CAPACITIVE VOLTAGE SENSORS FOR AN AUXILIARY FAULT LOCATING SERVICE WITH TRAVELING WAVES

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ABSTRACT

Power system operators worldwide rely on faulted circuit indicators for fast fault isolation in medium voltage grids. Thereby, directional fault information may be provided to the network control center via a communication link. However, if the communication should suffer from temporarily disturbances, then the fault isolation and service restoration process will be delayed. This paper presents an auxiliary fault locating service based on traveling wave analysis. Thereby, the main idea is to make use of the capacitive voltage sensors that are installed by default in substations standard for safety reasons.

INTRODUCTION

Electric power supply reliability is measured by the frequency of disturbances and the corresponding downtime of affected end-customers. With the rise of distributed generation in medium voltage level and the idea of process control automation, remote faulted circuit indicators with directional measurement are introduced as the backbone of fast isolation schemes, such as in [1]. Faulted circuit indicators are installed within the secondary substations along the feeder and provide directional fault information by local measurements to the network control center via a communication link. As the system operators rely on these devices, the risk of temporarily communication disturbance may delay the isolation process in the aftermath of a line fault event. This issue was addressed in [2] and an impedance based distance calculation such as in [3] was proposed. However, the accuracy of the approach may be affected by the distributed feed-in. Furthermore, the approach can be understood as a functional upgrade of faulted circuit indicators principle. Yet, in case of wireless communication disturbance not only a single but many or even all nodes of the feeder might not be able to provide the fault information to network control center. Especially in rural regions the line fault itself might cause wireless communication disturbance since base stations might be deployed without battery storage as power backup. In this work an auxiliary fault locating service based on traveling wave analysis is presented, that shall provide a fall-back option in case of communication disturbance. The service shall be integrated at substation feeder level and see beyond the feeder nodes in order to determine the fault distance. Thus, if a crucial faulted circuit indicator should fail, then the auxiliary service shall provide its fault distance information to network control center via a dedicated, wire-bound communication link.

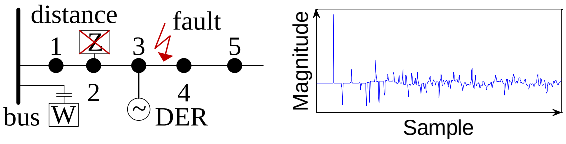

Figure 2: Proposed traveling-wave auxiliary fault locating service (W) with capacitive voltage sensor connection – grid (left) wavelet coefficients of wave reflection pattern at bus (right)

As indicated in Figure 2, the fault distance calculation is based on local transient measurements only and exploits the reflection pattern of the fault generated traveling waves. Whereas in many other works a Rogowski coil is the preferred solution for traveling wave measurement as in [4], this work is based on the idea to exploit the capacitive voltage sensors within the medium voltage substation, as suggested in [5]. Those are capacitive voltage dividers as known from high voltage applications. They supply indicators that inform the personnel that a bay is under voltage or not. To confirm the proposal, the transfer functions of a capacitive voltage divider and a Rogowski coil are compared in simulation.

FAULT LOCATING SERVICE

The methodology for the fault locating service is based on single ended traveling wave analysis. Thereby, the fault path characteristic frequencies are derived from the traveling wave reflection pattern of three phase voltage measurement and used to identify the fault path as in [6]. Following that, the reflection pattern from the fault is given as input to a support vector machine (SVM) classifier to determine the fault distance from the measurement site.

Principle of Traveling Wave Fault Locating

With the electric fault incident, electromagnetic waves are generated that propagate along the lines and get partly or totally reflected at points of discontinuity depending on the surge impedance ratio. Discontinuities are power transformers, short circuits, joints of parallel lines or open line terminals. The reflection factor of the voltage wave $\rho_{r,u}$ for an electrical fault can be calculated as in (1) with the surge impedance Z_0 and the fault resistance R_f.

$$\rho_{r,u} = -\rho_{r,i} = \frac{R_f||Z_0 - Z_0}{R_f||Z_0 + Z_0} \quad (1)$$

The wave velocity v can be calculated by (2) with the inductance L' in H/km and the capacitance C' in F/km.

$$v = \sqrt{1/(L'C')} \quad (2)$$

In a first step, the expected path characteristic frequencies are determined as in [6] according to (3) with the frequency $f_{p,i}$ of path p and propagation mode i, the velocity v, the path length l_p and the number of times until the same wave polarity is registered at the measurement site n_p. Thereby, the mode refers to Clarkes transform α-, β- and γ-mode.

$$f_{p,i} = \frac{v_i}{n_p l_p} \quad (3)$$

The expected path characteristic frequencies are compared to the measured frequencies. Thereby, signal processing technique such as fast Fourier transform as in (4) or continuous wavelet transform as in (5) may be used to identify the frequencies from the measurement.

$$X(k) = \sum_{n=0}^{N-1} x(n)\, e^{-j2\pi kn/N} \quad (4)$$

Thereby, *X(k)* is the complex Fourier coefficients for the frequencies specified by *k*, *x(n)* is the sampled signal and *N* the sample number.

$$C(a, iT_s) = T_s \frac{1}{\sqrt{|a|}} \sum_{n=0}^{N-1} \left(\vartheta^* \left(\frac{nT_s - iT_s}{a} \right) s(nT_s) \right) \quad (5)$$

Thereby, T_s is the sampling period, N the sample number, a the scale, iT_s the time shift and ϑ the mother wavelet. Whereas the continuous wavelet transform offers a higher frequency resolution and provides both frequency and time, the fast Fourier transform takes less computational effort and is easier to implement. Figure 3 shows the computed fast Fourier transform for a fault in 5.5687 km distance from measurement site.

