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ENHANCED POSITIVE-OFFSET MHO ELEMENT LOE PROTECTION OF SYNCHRONOUS GENERATOR IN THE PRESENCE OF STATCOM

BY

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Abstract. This research work presents an enhancement in the positive offset mho element that may be used in the loss of excitation (LOE) protection scheme of synchronous generator associated with a static synchronous compensator (STATCOM) in transmission line. This enhanced element of the protection scheme is based on recalculating the impedance at the relay location by eliminating the injected STATCOM current measured by phasor measurement unit (PMU). Under total or partial loss of excitation condition, the simulation results show that the new developed method improves the operation of the positive offset LOE protection by reducing the delay time that may be due to the presence of STATCOM.

Keywords: Synchronous Generato; Loss of Excitation (LOE); positive-offset mho element; static synchronous compensator (STATCOM); phasor measurement unit (PMU).

1. Introduction

Synchronous generator protection may have more advanced and reliable protection functions with respect to other power system elements that detects

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different possible abnormal operating conditions and faults (Mozina *et al.*, 1995). The most abnormal condition in synchronous generator is the loss of excitation (LOE) due to open or short circuit in the exciter, which results in voltage regulation problems and incorrect operations (Ostojić *et al.*, 2018). Statistics in china shows that LOE account for 69.5% of all generator failures (Wang, 2006). Moreover, when the LOE occurs, the generator will absorb reactive power from the system in order to continue generating the required active power. Hence, during this condition, both the generator and the power system may face instability problems. Therefore, LOE condition should be detected as rapidly as possible with high reliability and selectivity (Kundur, 1994; Reimert, 2005).

Furthermore, nowadays the flexible ac transmission systems (FACTS) controllers have been used in transmission subsystems for voltage and reactive power flow control. However, numerous studies reported that FACTS devices have adverse impacts on the performance of the impedance-based distance protection in transmission lines, in the form of under reach or delay time (Albasri *et al.*, 2007; Arroudi *et al.*, 2002). Since the LOE protection based on impedance measurement, its performance has been investigated under the presence of FACTS devices as well as STATCOM. The performance of the negative offset mho element LOE protection scheme under the presence of FACTS devices is investigated in (Elsamahy *et al.*, 2014; Ghorbani *et al.*, 2015). Furthermore, the impact of STATCOM on the positive offset mho element LOE protection scheme is presented in (Mati *et al.*, 2017). The results of these references show that the FACTS devices have adverse impacts on the impedance-based LOE protection relays in the form of delay time and/or under-reach.

In addition, improved or new techniques to achieve better generator LOE protection under the presence of FACTS devices are highly needed. Hence, in reference (Elsamahy *et al.*, 2014) adaptive neuro-fuzzy inference systems (ANFIS) classification techniques and support vector machines (SVMs) are proposed. Likewise, as a future work in (Mati *et al.*, 2017) the use of phasor measurement units (PMUs) or ANFIS is recommended. A new LOE detection method aiming to prevent the effect of FACTS is introduced in (Yaghobi, 2015). based on the variation of the magnetic flux linkage in the generator air gap. After that, a new algorithm used to recalculate the new active and reactive power at the relay location based on the measurements received from PMUs is presented in (Ghorbani *et al.*, 2016). Furthermore, based on Thevenin model parameters at STATCOM location used to modify the impedance trajectory seen by the LOE protection relay, a new adaptive impedance-based LOE protection scheme is demonstrated in (Yaghobi, 2017).

The main objective of this paper is to reduce the impact of STATCOM on the positive offset mho element LOE protection scheme in synchronous generator, by reducing the delay time. Therefore, a new enhanced scheme is presented in this work, based on eliminating the injected STATCOM current that has been measured using PMU at the relay location and introduces new impedance.

2. LOE Protection Schemes

All conventional LOE protection schemes are based on impedance measurement. The first impedance-based form has been introduced by Mason (Mason, 1949), which contains one negative offset mho element. After that this scheme has been enhanced by (Berdy, 1975), where two characteristic zones have been introduced to increase the relay security during transient power swings. In order to augment the security for close external faults, a positive-offset mho element combined with a directional unit has been proposed (IEEE Power System Relaying Committee). Some other types of LOE protection schemes have been established (Gazen *et al.*, 2014; Mahamedi *et al.*, 2016), but they have been not yet widely used.

2.1. Positive Offset MHO Element

This protection scheme uses a combination of two mho impedance-based units and a directional unit as shown in Fig. 1.

