Diyala Journal of Engineering Sciences

ISSN 1999-8716
Printed in Iraq

Vol. 09, No. 03, pp. 59-70, September 2016

STATCOM IMPACT ON DISTANCE RELAY PERFORMANCE

Qais M. Alias
Lecturer
Department of Electrical Engineering, University of Technology-Baghdad, Iraq
E-mail: qaismatti2004@yahoo.com[1], eng_ameer2012@yahoo.com [2]
(Received: 7/5/2015; Accepted: 4/10/2015)

ABSTRACT: - Flexible AC Transmission System devices provide for better utilization of already existing transmission systems as well as newly installed and upgraded systems. The use of such devices in the power transmission systems introduce new situations and variable operating conditions that need to be addressed in the fields of power system protection, system stability etc.

In this work, the effect of introducing a STATCOM device in the send-end and mid-point of a moderately long transmission line is analyzed. The analysis concerns the effect of such device on the performance of the power line distance protection. Extensive series of various fault studies were conducted using MATLAB/SIMULINK models of a distance relay, STATCOM device, and the power transmission system under study. Obtained results confirmed the idea of varied apparent impedance seen by the distance relay. In conclusion a distance relay may not operate dependably in presence of STATCOM device without prior actions considered in the relay setting stages.
Keywords: Distance relay; FACTS devices; Relay apparent impedance; Relay reach; Line distance protection.

INTRODUCTION

Electric power systems are made up of infrastructure to generate, transmit and distribute electrical energy. These power systems are the most complex and costly systems. Faults in these power systems are an unavoidable reality. Electrical faults impose strain on all levels of this infrastructure. If left uncorrected, these faults would quickly destroy this infrastructure and lead to the collapse of the power system. This fact identifies the need for another system responsible for the protection of the infrastructure against faults and abnormal operating conditions [1].

The continuous pressure to cut down expenditure and the difficulty in obtaining power transmission lines rights of way drove the power utilities to look for better and efficient use of the available transmission capabilities [2]. Such notion, confronted by the constraints of the various system stability criteria, is worthless unless modern techniques are introduced. Flexible AC Transmission (FACTS) devices are among the lately introduced techniques to the power transmission sector in order to manipulate the system dynamics towards better and optimal use of the existing power transmission corridors and raise the stability markers up [3].

The use of FACTS devices in the power transmission systems gave rise to many new conflicting issues regarding the requirements for the power system protection philosophy. Due to the presence of the FACTS device in the fault current path, the relaying point signals (voltage and current) are definitely affected in the steady-state as well as in the transient state [4]. Therefore, the protection system performance, for example a distance protection scheme, will be definitely changed compared with that when no FACTS devices are present.

Moreover, the timing issue is of importance as FACTS devices are fast, and whichever protection scheme is to be used, its performance need to be analyzed carefully [5].

One of the shunt FACTS devices is the STATCOM; it is designed based on conversion of voltage sources. The device can inject a 3-phase sinusoidal current wave with variable amplitude to the power system. In general STATCOM's have been connected at the mid-point of power transmission lines or at buses in high power loading areas in order to control the voltage at the device connection point. The voltage control strategy is based on absorbing/injecting reactive power at the connection point [6].

This work reports the results of a comprehensive study carried out to explore the impact of a STATCOM device installation on the distance protection relaying system in a power transmission line. Important issues like settings, timing are need to be identified and explored and protection engineers need to consider during the stages of design and operation of the distance-protection system.

1.1 STATCOM Compensator

The STATCOM is a shunt connected reactive power compensation FACTS device. It is capable of generating and/or absorbing reactive power which can be varied to control specific parameter in an electric power system (see **Figure (1)**). It is a voltage source converter that, from a given input of DC voltage, produces a set of three-phase AC outputs, each coupled to the corresponding AC system voltage through a relatively small reactance (which is provided by either an interface reactor or the leakage inductance of a coupling transformer). The DC voltage can be provided by an energy storage capacitor [7].

1.2 STATCOM principles of operation

Basically, the STATCOM controls its terminal voltage via reactive power injection or absorption at the point where it is connected to the system. The STATCOM acts capacitive to boost the system low voltage, and acts inductive to reduce system high voltage. The modes of operation is performed by means of a voltage source convertor (VSC) connected on the secondary side of the coupling transformer. The VSC uses forced-commutated power electronic devices (GTO's, IGBT's or IGCT's) to synthesize an AC voltage from a DC voltage source. **Figure (2)** shows the active power (P) and the reactive power (Q) transfer between the power system (source V_1) and the VSC (source V_2). In **Figure (2)**, V_1 represents the voltage to be controlled, while the voltage V_2 is that generated by the VSC, and is in phase with V_1 ($\emptyset_{statcom}$= 0º), so that only Q- power flows and (P=0). If V_2 is lower than V_1, Q flows from V_1 to V_2 (STATCOM is absorbing reactive power). If V_2 is higher than V_1, Q flows from V_2 to V_1 (STATCOM is generating reactive power). The amount of reactive power transfer is:

$$Q = \frac{V_1(V_1 - V_2)}{X} \qquad \textbf{(1)}$$

A capacitor connected on the DC side of the VSC acts as a DC voltage source. The voltage V_2 has to be phase shifted slightly behind V_1 in order to compensate for the transformer and VSC losses and to keep the capacitor charged [8].

