Power Quality Impacts of Series and Shunt Compensated Lines on Digital Protective Relays

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Abstract – **The proliferation of compensators, due to their nonlinear characteristics raises concern over the distortion levels they cause in voltages and currents at the transmission level. In this paper, series compensation by Thyristor Controlled Series Capacitor (TCSC) and shunt compensation by STATCOM are investigated in terms of power quality and their effects on protective relays behavior. For each issue, the discussion will review how power quality can positively or negatively impact power system protection. Since Thyristor controlled equipments generate fast transients, the power quality is evaluated by EMTP/ATP simulations for a sample network equipped by TCSC or STATCOM. The simulation considers various conducting angles and the amount of current distortion produced. Since, the relay receives data through current and voltage transformers, their effect on the relay performance is considered in the simulation. The relay function is investigated by a digital relay simulator prepared in the MATLAB environment. The generated data would be transferred from EMTP/ATP to MATLAB. It is shown that in normal operation the content of harmonics is not high and the relay operates as expected. The distortion increases rapidly with further increase in compensation level, and hence the operation of the relay is affected.**

Keywords – Harmonics, Power Quality, Power System Protection, Thyristor Controller Series Capacitor (TCSC), STATCOM

I. INTRODUCTION

The case for using high-power electronics equipment, under the concept of a flexible ac transmission system (FACTS) [1]-[2], to enhance and optimize the use of transmission facilities is compelling.

Literature reviews indicated that FACTS devices introduce new power system dynamics that must be analyzed by the system protection engineer [3]. These dynamics can be summarized as the following:

1) the rapid changes in system parameters such as line impedance, power angle and line currents;
2) the transients that are introduced by the associated control action;
3) the harmonics introduced into the adjacent ac power system.

Because of these concerns, the protection relays requirements cannot be clearly defined until a particular FACTS strategy is modeled and analyzed within its power system. Such protection requirements are:

1) a need for an adaptive relay characteristic as the system parameters and configuration are rapidly changed by the FACTS devices;
2) assurance that the various protective relays can accommodate different power system contingencies and control modes of the FACTS devices;
3) specifying the operating times and tripping schemes of the protection relays.

Series and shunt compensation could be fulfilled by FACTS devices. Increased transmittable power, improved power system stability, reduced transmission losses, enhanced voltage control and flexible power flow control are the reasons behind series compensation by installing Series Capacitors on long transmission lines. Series compensated systems can be mainly catalogued into switched capacitors systems and thyristor controlled switched capacitors (TCSCs) systems. TCSCs and their overvoltage protection devices (typically Metal Oxide Varistors, MOVs), when set on a line, create, however, certain problems for its protective relays and fault locators. Since the variation of series compensation voltage remains uncertain during the fault period, the protection of power systems with series compensated lines is considered as one of the most difficult tasks and is an important subject of investigation for relay manufacturers and utility engineers [4]-[6]. The protection of compensated lines equipped by TCSC is important from another point of view, i.e., the effect of thyristor controllers on the power quality, especially, the generation of harmonics.

Waveform distortion caused by insertion the TCSC, does affect the performance of protective relays and may cause relays to operate improperly or to not operate when required. In most cases, the waveform distortion of the load current has little effect on the fault current. However, for low magnitude faults, the load may consist of a large part of the load current and distortion can become a significant factor. Furthermore, the relay must function properly even with distorted load currents [7].

Protective relays more easily discriminate between fault and non-fault conditions when power quality is good. When power quality is poor, the threshold between normal and fault conditions becomes blurred. The relay application engineer can no longer rely on the performance of the relay under conventional normal system conditions. More information about the relay performance under conditions of poor power quality is needed. This information will enable the engineer to design applications that are more secure and dependable.

Protective relays designed to protect against excessive harmonics are not yet widely available. More standards are required to provide relay engineers with limits as to acceptable power quality. Harmonic limits are already well defined, but the proposed curve is limited in application [8]. No universally acceptable tolerances for harmonic limits for protective relays presently exist.

