Electrical Power and Energy Systems 65 (2015) 419–424

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Model of distribution system total supply capability considering feeder and substation transformer contingencies

Jun Xiao [a,*], Xin Li [a], Wenzhuo Gu [b], Fangxing Li [c], Chengshan Wang [a]

[a] Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin 300072, China
[b] Qinhuangdao Electric Power Company, Qinhuangdao 066000, China
[c] Dept. of EECS, University of Tennessee, Knoxville, TN 37996, USA

ARTICLE INFO

Article history:
Received 22 September 2013
Received in revised form 16 September 2014
Accepted 10 October 2014

Keywords:
Total supply capability (TSC)
Distribution system
$N-1$ contingencies
Load balance
System security

ABSTRACT

This paper proposes a model for calculating the total supply capability (TSC) for distribution system considering both feeder and substation transformer contingencies. Existing models and methods for TSC only consider substation transformer contingencies and ignore feeder contingencies. However, the feeder contingencies occur much more frequently than substation transformer contingencies in practice. Moreover, some operation state fail the feeder contingencies $N-1$ verification even they pass the transformer contingencies $N-1$ verification. In this paper, a TSC model is firstly proposed in which feeder and transformer $N-1$ contingencies are fully considered. This model is designed in feeder level, which means the topology of interconnection among feeders is accurately modeled. Secondly, a supplementary model for load balancing is set up for a better load distribution solution on feeders and transformers at TSC loading. Finally, the method is tested in a test distribution system and a real partial distribution network and the results are verified by the traditional $N-1$ simulation.

Introduction

Total supply capability (TSC) of a distribution system is the maximum load that it can serve under $N-1$ security [1]. The concept of TSC is similar to the total transfer capability (TTC) for transmission systems [2,3].

TTC and its related theory is one of the foundations of planning and operation for modern transmission systems. Under the global trend towards smart grid [4], TSC will play a very important role in future distribution systems, like TTC to transmission systems. The definition, model and calculation methods of TSC are proposed in recent years [1,5]. However, they are all based on substation transformers. Thus, they are referred to as "transformer-based" approaches which have two features: first, only the loads of transformers and their rated capacities are formulated, which provide relatively limited information on the system status; second, only $N-1$ contingencies and maintenance of substation transformers are considered, while the feeder contingencies and maintenance are ignored. It has shown that the existing TSC models are incomplete due to the ignorance of feeder contingencies and a new model is also proposed to solve the problem.

The concept of TSC is originated from $N-1$ security for distribution systems, which means a successful supply of all loads except the ones in the faulted section. The national electric code in China has enforced the $N-1$ security for all new and upgraded urban distribution systems [6]. Similar rules are also observed in some European cities [7]. In the past, the capacity of a substation, or its transformers was empirically analyzed based on the $N-1$ guideline, which assumes that transformers in the same substation can backup each other when one of them is unavailable [8]. Then as the development of the distribution automation (DA), the remote operation of switches in MV distribution network can be much faster. In this circumstance, many researches have been carried out on the identification of fault location, service restoration, and network reconfiguration [9–12]. All these works have improved the reliability of distribution systems. With the automated switches, load can be not only transferred within substation, but also transferred to adjacent substations through interconnected feeders. This means a MV distribution network after DA possesses the capability to provide stronger support to substations than before. Thus substation transformers could be operated at a higher loading rate with the same $N-1$ security standard, which can result in higher efficiency of the distribution system. However, very few researches on this aspect have been carried out, because DA has not been implemented in large scales in most MV feeders

* Corresponding author. Tel.: +86 136 0212 8544.
E-mail address: xiaojun@tju.edu.cn (J. Xiao).

http://dx.doi.org/10.1016/j.ijepes.2014.10.025
0142-0615/© 2014 Elsevier Ltd. All rights reserved.

around the world except some places, such as Japan [13]. Some researches have discussed the maximum load a substation or a distribution system can serve under $N-1$ contingencies after DA [14]. These researches provide some practical and preliminary methods to calculate supply capability, but they are not systematized and lack conceptual and theoretical foundations.

Under the context of smart grid, the advanced distribution operation (ADO) is to be developed in large scale in MV distribution network [15], which further increases the load transfer capability of distribution network. Meanwhile, in emerging and fast-developing markets like China, the rapid expansion of distribution systems makes it necessary to evaluate the supply capability of the existing distribution systems after huge investment. Some rigorous approaches to calculate supply capability of a distribution system have been reported in recent years. The present calculating methods for supply capability can be divided into two categories: the analytical methods and the linear programming model. Luo, Wang and Xiao have proposed an analytical method based on $N-1$ contingencies analysis of interconnected substation transformers [5]. In [16], this method is improved by taking into account the overload factor for transformers and the capacity of link lines. In [1], a mathematical model for TSC is set up as linear programming problem and the TSC is calculated with the aid of *Lingo*. Further, TSC is the most efficient operating point on the $N-1$ security boundary; and the concept and model of security boundary for distribution systems is then discussed [17]. Based on the framework of TSC in [1], a modified method for a more accurate TSC model is presented in [18].

