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Mesh/Radial Distribution Network Multi-Objective Operation considering Security-Constraints and Multi-DG Configurations with Integration of Demand Response

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ABSTRACT

This paper proposed a method for operational planning of Mesh/ radial distribution network considering security-constraints and multi-DG configuration with integration of demand response. The proposed method simultaneously minimises operational cost and energy losses in the network. The impact of multi-configuration of renewable DGs and demand response in a meshed network were also investigated. The ε-constraint method was used for the solution of multi-objective function. In this work, the distribution network is converted from radial to mesh to allow for alternative route for flow of electric power when N-1 distribution line contingency occurs in any of the branches. The lines for the mesh network were connected to the closest generator bus that offered least operating cost when optimized. Scenario-based approach is used to model the uncertainties related to photovoltaic (PV) cells and load demands. The effectiveness of the proposed method is demonstrated with 16-bus UK generic distribution system. The obtained results in using multi-objective functions ensures reduced operation cost and energy losses while considering multi-DG configuration and demand response in N-1 contingency.

Index Terms- *Distribution network, Multi-objective, Demand response, Power flow, multi-DG, SCOPF*

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Nomenclature

Indices

i,j	index for buses
Gen	index for generators
L	index for load
Line	index for distribution line
G	set of sub-station generators
Dg	set of PV generators
Parameters	
C_{Gen}^{i}	Price offered by PVs and sub-station generators to increase/decrease active power at bus i
C_{DR}^{i}	Price offered by load demand at bus I to decrease its active schedule in the context of demand response
$P_{gi}^{min}, P_{gi}^{max}$	Minimum and maximum active power for substation generators
$P_{dgi}^{min}, P_{dgi}^{max}$	Minimum and maximum active power for PV generators
$Q_{gi}^{min}, Q_{gi}^{max}$	Minimum and maximum reactive power for substation generators
$Q_{dgi}^{min}, Q_{dgi}^{max}$	Minimum and maximum re active power for PV generators
P_{ijc}^{*}	Maximum active power flow in distribution line
Q_{ijc}^{*}	Maximum reactive power flow in distribution line
V_i^{min}, V_i^{max}	Minimum and maximum values of voltage at bus *i*
$\delta_i^{min}, \delta_i^{max}$	Minimum and maximum values of voltage angle at pre-contingency
$\delta_i^{*min}, \delta_i^{*max}$	Minimum and maximum values of voltage angle at post-contingency
P_l^i, Q_l^i	Active and reactive power of load demand at bus *i*
Variables	
P_{gi}, P_{dgi}	Active power of substation generator and PVs at each bus
Q_{gi}, Q_{dgi}	Reactive power of substation generator and PVs at each bus
$P_{DR(l)}^{i} Q_{DR(l)}^{i}$	Active and reactive power decrement in demand response program for load demand l at bus *i*

P_{ij}, P_{ijc}^{*}	Active power flow in distribution line at pre and post contingency
Q_{ij}, Q_{ijc}^{*}	Reactive power flow in distribution line at pre and post contingency
V_i	Voltage at bus *i*
δ_i	Voltage angle at bus *i* at pre-contingency
δ_i^{*}	Voltage angle at bus *i* at post-contingency

I. INTRODUCTION

A. Background and motivation

The task of optimal planning and operation of electric distribution system is so challenging due to great benefits it poses to distribution network operators (DNOs), generation companies and final consumer of electric power. Good planning brings about efficiency, reliability and security of the distribution network thereby encouraging optimal operation and investment cost as well as reduced power losses in the network [1,2]. Security constraints in the network ensure improved system continuity indices by minimizing consumer interruptions that are caused by faults in distribution lines. Distribution Network Operators (DNOs) have to develop a rational operating strategy taking into account dispatching distributed generators (DGs), interrupting loads, and purchasing power from the wholesale market while keeping the system security [3]. Operating the network in a security-constrained manner offers an alternative route to the flow of power when single line outage occurs in the network. As the world is transiting to greener energy sources due to global climate change, it is pertinent that distribution networks are planned and operated in a way that will allow for a higher penetration of renewable energy resources (RES). However, the intermittency and variability of renewable-type DGs (e.g., wind and PV) impose challenges when planning distribution systems [4]–[9].

Recent studies have pushed towards system operating conditions that satisfies single objective in the distribution system. This work considers a multi-objective function which is aimed at minimizing both the system operation cost and loss simultaneously. Therefore the system losses cannot be sacrificed anymore by taking it into account as an objective function beside the operational cost.

Continuous operation of the distribution network even when there is outage of a distribution line or generator is the reason for introducing security constraints to the network. Security constraints ensure that all load demands are met when there is sudden loss of a component in the network, as this will mitigate a possible black-out as a result of voltage rise. Optimal power flow considering security analysis is known as security constrained optimal power flow (SCOPF) [10], [11]. In SCOPF, contingency analysis is performed to ascertain the effect of loss of a component (generator, transformer and transmission/distribution line) in the system. Also, this work considers the impact of multi-DG configuration in the distribution system. Multi-DG configuration assesses the level of penetration of renewable energy resources with different combination of the renewable generators.

B. Literature Review and Research gap

Several studies have been carried out on the operation of electric distribution system with renewable energy penetration. The planning scope of maximizing DG penetration in distribution networks is taking priority of DNOs in most countries due to the increasing rate of DG integration [12]. In [13], the voltage problem associated with the random installation of customer owned DGs, in terms of location, type and size, is examined on a secondary distribution network. In [14], the proposed method incorporates voltage step change constraint to cater for the impact associated with sudden disconnection or connection of a DG. The results show significant reduction in the amount of DG capacity when voltage step constraint is applied, and a wider step constraint could result in higher DG capacity.