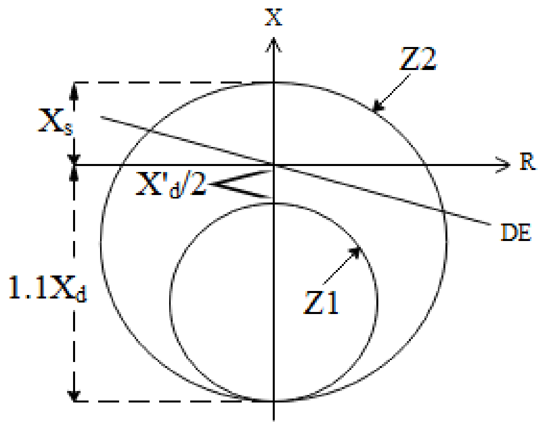

Fig. 1 − Positive-offset mho element characteristic.

The first Zone (Z1) has a negative offset mho characteristic, and it is set using the following equations:

$$Diameter = 1.1X_d - \frac{X_d^{'}}{2}, \tag{1}$$

$$Offset = \frac{X_d^{'}}{2}, \tag{2}$$

where: X_d is the generator direct axis reactance in per unit, and X'_d – generator transient reactance in per unit. A time delay of 0.1 to 0.3 second is recommended to prevent maloperation under transient swings (Coelho *et al*., 2014; Sandoval *et al*., 2007).

The second zone (Z2) has a positive-offset mho characteristic, and it is set using the following equations:

$$Diameter = 1.1X_d + X_s, \tag{3}$$

$$Offset = X_s, \tag{4}$$

where: X_S is the sum of all the impedances away from the generator terminals (up to relay location) in per unit. A time delay may be Considered between 0.25 to 1 second (Coelho *et al*., 2014; Sandoval *et al*., 2007).

Moreover, this positive offset element is controlled by a directional element to prevent maloperation when close external faults occur. The directional element is set at an angle between 10 and 20 degrees. Therefore, a failure on the minimum excitation limiter might occur. Hence, both the directional and the mho element operate and initiate an alarm. A one minute time delay may be introduced in many cases to trip the unit if the situation cannot be restored before the damage proposed (IEEE PSRC).

In order to construct the *R*-*X* diagrams for a balanced three phase conditions, the *R* and *X* should be determined as follow:

$$R = \frac{P \times V^2}{P^2 + Q^2}, \tag{5}$$

$$X = \frac{Q \times V^2}{P^2 + Q^2}, \tag{6}$$

in which, *P*, *Q* and *V* are the active power, the reactive power and the voltage of the relay location (generator terminals), respectively.

2.2. LOE Protection under the Presence of STATCOM

STATCOM that is one of the main types of the shunt FACTS devices is commonly utilized to regulate transmission line voltage by controlling the reactive power flow. It can also enhance the power quality by performing several compensations such as dynamic voltage control and system stability. In STATCOM, the reactive power output can be continuously changed between the capacitive and inductive reactance. The V-I characteristic of STATCOM shown in Fig. 2 clarifies the conditions (Shahnia *et al*., 2015).

In the other hand, according to reference (Mati *et al*., 2017) and as clearly shown in Fig. 3, the presence of STATCOM in transmission line affects on the operation of the positive-offset mho element LOE protection scheme by introducing the delay time.

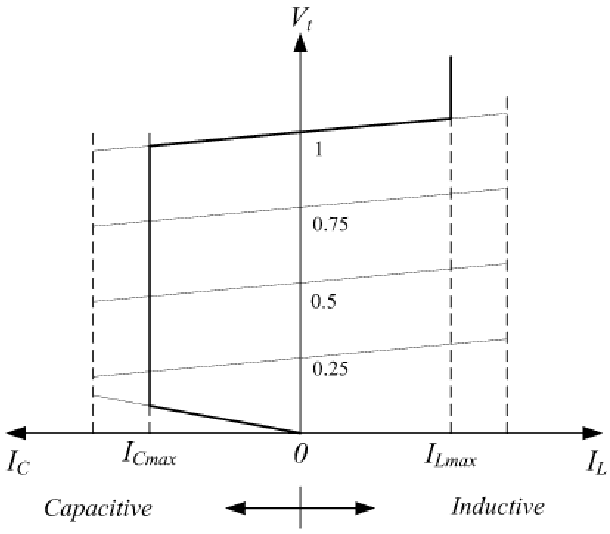

Fig. 2 − V-I characteristic of a STATCOM.

