Synchrophasor Assisted Adaptive Reach Setting of Distance Relays in Presence of UPFC

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***Abstract*—The operation of Flexible AC Transmission System Controllers (FACTS) in the power transmission system pose a challenge to the distance relaying scheme. This paper suggests an adaptive scheme for estimating the trip boundaries of a distance relay in presence of a Unified Power Flow Controller (UPFC), utilizing a Generalized Regression Neural Network (GRNN). Initially, the impact of the UPFC on the relay's trip boundary is studied for its automatic power flow control mode as well as bypass mode of operation. The GRNN has been trained off-line with the data generated from a detailed performance analysis of the power system for various faults considering the effects of the UPFC, fault resistance, and system loading conditions on the trip boundaries. This work has also proposed a strategy that computes the control parameters of the UPFC on-line, namely, series voltage and reactive current injections, utilizing the synchronized phasor measurements from Phasor Measurement Units (PMUs). Pre-fault system states, including the control parameters of the UPFC and the apparent impedance measured by the relay unit have been utilized by the GRNN for predicting the trip boundaries of the relay. The proposed scheme has considered Single Line-to-Ground (SLG), Double Line-to-Ground (LLG) and Three Phase-to-Ground (LLLG) faults and the effectiveness of the scheme has been tested on 39-bus New England system and also on a 17-bus system, a reduced equivalent of practical Northern Regional Power Grid (NRPG) system in India.**

***Index Terms*—Distance relay, generalized regression neural network (GRNN), synchrophasor, trip boundary, unified power flow controller (UPFC).**

I. INTRODUCTION

THE introduction of Flexible AC Transmission System (FACTS) [1] controllers in the power system opens up new challenges to the line protection as they change the impedance of the lines dynamically. Consequently, distance relays, in the associated transmission system, will have an overreaching or underreaching effect depending on the control modes of the FACTS controllers. Hence, determining the boundaries of operation of a distance relay, adaptively in the presence of FACTS controllers, is a challenging task.

An extensive analysis of the distance protection scheme, in the presence of various FACTS controllers, has been carried out in the literature [2]–[8]. It deals with the change in the apparent impedance measured by the relay in the presence of these controllers. The performance analysis in [3] utilizes a steady state voltage source model of the UPFC with fixed compensation levels for studying the effects of location of the UPFC and fault resistance on the distance relay operation. A more exhaustive analysis has been carried out in [4], [5] considering a detailed model of the UPFC. However, [3]–[5] do not discuss the strategies for mitigating the underreach/overreach issues in the distance relays.

The challenge in the distance protection in the presence of FACTS controllers such as UPFC, is due to the variation of its control parameters namely, the series voltage and reactive current injections. These protection issues can be addressed either through the development of dedicated schemes for fault location in transmission lines provided with UPFC [6], [7] or through the adaptive prediction of trip boundaries of the conventional distance relays. The development of dedicated schemes [6], [7] has attracted much more attention as compared to the adaptive trip boundary prediction. As a typical distance relay consists of fault detection, classification, measurement and trip region comparison units, replacing the fixed Mho/quadrilateral trip region comparison unit with an adaptive trip characteristics is an effective option for dealing with the protection issues in the presence of an UPFC. One such scheme has been proposed by the authors' in [8] and was demonstrated only for Single-Line-to-Ground (SLG) fault.

This paper proposes a scheme to predict the trip boundaries of a conventional distance relay in the presence of UPFC through the knowledge of the control parameters of the UPFC. It computes the series voltage and reactive current injection by the UPFC on-line with the help of synchronized phasor measurements [9] and these parameters are utilized in the adaptive trip boundary prediction. Additionally, the scheme also considers the fact that depending on the magnitude of the fault current, the UPFC may change its status to bypass operating mode [10], where series voltage injection is zero.

The proposed scheme is based on Artificial Neural Network (ANN), which has found applications in adaptive reach settings of the conventional distance relays [11], [12]. To adapt to the changes in the system, external to the protected line, an adaptive reach setting concept is presented using three Back Propagation Neural Networks (BPNN) in [11] and by using three Radial Basis Function Neural Networks (RBFNN) in [12], utilizing local signals. These ANN structures suffer from the drawback that they require large training time for learning the several possible combinations of the operating scenarios of the system.

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For overcoming the above drawback, the proposed scheme utilizes a single Generalized Regression Neural Network (GRNN) [13]. Pre-fault system data along with the impedance measured by the relay unit have been utilized by the GRNN for the estimation of the trip characteristics under various faults namely, Single Line-to-Ground (SLG), Double Line-to-Ground (LLG) and Three Phase-to-Ground (LLLG) faults.

The proposed scheme has been tested on 39-bus New England system [14] and also on a reduced equivalent of Northern Regional Power Grid (NRPG) system, India [15], [16]. Trip boundaries generated by the GRNN for various types of faults have been compared with the conventional Mho relay characteristics and also the capability of the GRNN to approximate the function has been compared with that of BPNN. Test results indicate that the proposed GRNN architecture is able to effectively track the relay trip boundary with the pre-fault operating conditions along with the pre-fault control settings of the UPFC.

