found in [3]. Also, in accordance to [3], the active power losses of the system are expected to be 1298.09 kW, with the minimum voltage of the system being 0.8783 p.u. at bus 116. The size and location of vRES were also adapted from [3] with slight differences. It is added to buses 25 and 29 one unit of PV and to buses 82, 116 and 121 one unit of wind power production. To bus 52 it is subtracted one unit of wind and PV. At bus 79, 101, 106, 117 and 119 it is added one unit of PV and retracted one unit of wind power production. Other data assumptions are as follows:

- A period of 24-hour was used to make the operational analysis.
- Maximum tolerable deviation of voltage at each bus is set to ±5% of the nominal value (11 kV).
- In all simulations, substation is the reference node. Therefore, voltage magnitude is set to the nominal value and angle set to 0.
- The power factor at the substation is set equal to 0.8. The power factor of vRES is 0.95. The two values are constant throughout the analysis.
- The emission rate at the substation is arbitrarily set to 0.4 $\mathrm{tCO_2e/MWh}$. Solar is set to 0.0584 $\mathrm{tCO_2e/MWh}$ and wind is set to 0.0276 $\mathrm{tCO_2e/MWh}$.
- The price of emissions is 6 $€/\mathrm{tCO_2e}$.
- The electricity price of solar is established to 40 €/MWh and wind power generation is established to 20 €/MWh.
- The cost of any unserved power is 3000 €/MW. This applies also to any unserved reactive power.
- Feeders {(1, 2); (2, 4); (1,66); (66,67)} have a maximum transfer capacity of 1200 A. Feeders {(4, 5); (5, 6); (6, 7); (4,29); (29,30); (30,31); (67,68); (67,81); (81,82); (1,105); (105,106); (106,107)} have each 800 A capacity limit. Remaining feeders have maximum capacity of 400 A.
- All big-M parameters are set equal to 20.
- The number of partitions considered for linearizing quadratic terms is 5, which is set according to the findings in [22].

In addition, the power generation profiles of solar and wind type DGs as well as the demand profiles are assumed to be uniform throughout the system. The uncertainty pertaining to wind and solar power outputs are accounted for by considering three different scenarios for each uncertain parameter. The uncertainty pertaining to demand was accounted for by considering six different scenarios (three residential scenarios and three industrial scenarios). It should be noted that each scenario represents an hourly profile of the uncertain parameter under consideration. The combination of the individual scenarios (which in this case are 81) form the set of scenarios finally considered for the analysis.

B. Discussion of Numerical Results

Three cases are considered here in order to assess the benefits of operating distribution grids in a meshed manner. The system considered in the case study features a significant amount of vRESs. The first case considers a radial configuration with no DGs integrated in the system. This is what will be hereinafter referred to as the Base Case. In this case, the lower voltage bound is relaxed to avoid unacceptably large unserved power in the system. In other words, in the absence of DGs as in the Base Case, it is not practically possible to simultaneously satisfy the voltage constraints and avoid unserved power. The second case, designated as "R-DGs", is the same as the Base Case but with DG integration. The third one considers meshed operation in the presence of DGs and will be referred to as "M-DGs" from now onwards. In the second and third cases, the upper and lower voltage limits have already been considered. Table I shows the total expected costs, its components, and the total expected power losses.

As expected, the Base Case has the highest expected cost of energy (*TEC*) among the three considered cases. This happens because all energy required in the system is imported through the substation, which is relatively more expensive and emission-intensive. As a result, the expected cost of emissions (*TEmiC*) in the Base Case is also the highest among the other cases. In the R-DGs case, *TEC* is reduced by 40% in comparison to that of the Base Case. This is mainly because of the increased power production by the "cleaner" and cheaper energy sources located throughout the network system, i.e. the wind and solar PV type DGs. The energy mix profile for the considered period is shown in Fig. 2. In addition, *TEmiC* is also reduced by 54.4%. Since the voltage constraints are imposed in the R-DGs case, the TENSC is higher than that of the Base Case. However, the overall cost in R-DGs case is a lot lower than that of the Base Case.

The energy mix related to the M-DGs can be seen in Fig. 3. The total cost is reduced by more than half (i.e. 51.4%) when compared with that of the Base Case. Likewise, the total cost of emissions, *TEmiC*, is also slashed even more than this, by 67.2%. In the third case, thanks to the benefits of the meshed operation, there are no costs related to unserved power. In terms of power losses, the case with meshed operation along DGs has the lowest values, as can be seen in Table I. Compared to the Base Case, active and reactive power losses in the system are 70.4% and 70.7% lower, respectively.

