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Security-Constrained Optimal Power Flow in an Electric Distribution Network

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ABSTRACT

This paper evaluates the benefits of operating an electric distribution network in a security-constrained optimal power flow (SCOPF) in order to mitigate against possible blackout in an N-1 contingency. A 16-bus UKGDS network was used for the analysis. An SCOPF was performed on the network by introducing N-1 line contingency to the network and this resulted to constraints violations. The infeasibility in the solution occurred due to the radial nature of the network. The operation of SCOPF is realised in a mesh network system, which was done by connecting branches between bus 5-7 and bus 12-16 to the network. The system was simulated to operate in SCOPF and N-1 line contingency was inserted to the network to test for constraint violation/ feasibility of the system. This resulted in feasible solution in all the line contingencies with no constraint violation.

I. Introduction

The operation of electric power systems depends critically on the ability to maintain economic efficiency in the presence of unexpected events. An electrical power system shall be not only secure and reliable, but also economically optimal and efficient, meaning that electricity shall be provided minimizing generation costs and distribution line losses, and in general, meeting several economic, operational, or environmental objectives and constraints. The classical optimal power flow formulation is done without considering the security constraints [1]. This representation can be expanded to “anticipate the future” and include hypothetical contingency scenarios. The scenarios reflect changes that can occur and endanger the operation of the system. The solution of this augmented formulation results in an operating state in which the target function is optimized and the system is kept within the admitted limits, not only for the current conditions but also for different possible abnormal conditions resulting from the anticipated scenarios.

The electric power being transferred to consumers depends on not only availability of electricity, but also takes into account a reliable, secure, quality and uninterrupted supply. The Optimal Power Flow is termed as security constrained optimal power flow (SCOPF) when the system meets with contingencies such as, generator/line/load/static or synchronous compensator failure/apparatus failure[2],[3]. It is much important that the system must be capable to withstand any contingencies. In SCOPF, a periodic contingency analysis is required to predict potential problems that will occur [2]. SCOPF ensures that there is no cascading failure in the distribution network when there is a loss of one distribution line, because the line overloading will be taken care of by the optimal security operation.

Several methods have been adopted in the past for the solution of security constrained optimal power flow. Earlier methods were of linearized DC load flow model of only the outage system [4-6]. The more accurate methodology has been proposed with the incorporation of the steady state security constraints into OPF, which allowed considering the reactive power and voltage constraints in outage case [7]. However, one another method based on new blender’s decomposition has been proposed for economic dispatch with security constraints. The post-outage corrections and separate the base case with contingency analysis together with generation rescheduling [8]. Some other decomposed method involving security constraints have been exposed [9-11]. A dual relaxation based solution for SCOPF has been reported in [12, 13]. In [14], power dispatch under normal state considers contingency states to ensure that contingency state satisfies all constraints. However, considering contingency states will change the dispatch and result in more expensive operation cost. Some methods have been utilized to solve SCOPF. Particle Swarm Optimization (PSO) has been used to solve SCOPF in [15] while Bender decomposition has been applied in [16, 17].

In this paper, SCOPF is evaluated in an AC distribution system with penetration of distributed generation. The proposed method was solved using General Arithmetic Mathematical system (GAMS) adopting non-linear programming (NLP). The method was applied in a 16-bus UK generic distribution system (UKGDS) with solar energy integration.

II. Problem Formulation

A. Optimal Power Flow

Optimal power flow (OPF) plays an important role in the Energy Management System (EMS) where the entire operation of the power system is supervised at regular

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intervals of time. OPF couples the Economic Dispatch (ED) calculation with a power flow calculation. Here both ED and power flow are solved simultaneously to obtain a common objective such as minimization of operating cost by fulfilling a set of constraints. The constraints include Real power flows, Reactive power flows, Voltage magnitudes and angles.