Power system protective devices respond to waveform distortions in many different ways. No single response is correct for all instances of the same type of distortion. In some cases, excessive waveform distortion is a normal characteristic of the parameters measured by a protective relay. However, even if the relays are sensitive to harmonics, they may over or under protect the line depending on their specific response to harmonics.

Unless special investigation is undertaken, the performance of protective relays to distorted waves is not usually known.

In several cases transmission line protective relays have undesirably operated in response to harmonics on the power system. In most cases, the relay performance has had to be improved by modifying the filtering, or by replacing the relays with better-filtered devices.

In this paper, the impact of TCSC as a sample of series compensation, and STATCOM, as a sample of shunt compensation, on power quality is investigated.

First, the sample network consists of a machine connected to an infinite source through lumped parameters of a transmission line. The line is compensated by using a fixed and a thyristor controlled component of capacitors. The thyristors of the TCSC are fired using a constant current controller. The machine is started up at constant speed. The TCSC is blocked during startup, it is deblocked at few seconds following startup. The machine is then released for normal operation with some delay. During normal operation, a fault is simulated on the line and the harmonic content of the line current for different percentage of series compensation is extracted. The behavior of a distance relay modelled in full detail would be evaluated under distorted waveforms. The relay simulator includes current transformer model and various analog and digital filters.

Among the different types of FACTS devices, the static var compensators (SVCs) are devices that control the voltage at their point of connection to the power system by adjusting their susceptance to supply or absorb reactive power [2]. In general, SVCs are characterized by their ability to rapidly vary the reactive output to compensate for changing system conditions [9]-[10]. The development in power electronic devices such as gate turn off devices (GTOs) allows implementation of the so-called advanced static var systems (SVS). The static synchronous compensator (SSC or STATCOM) is an example of the advanced SVS. The STATCOM consists of three-phase sets of several gate turn-off switch-based valves and a DC link capacitor and controller thus replacing the conventional reactive power compensators.

Since Thyristor controlled equipments generate fast transients, the power quality is evaluated by EMTP/ATP simulations [11] for a sample network equipped by TCSC or STATCOM. The simulation considers various conducting angles and the amount of current distortion produced. The relay receives data through current and voltage transformers. The important point in this regard is current transformer simulation and its behavior for different harmonics and fast transients. The relay function is investigated by a digital relay simulator prepared in the MATLAB environment. The generated data would be transferred from EMTP/ATP to MATLAB. The relay under consideration is distance relay and its different blocks would be simulated in order to evaluate its functioning before and during the fault. The role of analog and digital filters of the relay would be highlighted.

II. THYRISTOR CONTROLLED SERIES CAPACITOR (TCSC)

TCSC configurations comprise controlled reactors in parallel with sections of a capacitor bank. This combination allows smooth control of the fundamental frequency capacitive reactance over a wide range. The capacitor bank for each phase is mounted on a platform to ensure full insulation to ground. The valve contains a string of series-connected high-power thyristors. The inductor is of the air-core type. A metal-oxide varistor (MOV) is connected across the capacitor to prevent overvoltages. The characteristic of the TCSC main circuit depends on the relative reactances of the capacitor bank, and the thyristor branch. Fig. 1 shows a schematic diagram of a TCSC. The TCSC can operate in three fundamental modes with varying values of apparent reactance.

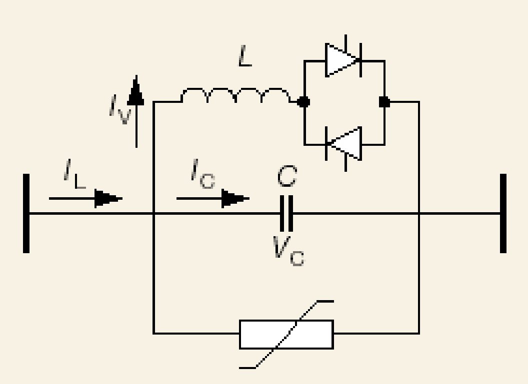


Fig. 1 Schematic diagram of a TCSC

III. STATIC SYNCHRONOUS COMPENSATOR (STATCOM)

The static compensator is based on a solid-state synchronous voltage source in analogy with a synchronous machine generating a balanced set of (three) sinusoidal-voltages at the fundamental frequency with controllable amplitude and phase angle. This device, however, has no inertia.

