PROGNOSTIC ALGORITHM FOR CONDITION MONITORING AND ESTIMATION OF REMAINING USEFUL LIFE OF CRITICAL ELECTRICAL INFRASTRUCTURE

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Abstract

Aerial Bundled Cables (ABCs) are multi-layer insulated bundled cables. XLPE insulation makes these cables less prone to pilferage. However, these cables are degraded rapidly in a coastal environment. The ABCs are insulated cables and are more frequently used and preferred over the traditional bare conductors in power-associated networks as they are highly reliable and safer than bare conductors with better operational expenses and minimum power losses. Despite all these benefits, ABCs are prone to various categories of failures after installation in coastal regions.

Since ABCs conductors are concealed under the XLPE insulation, the visual inspection of most damages that occur in it becomes impractical. This limitation creates a need for a highly advanced and sophisticated inspection method to assess the degradation growth estimation of such electrical infrastructures. This thesis has proposed a genuine framework to categorize the sound and degraded ABC cables of various degrees positioned in areas near the shoreline. The progressive damage (ABC cable insulation degradation and erosion of hidden bundled conductors) is detected utilizing the ultrasonic probe listening method in installed operational ABC cables. The built-in superheterodyne module of UT-probe translates the inaudible supersonic partial discharge signal into audible range. The captured NDT-based UT data is utilized in this research work for the diagnosis and prognosis of onshore ABC cables.

The UT probe's recorded partial discharge corona signal is highly scattered, discontinuous, and movable (or non-stationary) across the ABC cable. The Empirical Mode Decomposition (EMD) along with the Hilbert Huang Transform (HHT) scheme is utilized to extract the time-frequency-energy characteristics present in the recorded UT signal. The presented research approach can be utilized to assess the cumulative deterioration or degradation growth rate of ABC cables placed in different areas near seashore under harsh and corrosive climatic conditions. Further, the benefits of other states of the art Intrinsic Mode Functions (IMFs) extraction techniques such as Ensemble EMD (EEMD) and Complementary Ensemble EMD (CEEMD) production process is investigated for assessment of damaged live ABC cables. Hence, corresponding IMFs are utilized to determine the Hilbert Huang Transform (HHT) spectrums. The periodically obtained ultrasonic signals data from various locations of the coastal region are used for

the computation of HHT spectrums. A continuous progressive shift towards lower frequency ranges is observed in all three IMF extraction modes in the signal energy spectrum. This assists in determining and classification of the health state of operational ABCs. Although all the above-mentioned IMF-extraction techniques are very effective for the damage identification of in-service ABCs, the CEEMD is considered the most suitable technique among the aforementioned three techniques. The presented scheme is equally beneficial for the diagnosis and identification of the level of damage and for determining the health state classification and prediction of the probable remaining useful life of in-service ABCs.

Furthermore, the advanced knowledge of insulation damage is crucial for the upkeep of electrical infrastructure, including insulated power distribution lines (Aerial Bundled Cables). The preliminary damage information helps power distribution companies reduce their maintenance costs by avoiding unnecessary inspections and maintenance activities. The preliminary damage information can be obtained by utilizing a prognostic model that can predict the future degradation growth rate (Remaining Useful Life Factor) in the insulation of active Aerial Bundled Cables operational cables installed in coastal regions. This thesis presents the prognosis study of the energized ABCs failures under the harsh climate of coastal areas for the first time.

The novel Hybrid resampling scheme-based particle filter (PF) algorithm is proposed in the second phase of research. The hybrid-resampling scheme is a combination of classical Multinomial resampling and Residual resampling schemes. This scheme is introduced in the resampling step of the Particle Filter algorithm. The selection of each resampling scheme is based on the degeneracy rate of each particle. The performance evaluation of the Hybrid resampling scheme-based PF algorithm is done by inserting the artificial noise into the measurement data. The promising results highlight the efficacy of the proposed predictive algorithm.

In the third phase of the research, the posterior density function of degradation growth rate (Remaining Useful Life Factor) in the cable insulation is estimated using the proposed novel Hybrid resampling scheme-based particle filter (PF) algorithm. Furthermore, this improved scheme under the framework of the *f*-step prediction algorithm is applied on the actual super heterodyned Ultrasonic listening-based field acquired data of installed ABCs. The use of actual measurement data introduces more

accuracy as it captures the degradation trend in the cable insulation without any assumptions.

PF well handles the nonlinear state transitions and measurement functions for non-Gaussian / multimodal noise distributions. The proposed Hybrid resampling scheme-based PF algorithm is further complemented by a step error calculation method to analyze the prediction accuracy in the absence of measurement data. The promising results depict the benefits of the proposed technique.

