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Impact of STATCOM on Generator Positive-Offset *mho* element Loss of Excitation Protection

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Abstract— **In this paper simulation studies have been conducted using Simulink/MATLAB software in order to investigate the impact of STATCOM on the positive-offset mho element loss of excitation (LOE) protection scheme in synchronous generator. The obtained results show that the operation of the positive-offset protection scheme takes more time under the integration of STATCOM in the transmission line. Moreover, an under reach phenomena may occur under partial loss of excitation (PLOE) condition of a generator with lightly loading.**

Keywords- Loss of Excitation (LOE), positive-offset mho element, total LOE, partial LOE, static synchronous compensator (STATCOM).

I. INTRODUCTION

Loss of excitation (LOE) is one of the most abnormal/fault condition in synchronous generator, which may occur due to field open circuit, field short circuit, and a controlling problem or an operational error. When a synchronous generator loses its excitation, it operates as an induction generator obtaining its excitation from the system by absorbing reactive power. As a consequence, this absorbed reactive power causes problems for the generator, adjacent machines, and the power system which may threatens its stability [1, 2]. For these reasons, more sophisticated and reliable LOE protection schemes are required to detect the LOE condition as rapidly as possible while remaining insensitive to the other system disturbances.

Several methods have been proposed for LOE detection, the most popular and reliable ones are the negative-offset and positive-offset mho element protection schemes. The first approach based on a single-phase negative offset mho element has been introduced by Mason [3]. A later approach contains two characteristic zones has been introduced by Berdy [4], designed to improve the relay robustness during transient swings and low frequency disturbances. This approach has been improved by combining a positive-offset mho element and a directional unit, which provides security for close in external faults [5].

Nowadays, the use of Flexible Alternating Current Transmission System (FACTS) devices in various power system networks is continuously increasing. FACTS devices are used in transmission lines to control the voltage as well as it controls the power flow especially the reactive power flow that leads to change the currents and voltages of the power system [6, 7]. Therefore, FACTS devices have adverse impacts on the operation of the mho-element LOE protection relays that are based on the measurement of voltages and currents of the power system. In this concern, an important issue that must be taken into consideration during the performance of the mho-element LOE relays is the presence of FACTS devices in transmission systems. Recently, investigations on the performance of the negative-offset mho element LOE protection scheme under the presence of static synchronous compensator (STATCOM) have been reported in [8, 9]. The results of these investigations show that the presence of STATCOM has adverse impacts on the negative-offset mho element LOE relay in the form of delay time and/or under-reach phenomenon. Moreover, many techniques have been proposed to enhance LOE protection scheme under the presence of STATCOM; in [9], support vector machines (SVMs) and adaptive neuro-fuzzy inference systems (ANFIS) classification techniques are suggested. New flux-based LOE protection method is proposed in [10], which is based on the local variation of the flux linkage of the generator available at the relay location. In [11], a new modified LOE protection algorithm on the basis of synchronized phasor measurements received from phasor measurement units (PMUs) is proposed. A New Adaptive Impedance-Based LOE protection scheme utilizes unsynchronized measurements at STATCOM terminals to modify impedance trajectory seen by the relay is presented in [12].

In fact all these investigations have been done on the negative-offset mho element LOE protection scheme. However, no research work has been reported on the impact of STATCOM on the positive-offset mho element LOE protection scheme.

II. POSITIVE OFFSET MHO ELEMENT LOE PROTECTION SCHEME

The positive-offset *mho* element comprises of two mho zones and directional element as shown in Fig.1. Zone 1 has a negative offset that is equal to $X'_d/2$ and a diameter equal to

($1.1.X_d$ - $X'_d/2$). A time delay of 0.1 to 0.3 second is allowed to ride through stable swings and system transients. Zone 2 has a diameter equals to ($1.1.X_d$+ X_s) and an offset equal to (X_s), where (X_s) is the sum of the transformer reactance (X_t) and the system reactance (X_{sys}). A time delay of 0.25 to 1 second is recommended. The directional element angle is set between 10 and 20 degrees. The angle is adjusted to be equal to the arccosine of the minimum-rated power factor of the machine. This directional element is used to prevent pickup for close-in faults on the system [5, 13].