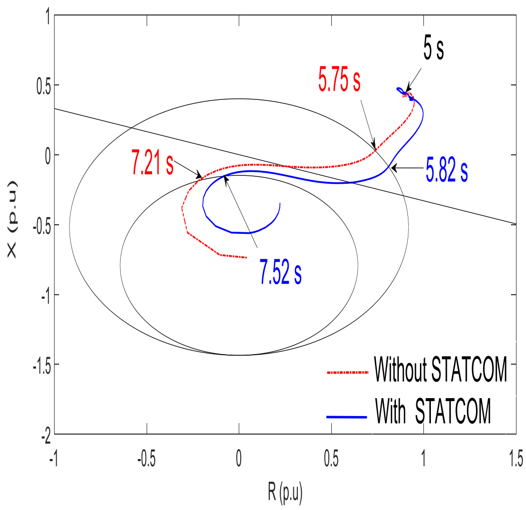

Fig. 3 − Impedance trajectories measured by positive-offset mho element, with/without STATCOM.

3. Enhanced LOE Protection Scheme under the Presence of STATCOM

A single machine infinite bus (SMIB) as shown in Fig. 4, is used in this study. It consists of a synchronous generator associated with its control system, connected to a large system through a transmission line.

A STATCOM is connected to the midpoint transmission line for voltage regulation. The data of this power system are given in Appendix.

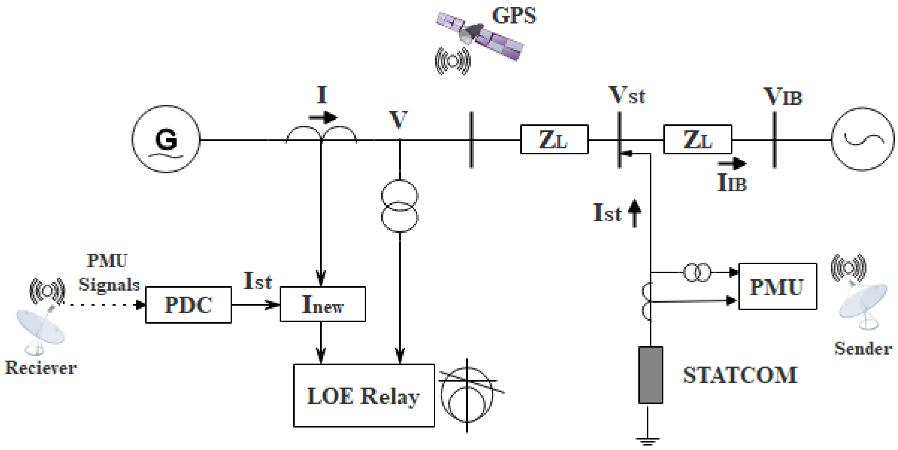

Fig. 4 – Single machine infinite bus of the Power system under study.

Applying Kirchhoff's current law at the midpoint gives:

$$I = I_{IB} - I_{st}, \tag{7}$$

where:

$$I_{IB} = \frac{V_{st} - V_{IB}}{Z_L}. \tag{8}$$

In which:

$$I = \frac{V_{st} - V_{IB}}{Z_L} - I_{st}, \tag{9}$$

The voltage at the midpoint can be written as:

$$V_{st} = V - IZ_L. \tag{10}$$

Therefore:

$$I = \frac{V - IZ_L - V_{IB}}{Z_L} - I_{st}, \tag{11}$$

$$I = \frac{V - V_{IB}}{2Z_L} - \frac{I_{st}}{2}. \tag{12}$$

Before installing the STATCOM, the current can be calculated as:

$$I_{old} = \frac{V - V_{IB}}{2Z_L}. \tag{13}$$

Finally, at the relay location, the current is expressed as:

$$I = I_{old} - \frac{I_{st}}{2}. \tag{14}$$

Analyzing the eq. (14), it can be noted that the injected STATCOM current affects on the operation of the LOE relay by the delay time. Therefore, in order to minimize this delay time, before installing the STATCOM, the current may be recomputed at the relay location as follows:

$$I_{new} = I_{old} = I + \frac{I_{st}}{2}\,. \tag{15}$$

Fig. 4, shows that the PMU installed at the STATCOM location can measure the current Ist and transfer it remotely to the relay location where the new current Inew can be calculated. Therefore, the new impedance at the relay location is determined as:

$$Z_{new} = \frac{V}{I_{new}}\,. \tag{16}$$

4. Performance of the Enhanced LOE Protection Scheme

To test the performance and evaluate the improved positive offset mho element LOE protection scheme based on PMU measurement, simulations have been investigated using Simulink / MATLAB program. Therefore, two different LOE case studies are conducted, namely:

Case study 1: Total loss of excitation (Ef = 0).

