Electrical Power and Energy Systems 73 (2015) 163–169

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Reliability evaluation of distribution transformers with high penetration of distributed generation

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ARTICLE INFO

Article history:
Received 18 October 2014
Received in revised form 12 March 2015
Accepted 18 April 2015
Available online 16 May 2015

Keywords:
Hottest spot temperature (HST)-dependant aging failures of transformers
Optimal loading
Reliability
Monte Carlo simulation (MCS)
PV DG
Wind turbine DG

ABSTRACT

In this paper, a novel methodology is presented to evaluate the micro-grids reliability concerning the dynamic thermal aging failure of transformers. The widespread presence of distributed generation (DG) units reduces the loading passing through the distribution transformers and consequently improves the dynamic thermal failures. The system reliability is investigated for various penetrations of different scenarios from the view of DG technologies. The introduced method is applied to a realistic distribution system comprising different distribution transformers in Iran. The sensitivity analysis corresponding to adequacy indices such as expected energy not-supplied (EENS) based on DG penetrations is performed. By the use of the novel methodology proposed, it is possible to recognize how different DG technologies and penetrations can impact on the system reliability. The results demonstrate that the diesel generators and hybrid systems including diesel generators, photovoltaic units, and wind turbines are the most promising DG technologies to improve the transformer failures and the reliability of micro-grids compared with renewable DG units.

Introduction

Economic and reliable supply of electrical energy is an essential and important criterion from the view of operating and designing the power system [1,2]. Many efforts such as reclosing [3,4], optimizing allocation of protective and switching devices [5,6], decreasing the failures of system elements [1,2,7], reconfiguring the system [8,9], and using distributed generation units (DGs) [10,11] have been devoted to improve the electrical distribution system reliability.

Much effort has also been devoted to investigate the effects, impacts, and advantages of DGs. In addition to the well-known advantages of using DG units, e.g. line capacity release [12], reduction of negative environmental effects [13], improvement of voltage profile [14], loss reduction of transmission lines [13,14], price reduction of wholesale electricity market [15,16], and the reliability improvement of future grids in a widespread use of DG units have been studied in different references [10,11].

Moreover, the transformer loss-of-life (LOL) reduction by increasing the penetration of DG units is also described in [17,18]. On the other hand, the condition-dependent outage model of transformer and age-related failures affect the reliability evaluations [19–21]. Literature reviews show that a great deal of attention has been paid to studying the benefits of DG units. However, some important benefits of DGs have not been investigated. This paper focuses on the benefits of DGs to reduce the dynamic thermal failures of distribution transformers. By the implementation of low-voltage customer-owned DG units, the power and current passing through the distribution transformers are decreased. This can lead to a reduction in the time evolution of the transformers' hottest-spot temperature (HST); although authors in [17,18] have been identified how the LOL rate of transformer is reduced as a function of DG technology mix and penetration level, the impact of transformer LOL on the transformer failure rate and the system reliability has not been studied. Due to this literature reviews, there is a knowledge gap about the quantifying of micro-grids reliability as a function of DG units which lead to a reduction in the dynamic thermal failure of distribution transformers.

This paper tries to fill such a knowledge gap by introducing a novel methodology to identify the transformer dynamic thermal-aging failure reduction provided by the use of DG units. The probabilistic indicators are used for modeling of aging and loading-based of transformers based on Arrhenius–Weibull life-stress model. Several DG types consist of small-scale wind turbines (WT), diesel generators, and photovoltaic (PV) are modeled. The various penetration levels are considered for different DG technologies through a sensitivity analysis. The proposed methodology

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http://dx.doi.org/10.1016/j.ijepes.2015.04.013
0142-0615/