The positive-offset *mho* element LOE protection scheme based on calculating the impedances during a loss of excitation at the generator terminals using the following equations:

$$R = \frac{P \times V}{P^2 + Q^2} \tag{1}$$

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

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

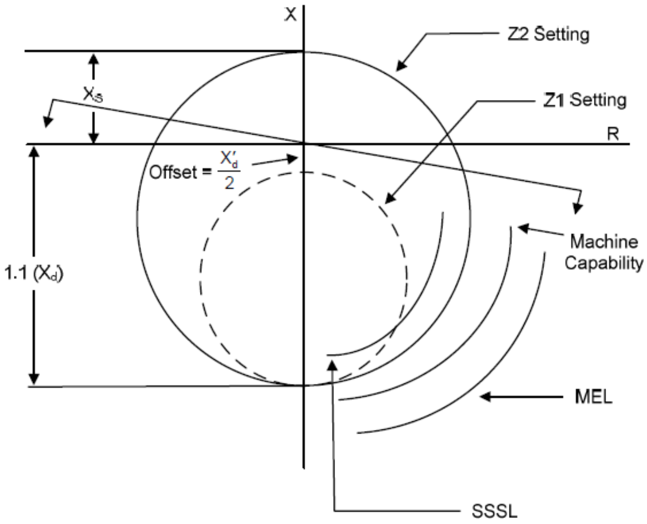

Fig 1. Positive-offset *mho* element LOE protection scheme characteristic.

In addition, during the operation of synchronous generator, two considerations may be taken into account. The first one is the generator capability curve (GCC) limit [13]. The generator can be damaged when it is operating below the under-excited operating limit of the GCC. In order to avoid this hazard, the minimum (under) excitation limiter (MEL) control may be used in the excitation system, which acts as primary protection. The second consideration is the steady state stability limit (SSSL), which indicates during normal mode of operation, how far the generator can operate in the leading power factor or the under-excited region of the GCC. Moreover, SSSL is used in coordination studies to adjust the generator under-excitation limiters (UEL) [9].

III. STATIC SYNCHRONOUS COMPENSATOR (STATCOM)

STATCOM is one of the shunt FACTS devices, which is commonly utilized to compensate the reactive power in the transmission lines. STATCOM can improve the power quality by performing several compensations such as dynamic voltage control, maintaining the stability during transients, and active and reactive power flow control in power system networks. In STATCOM, the reactive power output can be continuously changed between the capacitive or inductive mode. The V-I characteristic of STATCOM shown in Fig.2 illustrates this situation, where the STATCOM can perform capacitive or inductive compensation regarding to its line current.

In STATCOM, two converters may be used, multi-pulse or multilevel converters. The multi-pulse converters are switched in line frequency where it consists of line-commutated devices. On the other hand, multilevel converters including widely known Voltage Source Converters (VSC) topologies are commutated by pulse width modulation (PWM) or its improved methods. [14, 15].

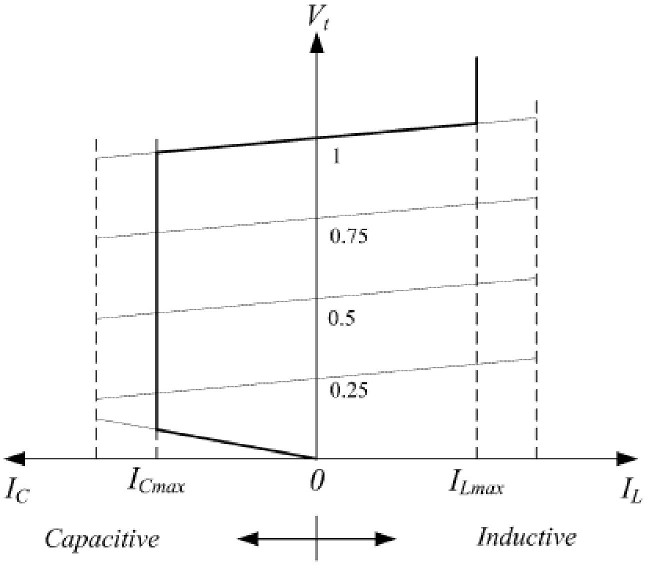

Fig 2. V-I characteristic of a STATCOM.

