Distribution Network Reconfiguration Considering Security-Constraint and Multi-DG Configurations

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***Abstract*- This paper proposes a novel method for distribution network reconfiguration considering security-constraints and multi-configuration of renewable distributed generators (DG). The objective of the proposed method is to minimize the total operational cost using security constrained optimal power flow (SCOPF). The impact of multi-configuration of renewable DGs in a meshed network is investigated. In this work, lines were added to the radial distribution network to analyse the network power flow in different network configurations. The added lines were connected to the closest generator bus which offered least operating cost. A 16-bus UK generic distribution system (UKGDS) was used to model the efficiency of the proposed method. The obtained results in multi-DG configuration ensure the security of the network in N-1 contingency criteria.**

Index Terms- Distribution network, Power flow, multi-DG configuration, Security Constraint Optimal Power Flow

Nomenclature

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
C_{Gen}^{i}	Price offered by PVs and sub-station generators to increase/decrease active power at bus i
$P_{gi}^{min}, P_{gi}^{max}$	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 reactive 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*
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_{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

UK government have marked 2050 as the deadline for Green House Gas (GHG) emissions as part of their energy target program. The optimal solution towards achieving this goal is to adopt low-carbon or renewable distributed generators (DGs) such as wind power and photo voltaic (PV) modules generators [1, 2].

In order to reduce the active power loss, improve the voltage profile and system reliability of the distribution network, renewable DGs will be of great benefit due to its flexibility and zero emission. Renewable DGs also have its drawbacks which include voltage fluctuation, three-phase imbalance and voltage rising at the connecting point. Some negative impacts of DGs can be attributed to the intermittent and unpredictable nature and to the typical network structure of the distribution system [3-5].

Deferment of investment and network reinforcement in distribution networks can be realised through proper planning with integration of renewable DGs. With regards to network topology, distribution networks are mostly operated in radial mode, which makes the power to flow in one direction and the main protection devices which are fuses or current relays, present a limiting constraint to DG penetration.

To achieve high penetration levels of DGs, there is need for system reinforcements to be able to accept and tolerate that penetration level, since the network which is designed and operated in radial form will pose limitations for this type of operation. Therefore, there is a need to accommodate growing penetration levels of DGs, including photovoltaic cells and wind energy generators.

The way distribution networks are operated in recent time has changed drastically due to the innovations in protection systems and distribution automation. Adoption of meshed network topologies can be used as an alternative for maximizing grid's ability to integrate larger amounts of renewable DGs. Operation of the distribution network in a meshed form increases the intricacy of planning and operating the network, and requires close monitoring of the protection system, which will impose extra operating costs to the system operators. Notwithstanding, meshed network

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system introduces several advantages to the system, which include increase in reliability, reduced system losses and voltage profile improvement. Overloading of transformers and lines will also be reduced by adopting meshed network operation. With proper planning, the negative impacts of meshed network operation can be reduced and the positive effects could be utilized [6].

Recently, with high penetration level of renewable DGs such as solar energy and wind, the security of the power system has become more important [7]. Conventionally, the deterministic N-1 security measures has been used to assess power system security [8]. In order to operate the network in an N-1 secure dispatch, additional constraints are added to the OPF to cater for the effect of component failures, leading to a security constrained optimal power flow (SCOPF). It refers to satisfying the security constraints when subjected to only one sudden component failure in the system [8].

B. *Literature Review and Research gap*

Various authors have carried out studies on the planning and operation of electric distribution network with integration of renewable energy and DGs. Due to the increasing rate of DG integration in the distribution system, distribution network operators (DNOs) are at the centre of the planning strategies towards maximizing renewable energy penetration in the distribution network [9-11]. In [12], the unplanned installation of DG considering size, type and location have led to voltage rise in the secondary side of distribution network. The method proposed in [13], integrates voltage fluctuation constraint to take care of the effects related to unforeseen connection or disconnection of a DG. The outcome depicts appreciable decrease in the capacity of DG when voltage fluctuation constraint is applied, and increased DG capacity could be achieved when a voltage fluctuation constraint is widened.