II. IMPEDANCE ANALYSIS WITH UPFC

A. Unified Power Flow Controller (UPFC)

An UPFC uses a combination of a shunt controller and a series controller interconnected through a common dc bus. Both series and shunt controllers use a Voltage Source Converter (VSC) [17]. One VSC, connected in shunt to the transmission line through a shunt transformer, is operated as a Static Synchronous Compensator (STATCOM). It controls the ac voltage at its terminals and also the dc bus voltage. Reactive current injection is self-adjusted to maintain the voltage at the bus, where the shunt branch is connected. Another VSC, connected to the system through a series transformer, is used to control the active and reactive power flow in the line. The series controller can operate either in automatic power flow control mode or manual voltage injection mode.

As installation of the UPFC requires a sub-station, in practice, it may either be located at the sending end or the receiving end of the line. In this study, the UPFC is located near to the sending end of the line.

B. Impedance Measured by the Relay in the Presence of UPFC

The effect of the UPFC on apparent impedance seen by the relay mainly depends on its location with respect to the fault point and its operating mode under the fault. The most common operating mode of the UPFC is automatic power flow control mode. In this mode of operation, series injection voltage is dynamically adjusted to maintain the power flow in the line to the reference settings. UPFC also assumes a self protection mode called bypass mode, in which power flow can not be allowed through the series controller beyond a certain level. Shunt controller may or may not be connected, if it is intended to provide a voltage regulation feature [10].

1) Automatic Power Flow Control Mode of UPFC: Fig. 1 shows an UPFC installed near a relay point in a line. In general, where the UPFC is included in the fault loop, the measured voltage at the relay consists of the voltage drop in the line, series voltage injection in the line, line drop due to the shunt current injection in the line and the voltage drop in the fault resistance.

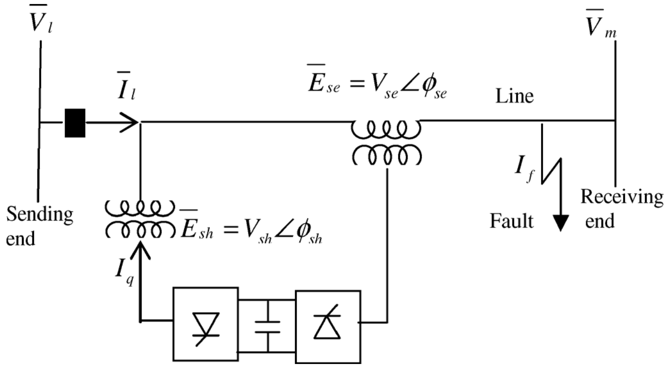

Fig. 1. Transmission line l-m with UPFC located near the relay end.

For a SLG fault, voltage measured at the relay point will be as follows:

$$\overline{V}_l = n\overline{I}_l\overline{Z}_1 + nI_{0l}\left(\overline{Z}_{0l} - \overline{Z}_1\right) + nI_q\overline{Z}_1 + \overline{E}_{se} + R_f\overline{I}_f \quad (1)$$

where $\overline{I}_l$ and $\overline{I}_{0l}$ denote the positive and zero sequence phase currents and $\overline{Z}_1$ and $\overline{Z}_{01}$ stand for the positive and zero sequence impedance of the transmission line. Series voltage source of the UPFC is represented by $\overline{E}_{se}$, $(= V_{se}\angle\varphi_{se})$. Voltage source of shunt branch is denoted by $\overline{E}_{sh}, (= V_{sh}\angle\varphi_{sh})$ and current injected by the shunt branch as I_q respectively and "n" represents fraction of the line length to the fault location from the relay point. Fault resistance and fault current are denoted by R_f and I_f, respectively.

Apparent impedance in (1), $\overline{Z} = \overline{V}_l/\overline{I}_l$ is affected by the series voltage and the shunt current injections by the UPFC apart from the fault resistance and shunt capacitance of the line. A fixed level compensation, based on the initial series voltage injection level and reactive current injection, is not feasible as these parameters are continuously changing in order to fulfill the control objectives. Hence, this work proposes to compute the control parameters of the UPFC on-line for ensuring the satisfactory operation of the conventional distance relay for the faults in its primary and backup zones.

2) Bypass Mode of UPFC: In the bypass mode, (1) gets modified as series voltage injection by the UPFC, $\overline{E}_{se}$ becomes zero. Hence, the measured voltage, at the relay location, becomes

$$\overline{V}_l = n\overline{I}_l\overline{Z}_1 + nI_{0l}\left(\overline{Z}_{0l} - \overline{Z}_1\right) + nI_q\overline{Z}_1 + R_f\overline{I}_f. \quad (2)$$

As this mode of operation causes apparent impedance to change considerably, the proposed scheme has considered this mode also while deriving the adaptive relaying strategy. The distance relays in the studies are assumed to be self–polarized.

III. COMPUTATION OF CONTROL SETTINGS OF UPFC

The control settings of the UPFC, under a given operating condition, are generally obtained using state estimation procedures [18]. However, the state estimation procedures involve nonlinear optimization techniques, which are time consuming. With the aid of Phasor Measurement Unit (PMU) based Wide Area Monitoring Systems (WAMS) [19], it is possible to get the information exchange between the line terminals. So, UPFC control settings namely, series voltage injection and reactive