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Incipient fault location formulation: A time-domain system model and parameter estimation approach

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ABSTRACT

Power systems faults are unavoidable events which affect distribution networks reliability. The fault process in underground cables is gradual and characterized by a series of sub-cycle incipient faults associated with an arc voltage. These events often are unnoticed and eventually result in permanent faults. This paper presents an incipient fault location formulation for distribution networks with underground cables. Presented formulation is composed by a time-domain system model and parameter estimation strategy. System model derivation considers distribution networks inherent features as unbalanced operation and underground distribution cables capacitive effect. Further, incipient fault characteristics as fault arc voltage are considered. The proposed system model is an overdetermined linear system of equations in which the fault location is estimated through a parameter estimation approach. Parameter estimation is made through a Non-Negative Weighted Least Square Estimator (NNWLSE). Smoothing and curve-fitting procedures are applied to input data aiming to decrease the noise effect. A load current compensation strategy is proposed to reduce its effect in the fault current estimation and a back substitution method is proposed for estimation refinement. Validation is performed using real-life distribution network with underground cable data simulated on ATP/EMTP. Test results are encouraging and demonstrate the method's potential for real life applications. An average error of 1.95% is obtained when compared with 6.48% derived using the state-of-art.

1. Introduction

The use of Underground Distribution Systems (UDS) has increased dramatically in recent years. UDS are defined in this manuscript as distribution networks with underground cables. This increase is due mainly to the benefits of UDS operation, as overall higher reliability, environment-friendly and low-maintenance requirements [1,2]. Moreover, UDS are normally used in big urban areas, with high population density and important loads. However, this greater use also presents new challenges to protection engineers, as incipient faults location.

Faults in underground cables are generally classified into two categories: (a) incipient faults and (b) permanent faults [1–4]. Incipient faults are the result of a gradual aging process which causes a local degradation in the insulation material. Other phenomena such as overvoltage in conjunction with mechanical defects, unfavorable environmental conditions and chemical pollution can also cause irreparable and irreversible insulation material damage [1,3,5–8]. Usually, incipient faults are Single Line-to-Ground (SLG) type and over time become permanent faults [2–5,8–10].

Different methodologies for Fault Location (FL) on Distribution Systems (DS) have been proposed throughout the years. The great majority of those are based on the apparent impedance estimation or on traveling wave analysis [3,11–14]. These techniques are designed for permanent faults and use one or more fault signal cycles data for FL estimation. Nevertheless, faults in cables are a gradual process and the transformation of an incipient fault into a permanent fault can last several months, in contrast to faults in overhead lines [1–3]. This is because faults in cables are initially self-clearing, sub-cycle incipient faults that do not sensibilize overcurrent protection equipment [4,8,10,15].

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Currently, distribution utilities mainly use two methods for FL on UDS, which are two-step based: pre-locate and pinpoint. The pre-locate step uses terminal methodologies, which measure electrical quantities at one or both line ends. After, tracer methods are used to pinpoint the FL and, usually request walking the cable route. Both approaches are off-line and on-site techniques, being implemented with the system out-of-service and characterized by low-performance efficiency [9,10].

On the other hand, recently, several incipient FL formulations for UDS have been proposed. A traveling wave based method is presented in [16]. The algorithm uses a Time-Domain Reflectometer (TDR) and a Transient Recording System (TRS). Encouraging results are presented. Nonetheless, equipment with high sampling frequency rate and precise wave front arrival time recording is required, which increase capital cost and may hinder real life applications. Methods as [17–22] present time-domain formulations for incipient or intermittent FL on UDS. These methodologies are impedance-based and use one-terminal measurements. Common approximations are made in the line model, such as not consideration of mutual inductances or shunt capacitances. Still, fault arc voltage is also not considered, with some methods assuming a zero resistance [17,18] or a constant non-zero resistance [19–22]. In addition, the inherent unbalanced operation of UDS is not taken into account [17,18,22]. However, typically an arc voltage is associated with incipient faults [8,23], underground cables have a considerable capacitive effect and UDS have an inherently unbalanced operation [24].