The average profile of active power losses is shown in Fig. 4. Meshed operation can contribute to reducing power losses, especially in the peak hours. This may be because meshing leads to more distribution of power flows and ease congested feeders.

In Fig. 5, the average voltage deviation profiles of the three cases are shown for comparison. The results in this figure reinforce the argument that a meshed operation of distribution grids enhances the overall system performance and increases system flexibility. It is evident to see in Fig. 5 that meshed operation leads to the best voltage profile among the considered cases. The aggregated energy mixes corresponding to the radial and meshed operations are shown in Figs. 2 and 3, respectively.

We can observe in these figures that the power imported from upstream is substantially lower in the M-DGs than in the R-DGs case. This further indicates that meshed operation leads to a better management and efficient utilization of available resources (wind and solar power).

The utilization of renewable energy in radial operation is 51% of wind and 6% of solar, which in total is 57%. Whereas, in the meshed operation, these utilization levels increase to 62%wind power and 10% solar power, bringing the aggregate level to 72%. In addition, in Fig. 3, it is noticed that, between hours 4 and 6, the imported power is very low, almost leading to an islanded and meshed distribution network. Generally, the results of the case study highlight the contributions of meshed operation in terms of enhancing system-wide flexibility and increasing the utilization level of variable RES power.

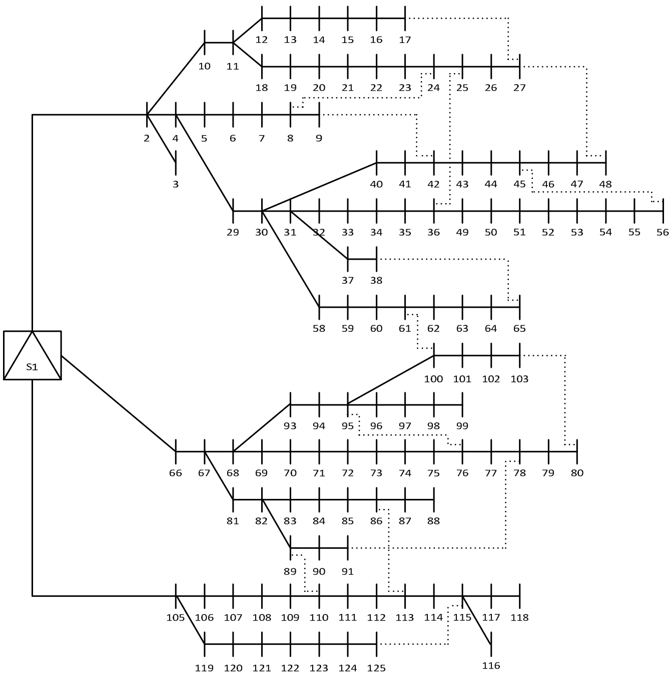

Fig. 1. Single line diagram of the considered system

TABLE I. COST TERMS OF OBJECTIVE FUNCTION AND LOSSES

	Base Case	**R-DGs**	**M-DGs**
TOC (€)	32217.38	27802.03	15664.99
TEC (€)	30349.82	18215.54	15265.23
TEmiC (€)	1219.56	557.47	399.76
TENSC (€)	647.99	9029.01	0
P Losses (MWh)	20.26	9.40	5.99

