1. Introduction

Throughout the world the demand of electrical power is increasing tremendously day by day, causing the existing transmission lines to increase power transfer capability. The reactive power compensation method is normally used to increase the power transfer capability of transmission lines. Flexible AC Transmission Systems (FACTS) using power electronic based static controllers played a vital role in the last two decades in supporting reactive power compensation, thus enhancing the power handling capacity of the existing transmission lines.

But, these FACTS devices increase the power transfer capability of the transmission line; high cost and reliability are the major hurdles which lower the commercial development of FACTS devices. To remove these hurdles, recently a new FACTS devices was developed from the Distributed Flexible AC Transmission Systems (D-FACTS) family with qualities similar to that of the FACTS counterparts, at reasonable cost.

The Distributed Static Series Compensator (DSSC) and Distributed Power Flow Controller (DPFC) are examples of D-FACTS devices, which are advanced FACTS devices. DSSC is directly connected to the transmission lines in distributed nature to improve power flow and transient stability by controlling the impedance of the transmission line. But due to the rapid changes introduced by these devices in the system, parameters like line impedance and performance of the distance relay are affected.

Protective relays are important equipment used for the protection of power systems ensuring reliable, fast and inexpensive protection. Impedance based distance protection relays are widely used to protect High Voltage/Extra High Voltage (HV/EHV) transmission lines due to their simple operating principle and ability to work independently under any circumstances.

The impact of various types of FACTS devices on the distance relay performance was investigated by many researchers and reported in literature. But no attempt

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Abstract

This paper demonstrates the impact analysis of the Distributed Static Series Compensator (DSSC), on the performance of distance relay protection of high voltage transmission lines. The concept of DSSC model with its control circuit and distance relay are described. A five bus test system with DSSC and distance relay is designed with the help of MATLAB/SIMULINK software. The impact of DSSC on distance protection relay for different fault conditions and various fault locations is analyzed. The results of simulation show that the connection of DSSC in the transmission system changes the transmission line impedance greatly as estimated by the distance relay to be less or greater than the actual impedance in fault conditions. Hence, the distance relay performance changes, either over reaches or under reaches.

Keywords: Distance Relay, Distributed FACTS Devices, Distributed Static Series Compensator, FACTS Controller, High Voltage Transmission Line

Impact Analysis of DSSC on Distance Relay Performance under Fault Conditions

R. Ilango† and T. Sree Renga Raja

1Department of EEE, MAM School of Engineering, Tiruchirappalli – 621105, Tamil Nadu, India; ilangorengaraju@gmail.com
2Department of EEE, Anna University BIT Campus, Tiruchirappalli – 620024, Tamil Nadu, India; renga_raja@rediffmail.com

*Author for correspondence
was made (to the best of the authors’ knowledge) to investigate the effect of distributed FACTS devices like DSSC on transmission line distance relay performance. So at present, it is important to analyze the effect of D-FACTS devices on distance relays to develop an effective distance relay protection method to locate the fault correctly. Hence, as a first step, an attempt is made in this paper, to study the impact of DSSC on distance relay protection and find a practical solution to mitigate the adverse effects created by it.

The paper is organized as follows: First, the basic concept of DSSC is introduced, and then the effect of DSSC on the distance relay is analyzed using MATLAB/SIMULINK software for different types of faults at various locations.

2. Concept of DSSC

The Distributed Static Series Compensator (DSSC) is connected along the transmission lines at various locations to improve the power handling capacity. The DSSC injects lagging or leading voltage with reference to line current which in turn decreases or increases the transmission line impedance. This is achieved by either direct control or indirect control. In direct control, the angular position and the magnitude of the output voltage are controlled. But in indirect control, the angular position of the output voltage alone is controlled.

![Figure 1. D-FACTS devices connected to power lines](image)

The conceptual schematic representation of the DSSC deployed in a power transmission line is depicted in Figure 1. The concept is based on the use of large numbers of DSSC modules suspended or clamped mechanically to the transmission line, in a distributed manner, so as to control the power flow of the transmission line by varying the line impedance. Each module has a low-power rated (1-20 kW) single phase inverter, a single winding transformer with required controls, power supply unit and communications circuit, which controls the impedance of the transmission line, allowing the control of active power flow through the line\(^{27}\). Operating more models improves the overall power flow in transmission lines. The reliability of the power transmission system is also increased because of more low power rating DSSC modules.

Figure 2 shows the circuit of the DSSC module. It consists of a low power single phase inverter, a single winding transformer, power supply unit and a communications circuit. The single winding transformer is directly connected to the transmission line, but suspended from the line which helps to supply/absorb the voltage. The transmission line conductor acts as secondary winding for single winding transformer of the DSSC. The inverter uses IGBTs, LC filters and DC capacitor to generate required voltage to supply the line. The Pulse Width Modulation technique (PWM) is used to control the output voltage of the inverter which is orthogonal to the line current. Wireless or power line communication techniques are used to provide needed control to the PWM inverter. A feedback current transformer is also used to give required control power, which operates DSSC model when the line current is higher than normal\(^{28}\).

![Figure 2. Circuit of a DSSC module](image)

3. Simulation Studies

3.1 Test System

The effect of DSSC on distance relay performance is analyzed considering an IEEE 5 bus test system, including DSSC and distance relay.
The single line diagram of IEEE 5 bus, test power transmission system, including DSSC under analysis, is shown in Figure 3. The test system consists of two equivalent sources G1 and G2 connected at the sending and receiving ends respectively. The system includes five buses, which are divided into two areas connected together with transmission lines. The DSSCs are distributed equally in the transmission line which is linked between the bus 2 and 4. The total length of the line is 100 km. The distance relay connected near the bus 2 is considered for analysis.

