Journal of Physics: Conference Series **1457** (2020) 012005 doi:10.1088/1742-6596/1457/1/012005

Performance Evaluation of Power Swing Blocking in Compensated Transmission Lines

A Çapar, E Ünverdi and A Basa Arsoy
Department of Electrical Engineering, Kocaeli University, Umuttepe 41380 Kocaeli, Turkey

Email: alkim.capar@kocaeli.edu.tr

Abstract. Traditional and modern compensation devices can increase power flow limit and enhance voltage drop in transmission lines. However, these systems can cause to malfunction of distance relays utilized to protect transmission lines. While compensation devices can effect distance relay operation, some disturbances like power swings are significant risk to ability of distance relays to distinguish faults. Power swing blocking (PSB) methods are used to discriminate faults from power swings. This study focuses on efficiency of conventional PSB methods when transmission lines are compensated with various compensation devices such as series capacitor (SC), thyristor-controlled series capacitor (TCSC) and static VAR compensator (SVC). A test system is simulated on PSCAD under various operating conditions. Conventional PSB methods (swing center voltage, reactive power change and change rate of impedance) are tested under these scenarios. The study revealed that compensation devices significantly affect the accuracy of PSB algorithms, therefore it is recommended to develop an adaptive PSB method to block power swing in the case of various operating conditions.

1. Introduction

Generation of electrical energy and delivering this energy to consumer are main subjects in the area of power system consisting of generating units, transmission lines and loads. The ever-growing electrical energy demands are causing problems for transmission lines such as insufficient power transfer capability, low voltage profile and power quality and stability issues. Traditional and modern compensation devices like flexible AC transmission system (FACTS) controllers can provide a way of solutions to the mentioned problems [1-4].

Changes in loading or grid configuration may cause power swing. If power swings cannot be discriminated from faults, distance relay may result in undesired operation. To overcome this situation, power swing blocking algorithms have been developed. Conventional PSB algorithms may be sufficient for uncompensated transmission lines. As compensation devices are integrated into the system for enhancement, the behaviour of the system changes therefore may result in affecting the operation of protection relays adversely. Especially distance relays may have accuracy problems in compensated lines [5-8].

This study examines conventional power swing blocking methods [5, 9, 10] under different compensation devices with stable and unstable power swing cases. This research focuses if conventional PSB methods with estimated threshold values for a test system can operate under different compensation devices while the same operating conditions exist. It is expected that when a compensation device malfunction and therefore disconnected from the power system, blocking function should still distinguish power swing from faults so the distance relay could operate as required. A test system [11] has been simulated at PSCAD with different compensation states such as; uncompensated state, series capacitor (SC) with MOV (metal oxide varistor), SVC (static VAR compensator) and TCSC (thyristor-controlled series capacitor). Various conventional PSB methods are examined at the simulated test system. Conventional PSB methods are given at Section 2 with details. The compensation devices used in the scenarios are discussed in Section 3. Test system, analyzed results and arguments are given in Section 4, following the conclusion.

2. Conventional power swing blocking methods

Power swings are defined as general oscillation problems in the power system owing to large disturbances like a fault, separation of a large group of generators/transmission lines/loads, etc. According to the system oscillation behavior after large disturbance, power swings are classified stable or unstable one. If the oscillation is self-damped, it is called as stable power swings. In the contrary, unstable power swings can be damped with power system controllers. If power swings are not blocked for distance relay, it could result misoperations and unwanted tripping of circuit breakers even it could cause severe damage to the generator. Power swing blocking methods are used for preventing these situations. Tested conventional methods are detailed in below.

2.1. Swing center voltage (SCV)

Swing center voltage is defined as the voltage whose value is zero at the location of a two bus equivalent system when the bus angles are 180 degrees apart [9]. Voltage and current measurements at the placement of relay are used for analysis, with these measurements SCV can be described as in;

$$SCV \approx |V| cos\varphi \tag{1}$$

Where V is the locally measured voltage and Φ is the angle difference between locally measured voltage and current. Both SCV and derivative of SCV can be observed with thresholds for detecting a fault and power swings (Figure 1).

