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Direct cyber-power interdependencies-based reliability evaluation of smart grids including wind/solar/diesel distributed generations and plug-in hybrid electrical vehicles

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ABSTRACT

Smart grid is a so-called "cyber-power system" because the cyber systems (control/monitoring/protection, and communication networks) are integrated to power systems in it. The less effort has been devoted in literature to reliability evaluation based on direct cyber-power Interdependencies (DCPIs) in widespread presence of distributed generations (DGs) and charging load of plug-in hybrid electric vehicles (PHEVs) as supply side uncertainties and demand side ones. The consideration of uncertainty regarding the PHEVs in addition to other uncertain aspects inside the DCPIs is one of the most important contributions of this paper. In addition, the sensitivity analysis of reliability versus the variation of failures in power and cyber elements is essentially analyzed. The introduced method is applied to two realistic case studies. The test results infer that the DCPI-based reliability evaluation of smart grids including DGs and PHEVs is achievable through use of the proposed method. Because of using the Monte Carlo simulation (MCS), it is possible to extend the proposed method by integration of future uncertain and stochastic subjects without any limit. Further, the test results illustrate that the communication failures as direct network-element interdependencies (DNEI) is more important than direct element-element interdependencies (DEEI). The numerical results also imply that the risk level due to DCPIs increases due to inappropriate cyber network configurations.

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1. Introduction

The integration of control, monitoring, protection, information, and communication infrastructures to power network leads to create a so-called "cyber-power system". The power and cyber networks of smart grid are governed by their own different laws, protocols, and characteristics [1–3]. The literature on the modernized power systems reliability examining the cyber elements is numerable [4]. Singh and Sprintson [4] focused on the reliability assurance of cyber-physical systems, and introduced a novel classification of cyber failures. It should be noted that the reliability evaluation of cyber-physical systems based on mutual cyber-power interdependencies is an interesting subject.

In addition to smart grid and power systems, the reliability evaluation of heterogeneous cyber-physical system has attracted a lot of attentions. L. Zhang, et al. [5] introduced a method for improving the energy efficiency and system reliability for precedence constrained tasks in heterogeneous systems. The reliability optimization with energy conservation for parallel task scheduling in a heterogeneous cluster was focused in [6]. K. Li et al. [7] in heterogeneous cluster systems studied the scheduling precedence based on constrained stochastic tasks. These researches illustrate the importance of reliability evaluation of cyber-physical and heterogeneous systems. The cyber networks may adversely affect the modernized power system, and the power and energy systems may adversely affect the reliability of computing systems. Therefore, developing the novel reliability evaluation method based on