3.2 Distance Protection
The distance relay performance is evaluated using MATLAB/SIMULINK software. The Mho relay characteristics are used to detect faults. The relay is assumed to be set to protect 80% (80 km) of the transmission line. The distance relay calculates the apparent impedance at the relay location considering the voltage and current measured at the relay point. It is anticipated that like other FACTS controllers, the introduction of DSSC controller in the transmission lines affects the seen impedance of the faulted line and hence distance relay performance is affected.

4. Simulation Results
Several cases involving all types of faults at various locations of the transmission line between buses 2 and 4 were simulated. In the present study, a single line to ground fault (‘A’ phase-to-ground fault) with zero fault resistance occurring at various locations “n” along the line 2-4 is examined.

4.1 Effect of Single Phase Fault Occurring in 25% of the Line
The test results of the test system for ‘A’ phase-to-ground fault are shown in Table 1. When the fault occurs at 25 km, (25% of the line in this case) the apparent impedance calculated by the distance relay with DSSC inclusion is 15.17 ohms, and without DSSC inclusion, 12.31 ohms.

It clearly shows that, when the fault occurs at 25 kilometers, the apparent impedance of the system is greater than that for the system without DSSC, as the 5 numbers of DSSC are included in the fault loop; the injected/absorbed voltage of the DSSC changes the apparent impedance calculated by the distance relay.

4.2 Effect of Single Phase Fault Occurring in 50% of the Line
When the fault occurs at 50 km, (50% of the line, in this case) the apparent impedance calculated by the distance relay with DSSC inclusion is 29.92 ohms, and without DSSC inclusion, 24.12 ohms.

It clearly shows that, when the fault occurs at 50 kilometers, the apparent impedance of the system is greater than that for the system without DSSC, as the 10 numbers of DSSC are included in the fault loop; the injected/absorbed voltage of the DSSC changes the apparent impedance calculated by the distance relay.

4.3 Effect of Single Phase Fault Occurring in 75% of the Line
When the fault occurs at 75 km, (75% of the line, in this case) the apparent impedance calculated by the distance relay with DSSC inclusion is 43.86 ohms, and without DSSC inclusion, 35.09 ohms.

It clearly shows that, when the fault occurs at 75 kilometers, the apparent impedance of the system is greater than that for the system without DSSC, as the 15 numbers of DSSC are included in the fault loop; the injected/absorbed voltage of the DSSC changes the apparent impedance calculated by the distance relay.
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4.4 Estimated Fault Location

Table 2. Fault Location estimates obtained by the distance relay

| Actual Fault location (in km) | Estimated fault location without DSSC (in km) | Estimated fault location with DSSC (in km) |
|------------------------------|-----------------------------------------------|--------------------------------------------|
| 5                            | 5.30                                          | 6.24                                       |
| 10                           | 10.58                                         | 12.46                                      |
| 15                           | 15.82                                         | 18.65                                      |
| 20                           | 21.03                                         | 24.82                                      |
| 25                           | 26.19                                         | 30.95                                      |
| 30                           | 30.06                                         | 37.06                                      |
| 35                           | 35.64                                         | 44.02                                      |
| 40                           | 40.56                                         | 50.17                                      |
| 45                           | 45.44                                         | 56.28                                      |
| 50                           | 50.26                                         | 62.33                                      |
| 55                           | 55.01                                         | 69.78                                      |
| 60                           | 59.69                                         | 75.82                                      |
| 65                           | 65.00                                         | 81.78                                      |
| 70                           | 70.22                                         | 89.52                                      |
| 75                           | 74.66                                         | 95.34                                      |
| 80                           | 80.61                                         | 100.90                                     |

The simulation results of the single phase fault with different fault locations are presented in Table 2. The first, second and third columns of Table 2 give the actual fault location, fault estimation of the distance relay without DSSCs and fault location estimated by the distance relay with DSSCs respectively. Consider an example, when the fault is at 70 km, the estimated fault location of the distance relay with DSSC is 89.52 km, but estimated fault location of the distance relay without DSSC is 70.22 km. It is found from the results that when DSSCs are included in the transmission line the distance protection is unable to estimate the fault location accurately.

5. Discussions

It is proved from the results that, the presence of the DSSC’s in the transmission lines changes line impedance during the fault durations, so that the distance relay operates incorrectly.

It is also understood from the results that during a fault, the apparent impedance increases if the DSSC injects reactive power to the system and the apparent impedance decreases if the DSSC absorbs reactive power from the system. The distance relay under reaches when the DSSC supplies the reactive power, and over reaches when the DSSC consumes the reactive power.

Further from analysis, it is evident that the inclusion of the DSSC in the transmission line significantly changes the apparent reactance and apparent resistance calculated by the distance relay during fault conditions.
6. Conclusion

The effect of the distributed static series compensator on the distance relay protection was analyzed with various fault types. Simulation results proved that, the presence of the DSSC devices along the transmission lines changes the magnitude of the voltage and current at the relay point during fault conditions. Hence the conventional distance relay results under/over reach, which in turn provides a wrong estimation of the fault location. So when HV transmission lines are connected with DSSC the control algorithm of the inverters adopted in the DSSC must be designed to obtain the correct estimation of the fault location.

7. References

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