2. Transmission Line Distance Protection

Protective relays are the most important piece of equipment used in the protection of power systems. Distance relay is one of the effective protective relays that are used for the protection of extra high voltage transmission lines. Distance relays are considered of the high speed class and can provide both primary and back-up protections [9].

Distance protection principles involve the implementation of Ohm's law at the relaying point, i.e. $Z_{apparent}$= (V/I). The apparent impedance so calculated is compared with the relay reach point impedance (i.e. zone setting). If the apparent impedance is less than the reach point impedance, i.e. relay to fault point distance is less than the zone setting, the distance relay must initiate the removal of the fault [10].

2.1 Mho self-polarized characteristics

The mho-relay characteristic is defined as a circle in the impedance plane which passes through the origin. The characteristic can be obtained by using phase comparison of sets of vectors derived from the current and voltage signals of the protected line at the relaying point. The phase comparator input signals of the mho characteristic can be represented by the following equations:

$$\left.\begin{aligned} S_1 &= I_r Z_R - V_r \\ S_2 &= V_r \end{aligned}\right\} \quad (2)$$

Where;

S_1 the operating voltage;

S_2 the polarization voltage;

I_r fault loop current;

V_r impedance loop voltage;

Z_R reach setting of the distance relay.

To represent the mho-relay characteristic in the R-X diagram, it is necessary to use the voltage phasors S_1 and S_2 in the impedance plane. This is accomplished by dividing **Equation (2)** by the current (I_r), yielding:

$$\left.\begin{aligned} S'_1 &= Z_R - Z_r \\ S'_2 &= Z_r \end{aligned}\right\} \quad (3)$$

Where; Zr is $Z_{apparent}$ seen by the distance relay.

Figure (3 a) demonstrates an example of the mho-relay with the operating conditions met. It can be seen that with Zr measured inside of the characteristic circle, the angular difference between S'_1 and S'_2 will be less than 90 degrees, which fulfils the operating condition. **Figure (3 b)** demonstrates an example of the mho-relay with the operating conditions not met [11].

2.2 Relay modeling and simulation

Distance relay zone settings are based upon the line positive sequence impedance, therefore, appropriate voltage and current inputs and a processing algorithm are required to calculate the line positive sequence impedance seen by the relay at the relaying point for all fault types.

A MATLAB/SIMULINK phasor model of mho-characteristic distance relay is built based on the apparent impedance equations for each fault type with phase comparator inputs of the forms given in **Equation (2)** for mho-characteristic. The distance relay model contains 6 elements, 3 for multi-phase faults and the other 3 elements for phase to ground faults. The inputs for the phasor relay model are the fundamental frequency component of voltages and currents at the relaying point. The structure of the phase element models of a 3-zone distance relay is presented in **Figure (4)**, ground elements have similar structure to that of the phase element but with two alterations, using zero sequence compensation factor and apparent impedance equations for faults including ground.

2.3 Distance relay zones setting

Selectivity in distance relays is provided by using different impedance reaches in conjunction with different time delays associated with those settings. Careful selection of the reach settings and tripping times for the various zones of protection enables correct coordination between distance relays in a power system [12]. Typical settings for three forward-looking zones of a basic distance protection system are given in the following sub-sections:

A. Zone-1 setting

The impedance reach of zone-1 is usually set on 80% to 85% of the transmission line impedance (depending on relay accuracy), leaving the remaining 20% to 15% of the line impedance as a safety margin. Zone-1 of protection has no intentional time delay, i.e. operate instantly [10].

B. Zone-2 setting

The reach setting of zone-2 protection should be at least 120% of the protected line impedance or a maximum equal to the protected line section plus 50% of the shortest adjacent line. To allow for selectivity, time setting of zone-2 must be graded with the operating time of zone-1 plus circuit breaker trip time [10].

C. Zone-3 setting

The main function of zone-3 is to offer remote back-up protection for faults occurring in lines emanating from the remote bus, that is time delayed to discriminate with zone-2 protection plus circuit breaker trip time for the adjacent line. Zone-3 reach should be set to at least 1.2 times the impedance presented to the relay for a fault at the remote end of the second line section [10].

3. Apparent Impedance Analysis

The mathematical analysis of a power transmission system including a STATCOM device connected at mid-point is dealt with here. The formulation concerns the calculation of $Z_{apparent}$ seen by the line distance relay. The same procedure can be followed if the STATCOM is situated at any other location along the line.

A simplified impedance equivalent circuit of a power system is shown in **Figure (5)**, for a fault in the second half of the power transmission line (i.e. after the STATCOM position). For a fault before the STATCOM, (fault in the first half of the transmission line) the apparent impedance seen by the distance relay can be calculated conventionally. From the previous sections, the STATCOM device can be represented as a shunt branch containing, a voltage source with impedance in series. The $Z_{apparent}$, seen by the distance relay, will be derived for a single phase to ground (Ph-G) fault in the following subsection (same procedure can be followed for the other types of fault).

