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Optimum network reconfiguration based on maximization of system loadability using continuation power flow theorem

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ABSTRACT

This paper presents a new algorithm for network reconfiguration based on maximization of system loadability. Bifurcation theorem known as Continuation Power Flow (CPF) theorem and radial distribution load flow analysis are used to find the maximum loadability point. Network reconfiguration results are also compared with existing technique proposed in literature. In the proposed method, to find the optimum tie-switch position, a Discrete Artificial Bee Colony (DABC) approach is applied. Graph theory is used to ensure the radiality of the system. The proposed algorithm is tested on 33-bus and 69-bus radial distribution networks, each having 5-tie switches. The result shows that using the proposed method the kVA margin to maximum loading (KMML) increases, overall voltage profile also improved and the distribution system can handle more connected load (kVA) without violating the voltage and line current constraints. Results further show that the voltage limit is an important factor than the line current constraints in adding further load to the buses.

1. Introduction

With the ever increasing load demand and the lack of capital investment in the transmission system, the importance of enhancing the existing distribution system capacity has increased. The system capacity is usually limited by two factors, namely *thermal limits* and *voltage limits*. Thermal limit or thermal capacity is the ampacity or maximum current carrying capacity limit of the conductor. The current carrying capacity is limited by the conductor's maximum design temperature [1]. However the voltage limit is the allowable minimum–maximum voltage variation for safe operation of power system and connected load. The study in [2] has concluded that the maximum loadability of the distribution system is limited by the voltage limit rather than the thermal limit.

In literature, minimization of losses in power system was a major concern for power system researchers. Among different techniques for power loss reduction including Distributed Generation (DG) placement and shunt capacitor placement, network reconfiguration is also utilized. Network reconfiguration is defined as altering the topological structures of the distribution feeders, by changing the position of tie and sectionalizing switches. Network reconfiguration is a key tool in operation of medium voltage distribution system and in improving the reliability of the system. The structure of medium voltage distribution network is designed mesh, provided with tie and sectionalizing switches. However under normal operation, medium voltage distribution networks operates in radial manner [3,4].

Most of the researchers have considered power losses as an objective function in network reconfiguration. Analytical and heuristic search based optimization techniques have been utilized by different researchers to perform the network reconfiguration. Authors have formulated the problem in different manners. In [3], Civanlar has analyzed the problem of network reconfiguration considering minimization of losses, load flow based approach was utilized. In [5], Baran and Wu extended the work of [3] and included a new load balancing index in addition to minimization of losses, simplified load flow approach is used. In [6], Shirmohammadi utilized the heuristic approach to find the minimum losses of the network. The radial system is converted to mesh, later-on optimum power flow pattern is made and the branch carrying the minimal current is removed.

Later on, several optimization based algorithms have been developed considering minimization of losses as an objective function. Zhu utilized the refined genetic algorithm [7], Venkatesh et al. utilized the Fuzzy adaptation of Evolutionary Programming technique [8], Zhu et al. performed the network reconfiguration based on modified heuristic solution and experience system operation rules [9]. Srinivasa et al. in [10] used the Harmony Search Algorithm, Sathish in [11] solved the problem using Bacterial Foraging Algorithm, Yuan-Kang et al. [12] utilized the Ant Colony Algorithm. de Oliveria et al. [13] mixed the problem of network

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reconfiguration with capacitor placement considering minimization of total energy loss as an objective function. Zin et al. in [14] has used the heuristic search algorithm to find the minimum power losses as an objective function, introduced by the author in [5]. The update principle of heuristic search is made by finding the branch having minimal current, till the optimum solution is made. In the latest research, Rao et al. in [15] has combined the network reconfiguration with distributed generation placement, considering minimization of power losses as fitness function. Most of the existing research is based on finding optimum tie switch combinations based on minimization of power losses.

In the present study, a new strategy, based on voltage stability criteria is proposed for solving the reconfiguration problem. The objective is to maximize the system loading margin or kVA margin to the point of maximum loadability of the system. Loadability is defined as the capacity of the system with which the maximum load could be connected without going into the voltage instability region. Voltage stability has been used in solving other power system problems including optimal power flow solution [16] and optimum DG placement [17,18]. The major research considering maximum loadability in network reconfiguration is found in [8]. In [8], the author has developed the Maximum Loadability Index (MLI) based on the voltage stability criteria and used as a fitness function to solve the network reconfiguration problem. Fuzzy-EP approach was used by the author to find the optimum tie switch combinations.

In the proposed method, Continuation Power Flow (CPF) is used for finding the maximum loading margin of the system. With CPF, the maximum loadability margin or maximum loadability index λ_{max} is calculated which corresponds to saddle node bifurcation (SNB) point or point of voltage collapse. The CPF results will also be compared with the radial distribution load flow methods. Network reconfiguration differs from other optimization problems (e.g. DG sizing, shunt capacitor sizing, unit commitment and others), the tie switch positions always occur in a discrete manner (e.g. 7, 13, 19, 25, 28) thus a Discrete Artificial Bee Colony (DABC) approach is proposed in finding the optimum tie switch combinations. To ensure the radiality of the system for different switch combinations, Graph Theory (GT) approach is applied.