The correlation observed in violation of steady-state voltage and making the best use of DG capacity was analysed using a voltage sensitivity factor in[14]. An effective method is proposed in [15] which allocate DGs based on investigating different constraints in relation to each bus to mitigate against network sterilization. Network sterilization is a situation where there is individual allocation of DG units instead of group allocation at some points that may lead to the network not operating at its full potential, thereby reducing the capacity of the connected DG. Identification of robust and weak buses was proposed in [15], and the outcome was used in allocating DGs at buses with high tolerance in voltage stability. Placement of wind turbines in the most appropriate locations in distribution networks which is targeted at minimizing yearly energy losses was presented by author in [16]. The authors in [17] proposed a model that investigates the DG allocation in distribution systems which is aimed at minimizing the total operation cost and investment in DGs. The effect of shape of DG generation history and inconsistency in demand with multi-period optimal power flow (MOPF) technique was reported in [17-19]. These studies were carried out with single DG-configuration (all DGs operating). In [20-23], the authors have not addressed the impact of multi-DG configuration on the planning and operation of a distribution system. In [13] the analysis was made using OPF with voltage step constraints and not considering security constraints. The above studies show that the past works published on this only considered the optimal power flow in the radial network without considering security constraint and the effect multi-DG configuration will have on the network. In reference [9] , the author worked on the impact of multi-DG interaction on the amount of DG penetration into the network without considering the security constraints. Also, the author in [12] made his analysis based on the impact of voltage profile on different location of DGs without taking note of security of the network. According to the author's knowledge, there is no study that considers the DGs in mesh network with taking into account both security-constraints and multi-configuration of renewable distributed generators (DG) which is necessary to maintain the optimal operation of the network when there is sudden loss of any distribution line in the network.

C. Aim and Contributions

In this paper, a new method for distribution network reconfiguration including security-constraints and multi-configuration of renewable distributed generators (DGs) has been proposed in order to minimize the operational cost. Also, the impact of multi-configuration of renewable DGs in a meshed network has been investigated.

The main contributions of this paper are highlighted as follows:

- To analyze the impact of multi-DG allocations in the operation of distribution network with optimal security constrained OPF.
- To 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.
- To propose a new SCOPF-based planning technique that considers the operational status of DG units.
- To model the uncertainties associated with solar irradiation and load demand using Scenario Tree approach.

D. *Paper organization*

The rest of the paper is organised as follows: multi-PV configurations is presented in section II. Problem formulation and structure of SCOPF formulation is presented in section III, illustration of a case study in section IV, simulation results are presented in section V and finally section VI 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 define the operational state of PVs and distribution network planners determine which PV should be in operation at any given time. The total number of all possible multi-configurations for any number of PVs can be expressed as follows [24]:

$$1 \le NC \le \left(2^{NPV} - 1\right) \tag{1}$$

(NC) in equation (1) represents the number of multi-PV configurations. To illustrate this, if a system has five PVs, there will be up to 31 possible multi-PV configurations from which distribution network planners can make a decision. Operational status of PVs at i^{th} bus are represented by a binary parameter which ensures that each PV can either be ON or OFF at any point in time for configuration c. Equations (2) and (3) respectively, represents the operational status of each PV and all PVs.

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

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

In this method, a constraint is introduced to limit the power generated by each PV with regards to its operational status for each configuration and it is given by the equation below:

$$P_{i,c}^{pv} = \begin{cases} 0 \le P_{i,c}^{pv} \le P_{i,c}^{pv,max}, & \forall \beta_{i,c} = 1 \\ 0, & \forall \beta_{i,c} = 0 \end{cases} \tag{4}$$

III. PROBLEM FORMULATION

A. Objective function

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

In this work, constraints are put in place to ensure the security of the network in a contingency scenario. Taking these into considerations, the objective of the proposed operation problem is to minimize the total operational cost while considering the security of the network when there is a sudden loss of a component.

The objective function is optimized at different multi-DG configurations.

$$\text{Minimize } F_{obj} = \sum_{i=1}^{NB} \sum_{Gen=1}^{NGen} \sum_{c=1}^{Nc} C_{Gen}^{i} P_{G_{Gen}}^{i} + \sum_{i=1}^{NB} \sum_{Gen=1}^{NGen} \sum_{c=1}^{Nc} C_{Gen}^{i} P_{DG_{Gen}}^{i} \tag{5}$$

B. Constraints

$$\sum_{Gen=1}^{Gen} P_{g(Gen)} + \sum_{Gen=1}^{Gen} P_{dg(Gen)} - \sum_{l=1}^{l} \left(P_l^i \right) = \sum_{lin=1}^{lin} \sum_{l=1}^{i} P_{ij(line,j)} \tag{6}$$

$$\sum_{Gen=1}^{Gen} Q_{g(Gen)} + \sum_{Gen=1}^{Gen} Q_{dg(Gen)} - \sum_{l=1}^{l} \left(Q_l^i \right) = \sum_{lin=1}^{lin} \sum_{l=1}^{i} Q_{ij(line,j)} \tag{7}$$

$$\sum_{Gen=1}^{Gen} P_{g(Gen)} + \sum_{Gen=1}^{Gen} P_{dg(Gen)} - \sum_{l=1}^{l} \left(P_l^i \right) = \sum_{lin=1}^{lin} \sum_{j=1}^{i} P_{ijc(line,j)}^{*} \tag{8}$$