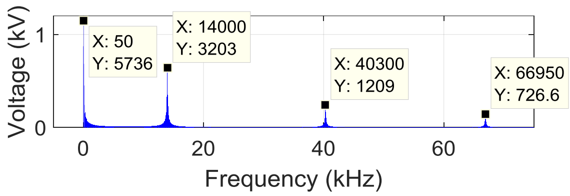

Figure 3: Fast Fourier transform of α-mode fault voltage measurement (l_1=5.5687, n_1=4, v=0.2998 *km/µs*, $f_{1,\alpha}$ =13.36 *kHz*)

Whereas the expected path characteristic frequency was calculated to be 13.36 *kHz*, instead a path frequency of 14.0 *kHz* is identified with the fast Fourier transform. In comparison, the continuous wavelet transform provides with 13.29 *kHz* a value very close to the expected frequency. Figure 4 shows the corresponding scalogram with the frequency and the wavelet transforms coefficients.

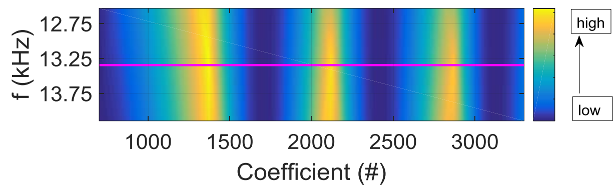

Figure 4: Continuous wavelet transform of α-mode fault voltage measurement (l_1=5.5687, n_1=4, v=0.2998 *km/µs*, $f_{1,\alpha}$ =13.36 *kHz*)

In the final step, the reflection pattern is used as input for a SVM-classifier that is specifically trained for the determined fault path or rather the faulted feeder section. SVM is a method from machine learning to separate input data representing different classes from each other according to specific features. The optimization problem is given by the dual problem formulation $L_D(w,b,\alpha)$ as in (6) with the weights w, the bias b the support vectors α, the classes y, the Kernel function K, the input values x and the number of input entities n.

$$L_D(w, b, \alpha) = \sum_{i=1}^{n} \alpha_i - \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} \alpha_i \alpha_j y_i y_j\, K(x_i x_j) \quad (6)$$

Thus, the fault distance to the measurement site is determined.

Measurement of Traveling Waves

Conventional sensors such as inductive transformers have only a limited bandwidth and may distort signals with high frequency components. Instead, Rogowski coils for current measurement show linear behaviour, have a wide bandwidth and don’t suffer from iron core saturation. As an alternative capacitive voltage dividers can be used for traveling wave measurement.

Rogowski coil

Figure 5 shows the Rogowski coil electrical circuit according to [4] with the input voltage u_{in}, the output voltage u_{out}, the resistance R, the inductance L, the capacitance C and the termination impedance Z.

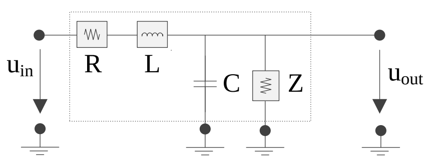

Figure 5: Common Rogowski coil circuit

The corresponding transfer function H_1 is as in (7). The assumed parameters are from the same literature and are listed as parameter set *#1* in Table 1.

$$H_1(s) = \frac{Z}{LZCs^2+(L+RZC)s+(Z+R)} \quad (7)$$

Table 1: Rogowski coil parameters

Set (#)	*R* (*Ω*)	*L* (*µH*)	*C* (*nF*)	*Z* (*kΩ*)
1	0.11	0.6	50.3	2
2	0.11	0.6	50.3	0.01

Capacitive voltage divider

Figure 6 shows the circuit of the capacitive voltage divider as given in [5] with the input voltage u_{in}, the output voltage u_{out}, the resistances R_1 and R_2, the capacitances C_1 and C_2 and termination resistance R_m.

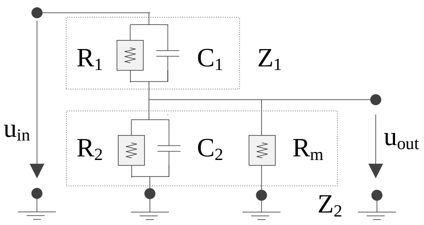

Figure 6: Circuit of capacitive voltage divider representing the voltage sensor characteristics

The corresponding transfer function of the capacitive voltage divider is as in (8).

$$H_2(s) = \frac{u_{out}}{u_{in}} = \frac{Z_2}{Z_1+Z_2} = \frac{Numerator}{Denumerator} = \frac{N_1 s+N_2}{D_1 s+D_2} \quad (8)$$

with:

$N_1 = C_1 R_1 R_m R_2$ $\quad N_2 = R_m R_2$

$D_1 = R_1 R_m R_2 (C_1 + C_2)$ $\quad D_2 = R_m R_2 + R_1 R_m + R_1 R_2$

The assumed parameters are listed in Table 2 as in [5].