IV. POWER SYSTEM UNDER STUDY

The power system used in this study is a single machine infinite bus (SMIB) as shown in Fig 3. It consists of a 200 MVA hydro-generator associated with its control system (excitation system, AVR, PSS and prime mover), connected via step-up transformer to a large system through a 230 kV, 150 Km transmission line. A STATCOM is connected to the transmission line midpoint to improve its voltage profile and increase its power transfer capability. The system data are given in Appendix. The hydro-generator capability curve GCC, UEL and SSSL are plotted in Fig.4. Moreover, the setting values of the positive-offset LOE protection scheme are presented in Table I. Figure 5 shows the positive-offset LOE protection scheme characteristics along with GCC, and the SSSL on the R-X plane.

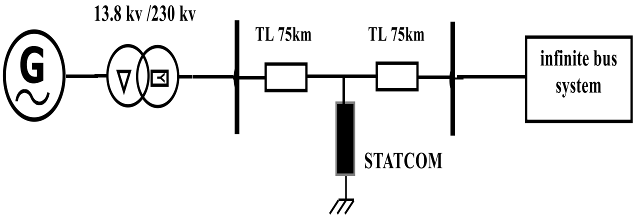

Fig 3. Power system under study.

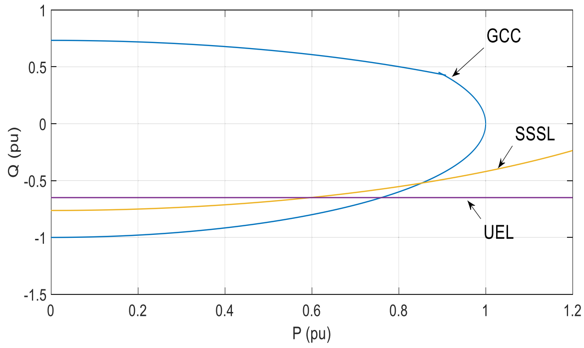

Fig 4. Hydro-generator capability curve GCC, UEL and SSSL.

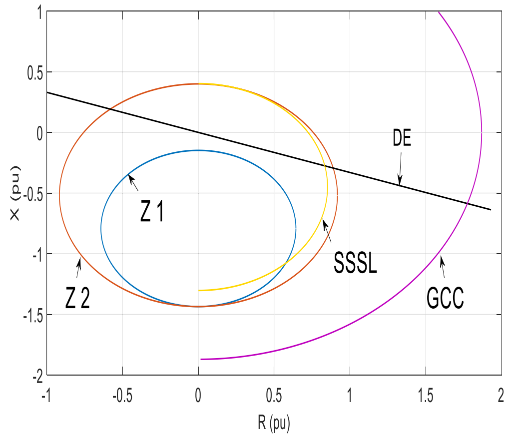

Fig 5. Positive-offset LOE protection scheme characteristics along with GCC and the SSSL on the R-X plane.

TABLE I. POSITIVE-OFFSET MHO ELEMENT SETTINGS

	ZONE 1	ZONE 2
Circle diameter (pu)	1.287	1.835
Offset (pu)	- 0.148	+ 0.4
Time delay (s)	0.1	1

Directional element: set with angle -18°

V. SIMULATION STUDIES

Simulation studies have been conducted using Simulink/MATLAB software, where the performance of the positive-offset mho element LOE protection scheme is investigated under the presence of STATCOM in transmission line. Therefore, two different LOE strategies are considered, namely, a total LOE (TLOE) and partial LOE (PLOE) after 5 s of starting the simulation time.

A. Investigation under total loss of excitation (TLOE)

Figure 6 shows the generator real power transient time responses with/without STATCOM, with initial load S=0.9+j0.43 pu. It can be seen that due to the TLOE at 5 s, the generator real power keeps almost constant at around 0.9 p.u before loss of synchronism at 7 s in case without STATCOM. However, with the presence of STATCOM the loss of synchronism occurred at 7.5 s.

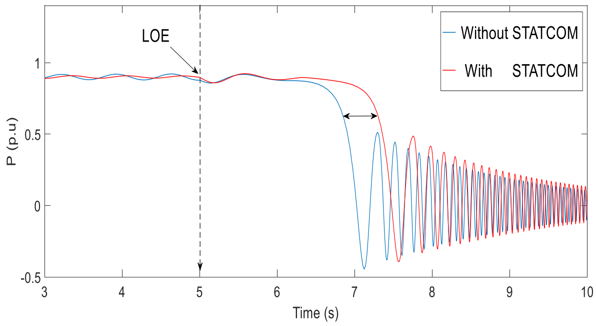

Fig 6. Generator real power with and without STATCOM.

