Impact of VSC-Based Multiline FACTS Controllers on Distance Protection of Transmission Lines

Mojtaba Khederzadeh, *Senior Member, IEEE*, and Amir Ghorbani

***Abstract*—By utilizing multiline voltage-source (VSC)-based flexible ac transmission system (FACTS) controllers, independent controllability over each compensated line of a multiline system can be achieved. While VSC-based multiline FACTS controllers emerged as a new opportunity to control two independent ac systems, the main constraints and limitations that are presented to the conventional transmission-line protection systems need to be investigated. In this paper, the impacts of VSC-based FACTS controllers on distance relays while controlling the power flow of compensated lines are evaluated analytically and by detailed simulations for different fault types and locations.**

***Index Terms*—Distance relay, flexible ac transmission systems (FACTS) controllers, generalized interline power-flow controller (GIPFC), generalized unified power-flow controller (GUPFC), static compensator (STATCOM), static synchronous series compensator (SSSC).**

I. Introduction

NEW TYPES of flexible ac transmission system (FACTS) controllers have been investigated in recent years to increase power system operation flexibility and controllability, to enhance system stability, and to achieve better utilization of existing power systems [1]–[7]. However, the employment of series/shunt compensation of transmission lines by these devices creates certain problems for their protective relays and fault locators using conventional techniques because of the rapid changes introduced by the associated control actions in primary system parameters, such as line impedances and load currents. The most important singularity lays in the fact that the positive-sequence impedance measured by traditional distance relays is no longer an indicator of the distance to a fault. The apparent impedance seen by the relay is affected due to the uncertain variation of series compensation voltage during the fault period [8]–[17].

A unified power-flow controller (UPFC), which consists of a series and a shunt converter connected by a common dc-link capacitor, can simultaneously perform the function of transmission-line real/reactive power-flow control in addition to the UPFC bus voltage/shunt reactive power control. However, if power flows in more than one line need to be controlled simultaneously, UPFC seems out of its merits. Hence, multiline voltage-source (VSC)-based FACTS controllers, such as an interline power-flow controller (IPFC) [5]; generalized interline power-flow controller (GIPFC) [6], [7]; and generalized unified power-flow controller (GUPFC) [4] are introduced to control the power flows of multilines simultaneously. Multiline VSC-based FACTS controllers can control different variables of the power system, such as the bus voltage and independent active and reactive power flows of two lines by combining three or more converters working together. So it extends the concepts of voltage and power-flow control beyond what is achievable with the known two-converter UPFC controller.

Some research has been conducted to evaluate the performance of a distance relay for transmission systems with FACTS controllers. In [8], an apparent impedance calculation procedure for a transmission line with UPFC based on the power frequency sequence component is investigated; the studies include the influence of setting UPFC control parameters and the operational mode of UPFC. The work in [9] presents the operation of impedance-based protection relays in a power system containing a STATCOM; it is based on the steady-state analysis of the STATCOM and the protection relays. The work in [16] also presents steady-state analysis of the transmission-line protection in the presence of series-connected FACTS devices. In [10], the performance of distance relays of the lines compensated by two types of shunt FACTS devices, SVC and STATCOM, are investigated. In [11], the impact of FACTS devices on the tripping boundaries of distance relay is presented. The works in [12] and [13] present a comprehensive analysis of the impact of thyristor-controlled series capacitor (TCSC) on the protection of transmission lines and show that not only does the TCSC affect the protection of its line, but the protection of adjacent lines would experience problems. The studies in [14] indicate that the parameters of FACTS controllers and their location in the line (middle or line ends) have an impact on the trip boundary of a distance relay.

Fig. 1 shows the generic representation of a multiline VSC-based FACTS controller. Different controllers are achieved by the status of the dc switches, as Table I. According to this table, when all of the dc switches are closed, it represents a GUPFC [7]. SSSC1 and SSSC2 in Table I indicate the static synchronous series compensators (SSSCs) configured in *Line 1* and *Line 2*, respectively.

If *Line 1* and *Line 2* are connected to separate buses in Fig. 1, then a GIPFC is established. In the GIPFC configuration, it is possible to control the power flows of independent lines or even lines that are physically close but operate at different voltage levels.

$R1$ and $R2$ in Fig. 1 present a distance protective relay for *Line 1* and *Line 2*, respectively. In this paper, the behaviors of $R1$

Manuscript received July 04, 2010; revised July 18, 2011; accepted September 02, 2011. Date of publication October 18, 2011; date of current version December 23, 2011. Paper no. TPWRD-00502-2010.

The authors are with the Department of Electrical Engineering, Power and Water University of Technology (PWUT), Tehran 1658953571, Iran (e-mail: khederzadeh@pwut.ac.ir).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPWRD.2011.2168428

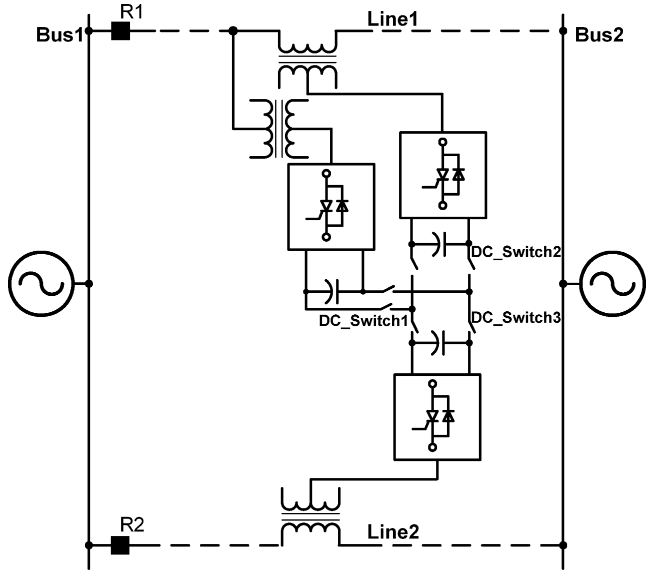

Fig. 1. Simplified one-line diagram of multiline FACTS controllers connected to the middle of the transmission lines.