*** Single (Ph-G) fault:**

The relay point sequence voltages for (Ph-G) fault in the transmission line second half (fault location, $H \geq 0.5$) can be expressed as:

$$V_{Rx} = 0.5\, Z_{Lx}\, I_{sx} + (H - 0.5) Z_{Lx}\, (I_{shx} + I_{sx}) + I_{fx} R_f \quad \textbf{(4)}$$

Where;

x = (0, 1, or 2) zero, positive and negative sequences notation respectively
V_{Rx} = relay point voltage of marked sequence
H = per-unit fault location distance w.r.t. relay point

$I_{sh\,x}$ = the STATCOM marked sequence current
$I_{s\,x}$ = the relay point marked sequence current
$I_{f\,x}$ = fault resistance marked sequence current
R_f = fault path resistance
ZL_x = the line impedance of marked sequence

The relay point voltage is:

$$V_R = V_{R1} + V_{R2} + V_{R0} \quad \textbf{(5)}$$

Assuming $Z_{L1} = Z_{L2}$, and simplifying, we get:

$$V_R = H\, Z_{L1}\, I_s + T1 + T2 + T3 \quad \textbf{(6)}$$

Where;

$I_s = I_{s1} + I_{s2} + I_{s0}$; $T1 = H\, I_{s0} (Z_{L0} - Z_{L1})$;
$I_{sh} = I_{sh1} + I_{sh2} + I_{sh0}$; $T2 = (H - 0.5) Z_{L1} I_{sh0} (Z_{L0} - Z_{L1})$;
$I_f = I_s + I_r + I_{sh}$; $T3 = (H - 0.5) Z_{L1} I_{sh} + I_f R_f$;

Due to the use of Y-Δ coupling transformer in connecting the STATCOM, no zero-sequence current will flow. Therefore, **Equation (6)** can be reduced to **Equation (7)** and simplifying, we get:

$$V_R = H\,Z_{L1}\,(I_s + mI_{s0}) + (H - 0.5)Z_{L1}I_{sh} + I_f R_f \qquad \textbf{(7)}$$

Where:

m = $(Z_{L0} - Z_{L1})/Z_{L1}$ is the current compensation factor for the zero-sequence component.

The ground measuring unit of a distance relay uses the phase voltage at the relay location (V_R) and the corresponding phase current suitably compensated by the zero-sequence current (I_R), so that it correctly measures the positive sequence impedance of the line. As a result, the apparent impedance seen by the ground distance unit is given as:

$$Z_{relay} = \frac{V_{relay}}{I_{relay}} = \frac{V_R}{I_R} \qquad \textbf{(8)}$$

Where: $I_R = (I_s + m\,I_{s0})$

Substituting **Equation (7)** in **Equation (8)**, the $Z_{apparent}$ seen by the relay ground unit is given by:

$$Z = H\,Z_{L1} + (H - 0.5)Z_{L1}\left(\frac{I_{sh}}{I_R}\right) + R_f\left(\frac{I_f}{I_R}\right) \qquad \textbf{(9)}$$

When the fault resistance is negligible, **Equation (9)** becomes:

$$Z = H\,Z_{L1} + (H - 0.5)Z_{L1}\left(\frac{I_{sh}}{I_R}\right) \qquad \textbf{(10)}$$

The first term ($H\,Z_{L1}$) in **Equation (10)**, represents the line impedance to a solid fault with no STATCOM. The error in $Z_{apparent}$ introduced as a result of the STATCOM installation is given as:

$$Z_{error} = (H - 0.5)Z_{L1}\left(\frac{I_{sh}}{I_R}\right) \qquad \textbf{(11)}$$

From **Equation (11)**, the error, is directly proportional to the fault position (H) and the current ratio$\left(\frac{I_{sh}}{I_R}\right)$.

The positive value of this current ratio, as a result of current injection by the FACTS device, would lead to higher impedance seen by the relay, which would result in relay underreach. On the other hand, the negative value of the current ratio would result in the relay seeing the fault at a closer position than the actual location and hence would lead to an overreaching effect.

4. Simulation Results

Following the above given analysis, the model system of **Figure (6)** was built to explore the impact of installing a STATCOM device on distance relay performance. The STATCOM model is a phasor type uses an IGBT PWM voltage source converter, the system parameters are given in **Table (1)**. The overall system model shown in **Figure (6)** combines the transmission system, the distance relay and the STATCOM models. Throughout the study, two STATCOM connection points to the power system have been considered and as follows:

A. STATCOM connected at bus-1

With reference to **Figure (6)**, the STATCOM positioned at bus-1 station, **Figures (7 a) and (7 b)** show the impedance trajectory seen by the mho distance relay for a (Ph-G) and 3Ph faults at 135 km distance from bus-1. **Table (2)** shows the relay performance for a (Ph-G) fault, in this table the without STATCOM column represents the system relay performance considering No STATCOM connected to the line for comparison purposes. **Figure (8)** shows the elements of the apparent impedance seen by the relay for 3Ph fault along the line with STATCOM device connected to bus-1 in the transmission line system. For both (Ph-G) and 3Ph faults, the results show the state of higher impedance seen by the relay with the presence of the STATCOM at bus-1 station.

B. STATCOM connected at mid-point

With reference to **Figure (6)**, the STATCOM positioned at the mid-point under the same loading conditions, **Table (3)** shows the relay performance for a (Ph-G) fault. **Figures (9 a) and (9 b)** show the impedance trajectory with mho distance relay for 3Ph and (Ph-G) faults at 135km from bus-1. **Figure (10)** shows the elements of the apparent impedance seen by the relay for a 3Ph fault along the line length. Similar to bus-1 STATCOM position; the impedance seen by the distance relay is increased with the STATCOM connected at mid-point.

5. Conclusions

The primary system studied throughout this work involved a 177km, 400kV transmission line. Comprehensive series of simulation studies were conducted to evaluate the effect of the FACTS device (STATCOM in this work) on the distance relay situated at bus-1 station.