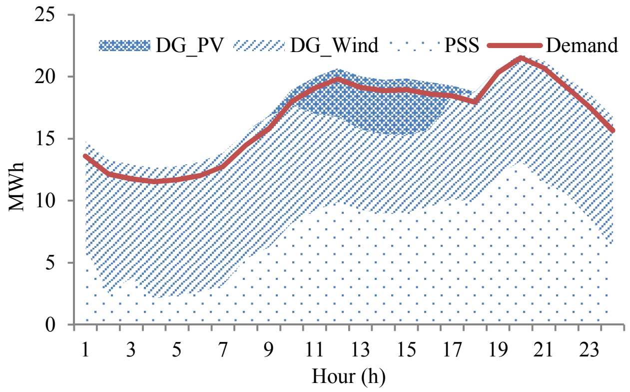

Fig. 2. Aggregated energy mix of radial operation with DGs

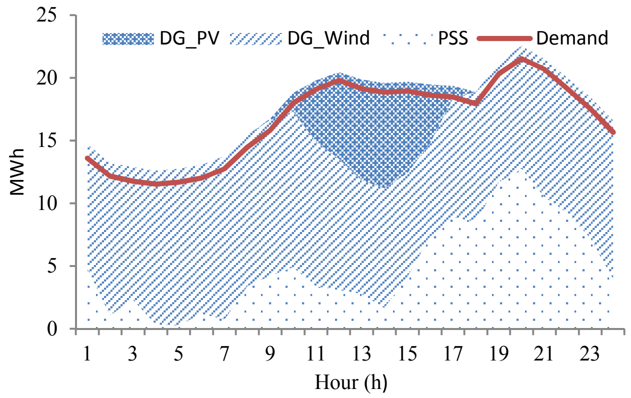

Fig. 3. Aggregated energy mix of meshed operation with DGs.

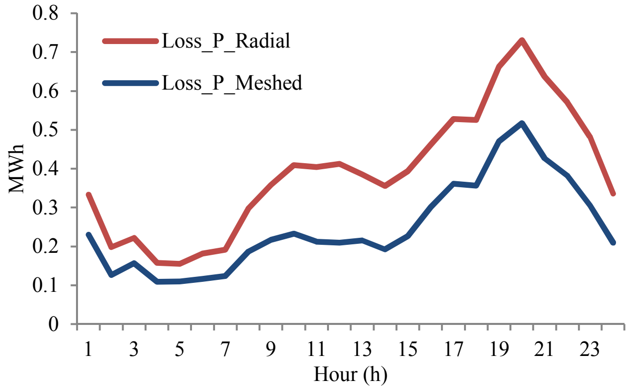

Fig. 4. Comparison between average active power losses of radial operation and meshed operation.

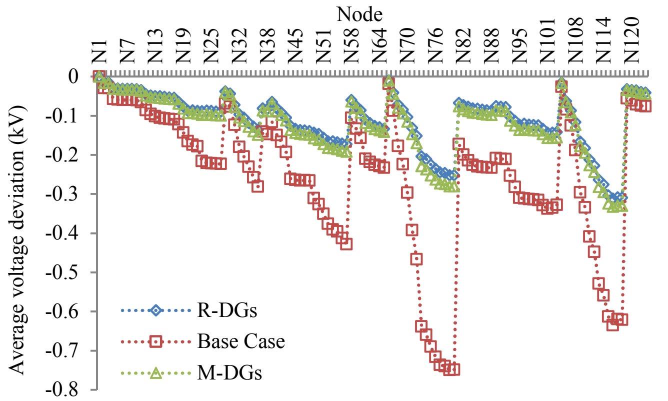

Fig. 5. Average voltage deviation profile of the cases considered.

V. CONCLUSIONS

This paper has investigated the prospects of meshed operations of distribution grids with the aim of adding flexibility to existing systems and thereby enabling more integration of variable RES power. For performing this analysis, a stochastic MILP optimization model has been used, employing a large-scale distribution network as a test system. The optimization model is based on a linearized AC power flow, and minimizes the sum of relevant cost terms while satisfying a number of operation constraints. Numerical results from the case study reveal that the meshed operation strategy in distribution systems can lead to a more efficient utilization of resources (in this case, wind and solar power sources) compared to the conventionally known radial operation scheme. The utilization level of variable RES power in the meshed operation case has reached 72% without posing any negative effects on the operation of the system from the technical perspective. In contrast, for the considered system, a maximum of 57% has been achieved in the radial operation scheme. The voltage profile in the system is also enhanced. The results generally indicate the strong viability of the new operation strategy in terms of adding flexibility and scaling up the utilization level of variable RES power in the considered system.

REFERENCES

[1] G. Papaefthymiou and K. Dragoon, "Towards 100% renewable energy systems: Uncapping power system flexibility," Energy Policy, vol. 92, pp. 69–82, maio 2016.

[2] International Energy Agency (IEA), "Empowering Variable Renewables - Options for Flexible Electricity Systems," OECD, 2008.

[3] S. F. Santos, D. Z. Fitiwi, M. R. M. Cruz, C. M. P. Cabrita, and J. P. S. Catalão, "Impacts of optimal energy storage deployment and network reconfiguration on renewable integration level in distribution systems," Appl. Energy, vol. 185, pp. 44–55, Jan. 2017.

[4] A. S. Brouwer, M. van den Broek, A. Seebregts, and A. Faaij, "Impacts of large-scale Intermittent Renewable Energy Sources on electricity systems, and how these can be modeled," Renew. Sustain. Energy Rev., vol. 33, pp. 443–466, maio 2014.