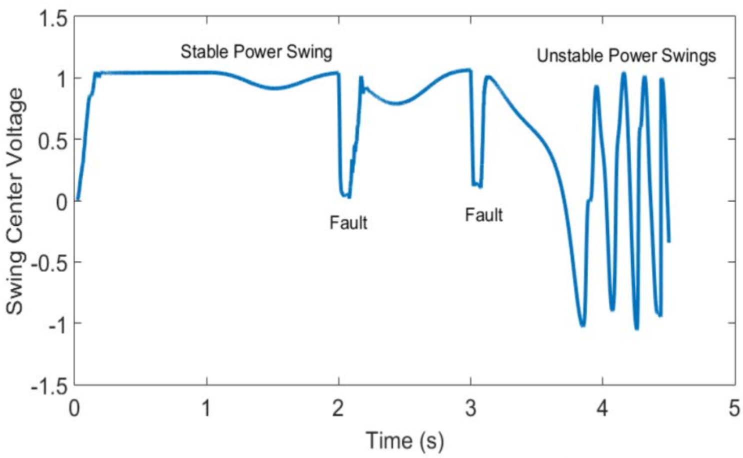

Figure 1. Example of SCV under fault and power swings.

2.2. Reactive power change

When locally available measurement quantities are examined under fault, a significant change occurs on reactive power of the line, unlike power swings. This change (dQ/dt) is observed with a threshold for identification of faults (Figure 2).

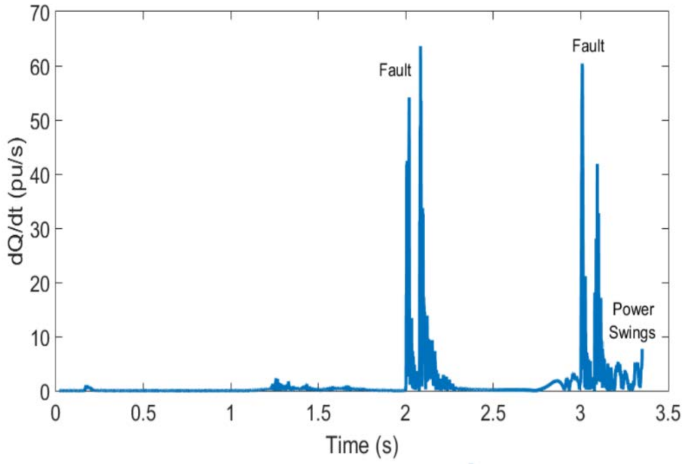

Figure 2. Reactive power change of a system with faults and power swings.

2.3. Change rate of impedance

Change rate of impedance method is one of the basic and most used methods. When a stable or unstable power swing occurs, the change rate of impedance vector is slow, on the other hand during a system fault, it is significantly fast. This criterion is used to distinguish power swings from faults with a threshold.

3. Compensation devices for transmission system

Compensation devices are used in transmission lines for enhancing power system stability, transfer capability, voltage stability etc. There are various traditional and modern compensation devices. In this chapter, compensation devices integrated into the test system are explained in a basic manner.

3.1. Series capacitor (SC) with metal oxide varistor (MOV)

The series capacitor is the most effective traditional way to increase power transfer capability. Overvoltage protection of the SC is achieved with parallel connected MOV. The MOV has a nonlinear characteristic hence it must be taken into attention in studies having overvoltage cases [12].

3.2. Thyristor-controlled series capacitor (TCSC)

Series capacitors are most simple and economical way to increase power transfer capability however series capacitors can cause sub-synchronous resonance [13]. To overcome this problem TCSC is developed. TCSC consists of a thyristor controlled inductance and capacitance. A predetermined power system value/values (control modes) are observed to set firing angle of thyristors.

3.3. Static VAR compensator (SVC)

In early years, SVC was used for load compensation of fast changing loads. Nowadays, SVC is integrated to transmission lines both the above-mentioned purposes and improvements such as increase power transfer capability in long lines, improve stability, control dynamic overvoltages, etc [13]. Ideal placement for SVC is the middle of the line or electrical middle point of the power system.

4. Simulated test system and compensation systems details

4.1. Test system modeling

A test system given in figure 3 is simulated with various compensation devices to compare the performance of PSB methods. The parameters of the test system are given at table 1.