The simulations revealed that, the STATCOM main impact is on the relay seen apparent impedance. That impact is presented as relay underreach for all fault positions when the STATCOM is situated at bus-1. That was true also for faults beyond mid-point when the STATCOM was connected there. Furthermore, translated as relay underreach for all fault positions when the STATCOM is situated at bus-1, the results show clearly the dependency of the distance relay operation on many design and operational factors. These include the FACTS device connection point or location, the fault type and fault point location along the line. Finally, in order to mitigate FACTS impact, adaptive settings of the distance relay tripping boundaries need to be investigated instead of fixed type settings.

REFERENCES

[1] Aggarwal, R. K. et al., (2005), "Power System Protection: Principles and components", The Institution of Electrical Engineers, England,.

[2] Song Y. H., and Johns A. T., (1999), "Flexible AC Transmission Systems", IEEE Press, New York.

[3] Hingorani N. G., and Gyugyi L., (2000), "Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems", IEEE Press, New York.

[4] Wen-Hao Zhang, Seung-Jae Lee and Myeon-Song Choi, (2010), "Setting Considerations of Distance Relay for Transmission Line with STATCOM", Journal of Electrical Engineering and Technology, Vol. 5, No. 4, pp. 522-529.

[5] Dash P. K., et al., (2000), "Adaptive Relay Setting for Flexible AC Transmission Systems (FACTS)", IEEE Trans. Power Delivery, Vol. 15, No. 1.

[6] Gharedaghi F., et al., (2011), "Analysis of Statcom Operation in Electric Transmission System", Journal of Basic and Applied Scientific Research, Vol. 1, No. 12, pp. 2908-2915.

[7] Javid Akhtar, and Sinto George, (2012), "Modeling and Simulation of STATCOM for a Power System Network Using MATLAB/SIMULINK", IOSR Journal of Engineering (IOSRJEN), Vol. 2, Issue 8, pp. 12-17.

[8] Gabriela Glanzmann, (2005), "FACTS Flexible Alternating Current Transmission Systems", EEH-Power System Laboratory, ETH Zurich.

[9] General Electric Company, Alsthom Measurements Limited, (1987), "Protective Relays Application Guide", Stafford Eng., 3rd edition, England.

[10] AREVA T&D Energy Automation & Information, (2002), "Network Protection and Automation Guide",1st edition, Cayfosa, Spain.

[11] J. Roberts, et al, (1993), " Z=V/I Does Not Make a Distance Relay", 20th Annual Western Protective Relay Conference, Washington.

[12] Les Hewitson, Mark Brown, and Ben Ramesh, (2004), "Practical Power Systems Protection", Newnes-Elsevier, Oxford.

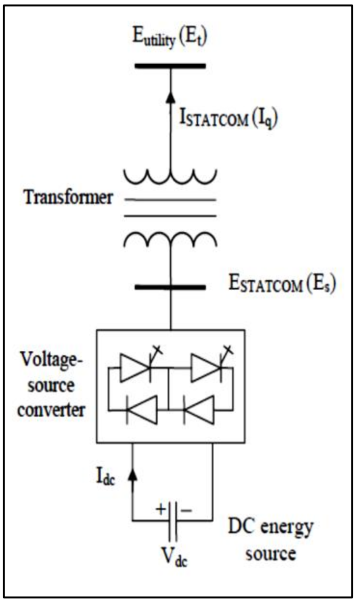


Figure (1) A STATCOM device circuit diagram [7]

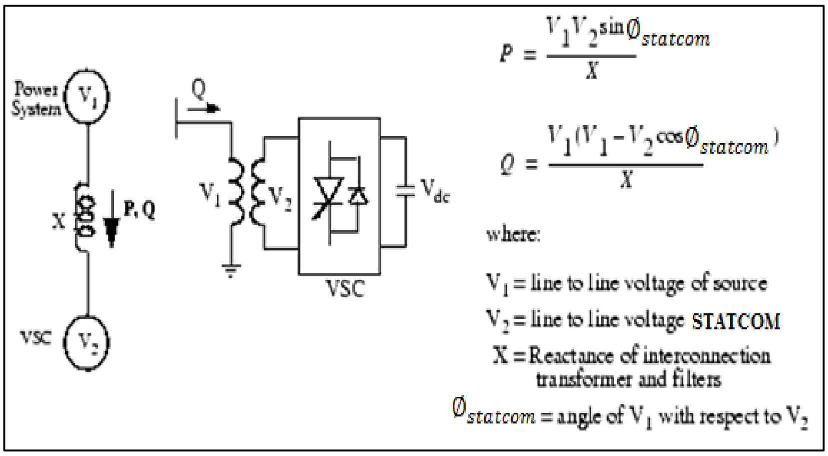


Figure (2) Operation principles of a STATCOM [8]