A static compensator consists of a voltage source converter, a coupling transformer and controls. In this application the DC energy source device can be replaced by a DC capacitor, so that the steady-state power exchange between the static compensator and the AC system can only be reactive, as illustrated in Fig.2. *I*q is the converter output current, perpendicular to the converter voltage *V*i. The magnitude of the converter voltage, and thus the reactive output of the converter, is controllable. If *V*i is greater than the terminal voltage, *V*t, the static compensator will supply reactive power to the AC system. If *V*i is smaller than *V*t, the static compensator absorbs reactive power.

A basic three-phase three-level voltage source converter consists of twelve self-commutated semiconductor switches, each of which is shunted by a reverse parallel connected diode, and six diode branches connected between the midpoint of the capacitor and the midpoint of each pair of switches. By connecting the DC source sequentially to the output terminals the inverter can produce a set of three quasi-square voltage forms of a given frequency.

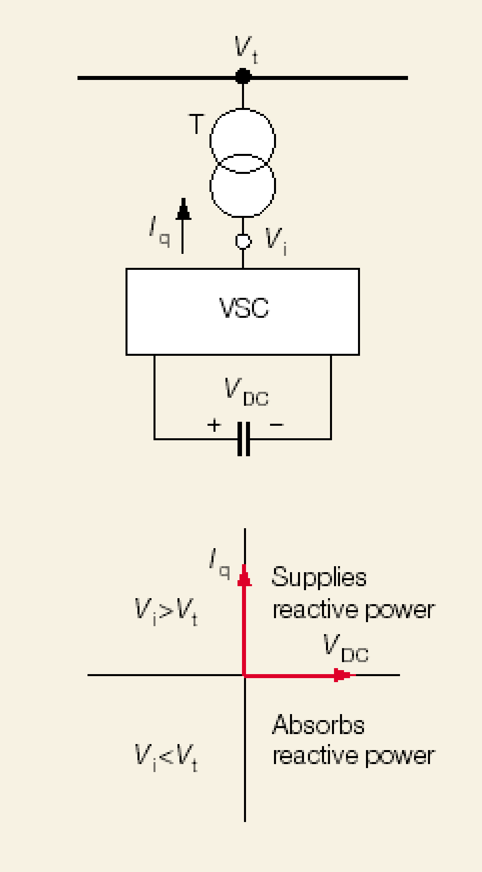


Fig. 2 STATCOM, comprising VSC, coupling transformer, and control

The frequency, amplitude and phase of the AC voltage can be varied by suitable control. Thus, the voltage source converter can be considered as a controllable voltage source.

IV. POWER QUALITY IMPACTS ON PROTECTIVE RELAYS

Power system protection is more closely related to power quality than might be apparent from cursory consideration. Protection is primarily concerned with clearing short circuits while power quality is concerned with reliable delivery of power within certain parameters.

With little further reflection, relationships begin to emerge. Short circuits depress voltages and result in sags that affect power quality. Protective relays discriminate between normal and abnormal parameters by assuming that normal parameters lie with the bounds required by good power quality. Poor power quality therefore blurs the boundary between normal and abnormal conditions. Protective relays perform better when there is a clear boundary to discriminate as to the presence (or absence) of a fault within their protective zones.

IEEE Standard 519 [8] defines acceptable degrees of waveform distortion in good quality power. However there are a large variety of normal and abnormal situations in which harmonic distortion levels specified in Standard 519 are exceeded. Every relay performs differently in the presence of waveform distortion. Different manufacturer's models of the same type of relay respond very differently to the same distortion. Relays of the same type and model from one manufacturer may even respond differently to the same distortion. Distortion may cause a relay to fail to trip under fault conditions, or it may cause nuisance tripping when no fault exists. Varying the phase angle between the fundamental and harmonic components of a voltage or current waveform may significantly alter a relay's response. For dual input relays, performance can be affected by the phase relationship between the respective input harmonics. Most studies published have evaluated electromechanical and electronic relays but there is little information on the new digital relays.