The relationship between maximizing DG capacity and steady-state voltage violation is investigated using a voltage sensitivity factor in [15] and [16]. In [16], an effective method is proposed that allocates DGs based on analyzing various constraints associated with each bus to ensure no network sterilization occurs. Network sterilization results when DG units are allocated individually rather than a group at certain locations which can result in constraining the network, minimizing the total connected DG capacity and lowering the utilization of existing assets. In [17], another method is proposed that identifies strong and weak buses, and then, places DGs at buses with strong voltage stability margins. In [18], the authors proposed a cost based model to allocate DGs in distribution networks to minimize DG investment and total operation costs. In [19], a method for optimal placement of WTs in distribution networks to minimize annual energy losses has been proposed. The impact of variable demand and generation profiles is also investigated with multi-period optimal power flow (OPF)-based (MOPF) technique [20]–[22]. These studies are tested under “fixed” DG locations with only one DG-configuration (all DGs operating). In [23-26], the authors have not addressed the impact of multi-DG configuration on the planning and operation of a distribution system. Also, a single objective function was considered in their analysis. The author in [12] analysed the impact of multi-DG interaction on the amount of DG penetration into the network. In [14] the analysis was made with a single objective function using OPF with voltage step constraints. The authors in [33] considered the stochastic multi-objective model for scheduling of energy and reserve services in day-ahead markets. The approach could be used by ISOs to make a trade-off concurrently between system frequency profile and total operating cost to operate the power system securely in an economically efficient manner. Also [34] analysed system reliability and operational cost as a multi-objective function in energy management in distribution networks with energy storage systems. According to the author's knowledge, there is no study that covers the security of the network and multi-DG configuration with integration of DR Program multi-objective function, which is most important for any researcher in DGs operation and planning.

C. Aim and Contributions

Most of the literature reviews on operation of electric power distribution system considered only the optimal power flow in the system without taking into account both the security constraint and demand response of the network. Security of the network is necessary to maintain the optimal operation of the network when there is sudden loss of any distribution line in the network. Also, some of the works on distribution network planning and operation were carried with single objective function which is mostly system operational cost.

Therefore, this paper proposes a novel approach for the operation of the distribution network with multi-DG configuration considering the security of the network and the effect of integrating demand response on the network with multi-objective function.

The main contributions of this paper are highlighted as follows:

- Analyse the impact of multi-DG allocations in the operation of distribution network with optimal security-constrained OPF and demand response.
- Propose a new SCOPF-based planning technique that considers the operational status of DG units.
- Simulation of multi-objective function that minimizes both operational cost and system losses simultaneously using epsilon constraint method.
- Taking into account the uncertainty in the characteristics of the renewable energy sources and load demand using stochastic scenario-tree approach.
- Reconfiguration of the network by converting it from a weakly meshed to a mesh network type to ensure the security of the system at N-1 distribution line contingency.

D. Paper organization

The rest of the paper is organised as follows: multi-PV configurations is presented in section II, multi-objective optimization is discussed in III while uncertainty modelling was presented in IV. Problem formulation and structure of SCOPF formulation is presented in section V, illustration of a case study in section VI, simulation results is presented in section VII and finally section VIII has the conclusion.

II. MULTI-PV CONFIGURATIONS

In this work, PV renewable energy source was used for incorporating DG into the network. The multi-PV configurations defines the operational status of PVs and are chosen based on the decisions of distribution system planners. The total number of all possible multi-configurations for any number of PVs can be expressed as follows:

$$1 \le NC \le (2^{NPV} - 1) \quad (1)$$

In (1), the total number of configurations (NC) is referred to as the number of multi-PV configurations. For example, if a system has six PVs, there will be up to 63 possible multi-PV configurations for the system planners to choose. A binary parameter is defined to represent the operational status of PVs at *ith* bus for configuration c. The operational status of each PV and all PVs are described in (2) and (3), respectively.

$$\beta_{i,c} = \begin{cases} 1, & if\ a\ PV\ at\ i^{th}\ bus\ is\ operating \\ 0, & otherwise \end{cases} \quad (2)$$

$$\begin{pmatrix} \beta_{1,pv1} & \beta_{1,pv2} & \cdots & \beta_{1,pvN} \\ \beta_{2,pv1} & \beta_{2,pv2} & \cdots & \beta_{2,pvN} \\ \vdots & \vdots & & \vdots \\ \beta_{c,pv1} & \beta_{c,pv1} & & \beta_{c,pvN} \end{pmatrix}_{(NC \times NPV)} \quad (3)$$

In the proposed method, there is capacity constraint for PVs according to its operational status for each configuration which is described as follows:

$$P^{pv}_{i,c} = \begin{cases} 0 \le P^{pv}_{i,c} \le P^{2pv,max}_{i,c}, & \forall \beta_{i,c} = 1 \\ 0, & \forall \beta_{i,c} = 0 \end{cases} \quad (4)$$

III. MULTI-OBJECTIVE FUNCTION

Here, two objective functions are considered to be optimized simultaneously, which is the total operating cost and active power losses in the network. Pareto optimality technique is adopted for the solution of the multi-objective function.

A. *Pareto Optimality*

A solution is called Pareto optimal, if none of the objective functions can be improved without degrading some of the other objective values. The notion of optimality has been redefined in the context of pareto optimality and instead of aiming to find a single solution, it is tried to produce a set of acceptable compromises or trade-offs from which the decision maker can choose one. The set of all optimal solutions which are non-dominated by any other solution is known as Pareto-optimal set. The Pareto optimal (or efficient, non-dominated, non-inferior) solution is a feasible solution that other feasible solutions cannot be improved in all the objective functions simultaneously. The figure below illustrates the solution of multi-objective function using pareto optimality technique.