[5] M. S. Hossain, N. A. Madlool, N. A. Rahim, J. Selvaraj, A. K. Pandey, and A. F. Khan, "Role of smart grid in renewable energy: An overview," Renew. Sustain. Energy Rev., vol. 60, pp. 1168–1184, Jul. 2016.

[6] J. A. Schachter and P. Mancarella, "A critical review of Real Options thinking for valuing investment flexibility in Smart Grids and low carbon energy systems," Renew. Sustain. Energy Rev., vol. 56, pp. 261–271, Apr. 2016.

[7] H. Yenginer, C. Cetiz, and E. Dursun, "A review of energy management systems for smart grids," in Smart Grid Congress and Fair (ICSG), 2015 3rd International Istanbul, 2015, pp. 1–4.

[8] S. N. Kulkarni and P. Shingare, "A review on Smart Grid Architecture and Implementation Challenges."

[9] X. Zhou, H. Cui, Y. Ma, and Z. Gao, "Research review on smart distribution grid," in Mechatronics and Automation (ICMA), 2016 IEEE International Conference on, 2016, pp. 575–580.

[10] R. T. Bhimarasetti and A. Kumar, "A New Contribution to Distribution Load Flow Analysis for Radial and Mesh Distribution Systems," 2014, pp. 1229–1236.

[11] A. D. Udgave and H. T. Jadhav, "A review on Distribution Network protection with penetration of Distributed Generation," in Intelligent Systems and Control (ISCO), 2015 IEEE 9th International Conference on, 2015, pp. 1–4.

[12] R. F. Arritt and R. C. Dugan, "Review of the Impacts of Distributed Generation on Distribution Protection," 2015, pp. 69–74.

[13] A. K. Tiwari, S. R. Mohanty, and R. K. Singh, "Review on protection issues with penetration of distributed generation in distribution system," in Electrical Engineering Congress (iEECON), 2014 International, 2014, pp. 1–4.

[14] P. Yu, B. Venkatesh, A. Yazdani, and B. N. Singh, "Optimal Location and Sizing of Fault Current Limiters in Mesh Networks Using Iterative Mixed Integer Nonlinear Programming," IEEE Trans. Power Syst., vol. 31, no. 6, pp. 4776–4783, Nov. 2016.

[15] R. H. A. Zubo, G. Mokryani, H.-S. Rajamani, J. Aghaei, T. Niknam, and P. Pillai, "Operation and planning of distribution networks with integration of renewable distributed generators considering uncertainties: A review," Renew. Sustain. Energy Rev., vol. 72, pp. 1177–1198, May 2017.

[16] M.-C. Alvarez-Herault, N. N'Doye, C. Gandioli, N. Hadjsaid, and P. Tixador, "Meshed distribution network vs reinforcement to increase the distributed generation connection," Sustain. Energy Grids Netw., vol. 1, pp. 20–27, Mar. 2015.

[17] M. Davoudi, V. Cecchi, and J. R. Agüero, "Increasing penetration of distributed generation with meshed operation of distribution systems," in North American Power Symposium (NAPS), 2014, 2014, pp. 1–6.

[18] B. Chalapathi, D. Agrawal, V. Murty, and A. Kumar, "Optimal placement of Distribution Generation in weakly meshed Distribution Network for energy efficient operation," in Power, Control, Communication and Computational Technologies for Sustainable Growth (PCCCTSG), 2015 Conference on, 2015, pp. 150–155.

[19] D. Ivic, D. Macanovic, D. Sosic, and P. Stefanov, "Weakly meshed distribution networks with distributed generation—power flow analysis using improved impedance matrix based algorithm," in Industrial Electronics (INDEL), International Symposium on, 2016, pp. 1–6.

[20] H. Yang, T. Bae, J. Kim, and Y. H. Kim, "Load model technique for mesh-structured power distribution network," in Quality Electronic Design (ASQED), 2012 4th Asia Symposium on, 2012, pp. 219–222.

[21] L. Yu, D. Czarkowski, F. De León, and W. Bury, "A time sequence load-flow method for steady-state analysis in heavily meshed distribution network with DG," in Compatibility and Power Electronics (CPE), 2013 8th International Conference on, 2013, pp. 25–30.

[22] D. Z. Fitiwi, L. Olmos, M. Rivier, F. de Cuadra, and I. J. Pérez-Arriaga, "Finding a representative network losses model for large-scale transmission expansion planning with renewable energy sources," Energy, vol. 101, pp. 343–358, Apr. 2016.