In some cases, excessive waveform distortion is a normal characteristic of the parameters measured by a protective relay. For instance, significant levels of third harmonics are often observed under normal conditions in zero sequence currents and voltages. Residual quantities are measured by relays to detect fundamental frequency voltage or current unbalances that may be indicative of power system short circuits. Relays designed to measure zero sequence quantities are usually specifically designed to reject harmonics, particularly third harmonics.

In other cases, harmonics in phase currents or voltages may be harmful to equipment. For instance the health of shunt capacitor banks may be threatened by excessive harmonics in the power system. Harmonics tend to be absorbed to by capacitor banks and may cause eventual failure of the bank due to overload. If the banks are protected by phase overcurrent relays that are insensitive to harmonics, the relays may not adequately protect the bank. However, even if the relays are sensitive to harmonics, they may over or under protect the bank depending on their specific response to harmonics. Unless special investigation is undertaken, the performance of protective relays to distorted waves is not usually known.

Fig. 3. shows the responses of three different measuring principles to a waveform with 30% third harmonic imposed on a fundamental frequency, with zero phase shifts. The true rms measurement will be about 4% higher than the fundamental frequency measurement, and the peak measurement will be 30% higher than the fundamental frequency. Many modern digital protective relays measure only the fundamental frequency phasor.

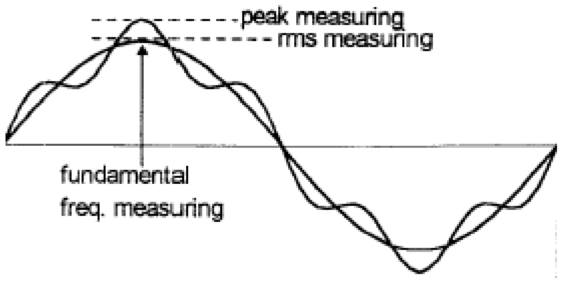


Fig. 3 Measuring a distorted wave

V. TCSC IMPACT ON POWER QUALITY

The proliferation of TCSCs, due to their nonlinear characteristics raises concern over the distortion levels they cause in voltages and currents at the transmission level. While harmonics generated by shunt devices like Static Var Compensator (SVC) are analyzed at great length, only a limited amount of articles addressing harmonics from TCSCs can be located. Ref. [12] reported that harmonic levels from series compensators are quite low (i.e., comparable to harmonics found in excitation current of a large transformer) and present TCSC installations do not require filtering. However, no analytical expressions relating the various circuit parameters and operating conditions were given. In [13] a detailed analysis of the waveform distortion in a transmission line equipped by TCSC is presented . It is concluded that the distortion increases rapidly with further increase in compensation level.

In [13] the waveform distortion is evaluated only during the normal operation, and the analysis during the fault is not considered. In this paper the harmonic content of current and voltage waveforms is extracted by EMTP/ATP simulations and compared by the analytic expressions of [13].

VI. SIMULATION RESULTS

A. Relay Simulation

The digital relay is simulated in MATLAB environment. It comprises of an ***Input Unit*** that delivers voltage and current obtained from the simulation of the sample network in EMTP/ATP. These signals are interpreted as analog signals. While the output of the EMTP/ATP is discrete, but the simulation step is many times higher than the digital part of the relay, so they could be evaluated as analog with reference to the digital parts. Two separate paths are designed for voltages and currents. ***Voltage path*** has different parts such as*: Isolation Transformers*, *Analog Low-Pass Filters*, *Analog Multiplexer* and *A/D.* ***Current path*** has the same components, except that the current is transformed to voltage. The other parts such as*: Isolation Transformers*, *Analog Low-Pass Filters*, *Analog Multiplexer* and *A/D* are the same. *Isolation Transformer* has the capability of changing the ratio by the user. *Low-Pass Filters* are really the *anti-aliasing filters.* Their characteristics can be selected by the user. For example, the type of the filter, i.e., Butterworth or Chebyshev could be selected. For each type, the order and the other related specifications are selectable. The filter frequency bode-plot is drawn automatically in order to check the cut-off frequency and overall filter performance. The *A/D* is designed for 16 Samples/Cycle. The output of this unit is plotted to observe the quality of the unit. After conversion of the voltage and current signals to digital form, they are processed in the *Protective Algorithm Unit*. This unit allows different algorithms to be implemented. For the case studies the *Differential Method* is used. It means the voltage and current differential equations are solved and the line resistance and reactance is calculated each time. *Setting Values* can be given as inputs to the associated unit. This consists of the impedances for the three zones and one reverse zone, plus the time setting for different zones. For the mentioned algorithm current and voltage phasors are required, so they are calculated by the Fast Fourier Transform. Each time the phasors are updated, the calculated impedance is compared with the setting values. The result could be a *Trip* command, issued by the ***Output Unit***. Finally, the trajectory of the impedance seen by the relay will be plotted against the relay characteristics, so the situation could be graphically checked, too. Fig. 4 shows the block diagram of the relay simulator, with different blocks. The blocks can be selected and configured.