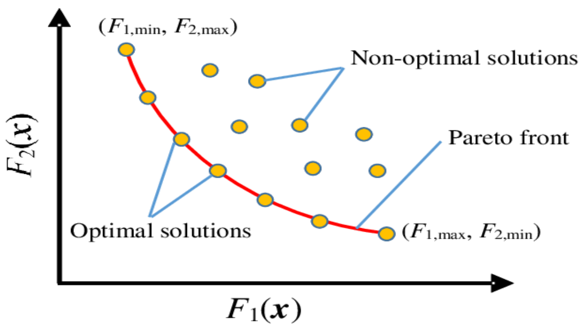

Fig 1: Pareto optimal Solution.

B. *The ε-constraint method*

In the ε-constraint method we optimize one of the objective functions using the other objective functions as constraints, while incorporating them in the constraint part of the model as shown below:

$\min f_1(x)$

s.t

$f_2(x) \leq e_2$

$f_3(x) \leq e_3$

...

$f_p(x) \leq e_p$

Therefore, by parametrical variation in the RHS of the constrained objective functions e_i the efficient solutions of the problem are obtained.

IV. UNCERTAINTY MODELLING

A. Solar irradiance modelling

The solar irradiance modelling is done by using the Beta PDF which is described as follows:

$$PDF(s) = \begin{cases} \dfrac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)+\Gamma(\beta)} \times s^{\alpha-1} \times (1-s)^{\beta-1} \\ 0 \leq s \leq 1,\ 0 \leq \alpha, \beta \\ 0 \qquad\qquad else \end{cases} \tag{5}$$

Where *s* represents the solar irradiance (kW/m^2).

α and β can be obtained as follows:

$$\alpha = \frac{\mu \times \beta}{1-\mu} \tag{6}$$

$$\beta = (1-\mu) \times \left(\frac{\mu \times (1-\mu)}{\alpha^2} - 1 \right) \tag{7}$$

Where μ is mean value and σ is the standard deviation of the random variable. To estimate the cell temperature, the solar irradiance, and the output power of PVs, Eqs. (8) and (9) are used [27,28]:

$$P_{pv} = P_{STC}\left\{\frac{G}{100}\left[1+\delta\left(T_{cell}-25\right)\right]\right\} \quad (8)$$

$$T_{cell} = T_{amb} + \left(\frac{NOCT-20}{800}\right)G \quad (9)$$

Where P_{pv}, P_{STC} are the output power and the power under standard test condition in (W) respectively. δ is the power-temperature coefficient in (%/ºC), T_{cell}, T_{amb} and NOCT are the cell temperature in ºC, the ambient temperature in ºC, and normal operating cell temperature conditions in ºC, respectively. G is solar irradiance in (W/m^2).

B. Load demand modelling

The Gaussian PDF is adopted for the load modelling. The PDF for load l is calculated as follows [29, 30]:

$$PDF\,(l)\frac{1}{\sigma_l\sqrt{2\pi}}\times exp\left[-\left(\frac{\left((l-\mu_l)^2\right)}{2\sigma_l^2}\right)\right] \quad (10)$$

Where μ_l is the mean value and σ_l is standard deviation.

V. PROBLEM FORMULATION

A. Objective function

The security of electric power system is of utmost concern to Distribution Network Operators (DNOs). They ensure that the network is operated to withstand any sudden loss of a component in the network.

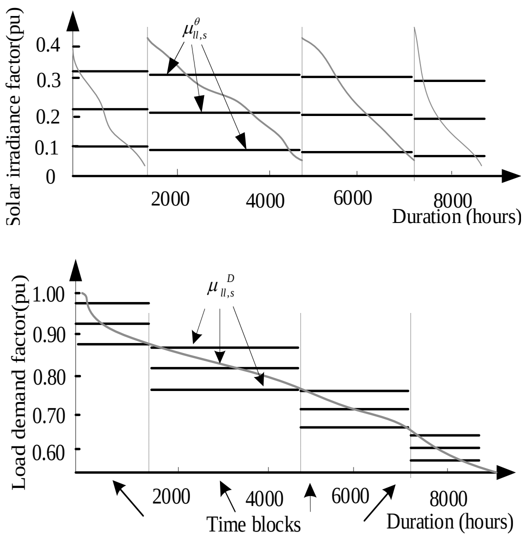

Fig 2: Solar Irradiance and load demand curves

In this work, constraints are put in place to ensure the security of the network in a contingency scenario. Also the integration of demand response is modelled as an active power injection to the network. Demand response aims at changing the consumption pattern of consumers to off-peak periods. This will allow for more penetration of renewable energy resources. Therefore, based on these considerations, the objective of the proposed operation problem is to jointly minimize the total operational cost and energy losses with integration of demand response program. The multi-objective function is optimized at different multi-DG configurations. The aim is to minimize operation cost and losses simultaneously. Cost minimization is represented by f_{obj1} while loss minimization is represented by f_{obj2}

$$Minimize\ F_{obj} = \sum_{i=1}^{NB}\sum_{Gen=1}^{NGen}\sum_{c=1}^{Nc} C^{i}_{Gen} P^{i}_{G_{Gen}} +$$

$$\sum_{i=1}^{NB}\sum_{Gen=1}^{NGen}\sum_{c=1}^{Nc} C^{i}_{Gen} P^{i}_{DG_{Gen}} + \sum_{i=1}^{NB}\sum_{l=1}^{L}\sum_{c=1}^{Nc} C^{i}_{DR(l)} P^{i}_{DR(l)} \quad (11)$$

s.t

$$f_{obj\ 2} = \sum_{i} \sum_{j} G_{ij} \left(V_i^2 + V_j^2 - 2V_i V_j \cos\left(\delta_i - \delta_j\right) \right)$$