Figure 7 shows the generator reactive power transient time responses with the same conditions as before. It can be seen that in the case with STATCOM the amount of reactive power (0.38 *p.u*) is decreased compared to the case without STATCOM (0.43 *p.u*). Figure 8 shows that the reduction of reactive power (with STATCOM case) is compensated by the STATCOM that keeps the transmission line midpoint voltage constant for longer time after TLOE as shown in Fig.9.

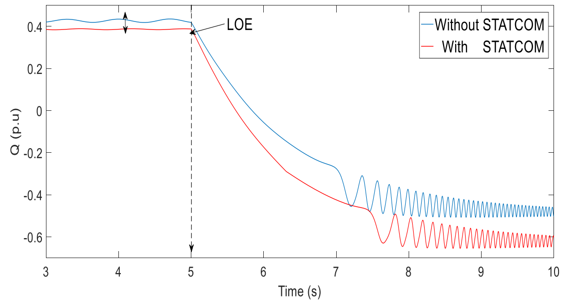

Fig 7. Generator reactive power with and without STATCOM.

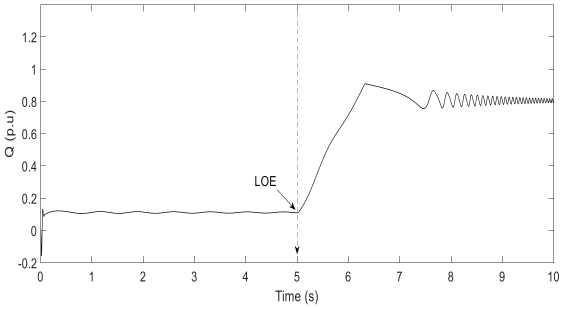

Fig 8. Reactive power supplied by the STATCOM.

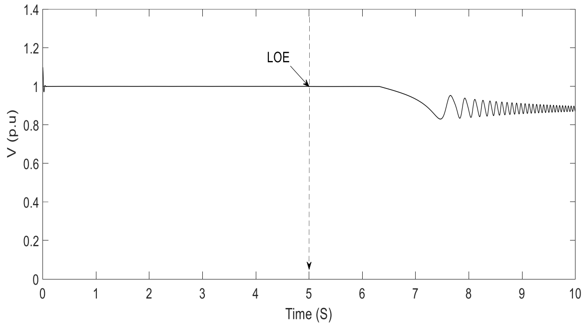

Fig 9. The transmission line voltage at STATCOM point.

Figure 10 shows the generator terminal voltages in both cases with/without STATCOM. Besides, the generator terminal currents are shown in Fig.11. The two figures show that the generator can operate for longer time without losing synchronism when TLOE occurs with the presence of STATCOM compared to the one with the absence of STATCOM.

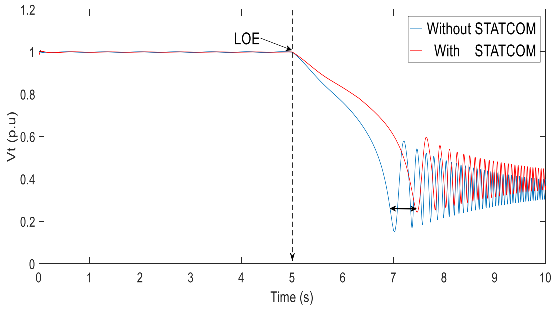

Fig 10. Generator terminal voltages with and without STATCOM.

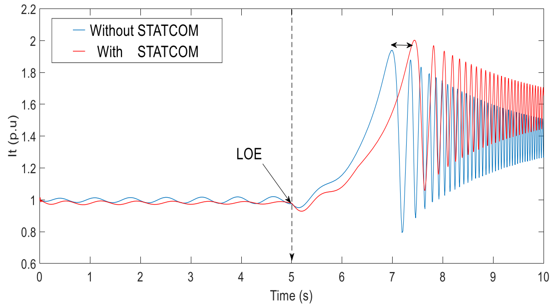

Fig 11. Generator terminal currents with and without STATCOM.

