Electric Power Systems Research 130 (2016) 266–276

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Optimal secondary distribution system design considering plug-in electric vehicles

S.F. Abdelsamad, W.G. Morsi*, T.S. Sidhu

Faculty of Engineering and Applied Sciences, UOIT, Oshawa, ON, Canada, L1H 7K4

ARTICLE INFO

Article history:
Received 17 April 2015
Received in revised form 16 August 2015
Accepted 9 September 2015
Available online 3 October 2015

Keywords:
Artificial intelligence
Monte Carlo methods
Distribution system design
Power quality

ABSTRACT

In this paper, the problem of secondary distribution system (SDS) design considering plug-in electric vehicles (PEVs) charging demand is addressed using meta-heuristic optimization to minimize the overall secondary system costs. The objective function and the necessary constraints are mathematically formulated and presented. The effectiveness of the proposed SDS design approach is evaluated in terms of the overall SDS costs and transformer loss of life (LOL). The proposed design approach represents an effective tool for electric utilities to accommodate PEVs during the planning stage of SDS and also when retrofitting existing SDS.

1. Introduction

In North America, the electric power system (EPS) is divided into two parts: (1) the primary distribution system (PDS) which starts at the distribution substation and ends at the distribution transformers and (2) the secondary distribution system (SDS) which starts at the distribution transformers and ends at the consumers' meters [1]. Most electric power utilities apply a rule of thumb (e.g., based on long-term operating experience or using diversity factor between consumers) [2,3] in designing many parts of EPS and in particular SDS. Many existing residential SDSs are designed without considering the radical change in EPS due to transportation electrification. The introduction of PEVs at large penetration levels into an EPS will have major impacts on many components making the SDS and, in particular, the distribution transformers which represent the most expensive asset in SDS. Studies [4,5] have shown significant degradation in distribution transformer LOL due to PEVs charging demand. According to [4], the estimated overload in distribution transformers may reach 130% at PEVs penetration of 46%. Also [5] showed that the transformer LOL can reach 0.206% for one day of operation at 50% PEV penetration. As a result, many electric utilities are now facing a challenge in their electricity network infrastructure to accommodate the projected increase in transportation electrification. For example, in 2011, Toronto Hydro spent over $400 million in infrastructure upgrades, including distribution transformers [6]. There is a dire need to optimally design a SDS that considers PEVs penetration by minimizing the total fixed and operating costs while maintaining the system voltage within the allowable limits in standards.

Studies [7–9] focused on distribution system design based on the selection of the optimal conductor sizing to minimize overall cost and system losses, the authors ignored distribution transformers in SDS design. On the other hand, studies [10,11] were applied only to three-phase distribution system. However, single-phase distribution transformers which are common in North America were not considered in the optimization procedure in these studies. Moreover, the transformer loss of life were not considered in the design process, and also the design presented in these studies did not consider the PEV load. Da Silva et al. [12] used mathematical programming for design primary and secondary distribution system to meet future load forecasting. The work in [12] aimed to design the distribution system with minimum total cost while focusing on the expansion of existing network. Shao et al. [13] proposed an expert system for radial SDS design that considered load growth over a certain time period to reduce both system costs and losses. In [14], the selection of optimal transformer's size and secondary circuit to minimize the SDS design cost was proposed. Sumic et al. [15] introduced a decision support system for optimal distribution system design by optimal sizing and placement of transformer and secondary circuit routs but without incorporating the system's operation cost. In [16], the minimization of total annual cost of distribution system design was implemented using expert system. In [17], the SDS modeling using pre-defined secondary circuit archetypes was presented. The design method

* Corresponding author. Tel.: +1 905 721 8668x5483; fax: +1 905 721 3370.
E-mail address: walidmorsi.ibrahim@uoit.ca (W.G. Morsi).