B. TCSC Simulation

The first case study consists of two power systems connected through a transmission line (Fig. 5).

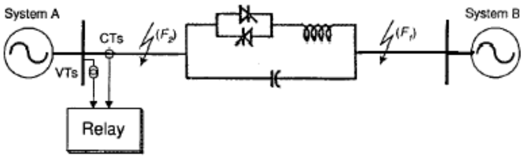


Fig. 5 Sample system with TCSC

System A delivers 1.0 p.u. real power at a lagging power factor of 0.9 at steady state. The steady state operating impedance of the TCSC is 0.209 p.u. The line is equipped with fixed capacitance. The fixed compensation is 0.147 p.u. The total compensation level is 0.356 p. u. and is approximately 71%. The resonance angle of the TCSC is 139 deg. The normal firing angle is 157 deg. The Xtcsc at 180 deg is 0.153 p.u. and at 152 deg is 0.323 p.u. Zbase is 325.55 ohms.

The distortion of the line current for normal case, i.e., firing angle 157deg is not very much. In this case, the third harmonic is only 0.818% fundamental frequency. Fig. 7 shows the thyristor current. The distortion in the TCSC loop is much higher than the line current. As already indicated the distortion of the current increases near the resonance point. Fig. 5 shows the line current with firing angle equal to 143 deg. A three phase fault has occurred after 0.4 sec. The fast fourier transform analysis of the line current indicates that, in this case the third harmonic is around 70% of the fundamental frequency, it means the distortion has raised considerably. In this situation the performance of the relay is not satisfactory.