***B**. Constraints*

$$\sum_{Gen=1}^{Gen} P_{g(Gen)} + \sum_{Gen=1}^{Gen} P_{dg(Gen)} + \sum_{l=1}^{l} \left(P_{DR(l)} - P_l^i \right) = \sum_{lin=1}^{lin} \sum_{l=1}^{i} P_{ij(line,j)} \quad (12)$$

$$\sum_{Gen=1}^{Gen} Q_{g(Gen)} + \sum_{Gen=1}^{Gen} Q_{dg(Gen)} + \sum_{l=1}^{l} \left(Q_{DR(l)} - Q_l^i \right) = \sum_{lin=1}^{lin} \sum_{l=1}^{i} Q_{ij(line,j)} \quad (13)$$

$$\sum_{Gen=1}^{Gen} P_{g(Gen)} + \sum_{Gen=1}^{Gen} P_{dg(Gen)} + \sum_{l=1}^{l} \left(P_{DR(l)} - P_l^i \right) = \sum_{lin=1}^{lin} \sum_{j=1}^{i} P^*_{ijc(line,j)} \quad (14)$$

$$\sum_{Gen=1}^{Gen} Q_{g(Gen)} + \sum_{Gen=1}^{Gen} Q_{dg(Gen)} + \sum_{l=1}^{l} \left(Q_{DR(l)} - Q_l^i \right) = \sum_{lin=1}^{lin} \sum_{j=1}^{i} Q^*_{ijc(line,j)} \quad (15)$$

$$P_{i,j} = \frac{V_i^2 \left(\cos\theta_{i,j} \right) - V_i V_j \cos\left(\delta_i - \delta_j + \theta_{i,j} \right)}{Z_{ij}} \quad (16)$$

$$Q_{i,j} = \frac{Q_i^2 \left(\sin\theta_{i,j} \right) - V_i V_j \sin\left(\delta_i - \delta_j + \theta_{i,j} \right)}{Z_{ij}} \quad (17)$$

$$P^*_{ijc} = \frac{V_i^2 \left(\cos\theta_{i,j} \right) - V_i V_j \cos\left(\delta^*_i - \delta^*_j + \theta_{i,j} \right)}{Z_{ij}} \quad (18)$$

$$Q^*_{ijc} = \frac{V_i^2 \left(\sin\theta_{i,j} \right) - V_i V_j \sin\left(\delta^*_i - \delta^*_j + \theta_{i,j} \right)}{Z_{ij}} \quad (19)$$

$$\theta = \tan^{-1} \frac{X}{R} \quad (20)$$

$$Z = \sqrt{X^2 + R^2} \quad (21)$$

$$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max} \quad (22)$$

$$P_{gi}^{min} \le P_{gi} + \Delta P^*_{gi} \le P_{gi}^{max} \quad (23)$$

$$Q_{gi}^{min} \le Q_{gi} \le Q_{gi}^{max} \quad (24)$$

$$Q_{gi}^{min} \le Q_{gi} + \Delta Q^*_{gi} \le Q_{gi}^{max} \quad (25)$$

$$P_{dgi}^{min} \le P_{dgi} \le P_{dgi}^{max} \quad (26)$$

$$P_{dgi}^{min} \le P_{dgi} + \Delta P^*_{dgi} \le P_{dgi}^{max} \quad (27)$$

$$Q_{dgi}^{min} \le Q_{dgi} \le Q_{dgi}^{max} \quad (28)$$

$$Q_{dgi}^{min} \le Q_{dgi} + \Delta Q^*_{dgi} \le Q_{dgi}^{max} \quad (29)$$

$$P_{ij} \le P_{ij}^{max} \quad (30)$$

$$P^*_{ijc} \le P_{ij}^{max} \quad (31)$$

$$Q_{ij} \le Q_{ij}^{max} \quad (32)$$

$$Q^*_{ijc} \le Q_{ij}^{max} \quad (33)$$

$$V_i^{min} \le V_i \le V_i^{max} \quad (34)$$

$$\delta_i^{min} \le \delta_i \le \delta_i^{max} \quad (35)$$

$$\delta_i^{*min} \le \delta^*_i \le \delta_i^{*max} \quad (36)$$

$$0 \le P_{DR(l)}^{i} \le P_{DR(l)}^{i(max)} \quad (37)$$

$$0 \le Q_{DR(l)}^{i} \le Q_{DR(l)}^{i(max)} \quad (38)$$

The above constraints can be categorized into two groups:

a) **Equality constraints:** Constraints (12)-(19) apply kirchhoff's law in the analysis. Constraints (12)-(15) ensure the active and reactive power balances in system nodes at pre-contingency and post-contingency situation. Equations (13)-(19) outlines the solution of active and reactive power flow in the line at pre-contingency and post-contingency state.

b) **Inequality constraints:** constraints (22)-(25) set the upper bounds for active and reactive power of substation at pre-contingency and post-contingency scenario. Also, constraints (26)-(29) limit the active and reactive power generation of PVs. The PVs generation depends on the solar irradiance. The active and reactive power flow limit in the line which ensures the security of the system are constrained by equations (30)-(33). Constraints (34)-(36) determines the acceptable range of voltage and angle at the buses. Finally, constraints (37)-(38) introduces the demand response limits.