http://dx.doi.org/10.1016/j.epsr.2015.09.009
0378-7796/

Nomenclature

S_T	transformer rating
IC_T	transformer initial cost
A_{SD}	service drop cross sectional area
$OC_{SD,cu}$	service drop copper loss cost
A_{SL}	secondary line cross sectional area
IC_{SL}	service line initial cost
IC_{SD}	service drop initial cost
IC_{PH}	poles and hardware initial cost
OC_T	transformer total operating cost
$OC_{SL,cu}$	service line copper loss cost
$P_{T,Fe}$	transformer core loss
$P_{T,CU}$	transformer copper loss
TAC	total annual cost
TAFC	total annual fixed cost
TAOC	total annual operating cost
LOL	transformer loss of life
F_{AA}	aging acceleration factor
F_{EQAA}	equivalent aging acceleration factor
Θ_{TO}	top-oil temperature
Θ_H	winding hottest-spot temperature
Θ_A	average ambient temperature
τ_W	winding time constant
τ_{TO}	oil time constant of transformer
P_{PEV}	plug-in electrical vehicle active power
K_i	ratio of initial load L to rated load
K_U	ratio of ultimate load L to rated load
Δt_n	time interval (1 h)
V_h	house entrance voltage
N_P	number of population
W	inertia weight
α	average number of vehicles per house
$Iter_{max}$	maximum number of iteration
$N_{archetypes}$	number of available archetype
P_{best}	best solution found by each particle
G_{best}	best solution found by all swarm
v_i	particle velocity
N_{Houses}	number of houses
SOC	vehicle state of charge
CDF	cumulative distribution function
C_1, C_2	learning coefficients
P_T	distribution transformer active power
P	vehicles penetration
P_h	active power consumed in house
$P_{line, loss}$	line power loss
R	ratio of load loss to no-load loss
$P_{T, loss}$	transformer power loss

proposed in [17] was used in [18] for SDS design. However, several alternatives were explored to reduce the system power loss. From the aforementioned literature review and to best knowledge of the authors there is a lack of an optimal design method for SDS that takes into consideration the effect of charging PEVs on the secondary system components, and on the life time of distribution transformers.

This paper presents a new approach to optimally design SDS in order to minimize the total cost while considering different PEVs charging demand taken in to account transformer loss of life and the different operating constraints, which has not been fully investigated in previous work. In this study, meta-heuristic optimization is used to solve SDS design problem after presenting the mathematical formulation. Monte Carlo (MC) methods are used in this study to exemplify the effectiveness of the proposed design approach.

2. Secondary distribution system design

In designing SDS, many factors need to be considered, such as transformer rating, secondary conductors service and service drop cross sectional area. Moreover the voltage at the consumers' service entrances must be maintained within the limits of the ANSI C84.1-2011 standard voltage limits [19]. The SDS can be typically modeled in terms of a few secondary circuit archetypes; these archetypes can be identified based on the number of secondary lines that extends on each side of the distribution transformer, and the number of poles and the service drop conductors' lengths that extend from the pole to the house service entrance. Fig. 1 depicts a single-line diagram of a sample archetype SDS.

2.1. Overview of secondary distribution system design: Mathematical formulation

The secondary distribution system's total annual cost (TAC) mainly depends on the distribution transformer costs and the cost of service lines. In order to calculate the total annual costs, the procedures outlined in [1] are followed to estimate the overall cost to establish the secondary distribution system in two parts: total annual fixed costs (TAFC) and total annual operating costs (TAOC). The mathematical formulation of the TAC costs is as follow:

$$TAC = TAFC + TAOC \quad (1)$$

$$TAFC = \sum IC_T + \sum IC_{SL} + \sum IC_{SD} + \sum IC_{PH},$$
$$TAOC = \sum OC_T + \sum OC_{SL,Cu} + \sum OC_{SD,Cu} \quad (2)$$

From Eq. (2) each component of SDS have fixed and operating cost; transformer IC_T represents the annual installed cost of distribution transformer and the associated protective equipment. This cost is mainly depend on the transformer rating (S_T), OC_T represent the annual operating cost of transformer exciting current and the annual cost of iron and copper losses ($P_{T,Fe}$, $P_{T,CU}$). The SL and SD fixed cost are very similar as both of them represent the annual installed cost of the triplex aluminum cables. However, their operating cost depend on the copper loss per unit length which will based on the A_{SL}, A_{SD} and the current flowing in the circuit corresponding to the installed loads. The IC_{PH} represents the annual cost of pole and hardware which depend on the SDS archetype. The TAC equation can be expressed in terms of eight constants as follows:

$$TAC = A + \frac{B}{S_T^2} + \frac{C}{S_T} + D \times S_T + E \times A_{SL} + \frac{F}{A_{SL}} + G \times A_{SD} + \frac{H}{A_{SD}} \quad (3)$$

where the coefficients A to H values depend on the selected SDS archetype, and the energy cost reader can get more details for the constants calculation by referring to [1]. It is obvious that the TAC

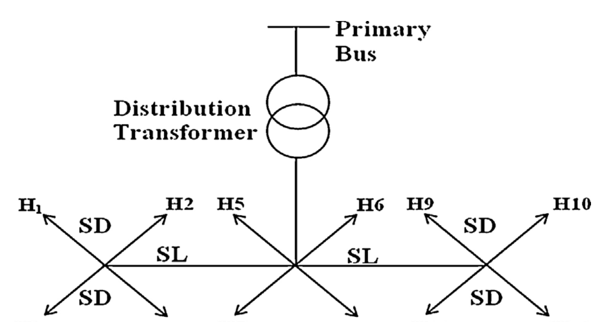

Fig. 1. Sample secondary distribution system.