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Nomenclature

υ, V	wind speed (m/s)
$F(V)$	Weibull cumulative density function (CDF) of wind speed
k, c	shape and scale parameters of Weibull CDF
σ	standard deviation
υ_m	mean wind speed (m/s)
$f(\upsilon), f(k_t)$	probability density function (pdf) of wind speed and clearness index
u	random number uniformly distributed on [0 1]
$P_W(\upsilon), P_{rated}$	output power of wind turbine (W) and rated output power of wind turbine (W)
$\upsilon_{ci}, \upsilon_{rated}, \upsilon_{co}$	cut-in, rated, and cut-off speed of wind turbine (m/s)
$K_t, \bar{K}_t$	instantaneous and mean value of hourly clearness index
G, G_0	irradiance on a horizontal plane and extraterrestrial total solar irradiance (kW/m^2)
α, β	position and shape parameter of Beta probability distribution
σ_{k_t}	standard deviation of clearness index
T_c, T_a	solar cell and ambient temperature (°C)
N_{OT}	nominal operating temperature of the solar cell (°C)
I	output current of the photo voltaic modules (A)
I_{sc}	short circuit current of photovoltaic modules (A)
K_I	current temperature coefficient (A/°C)
V, V_{oc}	output voltage and open circuit voltage of photovoltaic modules (V)
k_V	voltage temperature coefficient (V/°C)
P_{PV}	output power of the photovoltaic module
N_{PV}	number of photovoltaic modules
η	photovoltaic inverter efficiency
$MTTF_j, MTTF_j$	mean time to failure and mean time to repair of the j-th component
$Up\ time_j, Down\ time_j$	duration of in-service and out-of-service state of the j-th component
A_{segi}	availability probability of the i-th segment
ε	desired accuracy level
$E(X)$	expected value of parameter X
$SOC(t,n)$	state of charge (SOC) of the n-th plug-in hybrid electric vehicle (PHEV) in the t-th time segment
$\Delta LG, LUG$	difference between demand loads and generation capacities, and the largest unit of power generations
$N_C, N_P, N, N_{SW}, N_{EMU}$	total number of cyber elements, power elements, PHEVs, switches, and EMUs
$N_{SR}, N_{seg}, C, K, n_{bus}$	total number of servers, segments, operation modes, system elements, and buses
HS_m, MS_m, RS_m	healthy, marginal, and at-risk period of m-th iteration of MCS
R^n_{cons}, R^n_{chg}	electric energy consumption (kWh/km) and electric charging rate of n-th PHEV (kW)
$\Delta x(t,n), \Delta t(t,n)$	travelled distance and charging time of n-th PHEV in t-th time segment
$\sigma_{PHEV\_ETD}, \sigma_{PHEV\_MTD}$	standard deviation values of PHEV evening and morning traveling distance
$\mu_{PHEV\_ETD}, \mu_{PHEV\_MTD}$	mean values of PHEV evening and morning traveling distance
$\sigma_{PHEV\_AT}, \sigma_{PHEV\_DT}$	standard deviation values of PHEV arrival and departure times
$\mu_{PHEV\_AT}, \mu_{PHEV\_DT}$	mean values of PHEV arrival and departure times
$AT(n), DT(n)$	arrival time and departure time of n-th PHEV
$Availability(j,t)$	availability and unavailability of j-th element in the t-th time segment
$S(t), S'(t), S'(t)$	state vector of system in t-th time segment during ordinary (direct network-element interdependencies) DNEI, and (direct element-element interdependencies) DEEI mapped conditions
$S(t,i), S'(t,i), S'(t,i)$	the i-th element of state vector in the t-th time segment during ordinary, DNEI, and DEEI mapped conditions
$DNEL(j,i)$	binary element of direct network-element link (DNEL) matrix corresponding to the DNEI between the j-th cyber element and the i-th power one
$P_G, P_{DDG}, P_{G,DGs}$	total power generation, output power of dispatchable DG units, and output power of all DG units
$P_{Loads}, P_{MainSub.}P_{Loss}$	demand load, power provided by main 63/20 kV substation, and active power loss
$V_{t,i}, \delta_{t,j}$	voltage magnitude and phase angle of the i-th bus in the t-th time
Y_{ij}, θ_{ij}	magnitude and phase angle regarding the element of admittance matrix corresponding to the i-th row and j-th column
$P_l, P_{\max,l}$	power passing through the l-th distribution line and the power limit of i-th line
K_{D2T}	ratio of power generation of dispatchable DGs to all DG units

mutual cyber-power interdependencies is interesting and essential.

The most reliability studies which considered the cyber-power interdependencies (CPIs) focused on the conceptual insights [4,8,9]. Even in references like [1,10] which developed the quantitative evaluation methods for cyber-physical system, the stochastic behaviors were not discussed, in details.

In references like [11,12], the adequacy evaluation of power systems including wind/solar DG units were studied under various uncertainties. But in such references, the eventual effects of cyber system were not concerned. On the other hand, the proposed method of [1,10] which considered the effects of cyber systems on the power networks has not been coupled to previous approaches considering the uncertainties. Hence, the authors proposed the stochastic risk management for smart grids based on direct cyber-power interdependencies (DCPIs) [13] and indirect cyber-power interdependencies (ICPIs) [14]. In [13,14], various sensitivity analyses have been performed to investigate the pattern of DCPIs and ICPIs impacts as DG penetration level in different DG technology scenarios. Although, the stochastic-based reliability evaluation method has been in [13,14], but the uncertainty of demand-side such as PHEV charging load has been received less attention.

This paper tries to simultaneously consider the uncertainty and probabilistic behaviors of power system (supply- and demand-side) inside the DCPIs.

The introduced method is stochastic-based one using Mont Carlo simulation (MCS) [15]. But Refs. [1,10] presented the analytical approaches using P-table. Although, it is possible to develop the P-table to cover the uncertain supply and demand sides, but through using stochastic approaches similar to MCS, it would be more simplified to add the different stochastic parameters such as charging load of PHEVs as the uncertain loads. By using the MCS, it is achievable to accurate studying of stochastic behavior

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