***C**. Structure of SCOPF formulation*

The SCOPF starts by solving the system OPF with N constraints to find an operating point, and then contingency analysis is run which identifies the potential contingency cases. If there is no constraint violation, then the solution of SCOPF is obtained by the OPF. If a

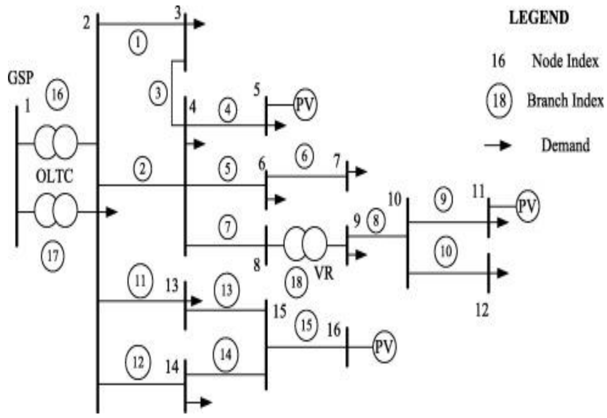

Figure 3. 16-bus UKGDS with candidate locations for PVs

security violation is caused by outages, the complete security constraints is added, and then the OPF and each of the contingency power flows is re-executed until the OPF has solved with all contingency constraints met. This new optimal operating point ensures that after any single line outage there are no voltage or branch limits violations. In optimal power flow solution the main objective is to obtain the minimum generation cost. In SCOPF, it includes pre contingency cost and the cost of each credible contingency. The objective function is constrained by terms in pre-contingency and post-contingency situations.

VI. CASE STUDY

The proposed method is applied and implemented on a 33kV 16-bus rural weakly meshed UKGDS. The data of this network is available in reference [31]. The single line diagram is shown in Fig. 2. The feeders are supplied by two identical 30-MVA 132/33 kV transformers.

In order to assess the impact of demand response on the SCOPF of the network, three 15MW PVs are installed at buses 5, 11 and 16. The upper and lower limit of the voltage at each bus is assumed to be 1.06 and 0.94 p.u. Each of them is composed of 15× 1MW solar panels with$\eta^{pv} = 18.6\%\ and\ S^{pv} = 10m^2$. Non-linear programming have been adopted for the solution of the problem. The proposed method is applied to the above mentioned distribution network and implemented in GAMS and solved using IPOPT solver [32] on a PC with Core i7 CPU and 16GB of RAM.

A. *Meshed Network Configuration*

Existing studies show that once a meshed network is adopted, the additional fault level contribution from adding DG is not significantly higher. However, protection coordination can be more complicated [22]. The disadvantages in fault level contribution are offset by increases in network stability and reliability [23]. A meshed network will aggregate variations in both load and generation, and can increase reliability by providing multiple routes from supply to the load points.

A 33KV 16-bus rural weakly meshed UKGDS was used for the study. In the process of simulating the system for SCOPF, it was observed that the solution proved infeasible because of open circuited lines within the network thereby isolating power supply to some buses/feeders in a contingency scenario. The affected lines where lines connected between buses 6-7 and 10-12. Buses 7 and 12 were connected to the closest generator buses in order to establish a mesh network in the distribution system. The table 1 below shows the connections for the buses, their respective solution status when a line contingency is introduced to the system, informed the decision of the selected bus connections.

Table 1: Bus Connection for a mesh network

Solution Number	Bus combination	Bus combination	Line Contingency
1	5-7	11-12	Infeasible solution
2	5-7	12-16	Optimal solution
3	7-11	12-16	Feasible solution
4	7-11	11-12	Infeasible solution

The Table 1 above shows the bus connection for buses 7and12 and the solution when a line contingency was introduced to the network.

All the possible connections exhibited infeasible solution but when line contingency was introduced to the network, only solution number 2 having connections 5-7 and 12-16 showed optimality in solution and therefore was adopted for the mesh network connection. In order to operate the network considering N-1 security, the network was converted to a meshed type by adding branches L19 and L20 as seen in the dotted line in Fig. 2. The choice of the buses for addition of the new branches where made having considered the branch with least operating cost. There is an assumption that distance between the buses are the same.

VII. SIMULATION RESULTS

The result is presented in three parts as follows:

A. *Operation of radial and mesh distribution network for N-1 security*

The results obtained by introducing an N-1 line contingency in the radial and meshed network are presented in the table 2:

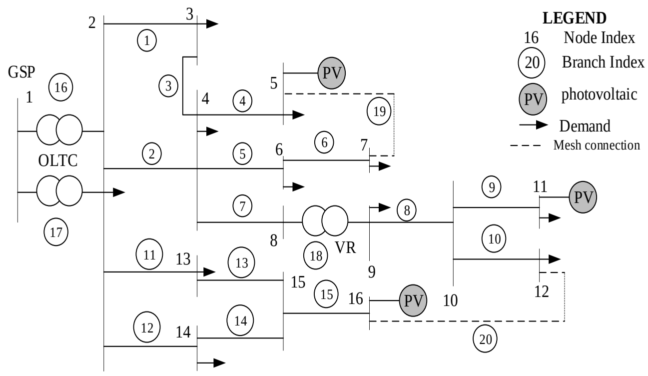

Figure 4. 16-bus UKGDS meshed with candidate locations for PVs

From table 2, line contingency in radial network on lines L5, L6 and L10 connected between bus 4 and bus 6, bus 6 and bus7 and bus 10 and bus 12, respectively, resulted in an infeasible solution and simulation error. This shows that some of the constraints for optimal operation of the network at N-1 distribution line contingency have been violated. In order to mitigate against these constraint violations, the network was converted to a mesh type by introducing lines L19 and L20 which have been explained earlier. The N-1 distribution line contingency inserted in the mesh network, all proved feasible, showing that when there is N-1 distribution line contingency in any of the lines, there will not be any violation on the network.