Case study 2: Partial loss of excitation (Ef = 0.2 p.u and Ef = 0.4 p.u).

4.1. Case Study 1

A total loss of excitation (TLOE) is measured at five second of the simulation. Therefore, three scenarios can considered; integrating the performance of the positive-offset mho element LOE protection scheme without STATCOM, with STATCOM and the performance of the improved LOE protection scheme.

Fig. 5, shows the generator output reactive power with/without the STATCOM, under full load (S = 0.9 + j0.43 pu). It can be noticed that after the occurrence of TLOE at 5s, the output reactive power decreases gradually to zero. Then, the generator starts to absorb the reactive power from the power system until reaching negative value. The synchronism loss may be appeared at 7s. In the other hand, through the use of STATCOM, the amount of reactive power is reduced compared to the situation without the STATCOM. However, this reduction is compensated by the supplied STATCOM reactive power. When the generator reactive power decreases due to the TLOE, the supplied STATCOM reactive power increases trying to stabilize the system until the loss of machine synchronism.

Furthermore, Fig. 5, shows that the generator can operate for longer time. When TLOE is occurred with STATCOM without losing synchronism unlike the case without STATCOM, it will affect on the operation of the mho impedance LOE protection by introducing the delay time.

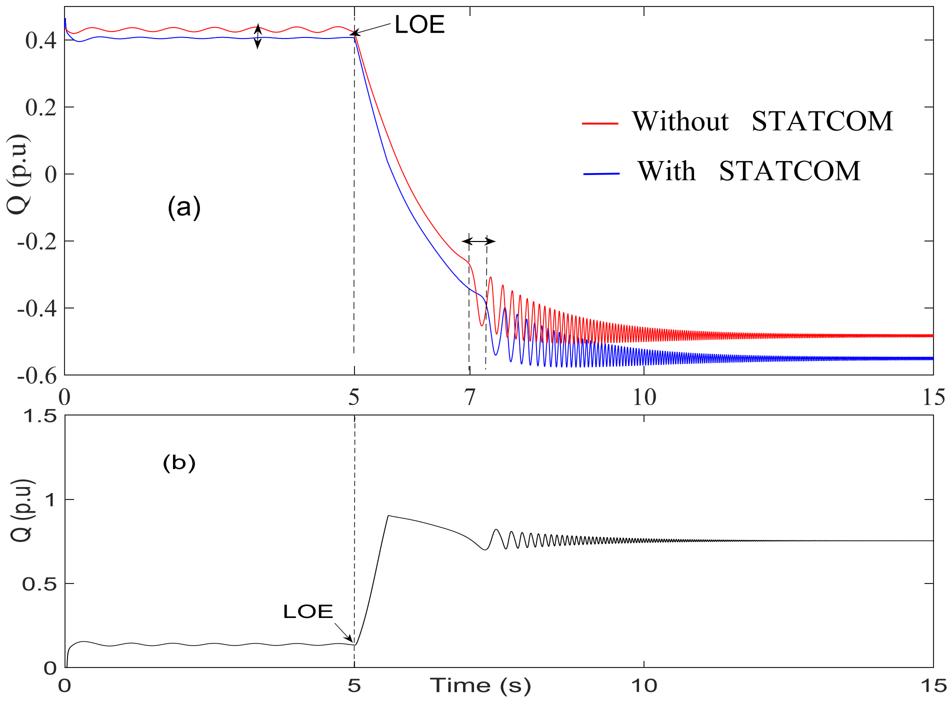

Fig. 5 – a) Generator output reactive power with and without STATCOM. Under TLOE. b) Reactive power supplied by the STATCOM.