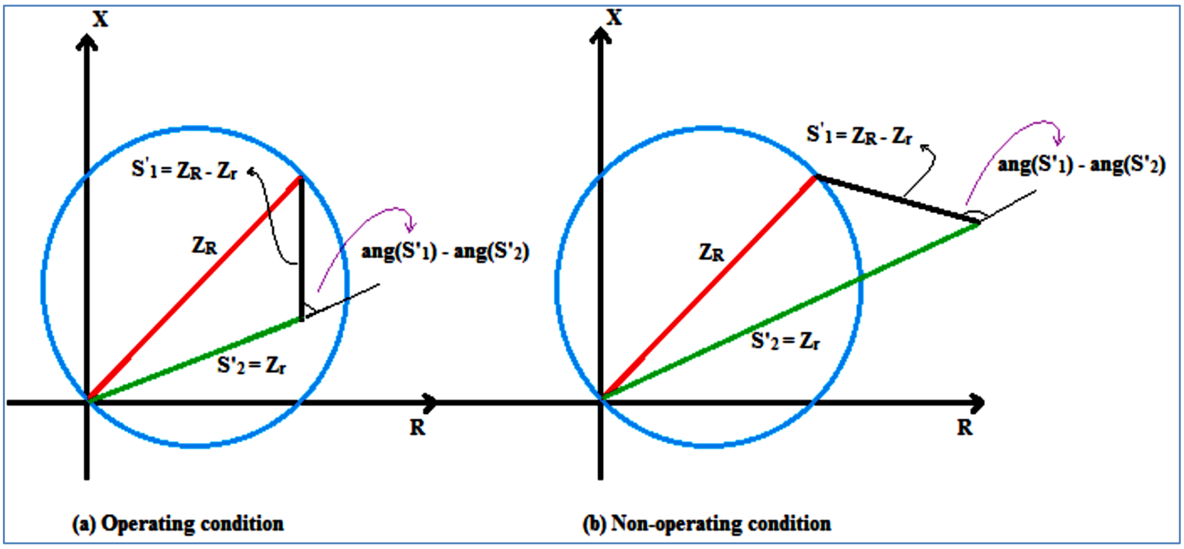


Figure (3) Sample Mho-relay characteristics

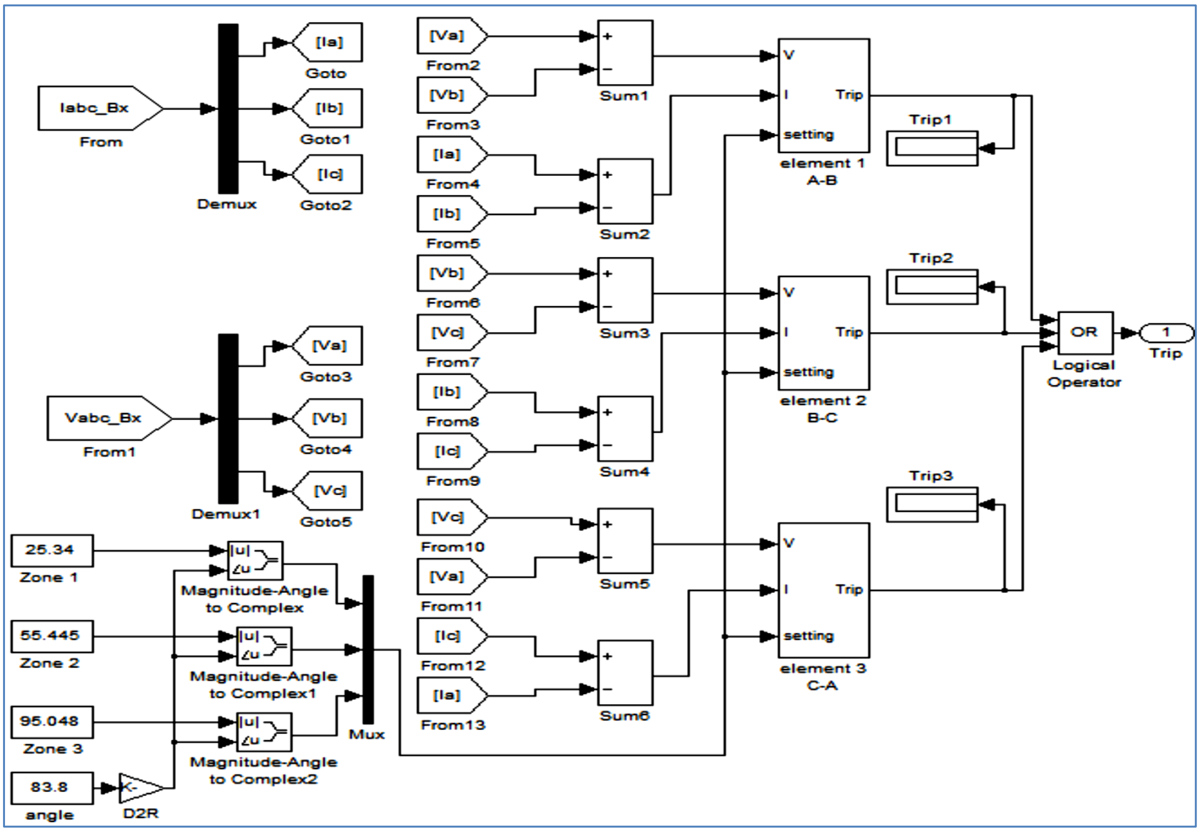


Figure (4) SIMULINK phase mho relay model