The paper is organized as follows: In Section 2, the overview of Continuation Power Flow (CPF) is presented and the mathematical model is given. Section 3 presents the graph theory approach in checking the radiality of the system for different tie switch combinations. Section 4 presents Discrete Artificial Bee Colony (DABC) for finding the optimum switch configuration. Section 5 provides the definition of Voltage Deviation Index (VDI) for measuring power quality and kVA Margin to Maximum Loadability (KMML). In Section 6, the proposed algorithm is presented and in the last section 7, the proposed algorithm is applied on 33-bus and 69-bus radial distribution test systems. The results are shown and also discussed in detail.

2. Continuation Power Flow (CPF) theorem

CPF theorem is commonly used in power system to solve the load flow problem. Most of the theorems get diverges after reaching the critical point or point of voltage collapse as in the case of Limit Induced Bifurcation or Saddle-Node Bifurcation (SNB), and thus the power flow equations have no solution at SNB point. In comparison to other power flow theorems, CPF has an advantage in terms of complete solution of nose curve even after reaching the SNB point. CPF theorem is based on bifurcation model. Bifurcations occur when the system stability changes due to a change of system parameters [19,20]. In CPF, predictor–corrector approach is used to solve the PV or λV nose curve, as shown in Fig. 1.

In this paper, the parameter that is used to characterize the loadability of the system is the maximum loadability margin λ_{max}, as shown in Fig. 1. The loadability factor λ is used to modify connected load as given by Eq. (1) [21]:

$$\left.\begin{aligned} P_{L1} &= P_{L0} + \lambda' P_D \\ Q_{L1} &= Q_{L0} + \lambda' Q_D \end{aligned}\right\} \tag{1}$$

where P_{L0} and Q_{L0} are the initial active and reactive power loads respectively.

P_{G1}, P_{L1} and Q_{L1} are the modified active and reactive power loads respectively.

λ' is the initial loadability factor that multiplies variable powers P_D and Q_D, also called power directions.

When power directions P_D and Q_D are in the vector direction defined by P_{L0} and Q_{L0}, Eq. (1) changes to Eq. (2):

$$\left.\begin{aligned} P_{L1} &= (1+\lambda')P_{L0} = \lambda P_{L0} \\ Q_{L1} &= (1+\lambda')Q_{L0} = \lambda Q_{L0} \end{aligned}\right\} \tag{2}$$

where $\lambda = 1 + \lambda'$ is the loadability factor.

The CPF method utilizes predictor–corrector approach for the complete solution of PV nose curve. Predictor step is based on the computation of the tangent vector and a corrector step is obtained either by means of a local parameterization or a perpendicular intersection [19,20,22]. For mathematical modelling of CPF, consider a curve AC, shown in Fig. 2, given by the following model

$$g(y, \lambda) = 0 \tag{3}$$

where y represents the state variables and λ represents system parameter used to drive the system from one state of loading to another.

2.1. Predictor step

To find the predictor vector, consider an equilibrium point 'P' in Fig. 2. At equilibrium point 'P', the following relation applies:

$$g(y_p, \lambda_p) = 0 \tag{4}$$

$$\left.\frac{dg}{d\lambda}\right|_p = 0 = \nabla_y g|_p \left.\frac{dy}{d\lambda}\right|_p + \left.\frac{dg}{d\lambda}\right|_p \tag{5}$$

And the tangent vector can be approximated by:

$$\tau_p = \left.\frac{dy}{d\lambda}\right|_p \approx \frac{\Delta y_p}{\Delta \lambda_p} \tag{6}$$

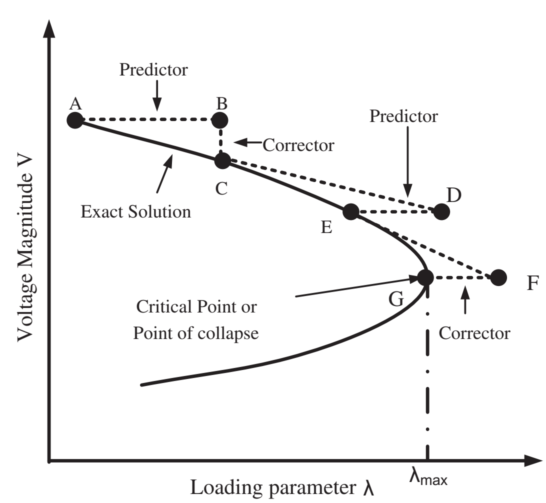

Fig. 1. Continuation power flow theorem – solving approach.