The performance of the positive offset mho element with and without STATCOM, and the improved LOE protection scheme under TLOE that occurred at 5 seconds and with initial load (S = 0.9 + j0.43 pu) is illustrated in Fig.6. The latter shows that under the three scenarios the TLOE is detected. However, the detecting time is different, in case without STATCOM the LOE fault can be detected at 6.753 seconds however in case with STATCOM, the fault detection is delayed until 6.823 seconds. Therefore, using the improved method with the presence of STATCOM, the LOE fault detection time may be reduced to 6.763 seconds which is close to the one without STATCOM (6.753 seconds). It can be noticed that the impedance trajectory can be illustrated as shown in Fig. 6. The impedance locus of the improved scheme is close to the locus of the positive offset scheme without STATCOM, and hence it proves its effectiveness, however, the effect of delay time that produced by the presence of STATCOM can be reduced.

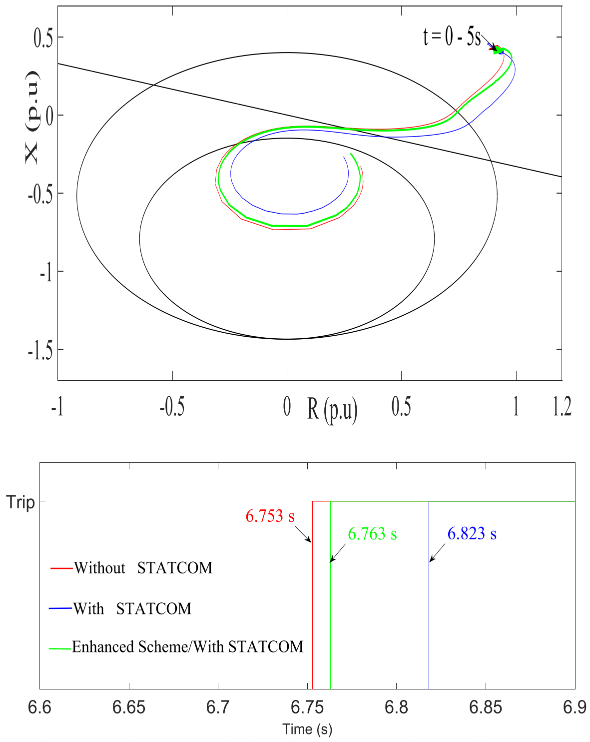

Fig. 6 − The impedance trajectory of the three scenarios under TLOE and the tripping times.

To evaluate this result, six different generator initial loading conditions have been chosen. The simulation results of the three scenarios are given in Table 1. It can be noted that when the TLOE occurs under all loading conditions, the clearing time of the positive-offset mho element LOE protection scheme in case without STATCOM will be delayed as compared to the case with STATCOM. Therefore, this delay time will be reduced using the new improved LOE protection scheme under all conditions.

Table 1
The Clearing Time of the Three Scenarios under TLOE

TLOE $E_F = 0$		**Initial load S = P + jQ (pu)**					
		0.9 + + j0.43	0.7+ + j0.33	0.5+ + j0.25	0.3+ + j0.25	0.2 – – j0.2	0.1+ + j0.15
Clearing time (s)	With-ST	**<u>1.823</u>** Z2	**<u>2.27</u>** Z 2	**<u>2.90</u>** Z2	**<u>3.52</u>** Z 1	**<u>4.09</u>** Z 1	**<u>4.68</u>** Z 1
	W/out-ST	1.753 Z 2	2.23 Z 2	2.88 Z 2	3.10 Z 1	3.65 Z 1	4.21 Z 1
	Enhanced scheme	1.763 Z 2	2.24 Z 2	2.86 Z 2	3.24 Z1	3.68 Z1	4.09 Z1

4.2. Case Study 2

A partial loss of excitation (PLOE) with two different values of the field voltage (Ef = 0.2 p.u and Ef = 0.4p.u) is considered in this case. Therefore, three scenarios as case study 1 can be simulated.

The behavior of the generator output reactive power with/without STATCOM and the supplied reactive power by the STATCOM under PLOE (Ef = 0.2 p.u) with initial load (S=0.9+j0.43 pu) is illustrated in Fig. 7.