A traditional $N-1$ simulation test is to verify the $N-1$ security of a distribution system in case of a feeder or a substation transformer contingencies (or maintenance) case-by-case. Despite of long computing time, $N-1$ simulation is a broadly used method to evaluate the security of a distribution system. This paper designs a method based on $N-1$ simulation to verify the accuracy of the TSC calculation. The simulation approach shows the phenomena that sometimes it fails the feeder $N-1$ verification even it passes the transformer $N-1$ verification. To solve this problem, this paper proposes a TSC model, in which the topology of interconnection among feeders and feeder $N-1$ security are both addressed. The accuracy of this TSC model is successfully verified by the traditional $N-1$ simulation approach.

Basic concepts of TSC and $N-1$ security

$N-1$ security for distribution system

The TSC definition is based on the concept of $N-1$ security, which is widely accepted in the planning and operation of distribution systems. The distribution system $N-1$ security consists of two scenarios: feeder $N-1$ contingencies (or maintenance) and substation transformer $N-1$ contingencies (or maintenance).

Here, if a feeder is $N-1$ secure or passes $N-1$ test, it means that when fault occurs at any location of a feeder or a feeder needs maintenance, the load of the feeder should be successfully transferred to other feeders via closing a normally open switch among feeders; and all the components in the system operates normally without overload or over-voltage after the load transfer. In a distribution system, a feeder is usually divided into different sections and connected to other feeders [19], thus when fault or maintenance occurs along a feeder, load of the feeder can be transferred to other different feeders.

The $N-1$ security of substation transformers is similar to that of feeders. If a fault occurs to a transformer or it needs maintenance, load of the transformer should be transferred to other transformers successfully; and all the components in the system should be operated normally without overload or over-voltage after the load transfer. The load of a transformer can be transferred in two ways: one way is to be transferred to transformers within the same substation through the bus connecting the two transformers; the other way is to be transferred via closing normally open switches among feeders, which is the same when a feeder $N-1$ contingency or maintenance occurs. It can be seen that in order to make all the components in the system operates normally without overload or over-voltage, only load of the feeders that passes the $N-1$ security test can be transferred through the feeder switch. In other words, the transformer $N-1$ security analysis is on the basis of feeder $N-1$ security analysis.

Concept of TSC

The total supply capability (TSC) of a distribution system is defined as the maximum load that it can serve under the $N-1$ guideline, taking into account the capacities of substation transformers and feeder, network topology, and some operational constraints [1]. This concept is similar to the total transfer capability (TTC) for transmission systems. They are all focused on the security boundary and the most efficient operating point for a complicated large system. The detail of TSC and its associated indices are described in literature [1].

The concept of TSC is very closely related to $N-1$ security, so the accuracy standard of TSC results can be set up based on traditional $N-1$ simulation. Since the TSC is the maximum load a distribution system can server under $N-1$ security, the operating point at TSC must pass the $N-1$ test for transformer and feeder contingencies or maintenance. Moreover, the distribution system cannot take any more load than TSC to keep its security. For this reason, the $N-1$ security test will fail when any load is added at the TSC point.

Accuracy verification based on $N-1$ simulation

To prove the accuracy of calculated TSC, the following two-step $N-1$ security simulation test is designed:

Step1: Set the load of the system at TSC calculated. Then perform the $N-1$ test for all transformers and feeders in the system. If all the transformers and feeders pass the $N-1$ tests, then go to step 2; otherwise the TSC is inaccurate and too high. It is worthy to point out that the present TSC methods can only give the load distribution on transformers at TSC and cannot give the load distribution on feeders. So this paper distributes the transformer load to its feeders averagely.

Step2: When the load of the system is equal to TSC, increase load of one feeder by a very small quantity. Then take $N-1$ test for all transformers and feeders in the system. Repeat this process by increasing load of another feeder until load of all feeders have been increased. This is to verify that when load of any feeder increases a bit, it will cause either transformers or feeders not pass the $N-1$ simulation test, which proves that the TSC is the maximum load of the system under the $N-1$ guideline.

TSC model considering feeder and transformer contingencies

TSC model considering feeder and transformer contingencies

This paper proposes a TSC model which considers $N-1$ security of both feeders and transformers. According to the concept of TSC and the $N-1$ security of feeders and transformers in section 'Basic concepts of TSC and $N-1$ security', the TSC model can be set up as a linear programming problem, in which the objective function