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List of Abbreviations

ABCs	Aerial Bundled Cables
AD	Adaptive Resampling
APIs	Average Pixel Intensities
Avg. EDR	Average Energy Distribution Ratios
Avg. PI	Average Pixel Intensities
AWGN	Additive White Gaussian Noise
CCs	Covered Conductors
CEEMD	Complementary Ensemble Empirical Mode Decomposition
CL	Cyclic Loading
CLE	Continuous Loading Effect
CPEC	China Pakistan Economic Corridor
CPU	Central Processing Unit
ECT	Eddy-Current Testing
EDR	Energy Density Ratio
EEMD	Ensemble Empirical Mode Decomposition
EMD	Empirical Mode Decomposition
EMD-HHT	Empirical Mode Decomposition Based Hilbert Huang Transform
ENS	Energy Not Supplied
ESB	Electricity Supply Board
FFT	Fast Fourier Transform
GPU	Graphics Processing Unit
GWUT	Guided Wave Ultrasonic Testing
HHT	Hilbert Huang Transform
HR	Hybrid Resampling
HT	High voltage Transmission
IGA	Intergranular Attack
IMFs	Intrinsic Mode Functions
IPC	Insulation Piercing Connector
IR	Infrared
KE	Karachi Electric
LT	Low Transmission
LT-ABC	Low Transmission Aerial Bundled Cable
LV	Low Voltage
MR	Multinomial Resampling
MRPC	Motorized Rotating Probe Coil
MSE	Mean Square Error
MV	Medium Voltage
NADA	Noise Assisted Data Analysis
NAPIs	Normalized Average Pixel Intensities

NDE	Nondestructive Evaluation
NDT	Nondestructive Testing
NPP	Nuclear Power Plant
PD	Partial Discharge
PDFs	Probability Density Functions
PF	Particle Filter
PMEs	Posterior Mean Estimates
R&D	Research and Development
RLA	Remaining Life Assessment
RLC	Resistance-Inductance-Capacitance
RMSE	Root Mean Square Error
RMSE	Root Mean Square Error
ROI A	Region of Interests A
ROI B	Region of Interests B
ROIs	Region of Interests
RR	Residual Resampling
RUL	Remaining Useful Life
SCC	Stress Corrosion Cracking
SCs	Spacer Cables
SGT	Steam Generator Tube
SHR	Super Heterodyned Receiver
SIR	Sampling Importance Sampling
SMC	Sequential Monte Carlo
SNR	Signal-to-Noise Ratio
SSE	Sum of Squared Error
SSWT	Synchro-Squeezing Wavelet Transform
TI	Thermal Imaging
UHF	Ultra High Frequency
UPL	Ultrasonic Probe Listening
UT	Ultrasonic Testing
UT-NDT	Ultrasonic Testing Based Nondestructive Testing
UV	Ultra-Violet
XLPE	Cross-Linked Polyethylene

List of Notations

x(t)	Arbitrary signal
D_g	Degradation growth
$x_j(t)$	Intrinsic mode functions
$r(t)$	Monotonic signal
P	Cauchy principal
$z(t)$	Analytical signal
$a(t)$	Instantaneous signal amplitude
$\emptyset(t)$	Instantaneous signal phase
$\omega(t)$	Instantaneous frequency
P_i	Sum of i_{th} pixel values in region of interest in a grayscale image
P_n	Total number of nth pixels in region of interest
API_0	average pixel intensity of initial UT NDT measurement data
API_n	average pixel intensity of initial UT NDT measurement data for n intervals (n = 0,1,..,4)
u_k	Predicted States
k	Number of days index K (k = 1,2,3, …, K)
U_c	Amplitude of the ultrasonic emissions
L_m	Equivalent inductance of the model
y_k	Measurements at instant k data (with additive noise)
$y_{1:k}$	Previous measurements 1 to k
$p(u_k\|y_{1:k})$	Posterior density
$p(y_k\|u_k)$	Likelihood density
$p(u_k\|y_k - 1)$	Prior density
$p(u_{K+F}\|y_{1:k})$	Predictive density
u_{K+F}	Future states at K + F days
F	Total number of predicted states
K	Maximum number of days (until which the measurements are available)
N_s	Total number of samples (drawn from importance density)
u_k^i	Total no. of i_{th} states with associated weights w_k^i at k instants
$p(u_k\|y_k)$	Posterior PDF
$q(u_{1:k} - y_{1:k})$	Importance density
β	Shape parameter
n_k	Random noise for kth instants
E_c	Electric field strength between the conductors
ω	Frequency of the ultrasonic discharge

a	Scalar value to control the variation in the results (predicted states)
c_d	D_{th} order Polynomial coefficient
u^*	State with updated weight
$\hat{u}$	State without updated weight
f	Total no. of required future states (f = 1, 2, 3,4,5 …, F)
$E_{k,f}$	Error between the actual sates (with updated weights) and the predicted states (without updated weights) at k instant
$E_{k,1}$	1-step error at k instant
$E_{k,2}$	2-step error at k instant
$E_{k,3}$	3-step error at k instant
$E_{k,4}$	4-step error at k instant
$E_{k,5}$	5-step error at k instant
S_p	Signal Power
N_p	Additional noise power
σ	Amplitude of computed signal
N_{rms}	Amplitude of additional noise in RMS form
n	Discretized Location
x_n	Flaw depth at discretized location (State)
z_n	NDE measurement at discretized location
N	Total number of discretized locations
$\bar{z}_n$	Set of measurements at the discretized location due to O measurement modes
$\vec{Z}$	Set of measurements correspond to all measurement modes O at all locations N
$\vec{X}$	Set of states
L	Parameter controlling size of the neighbourhood
x_n^i	i^{th} sample (particle) at n discrete location
w_n^i	Assigned normalized weight to x_n^i at location n
N_s	Total number of samples
N_{eff}	Effective sample size
N_T	Threshold level of degeneracy
N_{deg}	Degeneracy rate
$\hat{x}_{n\|n}^{MMSE}$	Posterior mean estimate
h^o	Function of measurement process by o^{th} measurement mode
x_m^*	New set of samples (after resampling)
o	measurement mode