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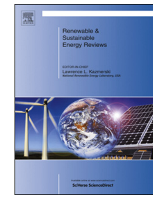

Optimum shunt capacitor placement in distribution system—A review and comparative study

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ABSTRACT

Shunt capacitors are commonly used in distribution system for reactive power compensation. Different analytical, numerical programming, heuristic and artificial intelligent based techniques have been proposed in the literature for optimum shunt capacitor bank (SCB) placement. This paper will present a very detailed overview of optimum SCB placement techniques. Six different approaches of optimum SCB placement based on minimization of power losses, weakest voltage bus approach and maximization of system loadability will be applied on four different radial distribution test systems. The results will be compared on the basis of power loss reduction, voltage profile improvement, system loadability maximization and the line limit constraint.

Contents

1. Introduction

Prior to 1950s the shunt capacitor banks (SCB) were placed nearer to the main substation for capacitive reactive power compensation, it helps in improving the power factor, reduces I^2R power losses and improving the voltage profile. SCB changes the power losses up to the point of coupling, however to get the maximum benefit it must be placed as nearer to the load as possible. With the availability of pole mounted equipment including SCB, the trend has changed. The capacitor banks are now placed on primary distribution lines as well [1–5].

The capacitor unit is considered as the basic building block of SCB. Capacitor units are connected in paralleled-series combinations and

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form a single-phase capacitor bank, within a steel enclosure. The series combination reduces the cost of dielectric while parallel combination increase the total capacitance of SCB. As a general rule, the minimum number of units connected in parallel is such that isolation of one capacitor unit in a group should not cause a voltage unbalance more than 110% of rated voltage on the remaining capacitors of the group. Equally, the minimum number of series connected groups is that in which the complete bypass of the group does not subject the others remaining in service to a permanent overvoltage of more than 110% [2]. The amount of reactive power (Q_C) from capacitor depends on applied voltage (V) and capacitive reactance (X_C), given by Eq. (1) [6].

$$Q_C = V^2/X_C \tag{1}$$

The recent power system blackouts [7,8] due to insufficient reactive power have also resulted in focused towards meeting reactive power demand of the system locally using static capacitor banks. The combined US Canada task force on August 2004 blackout also concluded that the reactive power supplies in Northeast Ohio were exhausted which resulted in loss of several critical bulk power supply systems and helped cascaded generator interruptions [9]. During low voltage emergencies e.g. generator rescheduling, line restoration or operated directed load tripping, the author in [10,6] proposed shunt capacitor bank series group shorting (CAPS) method. CAPS shorted section increases the reactive power supplied during periods of low voltages by shorting several series groups of capacitor units ($Q_C\uparrow = V^2/X_C\downarrow$). The shorted section in CAPS comprises of 20% to 33% of total bank. The detailed study and feasibility of CAPS on EHV and HV network are also presented in [11]. In case of highly loaded systems, it is believed that the optimum capacitor placement solve the minimization of losses more adequately and optimum setting of voltage regulators solve the voltage drop problems in a better manner [3].

The need for reactive power support in distribution system may be arises due to the following reasons.

1.1. Maximizing the distribution system efficiency

Distribution system usually suffers from two major problems, high power losses and poor voltage profile. Losses are defined as the difference between the energy into the system and the energy that is utilized by the end users. Generally electric system losses can be categorized as technical or non-technical losses [12,13]. Technical losses in distribution system occurs at different stages from the main substation till the consumer end, including substation transformer, primary lines, line equipment voltage regulators and surge arrestor, distribution transformer, secondary lines and consumer services. The loss calculation methods at different stages are discussed in detail in [14]. Electric Power Research Institute (EPRI) and Energy Information Administration (EIA) of U.S. concluded that [14,15]:

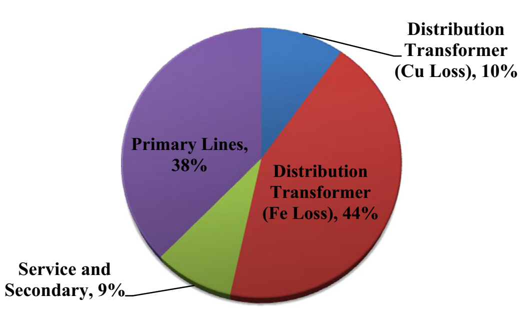

Fig. 1. Breakdown of distribution losses—EPRI study [14].

1. The distribution losses range from 33.7% to 64.9% of the total system losses.
2. About 7% of the total electricity production is transmitted in the United States as transmission and distribution losses [15].
3. EPRI research on 42 distribution circuits estimated that 54% of total losses are occurring in distribution transformer (although the efficiency of distribution transformer lies above 99%) and 38% of total distribution losses are occurring in primary lines, as shown in Fig. 1. One of the major reason for such a high losses in distribution transformer is total number of distribution transformer placed in distribution system [14]. In 2003, it is estimated that there are 50 million distribution transformers in use in United States [16].

With such a higher power losses in distribution system, it is highly necessary to reduce the line losses occurring in primary line as much as possible. The higher losses results in limiting the line capacity (*thermal limits*) as well as higher voltage drop (*voltage limits*) in the power system. In literature it has also been concluded that the maximum loading of the distribution system is limited by the voltage limit rather than the thermal limit [17]. Large power consumers also installed shunt capacitor to improve the overall power factor and thus save the cost of poor power factor penalty. Three different compensation techniques are available in literature including individual compensation; group compensation and centralized compensation to improve the power factor. Any one of the method or all of the method can be utilized to take the maximum advantage of improved power factor [18]. For power factor improvement, an unloaded synchronous motor can also be used instead of shunt capacitor. The amount of reactive power is controlled from its excitation system and thus it behaves like a variable capacitor [19]. Now-a-days, manufacturers are bound to design electrical equipment with higher efficiency and high power factor [20].

1.2. Reactive power management in deregulated power market

With the restructuring of power system, the complexity of power system has been increased. The vertically integrated power system has been separated into GenCOs, TransCOs, and DisCOs. A central regulating company Independent System Operator (ISO) and Regional Transmission Organizations (RTO) has been formed for maintaining the quality, reliability and security of electric service [21,22]. It is also a fact that the existing transmission systems in most of the countries are quite old. For example in United States, the 345 kV bulk transmission system and associated substation, cables and wires are 40 years old and above [23]. Such a system is not able to meet the growing demand and transfer the generated power from the centralized generation to the distribution system. Transmission investment has been falling for a quarter century at an average rate of almost US$50 million a year (in constant 2003 U.S. dollars), however there has been a small upturn in the last few years [23]. Other than constructing new transmission lines there are other options to release the transmission system congestion including distributed generator placement, static capacitor bank, FACTS (Flexible AC Transmission Systems) devices, voltage regulators and energy conservation [24,25]. It is also a fact that the generation the addition of extra kVAR on a generator operating at 0.9 power factor decreases the amount of real power output by about half a kilowatt [26]. Thus in restructured power market, the generator companies prefer to generate maximum active power (kW) and get maximum profit ($).

The reactive power (kVAR) market is not as simple as real power (kW) market. The fundamental difficulty with reactive power markets is that reactive power does not “travel” far, thus it is expected there would be extreme local geographical market