$$\sum_{Gen=1}^{Gen} Q_{g(Gen)} + \sum_{Gen=1}^{Gen} Q_{dg(Gen)} - \sum_{l=1}^{l} \left(Q_l^i \right) = \sum_{lin=1}^{lin} \sum_{j=1}^{i} Q_{ijc(line,j)}^{*} \tag{9}$$

$$P_{i,j} = \frac{V_i^2 \left(cos\,\theta_{i,j} \right) - V_i V_j \, cos\left(\delta_i - \delta_j + \theta_{i,j} \right)}{Z_{ij}} \tag{10}$$

$$Q_{i,j} = \frac{Q_i^2 \left(sin\,\theta_{i,j} \right) - V_i V_j \, sin\left(\delta_i - \delta_j + \theta_{i,j} \right)}{Z_{ij}} \tag{11}$$

$$P_{ijc}^{*} = \frac{V_i^2 \left(cos\,\theta_{i,j} \right) - V_i V_j \, cos\left(\delta_i^{*} - \delta_j^{*} + \theta_{i,j} \right)}{Z_{ij}} \tag{12}$$

$$Q_{ijc}^{*} = \frac{V_i^2 \left(sin\,\theta_{i,j} \right) - V_i V_j \, sin\left(\delta_i^{*} - \delta_j^{*} + \theta_{i,j} \right)}{Z_{ij}} \tag{13}$$

$$\theta_{ij} = \tan^{-1} \frac{X}{R} \tag{14}$$

$$Z_{ij} = \sqrt{X^2 + R^2} \tag{15}$$

$$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max} \tag{16}$$

$$P_{gi}^{min} \le P_{gi} + \Delta P_{gi}^{*} \le P_{gi}^{max} \tag{17}$$

$$Q_{gi}^{min} \le Q_{gi} \le Q_{gi}^{max} \tag{18}$$

$$Q_{gi}^{min} \le Q_{gi} + \Delta Q_{gi}^{*} \le Q_{gi}^{max} \tag{19}$$

$$P_{dgi}^{min} \le P_{dgi} \le P_{dgi}^{max} \tag{20}$$

$$P_{dgi}^{min} \le P_{dgi} + \Delta P_{dgi}^{*} \le P_{dgi}^{max} \tag{21}$$

$$Q_{dgi}^{min} \le Q_{dgi} \le Q_{dgi}^{max} \tag{22}$$

$$Q_{dgi}^{min} \le Q_{dgi} + \Delta Q_{dgi}^{*} \le Q_{dgi}^{max} \tag{23}$$

$$P_{ij} \le P_{ij}^{max} \tag{24}$$

$$P_{ijc}^{*} \le P_{ij}^{max} \tag{25}$$

$$Q_{ij} \le Q_{ij}^{max} \tag{26}$$

$$Q_{ijc}^{*} \le Q_{ij}^{max} \tag{27}$$

$$V_i^{min} \le V_i \le V_i^{max} \tag{28}$$

$$\delta_i^{min} \le \delta_i \le \delta_i^{max} \tag{29}$$

$$\delta_i^{*min} \le \delta_i^{*} \le \delta_i^{*max} \tag{30}$$

The constraints outlined above are classified into two groups:

a) Equality constraints**:** Constraints (6)-(9) maintains the active and reactive power balances in system nodes at pre-contingency and post-contingency states. Constraints (10)-(13) use Kirchhoff's law in the analysis. Equations (6)-(13) outline the solution of active and reactive power flow in the line at pre-contingency and post-contingency states.

b) Inequality constraints**:** constraints (16)-(19) are used to set the upper limit for active and reactive power of substation at pre-contingency and post-contingency scenario. Also, constraints (20)-(23) limit the active and reactive power generation of PVs. The PVs generation depends on the solar irradiance. The active and reactive power flow limits in the line are constrained by equations (24)-(27). This maintains the security of the system. Constraints (28)-(30) determine the acceptable range of voltage and angle at the buses.

C. SCOPF formulation

The flowchart for SCOPF formulation begins with the analysis of system OPF having N number of constraints so as to reach an operating point. This is followed by inserting contingency analysis in the network in order to identify the possible contingency cases. The solution of the SCOPF is obtained by the OPF if at the end of the analysis there is no record of constraint violation. But if an outage causes a security violation or overload of line, the entire security constraints will be added, and the optimal power flow (OPF) and each of the contingency power flows is run again 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 situation. 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.

IV. 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 [25]. The single line diagram is shown in Fig. 1. The feeders are supplied by two identical 30-MVA 132/33 kV transformers.