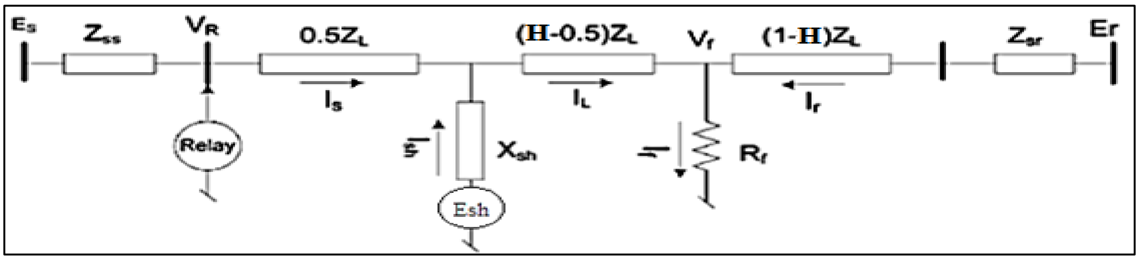


Figure (5) Simplified faulted network for a power system with STATCOM device

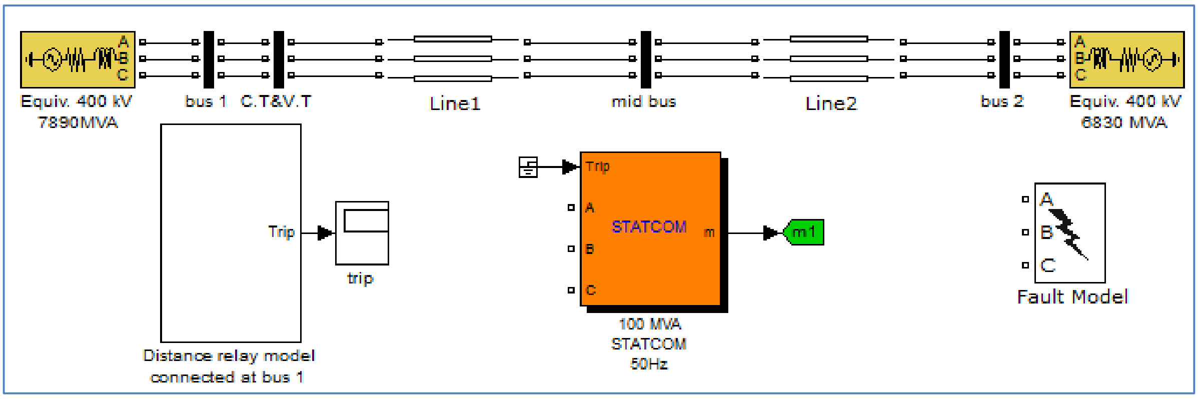
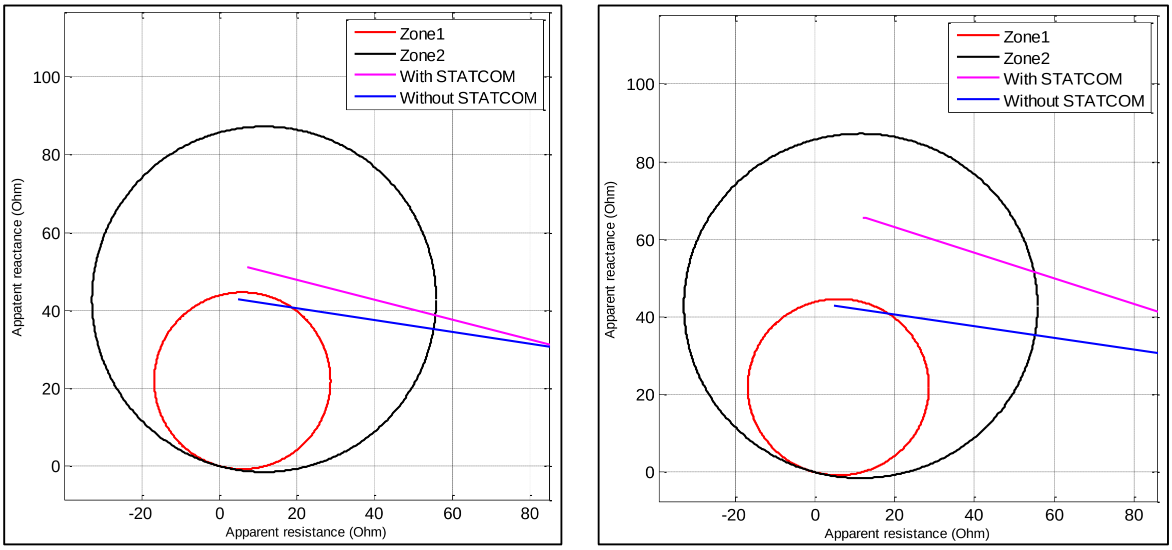


