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Adaptive ground distance protection for UPFC compensated transmission lines: A formulation considering the fault resistance effect

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ABSTRACT

This paper presents a mathematical deterministic adaptive distance protection formulation for UPFC compensated transmission lines. The proposed formulation is developed using a phase component approach and considers and compensates for various UPFC operation conditions and non-zero fault resistances. The proposed methodology is completely adaptive and independent of system characteristics (such as changes in transmission line impedances) or operating conditions (such as different load conditions and controlled reference parameters). Moreover, the proposed formulation uses local and remote end voltage and current signals as input data. The comparative test results demonstrate potential beneficial aspects of the proposed formulation for real-time applications.

Introduction

Increasing transmission capacities is always a difficult task. This is mainly due to environmental and political issues and the increasing difficulties involved in obtaining transmission rights of way. FACTS controllers (Flexible AC Transmission Systems) have been used as an alternative method to increase existing transmission line transmission capacities [1,2]. The FACTS concept is very broad, and prominent FACTS devices include Phase-shifting Transformers (PSTs), Thyristor-controlled Series Capacitors (TCSCs), Static Var Compensators (SVCs), Static Synchronous Compensators (STATCOMs), Static Synchronous Series Compensators (SSSCs) and Unified Power Flow Controllers (UPFCs). UPFCs, which are a combination of SSSCs and STATCOMs, are arguably the most versatile and complete FACTS device [1,2].

FACTS provide many benefits for electric power system operations. They enable the control of power flows and improve transient and steady-state stability [1,2]. However, the use of FACTS can result in various issues, such as the misoperation of transmission line distance protection relays [3], which constitute the main transmission line protection equipment [4–7]. The presence of FACTS devices introduces changes in transient and steady-state voltage and current signals that are not considered in current distance protection formulations. Thus, to provide a proper impedance estimation, the admittance added by the UPFC [3] should be considered.

In an attempt to address these issues, the negative effects of using FACTS on transmission line distance protection systems are presented in [3,8–15].

A study of the SSSC effect on distance protection and an adaptive protection methodology is presented in [11,16]. Similarly, [10,9] presents an adaptive methodology for distance protection in the presence of SVCs. In [15], the author presents an adaptive formulation to protect transmission lines compensated via STATCOM based on synchronized measurements. A study of the effects of UPFC on distance protection and novel adaptive distance protection methodologies is presented in [8,12–14].

All previously cited works were performed using symmetrical components. In these studies, new trip characteristics are generated by searching all possible system operating conditions, FACTS device control conditions and fault resistances. None of them performs the fault resistance estimation. Furthermore, any change in operating conditions (such as different load conditions and different controlled reference parameters) or system parameters (such as changes in transmission line impedances) imply the need to generate new trip characteristics. The work in [15] is the only work that presents an adaptive tripping characteristic without the need to generate new trip characteristic for every change in system operating characteristics. However, this work only considers STATCOM's compensation at the transmission line mid-point.

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This paper presents a ground distance protection mathematical deterministic formulation developed using phase coordinates. The formulation is developed using phase coordinates to suit both balanced and unbalanced systems as well as UPFC compensated systems. The proposed formulation considers the influence of the UPFC-controlled parameter knowledge-based scheme and the fault impedance estimation, thereby offsetting the influence of these properties on relay-estimated impedance. Additionally, the proposed formulation uses adaptive offset currents and voltages injected by the UPFC located at the sending end. The consideration of balanced and unbalanced systems, as the fault impedance compensation under those conditions, is a significant innovation compared with previous works and is considered to be the main contribution of this study to the state of the art. It is important to note that the proposed methodology is completely adaptive and independent of system characteristics or operation conditions. This means that any change in system operation parameters (different load conditions or different controlled reference parameters), transmission line impedances, fault impedances and UPFC-controlled parameters will be automatically compensated. The proposed formulation is not presented in previous works that addressed the fault impedance compensation of distance relays for unbalanced systems [17,18]. The faulted circuit impedance and fault impedance are obtained using measured signals at the sending end, as well as voltage and current phasors of the remote terminal, and using the UPFC considering the WAMS implementation. The formulation was developed as an embedded software package.

The remainder of this paper is as follows. Section 'UPFC modeling' describes the state-of-the-art UPFC model used in this work. Section 'Proposed methodology' presents and discusses the proposed distance protection formulation and demonstrates the derived equations. A case study and the results are presented in Sections 'Case study' and 'Results', respectively. Section 'Conclusion' describes the conclusions of this work.