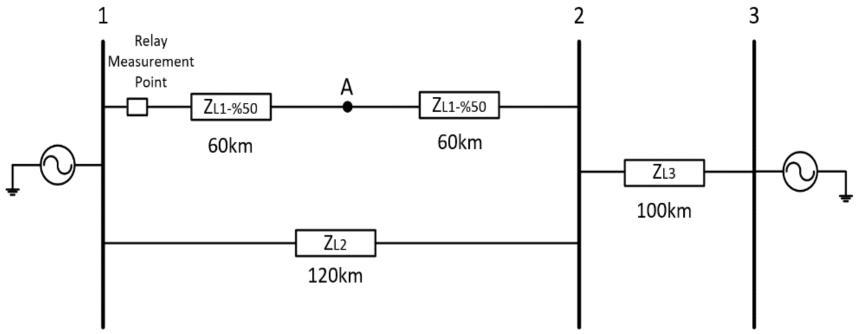

Figure 3. Test system.

Table 1. Test system details (uncompensated state).

System Parameters		Line Parameters	
Frequency	50Hz	**Line model**	π
H	4.4 MW●s/MVA	**R1**	2.2884e-07 [pu/m]
Bus voltages	400kV	**X1**	1.7781e-06 [pu/m]
Angle difference between two source equivalent system	25.5°	**B1**	6.5137e-07 [pu/m]
		R0	1.3307e-06 [pu/m]
		X0	4.5436e-06 [pu/m]
		B0	5.1154e-07 [pu/m]

Compensation devices are selected to be SC, TCSC and SVC to be integrated to the test system to observe their impact on different fault and swing conditions. This impact has been tested for each compensation case.

Series compensation devices (SC and TCSC) are placed at the midpoint of the protected line (point “A”) and capacitor values are chosen to be %40 level of compensation rate at the protected line. The ratio between inductance and capacitance is 0.133 at TCSC [14].

The TCSC has three different control modes available: active power, current and line impedance. The power flow control of the system is mainly focused on mentioned control modes [15, 16].

The SVC is placed at bus 2 with a control mode to limit voltage of the connected bus to one (1) per unit. Table 2 shows the SVC parameters.

Table 2. SVC parameters.

Parameters	Values
Thyristor Controller Reactor	100 MVAr
Thyristor Controller Capacitor	3x100 MVAr
Transformer Properties	400kV/16kV (Yg/d)

4.2. Comparison of compensated and uncompensated state effects on power swing conditions

To compare different compensation situations with fault and power swing scenarios, base conditions should be set beforehand. For this scenario, stable power swings are created by a mechanical torque disturbance (changing Tm value to 1.35pu) at 1s. After the stable power swing occurrence, a fault is simulated at 2s (Z_{L2} line, 3 phase fault, fault at 15. km of the line). Second fault is simulated on Z_{L1} line (3 phase fault, fault at 105. km of the line) to cause unstable power swings at 3s. Both faults have duration of 75ms.

Three different control modes, impedance control, active power control and current control, for TCSC are considered. Impedance control mode is based on the line impedance and determining the firing angle from changes with a delay while current control and active power control modes examine line current/active power values for the firing angle deciding factor.

The conventional PSB methods are usually based on the values of protected line impedance, current, voltage and change in power, these values are calculated with voltage and current measurements from the relay point. In this scenario, voltage and current values at the measurement point are observed to illustrate the effect of compensation devices and control modes (Figure 4).