In order to assess the impact of network reconfiguration and multi-DG configurations on the SCOPF of the network, three 15MW PVs are installed at buses 5, 11 and 16.

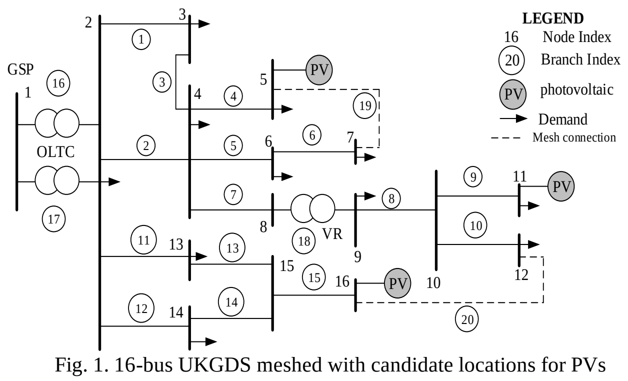

Fig. 1. 16-bus UKGDS meshed with candidate locations for PVs

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 has 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 [26] on a PC with Core i7 CPU and 16GB of RAM.

V. SIMULATION RESULTS

The result is presented in two 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 Table 1. From Table 1 it is seen that line contingency in radial network on line L6 and L10 connected between bus 6-7 and bus 10-12 respectively resulted in the simulation not running, showing a severe constraint violation which might result in a possible blackout in the entire network. Also, contingency in radial network on line L5 connected between buses 4-6 resulted in an infeasible solution showing that some of the constraints for optimal operation of the network have not been met. The value of objective function of contingency on line L5 was high as well. 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 1: LINE CONTINGENCY IN RADIAL AND MESH NETWORK

Contingency	**Bus Connection**	**Radial Solution**	**Mesh Solution**
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 presents all the possible multi-PV configurations for the three PVs locations using (1).

TABLE 2: 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 3: TOTAL DISPATCHED POWER FROM PV WITH AND WITHOUT DEMAND RESPONSE

Configuration	**Total Power dispatched from PV (MW)**
C1	0.207
C2	0.029
C3	0.052
C4	0.204
C5	0.206
C6	0.065
C7	0.205

TABLE 4: TOTAL OPERATIONAL COST WITH AND WITHOUT DEMAND RESPONSE

Configuration	**Total Operation Cost (£/h)**
C1	587.598
C2	760.487
C3	747.257
C4	584.116
C5	587.261
C6	726.914
C7	584.075

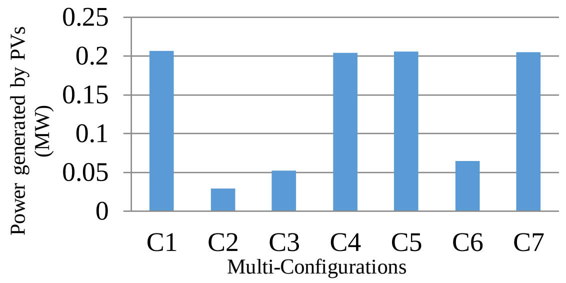

Fig 2: Total Dispatched power by PVs at multi-PV configurations

From the results presented in Tables 2, 3 and 4, it is evident that when a single PV is operating in configurations C1, C2, C3, it shows that C1 with PV generator at bus 5 produced the highest level of renewable energy penetration in the network compared to C2 with the least penetration of renewable energy. 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.

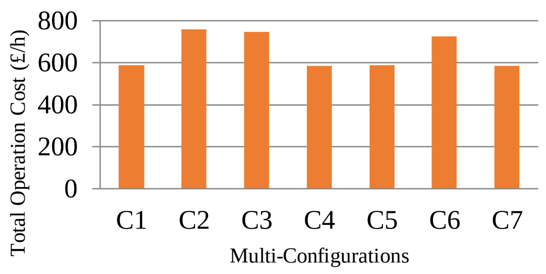

Fig 3: Total operation cost at multi-PV configuration

Since PV generators at buses 11 and 16 in configuration C1 cannot satisfy the load demand of the network when there is outage of generator at bus 5, therefore the shortfall in power will be purchased from the sub-station generator which is more expensive than the renewable DGs. Also, 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 level of penetration of renewable energy 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 at 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 as a result of 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 operational cost.

VI. CONCLUSION

This paper proposes a novel method for distribution network reconfiguration including both security-constraints and multi-configuration of renewable distributed generators (DGs) has been proposed in order to minimize the operational cost. Also, it used to investigate the impact of multi-configuration of renewable DGs in a meshed network.

The obtained results show that the availability of DGs at certain locations could critically impact the amount of DG capacity at other locations. This will give the system operators the required information on the best location and sizing of DGs for optimal planning of the network. 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.

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