TABLE 2: Line Contingency in radial and mesh network

Contingency	Bus Connection	Radial	Mesh
L1	2-3	Feasible	Feasible
L2	2-4	√	√
L3	3-4	√	√
L4	4-5	√	√
L5	4-6	Infeasible	√
L6	6-7	No solution	√

L7	4-8	Feasible	√
L8	9-10	√	√
L9	10-11	√	√
L10	10-12	No solution	√
L11	2-13	Feasible	√
L12	2-14	√	√
L13	13-15	√	√
L14	15-14	Feasible	√
L15	15-16	Feasible	√
L16	1-2	√	√
L17	1-2	√	√
L18	8-9	√	√
L19	7-5	-	√
L20	12-16	-	√

B. *Operation of distribution network in N-1 security constraint with multi-DG configurations.*
Table 2 below presents all the possible multi-PV configurations for the three PVs locations using (1).

Table 3: Description of Multi-PV configuration

Multi-configurations	PV status/location		
	Bus 5	Bus 11	Bus 16
C1	1	0	0
C2	0	1	0
C3	0	0	1
C4	1	1	0
C5	1	0	1
C6	0	1	1
C7	1	1	1

Table 4: Total Dispatched power from PV with and without Demand Response

Configuration	Total Power dispatched from PV (MW)	
	Without DR	With DR
C1	0.286	0.316
C2	0.029	0.026
C3	0.089	0.150
C4	0.283	0.342
C5	0.286	0.356
C6	0.179	0.179
C7	0.283	0.347

Table 5: Total operational cost with and without Demand Response

Configuration	Total Cost (£/h)	
	Without DR	With DR
C1	515.005	458.937
C2	760.487	724.118
C3	715.947	635.356
C4	511.227	426.170
C5	514.097	424.001
C6	639.907	604.352
C7	510.916	421.415

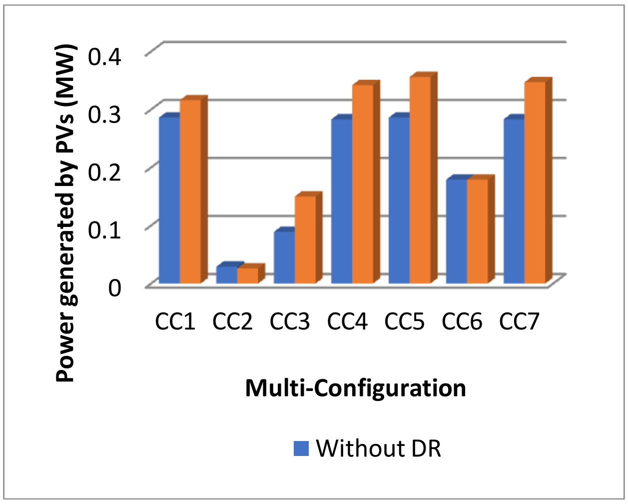

Fig 5: Total Dispatched power by PVs at multi-PV configurations

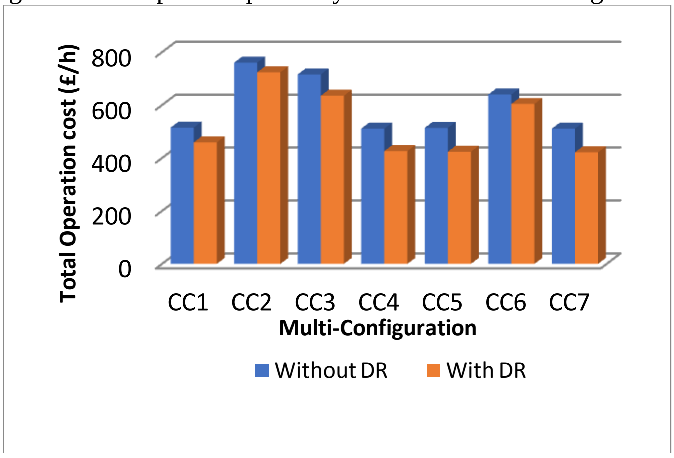

Fig 6: Total operation cost at multi-PV configuration

From the results presented in tables 4 and 5 above, when a single PV is operating in configurations C1, C2, C3, it shows that C1 with PV generator at bus 5 dispatched the highest amount of power the network compared to C2 with the least dispatched power . This shows that whenever there is outage of generator at bus 5 in configuration C1 in the network, there will be increased operational cost in the network. Since PV generators at buses 11 and 16 cannot satisfy the load demand of the network, thus an opportunity to purchase the needed power from the sub-station generator which is more expensive than the renewable generators. Also, at configurations C4, C5 and C6 having two PV generator combinations operating at the same time, C4 (PV generator connected at bus 5 and 11) and C5 (PV generator connected at bus 5 and 16) have higher dispatched power than C6 (PV generator connected at bus 11 and 16). The low level of dispatched power in configuration C6 can be attributed to the thermal limits and security constraints applied in the network. Meanwhile in configuration C7 (three PV generators operating), the total operational cost is the least as compared to other configurations. Configurations C2, C3 and C6 have high operational cost and this is due to the absence of generator at bus 5 in those configurations. DNOs should ensure that the PV generator connected to bus 5 is always operational to avoid increased cost of operation in the network. The results in tables 3 and 4 also show that the cost of operating the network with demand response program is cheaper at all configurations as compared to a situation without demand response. This is due to reduction in load demand by customers at peak load time.

C. *Comparison of Single Objective Function and Multi-Objective Function*

The results of single- and multi-objective optimization problems are obtained and presented below. For the single objective function, the active power loss function was minimized while the total operation cost function was set as a constraint. The procedure for the analysis is presented in the table shown below:

Table 6: Scenarios for single and multi-objective function.