A voltage-sag based approach for self-clearing sub-cycle incipient FL on DS is also presented in [25]. In this work, a half-cycle Discrete Fourier Transform (DFT) is used for phasor extraction. The proposed work presents most impressive results. Nevertheless, the location and number of measurement devices affect significantly the method's precision and increase capital cost. Additionally, an incipient FL formulation on time-domain for UDS based on one-terminal data is proposed in [2]. In this work the fault arc voltage is modeled as a square wave in phase with the arc current and precise estimation results are reported. Nonetheless, the formulation does not take into account several inherent UDS characteristics, as unbalanced operation, load currents effect and complete underground cable model.

Considering the previously exposed, this paper presents an incipient FL formulation for UDS, which is composed by a system model and parameter estimation strategy. The system model is developed on time-domain using phase components. During model derivation, inherent features of distribution networks as unbalanced operation, load currents effect and complete underground cable model are considered. Furthermore, the proposed formulation considers an incipient fault model with arc voltage and only local voltage and current measurements as input data. As a result, the system model is an overdetermined linear system of equations, which is solved using a Non-Negative Weighted Least Square Estimator (NNWLSE). The NNWLSE weight matrix is derived considering the measurement magnitude value [26]. Aiming to decrease the noise effect on parameter estimation, methods of smoothing and curve-fitting are applied. A load compensation strategy is proposed to reduce the load current effect on the fault current estimation. A back substitution method is applied to refine the estimation.

In summary, the main contributions of this work are:

- A new system model for SLG incipient faults. System model is on time-domain and uses phase components. Unbalanced operation, incipient fault model with arc voltage and the complete underground cable model are considered during system model derivation.
- A load current compensation strategy is proposed to reduce its effect. The hypothesis is that due to fast incipient fault dynamics, downstream from the FL load current is assumed constant during the fault period.
- A NNWLSE for parameter estimation of the overdetermined linear system model is proposed. Weight matrix calculation considering the measurement magnitude value is used.

The remainder of this paper is organized as follows. Theoretical background is presented in Section 2. Section 3 presents the proposed formulation. Case study and test results are presented and analyzed in Section 4. Conclusions of this work are presented in Section 5.

2. Theoretical background

2.1. Incipient faults characteristics

Usually, electrical overstress simultaneously with mechanical defects, insulation degradation due to aging and adverse environmental conditions causes incipient faults in underground cables. This phenomenon is very common in cable splice. When moisture penetrates the cable splice and isolation, an arc voltage is generated. After, moisture is evaporated creating high steam pressure, which in turn extinguishes the arc. The main physical characteristics of incipient fault are [4–6,8,27–29]:

- Fault duration can be of sub-cycles (¼ to ½ cycle) or multicycles (up to 4 cycles).
- Usually, the fault initiates near of the positive or negative peak of the voltage waveform, and ends when the arc voltage cools off, which occurs when fault current reaches zero.
- Due to the increase in the current magnitude in a short time, conventional overcurrent devices do not operate.
- Incipient faults are precursors of permanent faults. The frequency of incipient fault occurrence increases over time. Usually incipient faults are characterized initially by one or two isolated events, with occurrence frequency increasing just before it becomes a permanent fault.
- Generated arc voltage waveform is similar to a square wave with a small transient that occurs at each half cycle. Arc voltage and fault current are usually in phase.

Fig. 1 illustrates the voltage and current signals obtained from a simulation of an incipient fault using ATP/EMTP [38] and a programed arc dynamic model [31–34]. System data and simulation conditions are presented in the following sections.

2.2. Arc voltage modelling

An arc is a self-sustaining electrical discharge caused by a short-circuit [30,31]. Arc voltage remains constant over a wide range of arc currents and arc lengths, therefore, the arc resistance is a non-linear function of the arc voltage [8,30]. The presence of high odd harmonics causes the resemblance between the arc voltage and a square waveform [8]. In this context, the arc voltage can be modeled with dynamic [31–34] or static formulations [31,33,35–37] as follow.

2.3. Dynamic model

Dynamic formulations model the arc voltage considering that the voltage vs current characteristic resembles a hysteresis curve. Thus, an empirical differential equation for the dynamic conductance $g(t)$ is proposed, as presented in (1)(3). The arc voltage is