Table 2: Capacitive voltage sensor parameters

Set (#)	R_1 (*MΩ*)	C_1 (*pF*)	R_2 (*kΩ*)	C_2 (*nF*)	R_m (*MΩ*)
1	100	3	16.25	18.5	10

FAULT SIMULATIONS

For simulation of fault generated traveling waves a representative medium voltage power system has been modelled in MATLAB/Simulink® with a simulation step time of 0.05 *µs*. Then, simulated three phase voltage sequence has been used as input for the measurement equipment with the transfer functions H_1 and H_2.

Power System Model

The power system model for the fault simulations is based on the IEEE-34 distribution test network. However, some modifications have been made to simplify the setup. Figure 7 shows the modelled grid with the nodes 800 to 814, a DER and a voltage regulator at the termination of node 814.

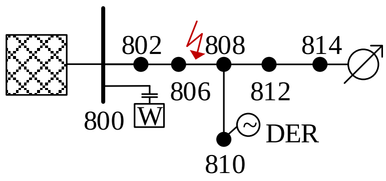

Figure 7: Modelled part of IEEE-34 distribution grid with auxiliary traveling wave fault locator (W) and capacitive voltage divider

Line model

The distributed parameter line model has been used since it considers the deterministic wave propagation, though without frequency dependent line parameters. The used line parameters for α-mode and γ-mode as well as the wave velocity are listed in Table 3.

Table 3: Line parameters and wave velocities

Mode	*R* (*Ω/km*)	*L* (*mH/km*)	*C* (*nF/km*)	Z_0 (*Ω*)	*v* (*km/µs*)
γ	0.984	2.367	5.832	638	0.269
α	0.136	0.908	12.43	270	0.298

Simulation Results

In this work solid three phase faults with a fault resistance of 1 *Ω* were considered. The simulated voltage *α*-mode at node 800 for a fault on section s_1 with a distance to the measurement site of 5.5687 km (see Figure 7) was used as input for the transfer functions of the Rogowski coil and the capacitive voltage sensor. Figure 8 shows the result for the Rogowski coil (H_1) with set *#1*. It can be seen that even though oscillations occur on the secondary measurement side, the ingress times of the traveling waves can be recognized.

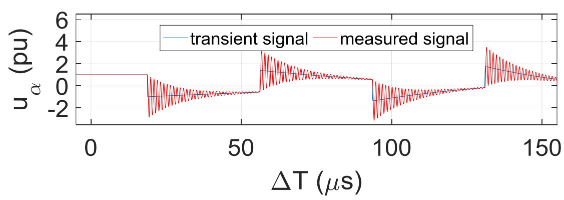

Figure 8: Measured signal for Rogowski coil with parameter set *#1*

However, for set *#2* the transfer function H_1 provides a better result as shown in Figure 9. Anyway, some oscillations still exist in the measured signal.

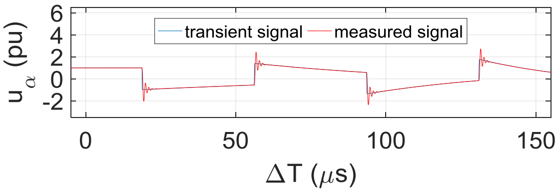

Figure 9: Measured signal for Rogowski coil with parameter set *#2*

In comparison, the capacitive voltage sensor with the transfer function H_2 and the parameter set *#1* provides a very accurate result without any oscillations on the secondary side of the measurement, as show in Figure 10.

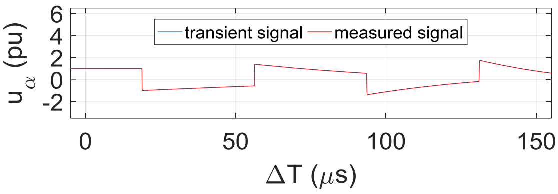

Figure 10: Measured signal for transfer function H_2 with parameter set *#1*

Since the measured signal for the capacitive voltage divider matches the expected signal, it can be concluded that it is suited well for traveling wave measurement and thus for the fault locating scheme as well.

CONCLUSION AND OUTLOOK

In this work an auxiliary fault locating service based on traveling wave analysis was presented, that makes use of the capacitive voltage sensors at substation site. Whereas a common Rogowski coil might have oscillations on the secondary measurement side which can influence the identification of path characteristic frequencies, the capacitive voltage sensor in this work shows no oscillations and therefore is suitable for traveling wave measurement. In future works it is planned to test the measurement with capacitive voltage divider and the fault locating scheme for different fault locations and fault types such as single pole fault. Furthermore, a field test of the fault locating scheme should be done in future works.

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