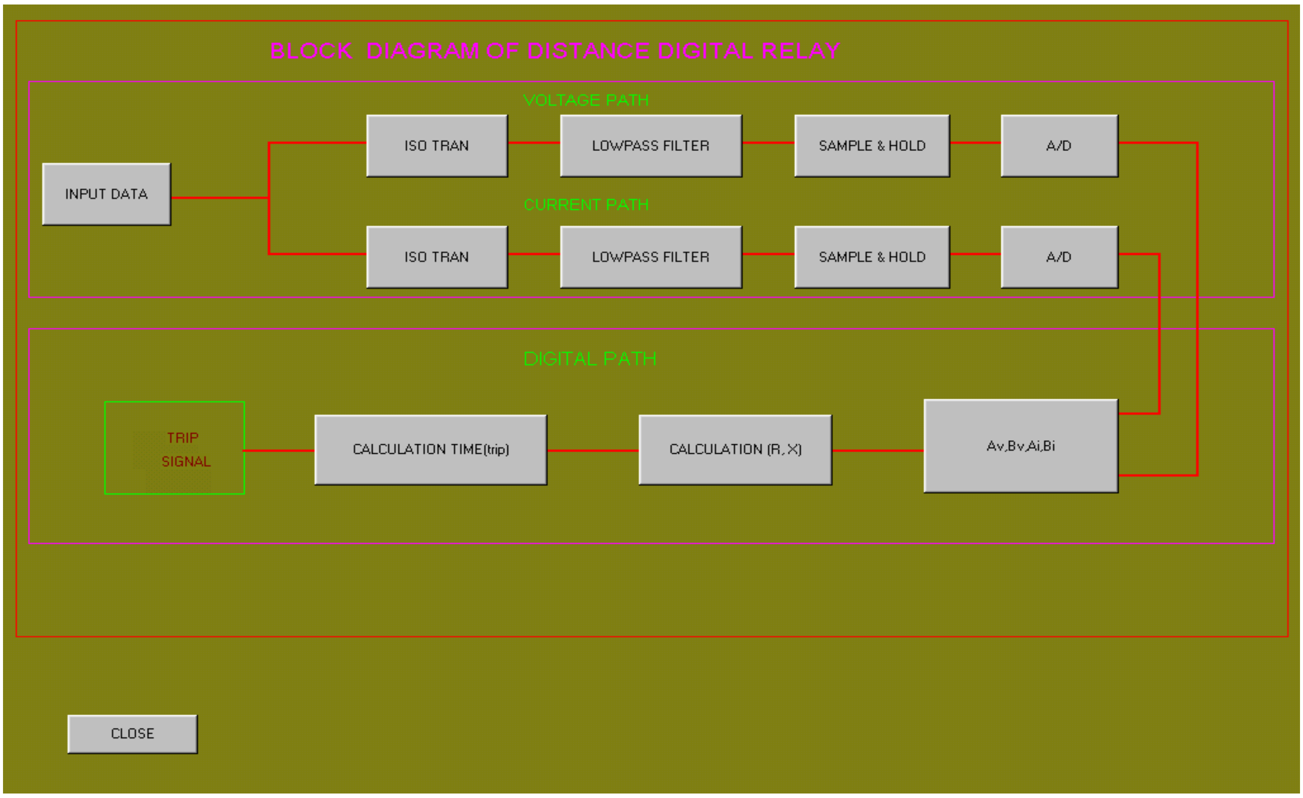
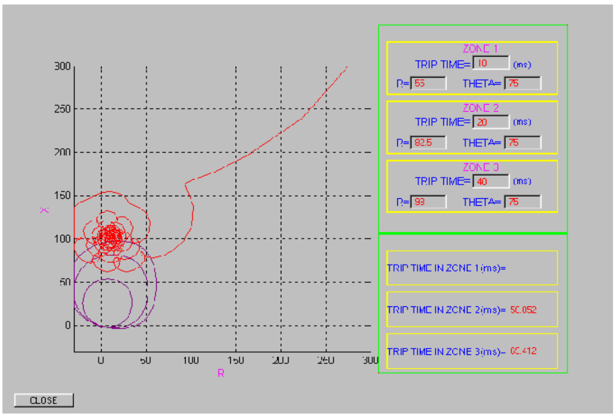


Fig. 4 Block Diagram of the Relay Simulator.

Fig. 6 shows the response of the relay simulator. In this case, the relay does not trip for a fault in the zone 1 of the relay; however, it trips in the second zone. It is concluded that high line current harmonics could disturb the relay function.



ZONE 1
TRIP TIME= 10 (ms)
R= 55 THETA= 75

ZONE 2
TRIP TIME= 20 (ms)
R= 82.5 THETA= 75

ZONE 3
TRIP TIME= 40 (ms)
R= 93 THETA= 75

TRIP TIME IN ZONE 1(ms)=

TRIP TIME IN ZONE 2(ms)= 50.052

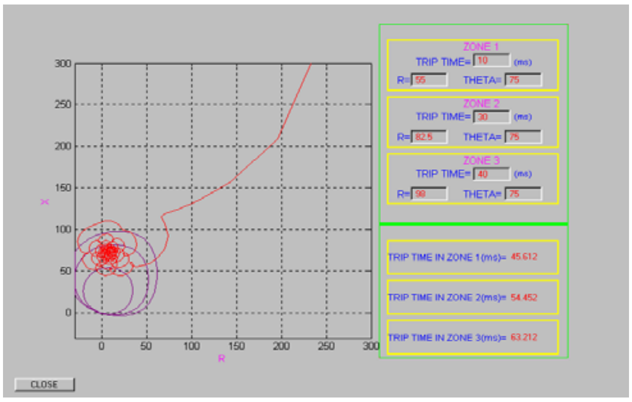
TRIP TIME IN ZONE 3(ms)= 60.412

Fig. 6 Relay performance with 143 deg. Firing angle, relay trips in second zone

In order to upgrade the relay performance to operate correctly in distorted conditions, the digital filtering of the relay promoted to reject the harmonics more efficiently. Fig. 7 shows the relay function after implementation of appropriate filtering. It shows that the relay has tripped in first zone in this case.

