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Stability constrained optimal distribution system reconfiguration considering uncertainties in correlated loads and distributed generations

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ABSTRACT

This paper proposes a small signal stability constrained distribution system reconfiguration (DSR) methodology under uncertainties associated with the load demand and the power output of the renewable energy based distributed generation. Further, the correlation among the uncertain load demand and among the uncertain DG power output has also been considered. This DSR problem is formulated for minimising real power loss, number of switching operations as well as maximizing the voltage stability margin. This formulation takes into consideration the system's probabilistic operational constraints such as maximum limit on line current, minimum and maximum limits on bus voltage magnitude, radiality of distribution system and probabilistic small signal stability constraint. A KnEA-PE approach, consisting of a knee point driven method and 3 point estimation method, is then utilized to solve this DSR problem. The effectiveness and feasibility of presented formulation has been tested on IEEE 33-bus, 69 bus and 119-bus distribution systems. The obtained results are compared with those obtained by the multi-objective NSGA-II-based method.

1. Introduction

Worldwide increasing concerns on the environmental effects of fossil fuels have motivated the installations of sustainable renewable energy based generations in power system in order to get clean power. However, inherent intermittencies of power generation and continuous load demand variations give rise to significant level of uncertainties. In the face of these uncertainties, distribution system (DS) planning strategies such as DSR become more challenging. In DSR, topology of the DS is altered by opening and closing normally closed and normally opened switches in the system, so that a feasible and optimized radial topological structure is obtained. In the literature, the multi-objective DSR problem under uncertainties has been well studied.

In [1,2] the interval analysis technique is utilized to deal with the effects of uncertainties. The neighbourhood search algorithm is presented in [1] to determine the best configuration in terms of reliability improvement and power loss minimization. In [2], a meta-heuristic Artificial Immune System (AIS) is implemented for minimising the power loss considering uncertainties in the power generation of wind based distributed generation (DG). However, the number of switching (NSW) operations has not been considered in [1,2]. A new modified harmony search algorithm (HSA) for reconfiguring the system with DGs to minimise the real power loss,cost of generated electric energy, energy not supplied and average interruption frequency index is presented in [3] under a stochastic framework. The methodology of DSR presented in [4] focused on minimizing various objectives such as real power loss, voltage deviation of the buses, total cost of power and emission produced by the grid and DGs (Fuel cells) using the methodology based on teacher learning algorithm (TLA). In [5], a Self adaptive modified TLA with fuzzy set theory is presented for DSR to minimise the real power loss, bus voltage deviation, cost of generated electric energy, and emission produced by substation. The work on DSR reported in [6] made use of modified Bee Algorithm for reducing total active power losses, SAIFI (System Average Interruption Frequency Index) and cost of produced power taking into account the variability in real and reactive loads and DG power generation. In [7], a Modified firefly algorithm (MFA) is presented for DSR with the aim of minimising the total active power losses, the total cost and the total emission produced by grid and DG. However, the NSW operations have not been considered in [3–7] and the 2 m point estimation method (PEM) has been utilized to model the uncertainty in [3–7]. In [8], the risk-based reconfiguration is presented for minimizing the switching cost, cost of loss and reward/penalty profit/cost with the consideration of load and generation uncertainty. These uncertainties are modelled as scenarios with different probabilities. In [9], scenario based stochastic multi-objective framework is presented for DSR to minimize total power losses, voltage deviation and total cost with the consideration of uncertainties related to DGs and load demand. In this work, adaptive

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modified particle swarm optimisation (AMPSO) is implemented deterministically for each of the scenarios. The work on DSR reported in [10] is aimed at reducing the seasonal energy losses and switching operation costs considering the variability in active and reactive loads and DG output power. An adaptive PSO with fuzzy set theory is discussed in [11] to minimise the real power loss, bus voltage deviation, cost of generated electric energy and emission produced during reconfiguration in presence of DGs (fuel cells and wind power generation (WPG)). In this paper, 2m + 1 PEM is employed to consider the uncertainties in the output of WPG and the power demand.

