Using Power Line Modems Measurements for Degradation Detection on Power Lines

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Abstract

We propose a novel approach for power line diagnostics using channel measurements of power line communication devices. This approach does not require the test subject to be taken out of service. Periodic channel measurements provide insight into possible quality degradations of cables as well as information on locations of degradations. We show to which extent reliable information can be obtained for the test subject and investigate the influence of various parameters, and of noise on the performance of detection.

Index Terms

PLC, cable degradation, TDR, FDR, TLT

I. INTRODUCTION

COST efficiency and supply reliability are of major interest for power grids and networks. In order to avoid outages due to cable faults, power cables are usually replaced at fixed service intervals. At medium voltage (MV) level it is best practice to carry out measurements to determine the remaining life time of cables. Very common approaches are time-domain and frequency-domain reflectometry (TDR and FDR), c.f. [1], [2], and [3]. Both methods exploit the fact that cable degradations lead to discontinuities in the wave impedance along the power line. These discontinuities cause reflections of waves that are injected at one end of the line. By measurements and signal processing the existence and location of cable degradations can be determined. The drawback of those methods is that the cable has to be taken out of service and thus the measurements are time-consuming and expensive. Therefore, this method is usually not applied in the low voltage domain. We introduce a novel approach for power line diagnostics using channel measurements of power line communication (PLC) devices employing pilot symbols within an orthogonal frequency-division multiplexing (OFDM) frame. This approach does not require the test object to be taken out of service, although relies on the same mechanism as TDR and FDR.

II. TRANSMISSION LINE MODEL

We use the common model for transmission lines, which divides the transmission line into N defined segments of equal length, much smaller than the wavelength of interest. Each of the segments is then described using the lumped-circuit approximation with discrete resistors, capacitors, inductors, and conductances. The discrete elements of the lumped-circuit are described using the *per-unit-length* parameters. A perfect power line would have constant per unit length parameters for its complete length. Due to aging processes, or damage to the insulation or core by physical stress, the parameters change for the aged or damaged part of the cable. At every change in cable parameters, part of an incoming wave's energy is reflected, a fact which is exploited by TDR and FDR, as well as by the proposed method.

III. PROPOSED DETECTION APPROACH

The channel transfer function $H(f)$ estimated by the power line modem in order to perform equalization is used to detect degradations. For an unknown cable possibly connected to an unknown network with unknown loads at the endpoints, we cannot decide whether the measured transfer function represents a healthy or a degraded cable. We therefore assume the power line modem is deployed while the cable is in healthy condition, and save the channel transfer function for this healthy state as $H_{\mathrm{healthy}}(f)$. We are then able to monitor for long-term changes in the channel transfer function, and

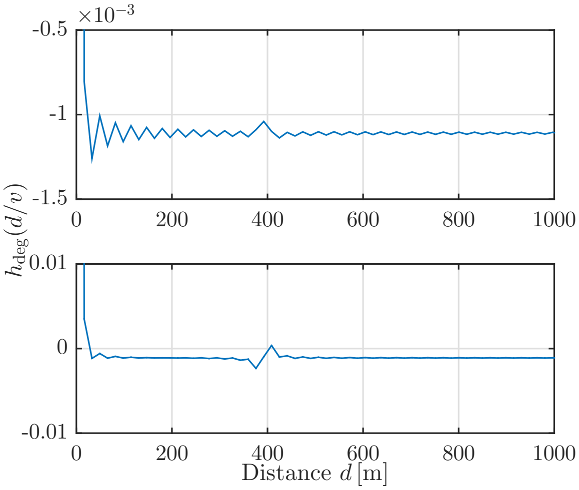


Fig. 1. Example estimated degradation transfer functions for a cable of $1\,\mathrm{km}$ length, a fault of $1\,\mathrm{m}$ which is located $200\,\mathrm{m}$ from the transmitter with a change in capacitance (upper) or conductance (lower)