C. STATCOM Simulation

For the simulation of the STATCOM, the TCSC is removed from the sample system, and a 12 pulse STATCOM inserted at the middle of the line. Fig 8 shows the sample system. The results indicate that the distance protection under-reaches for a fault at reach point as the line loading increases.



ZONE 1
TRIP TIME= 10 (ms)
R= 55 THETA= 75

ZONE 2
TRIP TIME= 30 (ms)
R= 82.5 THETA= 75

ZONE 3
TRIP TIME= 40 (ms)
R= 98 THETA= 75

TRIP TIME IN ZONE 1(ms)= 45.612

TRIP TIME IN ZONE 2(ms)= 54.452

TRIP TIME IN ZONE 3(ms)= 63.212

Fig. 7 Relay performance with 143 deg. Firing angle, relay trips in first zone with appropriate filtering

This is due to the operation of the STATCOM which tries to maintain the voltage at the midpoint to its nominal voltage. In other words, under the fault condition, the voltage at the midpoint dips from its nominal voltage and this requires the STATCOM to produce more reactive current to boost the voltage at the midpoint and thus increase the apparent impedance seen by the distance relay at bus “S”. The generated voltages and currents are transferred from the EMTP/ATP to the distance relay simulator in MATLAB. The results are in conformity with the results of [14], with the exception that the prepared distance relay simulator is able to perform a detailed analysis. The behavior and the role of different relay subsystems on the final relay performance could be checked and it is concluded that removal of the DC offset and application of a powerful method, such as Fourier enhances the performance of the relay in poor power quality environments.

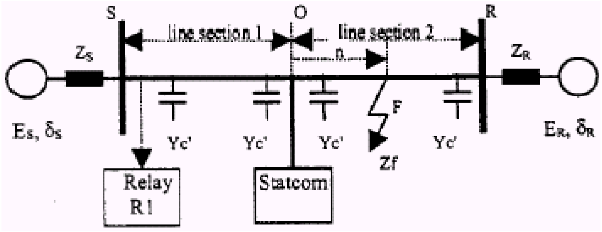


Fig. 8 Sample system with STATCOM

Fig. 9 shows the STATCOM topology used in the simulation of the case study. It is three-phase, two-level, 12-pulse GTO-based voltage-source inverter, 300 MVA rated power, 11 kV rated bus voltage. PWM switching frequency = 500Hz. Coupling power transformers are two Y-Y and Y-Δ. Y-Y transformer is three single-phase transformers and each one rated as 50 MVA, 63.5/6.36 kV and X=0.1 pu (on transformer rating). Y-Δ transformer is three single-phase transformers each one rated as 50 MVA, 63.5/11 kV and X= 0.1 pu (on transformer rating).

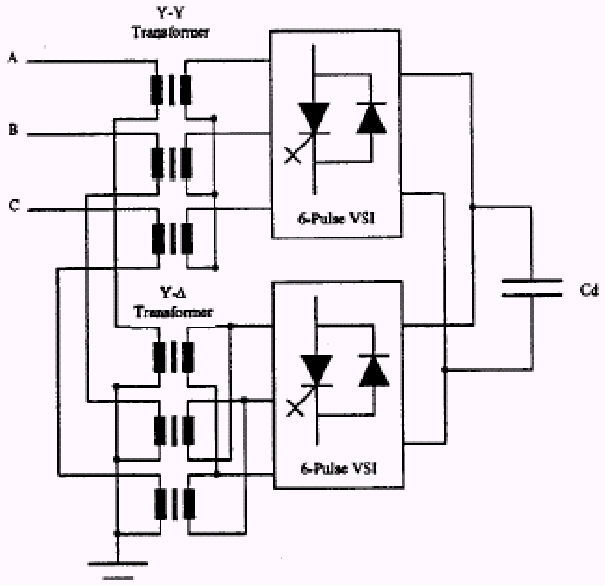


Fig. 9 STATCOM topology used in the simulation.