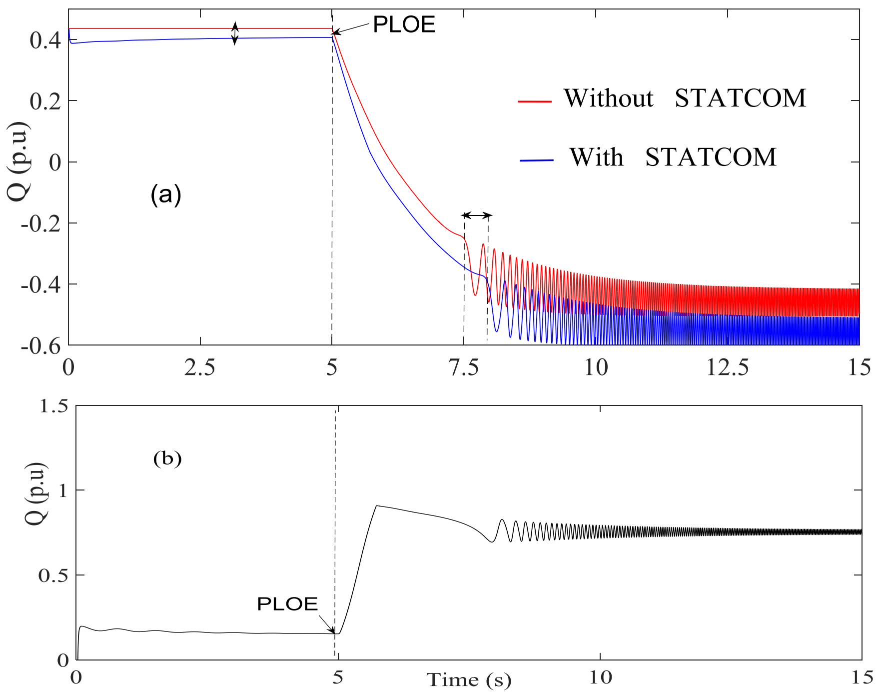

Fig. 7 – a) Generator output reactive power with and without STATCOM. Under PLOE (Ef = 0.2 p.u). b) Reactive power supplied by the STATCOM.

It can be noticed that the generator output reactive power follows the same chart as the one with TLOE, where it is clearly noticed that when PLOE occurs with STATCOM, the generator will operate for longer time without losing synchronism compared to the case without STATCOM. Hence, the operation of the mho impedance LOE protection will be affected by the delay time.

However, comparing the generator output reactive power with TLOE (Fig. 5a) and PLOE (Fig. 7a) shows that the reactive power under PLOE loses synchronism at 7.5 seconds and under TLOE at 7 seconds. Therefore, the operation of the positive offset mho element will take more time under PLOE compared to TLOE case.

Fig. 8, shows the impedance trajectories of the three scenarios under PLOE (Ef = 0.2 pu) that occurs at 5s and with initial load (S = 0.9 + j0.43 pu) may be associated with their tripping times. The PLOE is well detected under the three scenarios. In case without STATCOM, the fault is detected at 7.032 s and in case with STATCOM the fault detection time is delayed to 7.155 s. Therefore, using the improved method with the STATCOM, the PLOE fault detection time is reduced to 7.109 s. Hence, the improved method effectively reduces the delay time caused by the STATCOM under PLOE.

The simulation results of the three scenarios under the two PLOE cases (Ef = 0.2 p.u and Ef = 0.4p.u) are given in Table 2. It can be noticed that when the PLOE occurs under all heavy loading conditions, the fault will be detected. However, under light loading conditions and especially in case PLOE (Ef = = 0.4 pu), the fault will not be detected under all the scenarios. Furthermore, the results show that the clearing time of the positive-offset mho element LOE protection scheme will be delayed in case with STATCOM compared to the case without STATCOM. Therefore, under the improved LOE protection scheme this delay time will be reduced under all conditions.

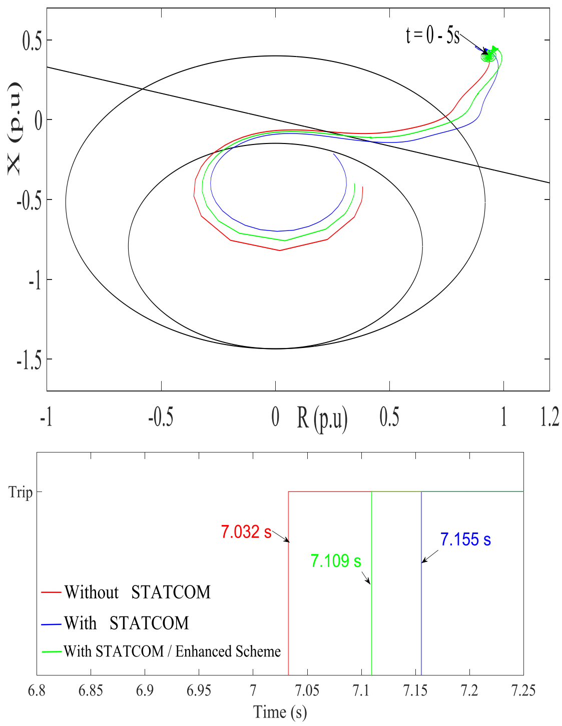

Fig. 8 − the impedance trajectory of the three scenarios under PLOE (Ef = 0.2 pu), and the tripping times.