Figure (6) overall Matlab/Simulink system model

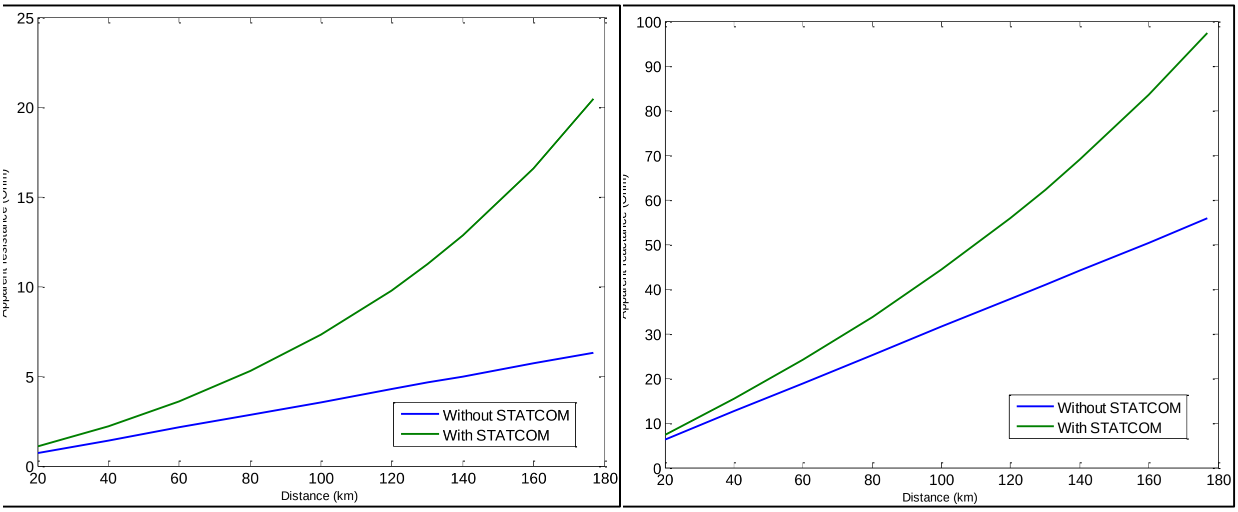
Table (1) Case study: System parameters

System Component	Ratings
Equivalent Source	400 kV , 50 Hz
Transmission Line (T.L.)	177 km
STATCOM rating	100 MVA
T.L positive sequence impedance	6.124 + j 55.789 Ω
T.L zero sequence impedance	53.072 + j172.656 Ω



(a) Ph-G at 135km (b) 3Ph at 135km

Figure (7) Impedance trajectory: STATCOM at bus-1



(a) Apparent resistance (b) Apparent reactance

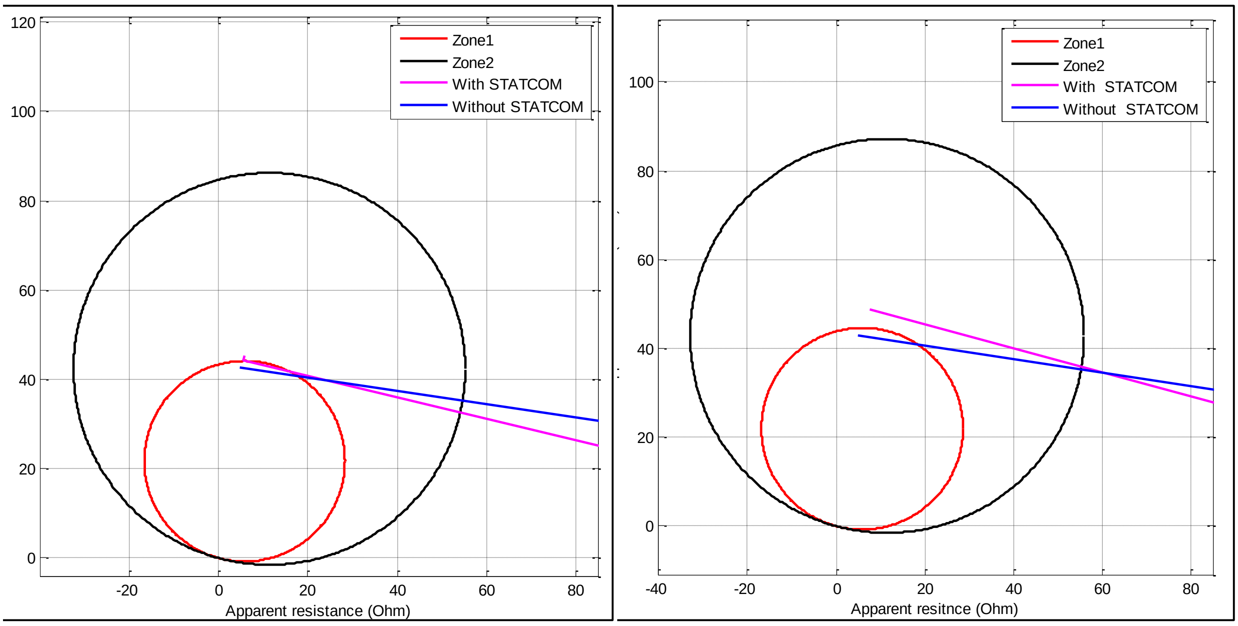
Figure (8) Apparent impedance against distance: 3Ph fault, STATCOM at bus-1

Table (2) Relay performance: (Ph-G) fault, STATCOM at bus-1

Fault position(km)	Results for Comparison			Zapp (Ω) (with STATCOM)	Relay Response	
	Zapp (Ω) (without STATCOM)	Relay Response				
		Zone1	Zone2		Zone1	Zone2
20	0.7120 + 6.3020i	Trip	—	0.7784 + 6.6561i	Trip	—
40	1.4240 +12.6040i	Trip	—	1.6333 +13.5866i	Trip	—
60	2.1360 +18.9060i	Trip	—	2.5701 +20.8169i	Trip	—
80	2.8480 +25.2080i	Trip	—	3.6024 +28.3746i	Trip	—
100	3.5600 +31.5100i	Trip	—	4.7429 +36.2943i	Trip	—
120	4.2720 +37.8120i	Trip	—	6.0011 +44.6184i	Trip	—
130	4.6280 +40.9630i	Trip	—	6.6901 + 48.946i	—	Trip
135	4.806 +42.53850i	Trip	—	7.0547 +51.1543i	—	Trip
140	4.9840 +44.1140i	Trip	—	7.4225 +53.3969i	—	Trip
160	5.6960 +50.4160i	—	Trip	9.0336 +62.7194i	—	Trip
177	6.3012 +55.7727i	—	Trip	10.6888 +71.1818i	—	Trip