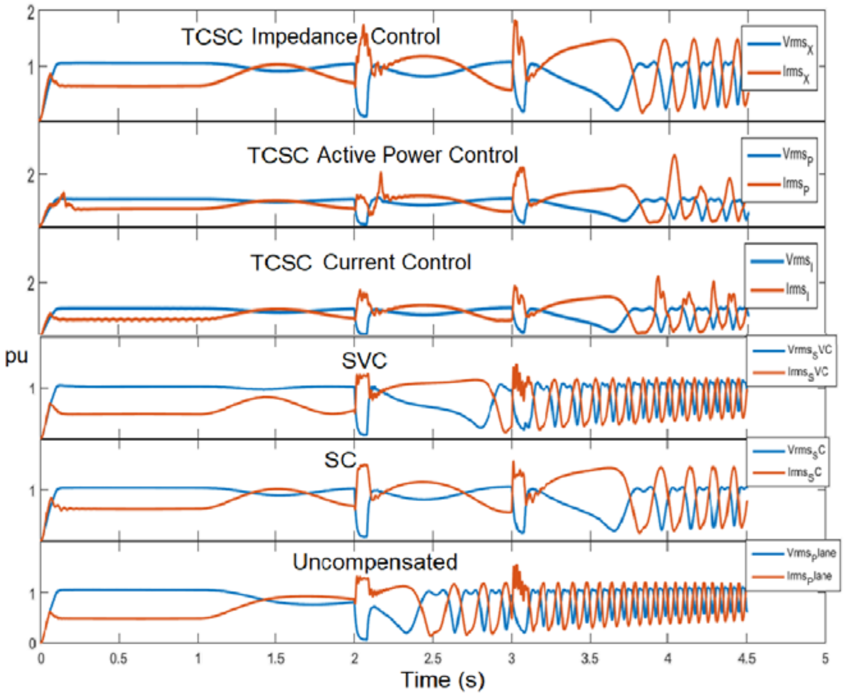

Figure 4. Voltage and current measurements taken from relay measurement point for different compensation scenarios.

Compensation devices can make the test system more stable against disturbances as seen in figure 4. Voltage and current waveforms are clearly different for each scenario. The some power swings could have higher current peak values than fault cases in the TCSC current and active power control modes. This situation causes accuracy problems for current or power monitoring based PSB methods.

Even under same conditions, observed peak values and waveforms have considerable changes especially during faults and power swings. The PSB methods utilize the values from these waveforms to determine the fault/disturbance cases, based on a fixed threshold value. All compensation devices can be disconnected from system due to maintenance/protection purposes therefore PSB methods should give high accuracy with same threshold values in both cases. Effects of both mentioned situations on PSB methods require further study for the test system as given in section 4.3.

4.3. Response of PSB methods under various operating conditions

As can be seen in figure 4, different compensation devices and different control modes of TCSC could change the system behavior significantly. This effect can be obtained by testing critical conditions of the test system.
PSB methods (SCV, reactive power change and change rate of impedance) are tested in various compensated scenarios.
In this scenario, the mechanical torque is changed to 1.35pu in 1s as a disturbance to simulate a stable power swing. A three phase fault is occurred on Z_{L2} line at 15. km of the line at 2s with a 75 ms duration. Another fault is simulated at %12.5 and %87.5 of the Z_{L1}, Z_{L2}, Z_{L3} lines at 3s with a 75ms duration. The second fault is considered as three phase and one phase to ground fault. The occurrence of unstable power swings are achieved by creating both faults with short time duration.
The PSB methods aim to distinguish between described two faults from power swings. The thresholds of methods are chosen by observing uncompensated state of power system. The success rate of each PSB method is given in percentage for various operating scenarios at table 3.

Table 3. Compensation devices effects on PSB methods.

PSB Method	Accuracy rate (percent)					
	SC	SVC	TCSC I	TCSC P	TCSC X	Uncompensated
SCV	91.7	91.7	50	91.7	58.3	75
Reactive Power Change	100	100	58.3	50	83.3	100
Change Rate of Impedance	58.3	75	33.3	58.3	75	83.3

The effect of compensation systems can be observed more noticeably by results of reactive power change method. Reactive power change method has a high accuracy with uncompensated, SC and SVC cases however the method accuracy significantly dropped at the TCSC cases. While the method has a high accuracy, the threshold value should be changed to increase efficiency of the method at the TCSC cases. The change rate of impedance method has an adequate accuracy at uncompensated state however the method cannot be used under any compensation, if the compensation system is bypassed, the method will cause malfunctions. However SCV method is not effected by this scenario while its accuracy is still under reactive power change method, the drop rate of accuracy is minimum, only because of Φ feature will be affected by compensation and effect on voltage could be only positive or minimal.
PSB methods should have high accuracy at both compensated and uncompensated cases, while SCV has overall adequate accuracy, it is clear that there is a need for an improvement on PSB algorithms.

5. Conclusion

Effects of compensation devices on PSB are examined under various scenarios. A two source equivalent system is used and simulated at PSCAD for this purpose. Compensation devices integrated to the test system are selected to be SC, TCSC and SVC cases.
The compensation significantly changed waveforms of current and voltage taken from distance relay measurement point and the response of PSB methods are varied. Due to fixed threshold values on conventional PSB methods, any variance of power system parameters affect accuracy of the swing blocking.
Any transition between a compensated to uncompensated situation should have minimum impact on accuracy of the PSB method. Incorrect operation of PSB could cause an unwanted tripping signal on distance relay. It leads to significant economical and stability problems in the power system.

Conventional PSB methods are not sufficient to discriminate faults from power swing depending on the type of compensation. From given arguments, requirement of new methods/approaches are essential for PSB in dynamic power system circumstances.

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