Table 2

The Clearing Time of the Three Scenarios under PLOE

PLOE E_F = 0.2 pu		Initial load S = P + jQ (pu)					
		0.9 + + j0.43	0.7 + + j0.33	0.5 + + j0.25	0.3 + + j0.25	0.2 – – j0.2	0.1 + + j0.15
Clearing time (s)	With-ST	**2.15** Z2	**2.69** Z 2	**3.87** Z2	**4.58** Z 2	**9.66** Z 1	**UR**
	W/out-ST	2.03 Z 2	2.62 Z 2	3.73 Z 2	4.39 Z 2	8.27 Z 1	UR
	Enhanced scheme	2.1 Z 2	2.58 Z 2	3.48 Z 2	3.78 Z2	5.87 Z1	UR

PLOE E_F = 0.4 pu		Initial load S = P + jQ (pu)					
		0.9 + + j0.43	0.7 + + j0.33	0.5 + + j0.25	0.3+ + j0.25	0.2 – – j0.2	0.1 + + j0.15
Clearing time (s)	With-ST	**2.68** Z2	**3.73** Z 2	**8.15** Z2	**UR**	**UR**	**UR**
	W/out-ST	2.4 Z 2	3.48 Z 2	6.64 Z 2	UR	UR	UR
	Enhanced scheme	2.55 Z 2	3.53 Z 2	6.89 Z 2	8.74 Z1	UR	UR

5. Conclusion

In this research work, the effect of STATCOM on the operation of the positive offset mho element LOE protection in synchronous generator is studied and a new improved LOE protection scheme is proposed. The effectiveness of the phasor measurement unit in measuring and sending phasors data is confirmed in this new scheme. The STATCOM injected current is eliminated at the relay location and new impedance is recalculated.

To test validity of the improved method, simulation studies have been investigated using Simulink/MATLAB program with different generator loading conditions. The obtained results show that under total or partial loss of excitation, the operation of the positive offset mho element LOE protection in the presence of STATCOM is improved through the use of the new scheme and hence the delay time is reduced.

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APPENDIX

1) Generator parameters: 200 MVA, 150 MW, 13.8 KV,

Xd = 1.305 pu, Xq = 0.474 pu, X'd = 0.296 pu, X''d = 0.252 pu.

2) Transformer parameters: 200 MVA 13.8 kV / 230 kV
3) Transmission line: 150 km, 230 kV, R1= 0.02546 Ohms/km, R0 = 0.3864 Ohms/km,
L1= 0.9337e-3 H/km, L0 = 4.1264e-3 H/km, C1 = 12.74e-9 F/km,
C0 = 7.751e-9 H/km.
4) Equivalent system: 230 Kv, Z = 0.529 + j5.2752 Ohm.
5) STATCOM: +/– 100MVA,
6) Positive-offset mho element settings:

Zone 1:

Circle diameter 1.287 pu.
Offset = 0.148 pu
Time delay: 0.1 s

Zone 2:

Circle diameter = 1.835 pu.
Offset = 0.4 pu.
Time delay: 1 s
Directional element: set with angle –18°.

REFERENCES

Albasri Fadhel A., Tarlochan Singh Sidhu, Rajiv K. Varma, *Performance Comparison of Distance Protection Schemes for Shunt-FACTS Compensated Transmission Lines*, IEEE Transactions on Power Delivery, 22.4, 2116-2125 (2007).

Berdy John, *Loss of Excitation Protection for Modern Synchronous Generators*, IEEE Transactions on Power Apparatus and Systems, 94.5, 1457-1463 (1975).

Coelho Aurélio LM, *et al*., *Loss-of-Excitation Protection and Under Excitation Controls Correlation for Synchronous Generators in a Real-Time Digital Simulator*, IEEE Transactions on Industry Applications, 51.5, 3579-3590 (2015).

El-Arroudi, Khalil, Geza Joos, Donald T. McGillis, *Operation of Impedance Protection Relays with the STATCOM*, IEEE Transactions on Power Delivery, 17.2, 381-387 (2002).