Scenarios	Single-Objective	Multi-Objective
A	√	x

B	x	√

The results obtained from the scenarios are presented in the tables below:

Table 7: Active power losses at different scenarios and multi-configuration

Configuration	Objective Function for active power loss (MW)	
	Scenario A	Scenario B
C1	0.016	0.009
C2	0.031	0.018
C3	0.050	0.042
C4	0.016	0.004
C5	0.066	0.008
C6	0.078	0.034
C7	0.067	0.003

Table 8: Total Operational cost at different scenarios and multi-configuration

Configuration	Objective Function for total operation cost (£/h)	
	Scenario A	Scenario B
C1	468.488	458.937
C2	787.116	724.118
C3	665.238	635.356
C4	468.553	426.170
C5	455.905	424.001
C6	671.146	604.352
C7	456.416	421.415

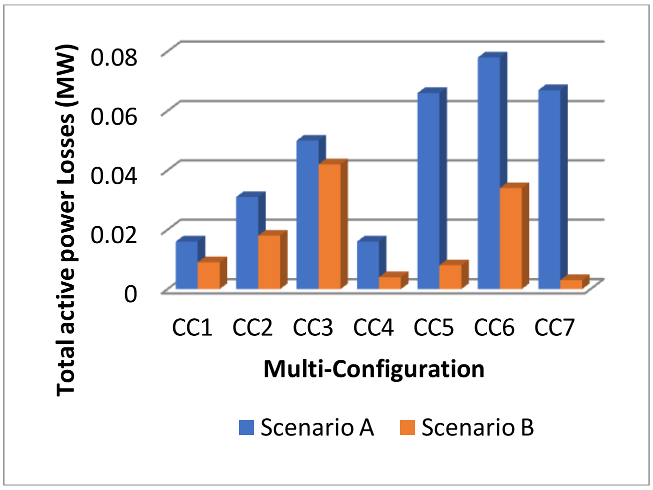

Fig 7: Total active power loss at different scenarios and multi-PV configuration

The results of the analysis are presented in figures 7 and 8 for the two scenarios when the system was operated as single and multi-objective function. The results show that favourable objective functions were obtained in scenario B with multi-objective function solution.

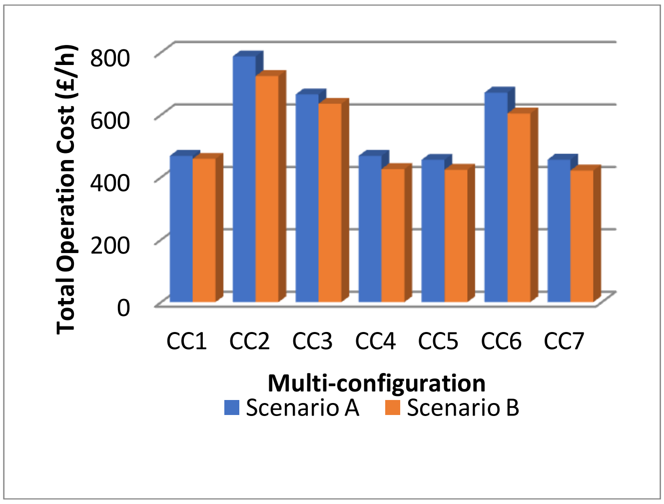

Fig 8: Total operation cost at different scenarios and multi-PV configuration

This shows that when two or more objective functions are to be optimized in a network, the best approach to adopt is to treat the objective functions as a multi-objective functions instead of analysing it individually as a single objective function. This will give better and favourable results towards obtaining the pareto optimal fronts.

VIII. CONCLUSION

This paper considers the security-constrained operation of a distribution network with multi-objective function, multi-DG configuration and demand response integration. The results have shown the benefit of adopting multi-objective function approach of analysis when dealing with more than one objective function in the network. Also, the security constraints ensure that the steady-state operation of the network is maintained when there is sudden loss of a single distribution line. The results from multi-DG configuration gives the system operators the required information on the best location and sizing of DGs for optimal operation of the network. The presence of demand response program reduced the operational cost of the network as consumers are encouraged to shift their load demand from peak to off-peak periods. The proposed method will equip the distribution network operators and planners with the necessary information towards managing the technical and economic problems that arise in distribution network.

REFERENCES

[1]. K. Moslehi and R. Kumar, "A reliability perspective of the smart grid," IEEE transactions on smart grid, vol. 1, no. 1, pp. 57-64, 2010.
[2]. A. Keane et al., “Evaluation of advanced operation and control of distributed wind farms to support efficiency and reliability,” IEEE Trans.Sustain. Energy, vol. 3, no. 4, pp. 735–742, Oct. 2012.
[3]. G. Mokryani, Y. F. Hu, P. Pillai, and H.-S. Rajamani, "Active distribution networks planning with high penetration of wind power," Renewable Energy, vol. 104, pp. 40-49, 2017.
[4]. Z. Liu, F. Wen, and G. Ledwich, “Optimal siting and sizing of distributed generators in distribution systems considering uncertainties,” IEEE Trans. Power Del., vol. 26, no. 4, pp. 2541–2551, Oct. 2011.
[5]. H. Yu, C. Y. Chung, K. P. Wong, and J. H. Zhang, “A chance constrained transmission network expansion planning method with consideration of load and wind farm uncertainties,” IEEE Trans. PowerSyst., vol. 24, no. 3, pp. 1568–1576, Aug. 2009.
[6]. K. Zou, A. P. Agalgaonkar, K. M. Muttaqi, and S. Perera, “Distribution system planning with incorporating DG reactive capability and system uncertainties,” IEEE Trans. Sustain. Energy, vol. 3, no. 1, pp. 112–123,Jan. 2012.
[7]. A. Soroudi and M. Afrasiab, “Binary PSO-based dynamic multi-objective model for distributed generation planning under uncertainty,” IETRenew. Power Gener., vol. 6, no. 2, pp. 67–78, Mar. 2012.
[8]. E. Ela and M. O’Malley, “Studying the variability and uncertainty impacts of variable generation at multiple timescales,” IEEE Trans.Power Syst., vol. 27, no. 3, pp. 1324–1333, Aug. 2012.
[9]. V. Hamidi, F. Li, and L. Yao, “Value of wind power at different locations in the grid,” IEEE Power Del., vol. 26, no. 2, pp. 526–537, Apr. 2011.
[10]. A. J. Wood and B. F. Wollenberg, Power Generation, Operation, and Control. Wiley, 2012.
[11]. Y. Xu, J. Hu, W. Gu, W. Su, and W. Liu, “Real-Time Distributed Control of Battery Energy Storage Systems for Security Constrained DC-OPF,” IEEE Trans. Smart Grid, hlm. 1–1, 2016.
[12]. S. Al Kaabi, H. Zeineldin and V. Khadkikar, “Planning Active Distribution Networks Considering Multi-DG Configurations,” IEEE Trans.Power Syst., vol. 29, no. 2, pp. 785–793, Mar. 2014.
[13]. P.-C. Chen et al., “Analysis of voltage profile problems due to the penetration of distributed generation in low-voltage secondary distribution networks,” IEEE Trans. PowerDel., vol. 27, no. 4, pp. 2020–2028,Oct. 2012.