The impedance trajectories measured by the positive-offset LOE protection scheme in the absence and presence of the STATCOM are shown in Fig.12. The impedance trajectory starts at 5 s after TLOE occurrence in both cases, and penetrates zone 2 at 5.75 s in case without STATCOM, then it penetrates zone 1 at 7.21 s. In this case, the protection scheme trips by zone 2 (after its timer of 1 s is timed out) at t = 6.75 s, thus, the clearing time is t = **1.75 s**. However, the impedance trajectory penetrates zone 2 at 5.82 s in case with STATCOM, then it penetrates zone 1 at 7.52 s. Therefore, the protection scheme trips by zone 2 at t = 6.82 s, thus, the clearing time is t = **1.82 s**. It can be noticed that the clearing time of the case without STATCOM is less than the clearing time of the case with STATCOM by 70 ms under the same initial load **(**S = 0.9+j0.43 *p.u*).

The same simulation study under different initial loading conditions have been repeated and presented in Table II. The results show that when a total loss of excitation occurs, the clearing time of the positive-offset mho element LOE protection scheme with the presence of STATCOM is greater than the one without STATCOM in all conditions. As conclusion, the presence of STATCOM in transmission line causes delay time to the positive-offset LOE protection scheme when TLOE occurs.

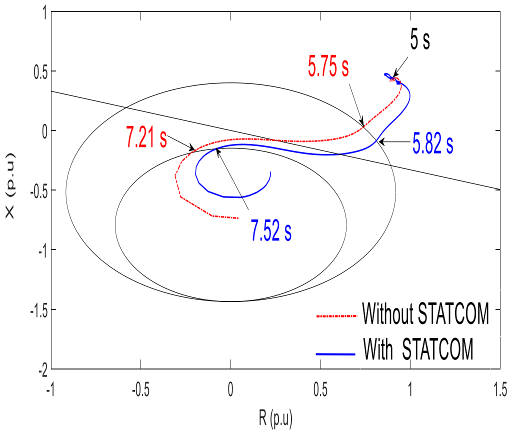

Fig 12. Impedance trajectories measured by positive-offset *mho* element, with/without STATCOM.

TABLE II. CLEARING TIMES OF THE POSITIVE-OFFSET LOE PROTECTION SCHEME UNDER DIFFERENT INITIAL LOADING AND WITH AND WITHOUT STATCOM.

		Initial load S = P + jQ (pu)					
		0.9+ j0.43	0.75+ j0.34	0.65+ j0.36	0.5- j0.34	0.3- j0.27	0.2- j0.26
Clearing time (s)	With-ST	**1.82** Z2	**2.14** Z 2	**2.38** Z 2	**2.44** Z2	**3.17** Z 1	**3.55** Z 1
	W/out-ST	1.75 Z 2	2.11 Z 2	2.37 Z 2	2.12 Z 2	3.05 Z 1	3.46 Z 1

B. Investigation under partial loss of excitation (PLOE)

Partial loss of excitation (E_f = 0.2 pu) is considered on the generator after starting the simulation by time of 5 s. Figure 13 shows the comparison between the real power during the absence and the presence of STATCOM with initial load S = 0.9+j0.43 pu. It can be seen that the generator can operate for longer time without losing synchronism when PLOE occurs with the presence of STATCOM compared to the one with the absence of STATCOM.

The impedance trajectories measured by the positive-offset LOE protection scheme in the absence and presence of the STATCOM are shown in Fig.14. In case without STATCOM, the protection scheme trips by zone 2 (after its timer of 1 s is timed out) at t = 7.03 s, thus, the clearing time is t = **2.03 s**. However, in case with STATCOM the protection scheme trips by zone 2 at t = 7.15 s, thus, the clearing time is t = **2.15 s**. therefore, the clearing time in case without STATCOM is less than the one with STATCOM by 120 ms.

The same comparative study under different initial loadings and with two different partial loss of excitation conditions *(*E_f = 0.4 pu / E_f = 0.2 pu*)* are given in Tables III and IV. The obtained simulation results show that when a PLOE occur under heavy load condition, the fault will be cleared. Therefore, the clearing time of the positive-offset scheme under the presence of STATCOM will be delayed compared to the one with the absence of STATCOM. However, when a PLOE with E_f = 0.4 p.u. occurs under lightly load situation, the fault will not be cleared (under reach).