In all above mentioned works, only the steady-state behaviour of DGs under uncorrelated uncertainties has been taken into account during system reconfiguration. However, when either induction machine or synchronous machine based DGs are integrated in the distribution system, the distribution system stability is also affected. Several studies have been carried out to analyze the impacts of penetration level of DG on the stability behavior of the power system. The impact of DGs on dynamic behaviour of the power system and active damping enhancement is discussed in [12]. Probabilistic small-signal stability of the power system with the grid connected wind turbine generation is carried out in [13] using analytical approach. In [14], the impact of synchronous machine based and DFIG based DGs on the small signal stability of distribution system is discussed. In [15], probabilistic small signal stability assessment is carried out to investigate the impact of the WPG uncertainty and it is shown that the system stability significantly deteriorates with high level of wind penetration. Hence, in the literature, small signal stability of distribution system is considered as an important probabilistic stability index for maintaining system security level. In particular, when the network topology changes (having the DGs installed at some fixed buses), the stability of distribution system may deteriorate or improve (as compared to the original configuration stability). Therefore, small signal stability of DS under uncertainties should be considered while solving the DSR problem.

To address the above-mentioned issue, the effect of uncertainties with correlations among loads and among power outputs of DGs are considered in stability constrained DSR of DS in this paper. As per the knowledge of the authors, this issue has not been fully addressed so far in the literature. In this paper, only synchronous generator based small hydro power plants (SHPP) are considered as the DGs. Moreover, it is presumed that the DGs placed in the distribution system do not have any power system stabiliser and thus, the system stability is completely dependent on the system operating condition (uncertain load injections, DG power generation and topology). Hence, there is no possibility of enhancing the system stability by employing any auxiliary controller. The key objective of this paper is to develop an optimum reconfiguration methodology while guaranteeing the small signal stability of the distribution system in an uncertain environment.

The paper is organized as follows. Section 2 provides the detailed formulation of the problem considered in this work. Stability assessment of distribution system is also addressed in this section. The application of KnEA-PE algorithm for DSR problem is explained in Section 3. The simulation results carried out on IEEE 33-bus, IEEE 69-bus and IEEE-119 bus, are discussed in Section 4 and conclusions are given in Section 5.

2. Problem formulation

2.1. System modelling

The formulated distribution system reconfiguration problem is a multi objective optimization problem (MOOP) subjected to various system operational constraints. The objectives in the proposed formulation are minimization of expected power loss, maximization of expected voltage stability margin, and minimization of the required number of switching operations. The presented formulation employs probabilistic approach to represent the stochastic nature of the loads and power generated by DGs. The proposed formulation accounts for the system constraints by: (1) energising all load points in the system, (2) preserving the system radiality, (3) ensuring that the probability of the system to remain dynamically stable is more than some pre-defined value and (4) ensuring that the probabilities of the branch currents and bus voltages to remain within their allowable limits exceed some pre-defined values.

A brief description of decision variables and various uncertain quantities is given below.

2.2. Decision variables

In this work, the decision variables are the branch numbers of the switches (tie or sectionalizing) in the system. In this work, the decision variables are represented as:

$$\boldsymbol{X} = [B_1, B_2, \ldots, B_{T_s}] \tag{1}$$

where $\boldsymbol{X}$ is a decision vector, B_i is the branch number with switch (either sectionalizing or tie) which should be opened in the ith loop obtained after closing the tie switch in the loop. T_s is the number of tie switches.

2.3. Uncertainty representation

In this work, two uncertain quantities are considered: (1) active and reactive power loads, (2) SHPP output power. The probabilistic models for the real as well as reactive power demand and the power generated by DG are described as follows.

(1) Probabilistic Load modelling: In this paper, the uncertain real and reactive power load is represented as a random variable with Gaussian probability distribution as [16].

$$f(L_k) = \frac{1}{\sigma_k\sqrt{(2\pi)}} e^{-1/2\frac{(L_k-\mu_k)}{\sigma_k^2}} \tag{2}$$

where L_k is real or reactive power load at the kth bus, while σ_k and μ_k are the standard deviation and mean of L_k respectively.

(2) Probabilistic generator modelling [17]: In this paper, the generation outputs (as percentage of rated capacity) of the SHPP are taken from [17] along with their associated discrete probability values. Table 1 shows the percentage output power of the SHPP and the associated probabilities [17] which have been used for SHPP modeling. The DG output power P_{DG} is calculated as $P_{DG} = P_{rated} * r/100$, where P_{rated} is maximum capacity of the DG unit and r is percentage output power (of rated capacity). Thus, at every state, the DG power output and the related probabilities are determined. Subsequently, the mean, standard deviation and other moments are computed. Further, correlation among the outputs of the SHPPs has also been considered in this work.

Table 1
Probabilities of SHPP power output.[17].

State no.	Output power as percentage of rated capacity (%r)	%Probability
1	0.000	2
2	28.43	5.52
3	37.73	5.96
4	45.70	11.03
5	50.80	14.24
6	55.14	14.24
7	60.30	15.67
8	65.90	14.24
9	73.71	9.49
10	83.62	5.74
11	100	1.87