The classical formulation of OPF is given as [18],

Optimize $f(x, u)$ (1)

Subject to:

$$g(x,u) = 0$$
$$h(x,u) \leq 0 \quad (2)$$
$$u_{min} \leq u \leq u_{max}$$

Where

$f(x, u)$: Objective function which is to be optimised

[u] : Control independent variables vector

[x] : State dependent variables vector

$g(x,u)$: Equality constraints (vector of power flow equations)

$h(x,u)$: Inequality constraint (vector of system operating limits

B. Security-constrained Optimal Power Flow

Enforcing branch limits while optimizing the generation will directly help to ensure that the power system is performing economically. However, the optimum operation conditions for a power system will often result in violation of system security. A secure power system is one where the power system continuous to operate even after some contingencies, such as generator and transmission line outages. Programs, which can make control adjustments to the base or pre-contingency operation to prevent violations in the post contingency conditions, are called Security Constrained Optimal Power Flow or SCOPF [15]. SCOPF is an optimal power flow taking into account outages of certain transmission lines or equipment. A SCOPF solution would be secure during all credible contingencies or can be made secure by corrective means depending on the level of security enforced in the optimization.

C. 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 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, its include pre contingency cost and the cost of each credible contingency. The cost function is constituted by two terms: first related with generating cost and second associated with contingency. The objective function defined as:

$$F(x) = min P_{gi} \sum_{i=1}^{NG} C_i(P_{gi}) \quad (3)$$

Where

C_i *Operation cost*

P_{gi} *Generator output*

NG No. of generator

Equality constraints at pre contingency

$$\sum_{i=1}^{NG}(P_{gi}) = \sum_{i=1}^{NL}(P_{di}) + P_l \quad (4)$$

$$\sum_{i=1}^{NG}(Q_{gi}) = \sum_{i=1}^{NL}(Q_{di}) + Q_l \quad (5)$$

Where

P_{di} *Active power demand at load bus*

Q_{di} *Reactive power demand at load bus*

P_l *Active power loss*

Q_l *Reactive power loss*

NL No. of load bus

Equality constraints at post contingency

$$\sum_{i=1}^{NG}(P^*_{gi}) = \sum_{i=1}^{NL}(P^*_{di}) + P^*_l \quad (6)$$

$$\sum_{i=1}^{NG}(Q^*_{gi}) = \sum_{i=1}^{NL}(Q^*_{di}) + Q^*_l \quad (7)$$

Where (*) denotes the post contingency control variables.

Inequality constraints at pre and post contingency

The active power generated by each unit must satisfy the maximum and minimum operating limits during pre and post contingency states

$$P^{min}_{gi} \leq P_{gi} \leq P^{max}_{gi} \quad (8)$$
$$P^{min}_{gi} \leq P_{gi} + \Delta P^*_{gi} \leq P^{max}_{gi} \quad (9)$$
$$Q^{min}_{gi} \leq Q_{gi} \leq Q^{max}_{gi} \quad (10)$$
$$Q^{min}_{gi} \leq Q_{gi} + \Delta Q^*_{gi} \leq Q^{max}_{gi} \quad (11)$$

Where

$P^{min}_{gi}, Q^{min}_{gi}$ *minimun active and reactive power limits of generators*

$P^{max}_{gi}, Q^{max}_{gi}$ *maximum active and reactive power limits of generators*

$\Delta P^*_{gi}, Q^*_{gi}$ *post contingency change in active and reative power generation*

The active power flow through each branch of the network must satisfy the security limits during both pre and post contingencies. The formulation is given below:

$$I_{ij} = \frac{V_i\angle\delta_i - V_j\angle\delta_j}{Z_{ij}\angle\theta_{ij}} \quad (12)$$

$$S_{ij} = (V_i\angle\delta_i)I_{ij} \quad (13)$$

$$P_{ij} = real\{S_{ij}\} = \frac{V_i^2}{Z_{ij}}\cos(\theta_{ij}) - \frac{V_iV_j}{Z_{ij}}\cos(\delta_i - \delta_j + \theta_{ij}) \quad (14)$$

$$Q_{ij} = Imaginary\{S_{ij}\} = \frac{V_i^2}{Z_{ij}}\sin(\theta_{ij}) - \frac{V_iV_j}{Z_{ij}}\sin(\delta_i - \delta_j + \theta_{ij}) \quad (15)$$

$$P_{ij} \leq P^{max}_{gi} \quad (16)$$
$$P^*_{ij} \leq P^{max}_{ij} \quad (17)$$
$$Q_{ij} \leq Q^{max}_{gi} \quad (18)$$
$$Q^*_{ij} \leq Q^{max}_{ij} \quad (19)$$