Nomenclature

υ, υ_m	instantaneous and mean value of wind speed (m/s)
σ, μ	standard deviation and mean value
$f(x)$	probability density function (pdf) of variable x
u	random number uniformly distributed on [0,1]
$P_{PV}(t), P_W(t)$	output power of solar-based and wind-based distributed generation (DG) (W)
P_{rated}	rated output power of wind turbine (W)
$\upsilon_{ci}, \upsilon_{rated}, \upsilon_{co}$	cut-in, rated and cut-off speed of the wind turbine (m/s)
G	irradiance on a horizontal plane (kW/m^2)
k_t	clearness index
t	time segment of Monte Carlo Simulation (MCS)
T_c, T_a	solar cell and ambient temperature (°C)
N_{OT}	nominal operating temperature of the solar cell (°C)
I, I_{sc}	output current and short circuit current of the photo voltaic (PV) modules (A)
K_I, K_V	current and voltage temperature coefficient (A/°C) and (V/°C)
V, V_{oc}	output voltage and open circuit voltage of the PV modules (V)
P_{PV}	power output of the PV module
N_{PV}	number of PV modules
η	PV inverter efficiency
$MTTF_j, MTTR_j$	mean time to failure and repair of j-th component
$Up\ time_j, Down\ time_j$	duration of in service and out of service time of j-th component
ε	maximum limit of stopping criteria
$E(X)$	expected value of parameter X
N_T, N_P	number of transformers and total number of power elements
$Availability(k,t)$	availability and unavailability of k-th element in the t-th time segment
$S^i_{m,t},\ S^i_{rated},\ K^i_{m,t}$	transformer load and its nameplate and their ratio in m-th iteration, t-th hour and i-th load point
R^i	ratio of rated and no load loss in i-th transformer
$\theta_u,\ \theta_{fl}$	ultimate and full load steady state top oil temperature rise over ambient temperature
$\theta^i_0,\ \theta^i i$	transient top oil temperature rise over ambient temperature in i-th transformer and load point
$\theta^i_g,\ \theta_{g(fl)}$	ultimate and full load hot spot temperature rise over top oil temperature in i-th transformer and load point
$\theta^i_{hst},\ \theta_a$	hot spot temperature in i-th transformer and load point and ambient temprature
$LOL^i_t,\ LOL^i_T,\ L_i$	loss of life in t-th hour and i-th transformer, loss of life in period of T and i-th transformer, expected life of i-th transformer
a, b	derive exponent to calculate θ_u, θ^i_g
A, B	experimental constants are assessed from historical or accelerated life testing data
$\Pr^i_t$	failure probability of i-th transformer in t-th hour

is applied to a realistic and modernized distribution system of Hormozgan regional electric company (HREC) in Iran.

The reminder of this paper is organized as follows. Section 'Problem statement' focuses on the problem description. Sections 'Load modeling', 'Modeling of DG units', and 'Dielectric failure of transformers based on dynamic thermal model' discuss the modeling of load, DG units, and dielectric failure of transformers based on dynamic thermal, respectively. Reliability assessment and the main contribution of thispaper are presented in Sections 'Reliability evaluation' and 'Reliability evaluation method concerning the dynamic thermal failures of transformers in wide spread presence of DG units'. The case study and the test results employed to justify the effectiveness of the proposed method are demonstrated in Sections 'Case study' and 'Test results'. Finally, the conclusion drawn from the proposed method appears in Section 'Conclusion'.

Problem statement

The main purpose of this paper is to evaluate the reliability of electric grids with regard to the aging and loading failures of transformers in widespread low-voltage and customer-owned DG units. To achieve the objective, the demand side including the load patterns of customers and patterns of the renewable resource of output power should be simulated in a statistic and stochastic domain. It is clear that by identifying the load and generation patterns, it is possible to identify the ratio of transformer load to its nameplate rating. Thus, the thermal response of a sample transformer can be computed and accordingly the aging and loading failures are identified. According to the precise failure of transformers, stochastic modeling of the output power of DG units and other uncertainties such as availability of system elements, the reliability of electrical grid in a widespread presence of DGs are evaluated. The various DG technologies and their penetration levels are examined. Therefore, selecting a satisfying set of economic and reliable DG technologies from the view of reliability is achievable.

In this paper, the Monte Carlo simulation (MCS) is used to simulate the electric distribution system. Subsequent to the system data and contents including the consumption pattern of low-voltage customer loads, ambient temperature, wind speed, solar irradiance, time to failure (TTF), and time to repair (TTR) of power elements, cumulative density functions (CDFs) are identified. According to inverse CDFs, a random number generation can provide sets of simulated variables and parameters. The nature of simulated variables is similar to the corresponding actual phenomena.

Load modeling

The consumption pattern of the customer loads can be derived from the historical data or assumed that it follows the IEEE-RTS system [22]. If the historical data is selected to be used, it is necessary to remove the time dependence of the recorded data [17]. In this case, the database contents should be classified into different typical days representing the working days and weekends of four seasons. In this paper, it is assumed that the consumption patterns of customer loads follow the IEEE-RTS system data. In addition, the voltage-dependency of low-voltage customers is modeled on the basis of [23] similar to the methodology used in [17,18]. The voltage supply of low-voltage customers also depends on the power flow calculations. The forward–backward sweep, ladder iteration method [1,24], and Zbus-Gauss method (considering the R/X ratio) [25] are some methods used to solve the power flow in radial distribution systems. In this paper, the ladder iteration method has been selected, because it is simple and easy to implement [1,24].

Modeling of DG units

Wind turbine (WT) units

As described in Section 'Problem statement', to chronologically simulate the output power of small scale wind-based DG units,