Elsamahy Mohamed, Sherif Omar Faried, Tarlochan Sidhu, *Impact of Midpoint STATCOM on Generator Loss of Excitation Protection*, IEEE Transactions on Power Delivery, 29.2, 724-732 (2013).

Gazen Yuri Neves, *et al*., *New Setting of Loss of Excitation Protection in PQ Plan in Order to Maximize the Operation Area of the Capacity Curve of the Synchronous Machine*, 2014 49th International Universities Power Engineering Conference (UPEC), IEEE, 2014.

Ghorbani Amir *et al*., *Operation of Synchronous Generator LOE Protection in the Presence of Shunt-FACTS*, Electric Power Systems Research , **119,** 178-186 (2015).

Ghorbani Amir, Soodabeh Soleymani, Babak Mozafari, *A PMU-based LOE Protection of Synchronous Generator in the Presence of GIPFC*, IEEE Transactions on Power Delivery, 31.2, 551-558 (2015).

Kundur Prabha, Neal J. Balu, Mark G. Lauby, *Power System Stability and Control*, **7**. New York, McGraw-hill, 1994.

Mahamedi Behnam, Jian Guo Zhu, Sayyed Mohammad Hashemi, *A Setting-Free Approach to Detecting Loss of Excitation in Synchronous Generators*, IEEE Transactions on Power Delivery, 31.5, 2270-2278 (2015).

Mason C.R., *A New Loss-of-Excitation Relay for Synchronous Generators*, Transactions of the American Institute of Electrical Engineers, 68.2, 1240-1245 (1949).
Mati Ayache, Hamid Bentarzi, *Impact of STATCOM on Generator Positive-Offset Mho Element Loss of Excitation Protection*, 2017 5th International Conference on Electrical Engineering-Boumerdes (ICEE-B), IEEE, 2017.
Mozina Charles J., Gardell J., *IEEE Tutorial on the Protection of Synchronous Generators*, IEEE Power Engineering Society, IEEE, **95**, 1-78 (1995).
Ostojić Mladen, Milenko Djurić, *The Algorithm for the Detection of Loss of Excitation of Synchronous Generators Based on a Digital-Phase Comparator*, Electrical Engineering, 100.2, 1287-1296 (2018).
Reimert Donald, *Protective Relaying for Power Generation Systems*, CRC press, 2005.
Sandoval Ramon, Armando Guzman, Hector J. Altuve, *Dynamic Simulations Help Improve Generator Protection*, 2007 Power Systems Conference: Advanced Metering, Protection, Control, Communication, and Distributed Resources. IEEE, 2007.
Shahnia Farhad, Sumedha Rajakaruna, Arindam Ghosh, eds. Static compensators (STATCOMs) in power systems, Springer Singapore, 2015.
Wang W., *Principle and Application of Electric Power Equipment Protection*, China Electric Power Press, Beijing (2002).
Yaghobi Hamid, *A New Adaptive Impedance-Based LOE Protection of Synchronous Generator in the Presence of STATCOM*, IEEE Transactions on Power Delivery, 32.6, 2489-2499 (2017).
Yaghobi Hamid, *Impact of Static Synchronous Compensator on Flux-Based Synchronous Generator Loss of Excitation Protection*, IET Generation, Transmission & Distribution, 9.9, 874-883 (2015).
* * * *IEEE Power System Relaying Committee*, *IEEE Guide for AC Generator Protection*, IEEE Std. C 37, 1-177 (2007).

ELEMENT IMBUNATAŢIT DE ADMINTANŢĂ COMPENSAT POSITIV PENTRU PROTECŢIA LA PIERDEREA EXCITAŢIEI GENERATORULUI SINCRON ÎN PREZENŢA COMPENSATORULUI SINCRON STATIC

(Rezumat)

Această lucrare prezintă o îmbunătăţire a elementului de admitanţă compensat pozitiv care poate fi utilizat în schema de protecţie la pierderea excitaţiei (PPE) la generatorul sincron asociat cu un compensator sincron static (STATCOM) în linia de transmisie. Acest element îmbunătăţit al schemei de protecţie se bazează pe recalcularea impedanţei la locaţia releului prin eliminarea curentului STATCOM injectat măsurat de unitatea de măsură a fazorului. În condiţiile pierderii totale sau parţiale a stării de excitaţie, rezultatele simulării arată că noua metodă dezvoltată îmbunătăţeşte funcţionarea protecţiei PPE cu compensare pozitivă prin reducerea timpului de întârziere care se poate datora prezenţei dispozitivului STATCOM.