UPFC modeling

The UPFC controller device was proposed by Gyugyi [1]. This is the most versatile of the FACTS devices and regulates the voltage and controls the power flow. Fig. 1 illustrates the basic structure of the UPFC. The UPFC consists of two Voltage Source Converters (VSCs), one connected in series and one in shunt. Each converter has a capacitor connected in parallel. When the circuit breakers that connect two converters are open, each converter can operate as a STATCOM and as a SSSC [2].

The series converter performs the main task of the UPFC by injecting a voltage in series with the transmission line through the coupling transformer. The series converter controls the magnitude and the angle of the injected voltage. The shunt converter performs the primary function of absorbing the active power to supply the series converter. The active component of the current drawn by the shunt converter depends on the power balance between the series and the shunt part. The shunt converter is independently controlled to provide a voltage support to the coupling capacitors [2,19].

Proposed methodology

The equation presented in [17] can be adapted based on Fig. 2, and the voltage on bus s in phase k can be calculated as follows:

$$V_{F_k} = V_{s_k} + V_{se_k} - Z_{se_k} \cdot I'_{s_k} - x \cdot [\mathbf{Z}l_k] \cdot [\mathbf{I}']_s \tag{1}$$

where

$$\mathbf{I}'_s = \mathbf{I}_s - \mathbf{I}_{sh} \tag{2}$$

and

V_{s_k} is the phase k sending end voltage in units of $[V]$;
V_{se_k} is the phase k UPFC series injected voltage in units of $[V]$;
V_{F_k} is the phase k faulted point voltage in units of $[V]$;
Z_{se_k} is the UPFC transformer phase k series impedance in units of $[\Omega]$;
$\mathbf{Z}l_k$ is the transmission line impedance phase k vector in units of $[\Omega]$;
$\mathbf{I}_s$ is the sending end current in units of $[A]$;
$\mathbf{I}_{sh}$ is the UPFC shunt current in units of $[A]$;
$\mathbf{I}'_s$ is the transmission line current in units of $[A]$;
x is the fault distance in units of line length percent $[\%]$; and
k is the faulted phase $k = \{a, b, c\}$.

The voltage at the sending end can be isolated from (1) as

$$V_{s_k} = -V_{se_k} + Z_{se_k} \cdot I'_{s_k} + x \cdot [\mathbf{Z}l_k] \cdot [\mathbf{I}']_s + V_{F_k} \tag{3}$$

In addition, the voltage at the fault point can be written as

$$V_{F_k} = I_{F_k} \cdot Z_f \tag{4}$$

where Z_f is the fault impedance in units of $[\Omega]$ and I_F is the fault current defined by

$$\mathbf{I}_F = \mathbf{I}'_s + \mathbf{I}_r \tag{5}$$

where $\mathbf{I}_r$ is the remote end current vector.

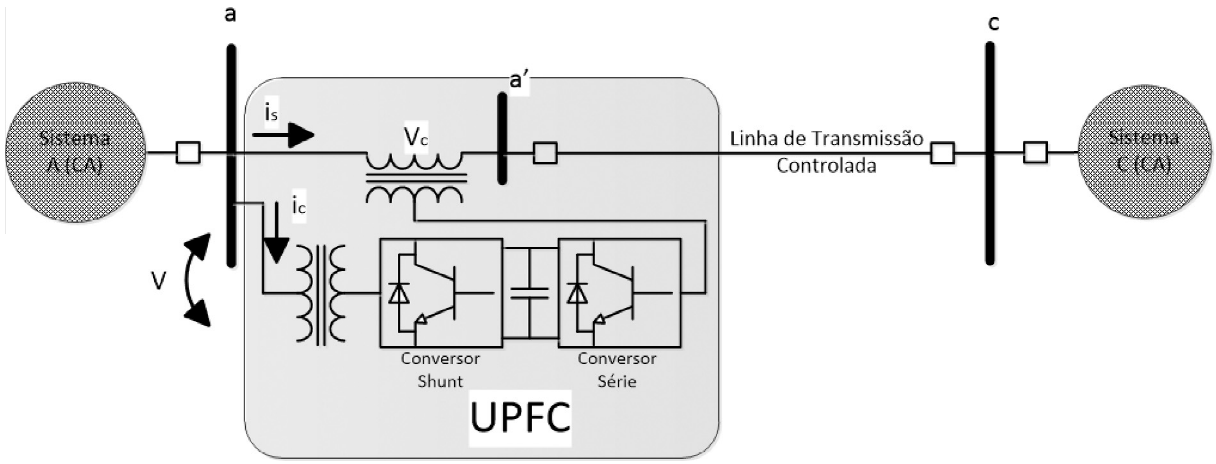

Fig. 1. Basic structure of a UPFC controller.