VI. CONCLUSIONS

Protective relays more easily discriminate between fault and non-fault conditions when power quality is good. Those relays designed to protect against excessive harmonics are not yet widely available.

In this paper, the power quality impact of TCSC and STATCOM as a sample type of FACTS devices on the protective relay behavior is investigated. The sample system is simulated by EMTP/ATP. The current and voltage signals before and after the fault are derived and transferred to a distance relay simulator designed in MATLAB environment. The relay model consists of signal conditioning subsystem and digital subsystem. Different blocks such as analog and digital filters are designed based on the manufacturers' data.

It is shown that for TCSC in normal operation the content of harmonics is not high and the relay operates as expected. The distortion increases rapidly with further increase in compensation level, and hence the operation of the relay is affected.

For the particular system studied, it was found that the-first-zone protection would not see a fault at the reach setting. This limit will vary with the system configuration, but generally, there will exist some limit to the first-zone-protection in the presence of a STATCOM.

In these circumstances, it is recommended to increase the filtering quality and/or the operational distance measurement algorithms. It is concluded that for the protection of compensated networks, sophisticated relays with advanced algorithms and digital filtering is required.

REFERENCES

[1] N. G. Hingorani, "Flexible AC transmission," *IEEE Spectrum*, vol. 3, pp. 40–45, Apr. 1993.

[2] R. Grunbaum, M. Noroozian, B. Thorvaldsson, "FACTS – Powerful System for Flexible Power Transmission", *ABB Review*, No. 5, 1999, pp. 4-17.

[3] M. Adamiak, R. Patterson, "Protection requirements for flexible AC transmission systems," *Proc. CIGRE*, Paris, France, 1992.

[4] F. Ghassemi, J. Goodarzi, and A. T. Johns, "Method to improve digital distance relay impedance measurement when used in series compensated lines protected by a metal Oxide Varistor," *IEE Proc. Gener. Transm. Distrib.*, vol. 145, pp. 403–408, July 1998.

[5] D. Novosel, B. Bachmann, Y. Hu, and M. M. Saha, "Algorithm for location faults on series compensated lines using neural network and deterministic methods," *IEEE Trans. Power Delivery*, vol. 11, pp. 1728–1736, Oct. 1996.

[6] M. M. Saha, J. Izykowski, E. Rosolowski, and B. Kasztenny, "A new accurate fault locating algorithm for series compensated lines," *IEEE PRWD*, Vol. 14, pp. 789–797, July 1999.

[7] IEEE Working Group, "Effects on Harmonics on Equipments", *IEEE PWRD*, Vol. 8, No. 2, pp. 672-680, April 1993.

[8] IEEE Std. 519-1992., "IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems".

[9] L. Gyugyi, "Dynamic compensation of AC transmission lines by solid state synchronous voltage sources," *IEEE PWRD,* Vol. 9, pp. 904–911, Apr. 1994.

[10] C. Schauder *et al.*, "Development of a 100 MVAR static condenser for voltage control of transmission systems," *IEEE PWRD*, vol. 10, pp. 1486–1496, July 1995.

[11]H.W. Dommel, "Digital computer solution of electromagnetic transients in single- and multi-phase networks," *IEEE Trans., Power App. and Syst.*, Vol. PAS-88 (4), pp. 388-398, 1969.

[12] E. V. Larsen, K. Clark, S. A. Miske and J. Urbanek, "Characteristics and Rating Considerations of Thyristor Controlled Series Compensators", *IEEE PWRD*, vol. 9, pp. 992–1000, July 1994.

[13] Y. Baghzouz and J. Black, "Waveform Analysis in Thyristor-Controlled Series Compensated Transmission Lines", *8th International Conference on Harmonics and Quality of Power ICHQP'98*, Athens, October 14-16, 1998, pp. 527-531.

[14] K. El-Arroudi, G. Joos, and D. T. McGillis, "Operation of Impedance Protection Relays With the STATCOM", *IEEE PWRD,* vol. 17, No.2, pp. 381–387, Apr. 2002.