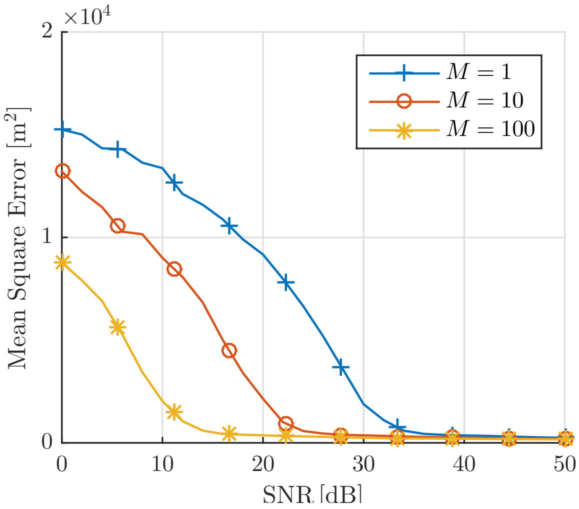


Fig. 2. Mean square error of location of degradation estimation, for various averaging factors of the received signal over SNR. Identical setup as figure 1

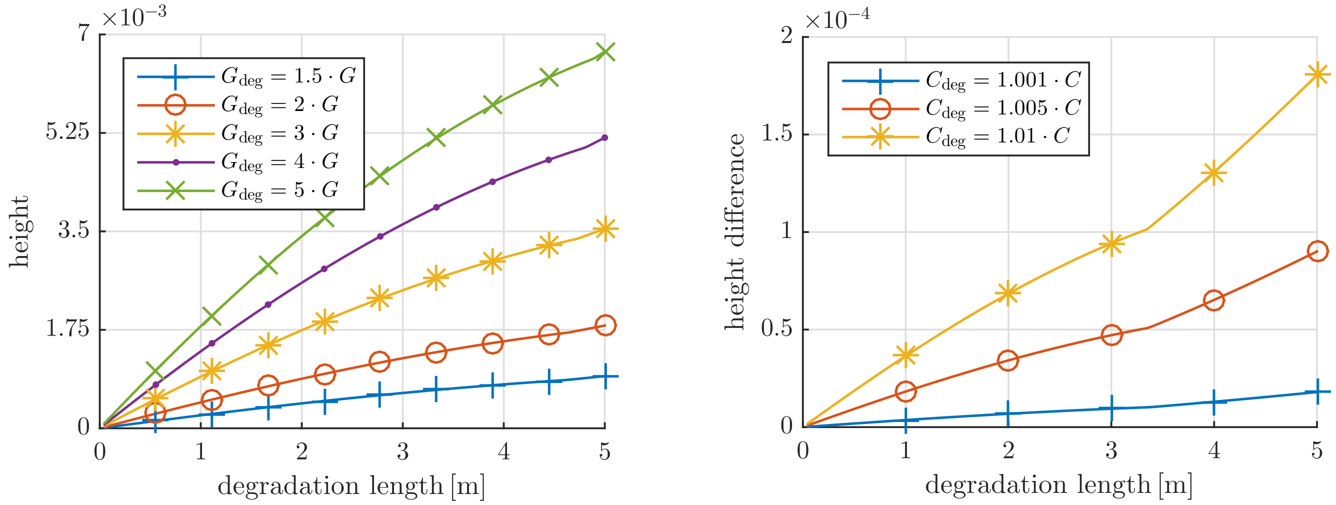
detect when and where the cable degrades. Considering a very small cable segment that is degraded, the estimated transfer function $H(f)$ may be written as a product of the recorded healthy transfer function $H_{\text{healthy}}(f)$ and a degradation transfer function, $H_{\text{deg}}(f)$, as $H(f) = H_{\text{healthy}}(f) \cdot H_{\text{deg}}(f)$. Or using time domain, the currently measured impulse response may be represented as convolution of the healthy impulse response with the degradation impulse response. In order to determine the location of the degradation, we use the time domain degradation impulse response. The straightforward approach would be to divide the measured channel transfer function by the recorded, healthy-state transfer function. However, the measurement of the transfer function is impaired by noise, which leads to an ill-posed problem: $H(f) = H_{\text{healthy}}(f) \cdot H_{\text{deg}}(f) + N(f)$. Reordering gives $\frac{H(f)}{H_{\text{healthy}}(f)} = H_{\text{deg}}(f) + \frac{N(f)}{H_{\text{healthy}}(f)}$, leading to noise-amplification at frequencies where $H_{\text{healthy}}(f)$ is small. A possible solution is water level regularization [4], which "fills" $H_{\text{healthy}}(f)$ up to a certain level: $G(f) = w$, if $|H_{\text{healthy}}(f)| = 0$, $G(f) = w \cdot H_{\text{healthy}}(f)/|H_{\text{healthy}}(f)|$, if $0 < |H_{\text{healthy}}(f)| \leq w$, and $G(f) = H_{\text{healthy}}(f)$ else. An approximation of the true degradation transfer function is then obtained as $\tilde{H}_{\text{deg}}(f) = H(f)/G(f)$.