Table (3) Relay performance: (Ph-G) fault, STATCOM at mid-point

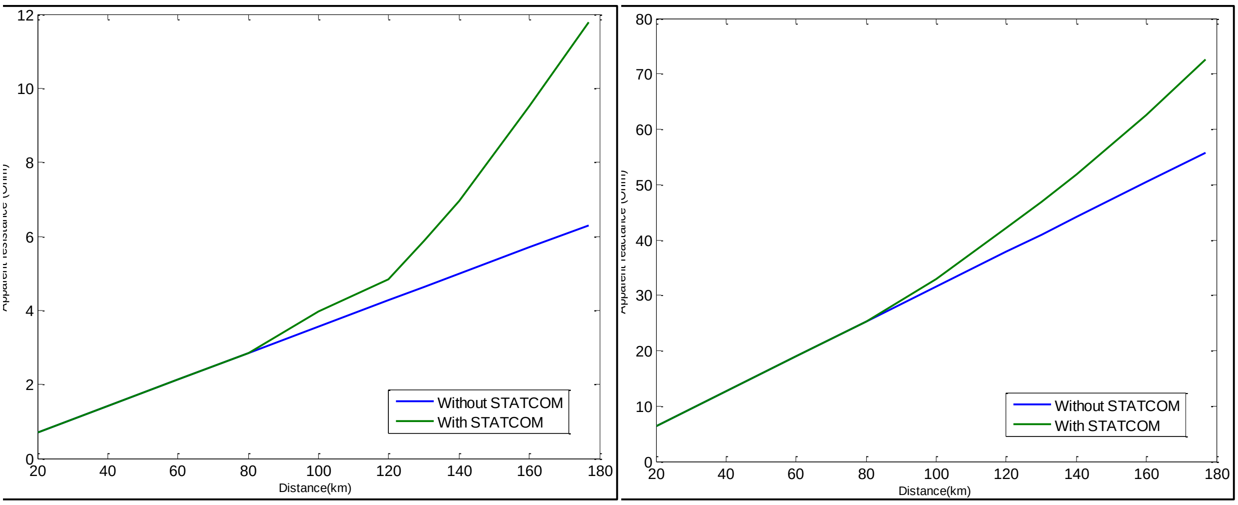
Fault position(km)	Results for Comparison			Zapp (Ω) (with STATCOM)	Relay Response	
		Relay Response				
		Zone1	Zone2		Zone1	Zone2
20	0.7120 + 6.3020i	Trip	—	0.71219 + 6.3037i	Trip	—
40	1.4240 +12.6040i	Trip	—	1.4222 + 12.61i	Trip	—
60	2.1360 +18.9060i	Trip	—	2.1299 + 18.923i	Trip	—
80	2.8480 +25.2080i	Trip	—	2.8348 + 25.247i	Trip	—
100	3.5600 +31.5100i	Trip	—	3.7229 + 32.066i	Trip	—
120	4.2720 +37.8120i	Trip	—	4.8352 + 39.494i	Trip	—
130	4.6280 +40.9630i	Trip	—	5.4405 + 43.338i	Trip	—
135	4.806 +42.53850i	Trip	—	5.7561 +45.2942i	—	Trip
140	4.9840 +44.1140i	Trip	—	6.0826 + 47.275i	—	Trip
160	5.6960 +50.4160i	—	Trip	7.496 + 55.465i	—	Trip
177	6.3012 +55.7727i	—	Trip	8.8697 + 62.831i	—	Trip



(a) (Ph-G) at 135 km

(b) 3Ph at 135 km

Figure (9) Impedance trajectory: STATCOM at mid-point



(a) Apparent resistance

(b) Apparent reactance

Figure (10) Apparent impedance against distance: 3Ph fault, STATCOM at mid-point

تأثير جهاز التعويض الساكن على اداء المناولة المسافية

د. قيس متي الياس
مدرس
الجامعة التكنولوجية – قسم الهندسة الكهربائية

الخلاصة

ان اجهزة نظم النقل المرن (FACTS) تدعم الاستخدام الامثل لانظمة نقل الطاقة الكهربائية المنشئة قديماً وحديثاً وانظمة القدرة المحدثة . ان استخدام مثل هذه الاجهزة في انظمة نقل الطاقة الكهربائية يؤدي الى حالات وظروف تشغيل جديدة موجبةُ الاخذ بنظر الاعتبار في مجال عديدة مثل حماية نظم القدرة, استقرارية نظم القدرة الخ.

في هذا البحث, تم تحليل تاثير استخدام جهاز نظام نقل مرن (STATCOM) يربط في جهة الارسال او نقطة المنتصف لخط نقل قدرة طويل نوعا ما, على نظام الحماية المسافية لخط النقل. تم دراسة عدة حالات اخطاء باستخدام برنامج MATLAB/SIMULINK وذلك بواسطة استخدام نماذج لكل من, مناولة الحماية المسافية, جهاز (STATCOM) ونظام نقل القدرة المستخدمين في الدراسة. بينت النتائج تغير الممانعة الظاهرية المرئية من قبل مناولة الحماية المسافية وبالتالي امكانية التشغيل الغير معتمد للمناولة في حالة وجود مثل هذه الاجهزة ما لم يؤخذ ذلك بنظر الاعتبار مسبقا في مرحلة التعيير لمناولة الحماية المسافية.