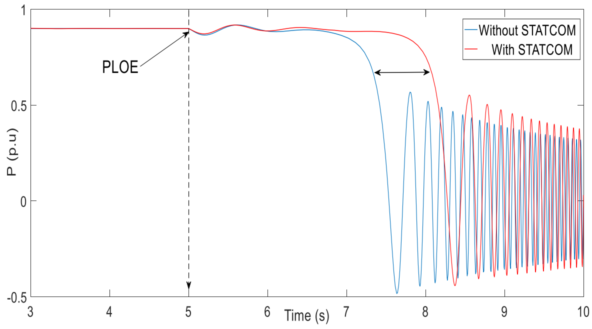

Fig 13. Generator real power with and without STATCOM under PLOE.

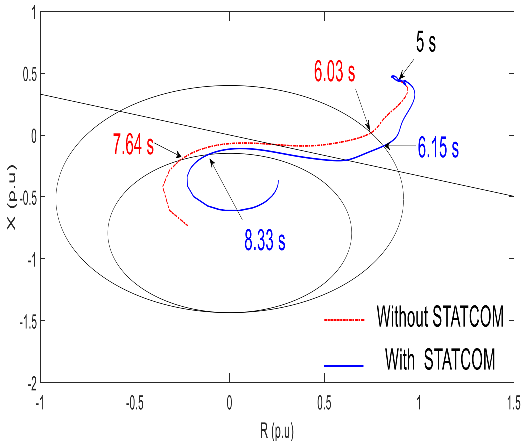

Fig 14. Impedance trajectories measured by positive-offset *mho* element, with/without STATCOM under PLOE.

TABLE III. CLEARING TIMES OF THE POSITIVE-OFFSET LOE PROTECTION SCHEME UNDER PLOE ***(E_F = 0.2 PU)***, WITH AND WITHOUT STATCOM.

		Initial load S = P + jQ (pu)					
		0.9+ j0.43	0.75+ j0.34	0.65+ j0.36	0.5- j0.34	0.3- j0.27	0.2- j0.26
Clearing time (s)	With-ST	**2.15** Z2	**2.47** Z 2	**3.03** Z 2	**5.2** Z2	**4.00** Z 2	**3.55** Z 2
	W/out-ST	2.03 Z 2	2.42 Z 2	2.8 Z 2	2.45 Z 2	3.47 Z 2	3.25 Z 2

TABLE IV. CLEARING TIMES OF THE POSITIVE-OFFSET LOE PROTECTION SCHEME UNDER PLOE ***(E_F = 0.4 PU)***, WITH AND WITHOUT STATCOM.

		Initial load S = P + jQ (pu)					
		0.9+ j0.43	0.75+ j0.34	0.65+ j0.36	0.5- j0.34	0.3- j0.27	0.2- j0.26
Clearing time (s)	With-ST	**2.68** Z2	**3.3** Z 2	**4.53** Z 2	**3.36** Z2	UR	UR
	W/out-ST	2.4 Z 2	3.14 Z 2	3.82 Z 2	3.23 Z 2	UR	UR

VI. CONCLUSION

In this paper, synchronous generator positive-offset mho element loss of excitation protection scheme is investigated under the presence of STATCOM in the transmission line. Dynamic simulation studies are used where a single machine infinite bus and positive offset mho element protection scheme are modeled and simulated in Simulink /MATLAB software. In addition, two LOE conditions are used in this investigation namely, a total LOE and partial LOE und different generator load conditions.

The results of these investigations have shown that the presence of STATCOM has adverse impacts on the operation of the positive-offset mho element LOE protection scheme in the form of delay time. Moreover, an under reach phenomena may occur under partial loss of excitation condition with light generator loading.

It can be highly recommended that the improvement of techniques to achieve better generator LOE protection under the presence of STATCOM is need. The authors are currently working to enhance generator LOE protection utilizing the phasor measurement units (PMUs) and adaptive neuro-fuzzy inference systems (ANFIS).

APPENDIX

1) Generator parameters: 200 MVA,150 MW, 13.8 Kv,
X_d=1.305pu, X_q= 0.474pu, X'_d= 0.296pu, X''_d= 0.252pu

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,

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