IV. RESULTS

Figure 1 shows a proof-of-concept for a setup with a cable of $1\,\mathrm{km}$ length, with a degraded segment of one meter length at $200\,\mathrm{m}$ distance from the transmitting modem, without noise. The degradation had a capacitance increased by one percent for the upper plot, and conductance five times as large as the undegraded cable for the lower plot. We are able to see a pronounced anomaly at a time equivalent to $400\,\mathrm{m}$: The original wave was reflected at the degradation at $200\,\mathrm{m}$, traveled back to the transmitter and was reflected there, again, resulting in an overall delay (compared to the original wave) of $400\,\mathrm{m}$.

a) Influence of noise on a simple detection algorithm: A simple algorithm that has low complexity and may therefore be implemented within power line modems is to first apply water level regularization, and then search the degradation impulse response for an anomaly. To assess the influence of noise on the detection quality, we added noise to the measured channel transfer function characterized by a signal to noise ratio (SNR). To combat noise, the algorithm averages up to 100 measurements of the transfer function. Results using the same setup as in figure 1 are shown in figure 2: Assuming a common signal to noise ratio for power lines of $20\,\mathrm{dB}$, 100 measurements were sufficient to detect and localize the degradation correctly.

b) Influence of degradation length, kind, and severity: The per unit length parameters most influenced by degradations are the conductance and capacitance of the cable. Typical conductance changes caused by degradations range up to five times the original conductance. The changes in capacitance are more subtle, ranging up to several percent [5]. However, small changes in capacitance have high influence on the resulting transfer functions: Due to the change in phase caused by the change of capacitance, the location of peaks is altered. The chosen approach of deconvolution yields an impulse response with decaying ripples. A deviation in conductance changes the attenuation only, yielding a deconvolved impulse response with one or more dirac-delta impulses. This makes changes in capacitance more probable to be detected, but hard



(a) Height of degradation peak for change in conductance

(b) Height of degradation peak for change in capacitance

Fig. 3. Influence of degradation length, severity, and kind on detection possibility

to localize (there is still one main maximum in the impulse response at the fault location, but it is more probable to miss this due to noise), and changes in conductance are hard to detect (as the single maximum may be mistaken for noise), but easy to localize. Example impulse responses for both changes in capacitance and conductance are shown in figure 1.

The spatial extent of the degradation has high influence on the possibility to detect the degradation. To investigate the influence of degradation length, we again use a line of $1\,\mathrm{km}$ length, with a degradation of varying length at $250\,\mathrm{m}$. To evaluate the influence, we measured the total height from local maximum to local minimum resulting from the degradation. Figure 3a shows the height of the local maximum produced by degradations resulting in conductance change, and figure 3b shows the height for degradations increasing the capacitance of the cable. Both length and severeness of the degradation determine the detectability. Increased length increases the height of the peak, while the severeness determines how much an increase in length increases the height of the peak.

c) Influence of loads at endpoints: The loads at the endpoints have high impact on the ability to detect anomalies: If the load at an endpoint matches or almost matches the line impedance of the connected power line, incoming waves will not be reflected but absorbed at that endpoint. Whether a matched line end impedance is an advantage for degradation detection or not depends heavily on the size of the network and on how many nodes in the network have matched impedances. If all endpoints are matched, the reflection at the degradation will only be visible at the transmitter of the original wave, rendering detection at all other endpoints impossible. The other extreme would be no matched endpoint, resulting in lots of reflections making it hard to distinguish between single reflections and to determine the origin of the reflection.

V. CONCLUSION

We proposed a novel approach for degradation estimation and localization for power lines using PLC modems, that is inspired by the well known time and frequency domain reflectometry methods. Preliminary results show promise in both detection and localization of degradations, even in noisy conditions. The ability to detect and to localize a degradation depends on the kind and size of the degraded part. Advantages over traditional reflectometry methods include that the measurement candidate does not have to be taken out of service, and that the proposed method can be implemented with already deployed hardware. We consider this a unique selling point for PLC devices, as the PLC device helps asset management by providing information about the deployed cables, saving both time and money.

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