Where P_{ij} is the pre contingency active power flow in lines, P^*_{ij} is the

P_{ij} *pre contingency active power flow in lines*

P^*_{ij} *post contingency active power flow in lines*

P_{ij}^{max} *maximum limit of active powerflow in lines*

Q_{ij} *pre contingency reactive power flow in lines*

Q_{ij}^{*} *post contingency reactive power flow in lines*

Q_{ij}^{max} *maximum limit of reactive power flow in lines*

The voltage security at each bus is also considered for both cases

$$\boldsymbol{V_i^{min} \leq V_i \leq V_i^{max}} \quad (20)$$

$$\boldsymbol{V_i^{min} \leq V_i^{*} \leq V_i^{max}} \quad (21)$$

Where

V_i *pre contingency voltage at bus*

V_i^{*} *post contingency voltage at bus*

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 [19]. The disadvantages in fault level contribution are offset by increases in network stability [20] and reliability [21, 22]. 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. These connections were aimed at achieving a mesh for the secured operation of the network. Solution 1 and 4 from table 1 exhibited infeasible while solution 3 shows feasible solution. Solution number 2 having connections 5-7 and 12-16 showed optimality in solution and therefore was adopted for the mesh network connection. There is an assumption that distance between the buses are the same.

III. Simulation and Results

Here, the distribution system used to test the proposed method is described. The following analyses were made based on 33KV 16-bus rural weakly meshed UKGDS whose data are available in Generation and Electrical Energy Centre [23]. The single line diagram is shown in Fig. 1. Two identical 30-MVA 132 /33 kV transformers supply the feeders.

Three 15MW PVs are installed at buses 5, 11 and 16. Each of them is composed of 15× 1MW solar panels with $\boldsymbol{\eta^{pv} = 18.6\%}$ $\boldsymbol{and\ S^{pv} = 10m^2}$.

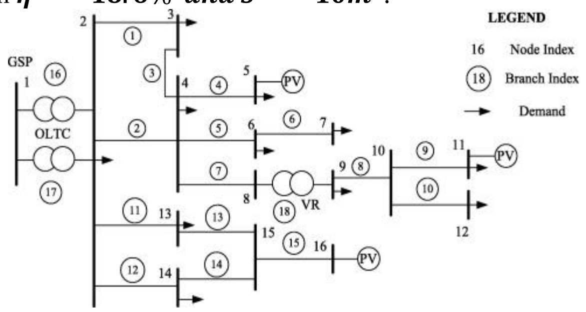

Figure 1. 16-bus UKGDS with candidate locations for PVs

The proposed method is applied to the above mentioned distribution network and implemented in GAMS and solved using IPOPT solver [24] on a PC with Core i7 CPU and 16GB of RAM.

The results obtained from simulation of the network when each line is taken off in the Optimal Power Flow (OPF) and Security-Constrained Optimal Power Flow (SCOPF) is presented in the table 2 below:

Table 2. Line Contingency in OPF and SCOPF

Contingency	OPF		SCOPF	
	Objective Function	Solution	Objective Function	Solution
L1.2.3	511.334	Feasible	510.430	Feasible
L2.2.4	511.305	√	510.392	√
L3.3.4	511.219	√	510.325	√
L4.4.5	512.219	√	510.399	√
L5.4.6	545.641	Infeasible	510.475	√
L6.6.7	0	No solution	510.355	√
L7.4.8	511.806	Feasible	510.546	√
L8.9.10	511.512	√	510.395	√
L9.10.11	512.031	√	510.553	√
L10.10.12	0	No solution	510.389	√
L11.2.13	511.275	Feasible	510.387	√
L12.2.14	511.238	√	510.345	√
L13.13.15	511.219	√	510.324	√
L14.15.14	511.220	Feasible	510.324	√
L15.15.16	511.220	Feasible	510.322	√
L16.1.2	511.221	√	510.325	√
L17.1.2	511.221	√	510.325	√
L18.8.9	511.806	√	510.546	√
L19.7.5	-	-	510.861	√
L20.12.16	-	-	510.679	√
Base Case	511.219		510.324	√

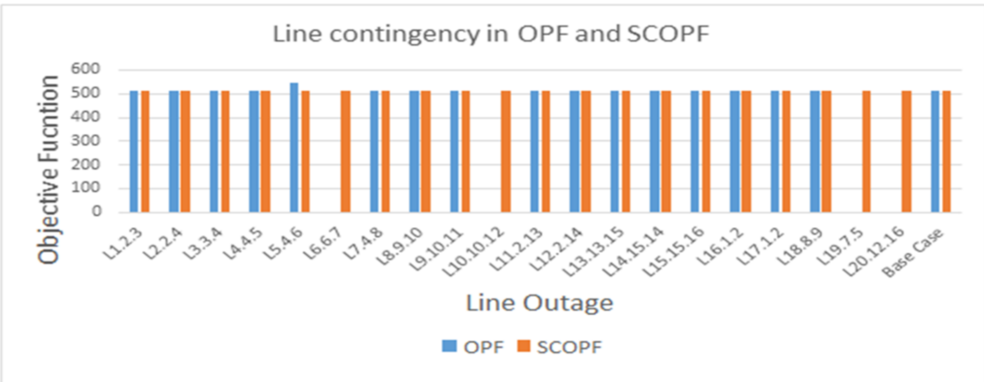

Fig 2. Line contingency in OPF and SCOPF.

From table 2 above, line contingency in OPF scenario 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 to a possible blackout in the entire network. In addition, contingency in OPF 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 line contingency inserted in the SCOPF scenario, all proved feasible, showing that when there is contingency in any of the lines, there will not be any violation on the network. In addition, the cost of operating the network at base case in SCOPF is cheaper than the cost in OPF because of two lines added for SCOPF operation, which allows for alternative route for the flow of power. However, a high value of objective function is recorded when line L5 connected between bus 4-6 goes off in an OPF scenario. Network operators should always bring back L5 into operation in shortest possible time whenever it goes off to reduce high cost of running the network.

IV. Discussion

The problem considers the operation of a network in a security-constrained environment. When contingency was introduced in the Optimal Power Flow (OPF), it was observed that there was infeasible/no solution in some cases. This is because the network was not able to accommodate the losses and line overload that resulted in the loss of a single distribution line. This is also a major cause of blackout in some cases due to cascading failures. Although the investment cost of the network is more economical if security constraints were not put in place, but the effect when a line contingency occurs, far outweighs the benefits. The network is made to be a mesh type for it to be operated in a security-constrained scenario. 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 line contingency was introduced in the SCOPF network and the network proved feasible/optimal for every single loss of a line in the network. The higher investment cost accrued by the addition of the two distribution lines is remedied by the security of the network when fault occurs on any of the line.

V. Conclusion

The SCOPF is an extension of the traditional OPF algorithm, which maintains the security requirements of the system. The paper proposes the operation of electric distribution network in a security-constrained scenario with penetration of distributed renewable generation. The method considered the operation of the distribution network in a contingency scenario when there is loss of a single line in the distribution network, and the technical effects it will have on the entire network. Though the method involves more investment cost in terms of adding the two lines to make it a mesh network, but the reliability of the network is maintained in the case of a sudden loss of a distribution line, thereby mitigating a possible cascading failure or blackout.

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