[14]. C. Dent, L. F. Ochoa, and G. P. Harrison, "Network distributed generation capacity analysis using OPF with voltage step constraints," IEEETrans. Power Syst., vol. 25, no. 1, pp. 296–304, Feb. 2010.
[15]. H. M. Ayres, W. Freitas, M. C. De Almeida, and L. C. P. Da Silva, "Method for determining the maximum allowable penetration level of distributed generation without steady-state voltage violations," IETGener. Transm. Distrib., vol. 4, no. 4, pp. 495–508, 2010.
[16]. A. Keane and M. O'Malley, "Optimal allocation of embedded generation on distribution networks," IEEE Trans. Power Syst., vol. 20, no. 3, pp. 1640–1646, Aug. 2005.
[17]. A. A. Tamimi, A. Pahwa, and S. Starrett, "Effective wind farm sizing method for weak power systems using critical modes of voltage instability," IEEE Trans. Power Syst., vol. 27, no. 3, pp. 1610–1617, Aug. 2012.
[18]. H. Falaghi, M.R. Haghifam, ACO based algorithm for distributed generation sources allocation and sizing in distribution systems, in: Proc. IEEE Power Tech, 2007, pp. 555-560.
[19]. Y.M. Atwa, E.F. El-Saadany, Probabilistic approach for optimal allocation of wind-based distributed generation in distribution systems, IET Renew. Power Generation. 5 (1) (2011) 79-88.
[20]. L. F. Ochoa, C. J. Dent, and G. P. Harrison, "Distribution network capacity assessment: Variable DG and active networks," IEEE Trans.Power Syst., vol. 25, no. 1, pp. 87–95, Feb. 2010.
[21]. [21] P. Siano, P. Chen, Z. Chen, and A. Piccolo, "Evaluating maximum wind energy exploitation in active distribution networks," IET Generation.Transmission. Distribution, vol. 4, no. 5, pp. 598–608, 2010.
[22]. L. F. Ochoa and G. P. Harrison, "Minimizing energy losses: Optimal accommodation and smart operation of renewable distributed generation," IEEE Trans. Power Syst., vol. 26, no. 1, pp. 198–205, Feb. 2011.
[23]. D. Devaraj, J. Preetha Roselyn, "Improved genetic algorithm for voltage security constrained optimal power flow problem", International Journal of Energy Technology and Policy, Vol. 5, No. 4, pp.475-488, 2007
[24]. J. Anjo, D. Neves, C. Silva, A. Shivakumar and M. Howells, ''Modelling the long-term impact of demand response in energy planning: The Portuguese electric system case study'' Energy 165 (2018) 456-468.
[25]. R. Singh, J. Singh and R. Singh, ''Power system security using contingency analysis for distributed network'', International journal of Engineering Research & Technology 2 (2013) 1256-1261
[26]. A. Attarha, N. Amjady, ''Solution of security constrained optimal power flow for large-scale power systems by convex transformation techniques and Taylor series'' IET Generation, Transmission and Distribution 10 (2016) 889-896.
[27]. Montoya-Bueno, S., Muñoz-Hernández, J., Contreras, J.: 'Uncertainty management of renewable distributed generation', J. Clean Prod., 2016, 138, pp. 103–118
[28]. Widén, J.: 'Correlations between large-scale solar and wind power in a future scenario for Sweden', IEEE Trans. Sustain. Energy, 2011, 2, pp. 177–184.
[29]. Reddy, S.S., Bijwe, P., Abhyankar, A.R.: 'Joint energy and spinning reserve market clearing incorporating wind power and load forecast uncertainties', IEEE Syst. J., 2015, 9, pp. 152–164
[30]. Reddy, S.S., Bijwe, P., Abhyankar, A.R.: 'Optimal posturing in day-ahead market clearing for uncertainties considering anticipated real-time adjustment costs', IEEE Syst. J., 2015, 9, pp. 177–190.
[31]. Distributed Generation and Sustainable Electrical Energy Centre, United Kingdom Generic Distribution System (UK GDS). [Online]. Available: http://www.sedg.ac.uk/.
[32]. Brooke, A., Kendrick, D., Meeraus, A., Raman, R., 1998. GAMS, A User's Guide. GAMS Development Corporation, Washington DC
[33]. S. Jadid, P. Rabbanifar, "Stochastic multi-objective frequency control in joint energy and reserve markets considering power system security," IET Generation.Transmission. Distribution, vol. 7, no. 1, pp. 76–89, 2013.
[34]. A. Azizivahed, E. Naderi, and H. Narimani, M. Fathi, M.R. Narimani, "A new bi-objective approach to energy management in distribution networks with energy storage systems," IEEE Trans. Sustainable Energy, vol. 9, no. 1, pp. 56–64, Jan. 2018.

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