TABLE I
FACTS CONTROLLERS ACHIEVED BY DIFFERENT CLOSE/OPEN CONFIGURATIONS OF DC SWITCHES IN FIG. 1

Case No.	Status of DC_Switches			FACTS Controllers
	DC_ Switch1	DC_ Switch2	DC_ Switch3	
1	Close	Close	Close	GUPFC
2	Open	Close	Close	STATCOM+IPFC
3	Close	Open	Close	UPFC extended on two lines
4	Close	Close	Open	UPFC+SSSC2
5	Open	Open	Open	STATCOM+SSSC1+SSSC2

and $R2$ during a fault on the transmission lines are investigated for different FACTS controllers according to Table I. It is worth noting that the impact of GIPFC on the protection of *Line 1* and *Line 2* could be regarded as the impact of an UPFC on relay $R1$ and an SSSC on relay $R2$, due to the fact that the *Line 1* and *Line 2* are separated from each other and not parallel. Meanwhile, the impact of GUPFC on the protective relays is more pronounced than GIPFC, because the current circulates in a loop comprising of *Line 1* and *Line 2* during different faults.

The objective of this paper is to analyze and investigate the impact of different multiline VSC-based FACTS controllers on the performance of impedance-based protection relays under normal operation and fault conditions at different load power flows. Different configurations of multiline VSC-based FACTS controllers are considered based on the cases 1 to 5 as in Table I. The controllers are modeled with detailed and sophisticated transient characteristics; the power system is designed with traveling-wave transmission-line models and advanced models are used for protective relays [18].

This paper is organized as follows. Section II explains the impact of multiline VSC-based FACTS controllers on the apparent impedance seen by the protective relays. The analysis is comprehensive and considers different effects including the mutual impedance between the lines. Section III presents sophisticated transient modeling of the series/shunt converters used

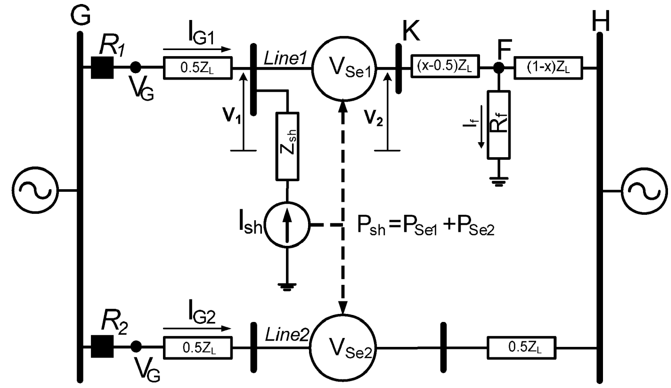

Fig. 2. Sample system with GUPFC.

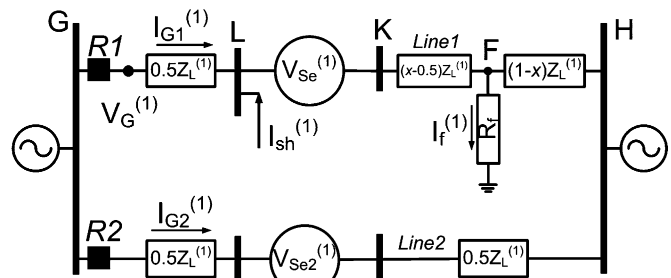

Fig. 3. Positive-sequence network of the sample system for a fault on Line1.

in the simulations. Section IV introduces the sample network. Simulation results of the sample network for different FACTS controllers based on Table I are presented in Section V.

II. MULTILINE VSC-BASED FACTS CONTROLLERS IMPACT ON APPARENT IMPEDANCE

The single-line diagram of the sample system used for the analysis is shown in Fig. 2. It consists of two parallel lines and resembles the GUPFC configuration. In this figure, the GUPFC is connected to the middle of the line to include the series compensators in the fault loop. V_{Se1} and V_{Se2} are the series-injected voltages powered by the shunt converter, represented by impedance Z_{sh} and current source I_{sh}. If the converter losses are ignored, then the active power drawn by the shunt leg is equal to the delivered power to lines 1 and 2.

The performance of relays $R1$ and $R2$ for different fault types, fault locations, and fault resistances R_f is analyzed to show the impact of different multiline VSC-based FACTS controllers on distance protection. Faults on *Line 1* at point F between K and H with the per-unit distance x from the relay location are considered. In this sense, x has a value between 0.5 and 1.0 for faults between K and H in the sample system. In Fig. 2, Z_L is the impedance of each line, and V_G is the voltage measured by $R1$ and $R2$ which is the same for both relays. The positive-sequence network of the sample system of Fig. 2 is shown in Fig. 3.

The negative-sequence network is the same as Fig. 3, except that the superscripts are changed to 2. The zero-sequence network of the sample system of Fig. 2 is shown in Fig. 4. $Z_m^{(0)}$