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Evaluation of Torsional Efforts on Thermal Machines Shaft with Gas Turbine resulting of Automatic Reclosing

Alvaro J. P. Ramos, Wellington S. Mota, Yendys S. Dantas

***Abstract*—** This paper analyses the torsional efforts in gas turbine-generator shafts caused by high speed automatic reclosing of transmission lines. This issue is especially important for cases of three phase short circuit and unsuccessful reclosure of lines in the vicinity of the thermal plant. The analysis was carried out for the thermal plant TERMOPERNAMBUCO located on Northeast region of Brazil. It is shown that stress level caused by lines unsuccessful reclosing can be several times higher than terminal three-phase short circuit. Simulations were carried out with detailed shaft torsional model provided by machine manufacturer and with the “Alternative Transient Program – ATP” program [1]. Unsuccessful three phase reclosing for selected lines in the area closed to the plant indicated most critical cases. Also, reclosing first the terminal next to the gas turbine gererator will lead also to the most critical condition. Considering that the values of transient torques are very sensible to the instant of reclosing, simulation of unsuccessful reclosing with statistics ATP switch were carried out for determination of most critical transient torques for each section of the generator turbine shaft.

***Keywords*—**Torsional Efforts, Thermal Machine, Gas Turbine, Automatic Reclosing.

I. INTRODUCTION

THE analysis of torsional efforts in shafts of gas turbines resultant of disturbances in the electric network was and still has been object of concerns and studies in U.S.A. and Europe have much time considering the tradition of the generating park of these regions with strong participation of thermal energy. The motivation of the analysis of these problems appeared of the occurrence of torsional oscillations that had caused high transient torques that had resulted in damages in shaft of machines and its mechanical couplings. The most known case in literature had been the shaft damages occurred in Mohave in U.S.A. in 1970 and 1971 where shaft demage of the set generator-turbine had resulted in fatigue of the steel submitted to repetitive efforts in the presence of the phenomenon that is known as “subsynchronous resonance” [2]. The occurrence of the subsynchronous resonance is associated, in the majority of the cases, the series compensation presence in the electrical system. The occurrence of these events of subsynchronous resonance excited the necessity of studying with bigger depth the interactions between the phenomena, until then seen as inherent to the electric net, with nature phenomena strict mechanics of turbogenerator shaft. For consequence, it appeared a great interest in analyzing certain transient of the electric network resultant of network reclosing without the presence of the resonance phenomenon subsíncrona. Later it was verified that the torsionais efforts appeared in gas the thermal machines shaft due to reclosing operations, in particular automatic and fast reclosing of lines can reach high values superior to those established by norm ANSI for short circuit in the machine terminals [3] which consist in the main reference for machines projects.

II. STUDIED SYSTEM

A. Electric System

The Termopernambuco Power Plant is connected to the substation Pirapama through two 230 kV transmission lines. Pirapama substation that is part of a regional system supplied from hydro plants through long 500kV and 230 kV transmission lines. A simplified one-line diagram covering the vicinity of Termopernambuco is shown in Figure 1. The main concern of this paper is the evaluation of the impact of fast tripolar reclosing of lines in the area of Termopernambuco machines.

B. Power Plant

The Termopernanbuco power plant is comprised of two 211.7MVA gas generator, and one 284.7MVA steam turbine.

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W. S. Mota is with the Electrical Engineering Department of the Campina Grande Federal University, Paraiba Brazil.(wsmota@ieee.org).

A. J. P. Ramos is part time professor with University of Pernambuco and a consultant of ANDESA (alvaro@andesa.com.br).

Y. S. Dantas is a consultant of ANDESA (sydney@andesa.com.br).

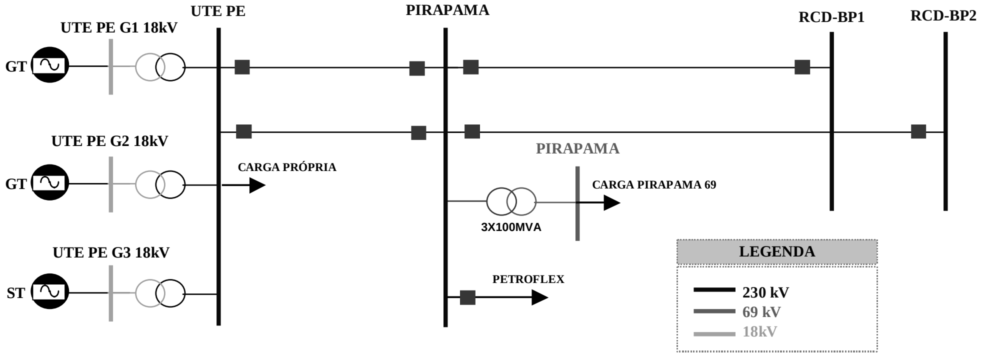

Fig. 1. Simplified one line diagram of the electric system in the vicinity of Termopernambuco.

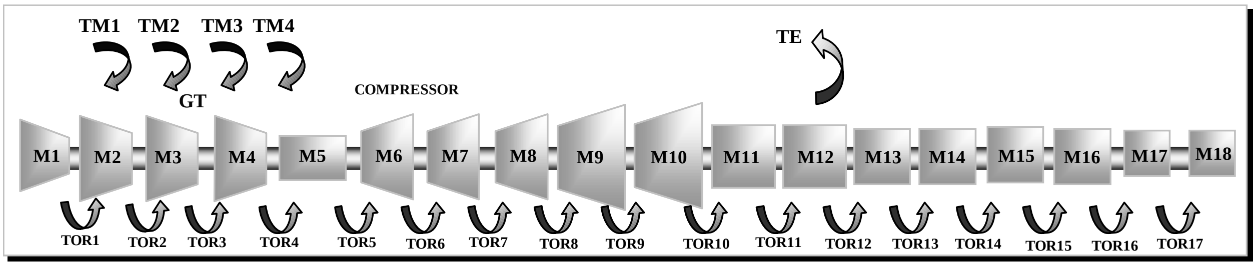

Fig. 2. Model of 18 masses for the set shaft gas generator-turbine for the units G1 and G2.

The manufacturer provided the data required for synchronous machine model 59 of ATP program [1] as well the shaft torsional model as is shown in Figure 2. This is a detailed eighteen masses model expected to be capable of representing the most significant machine torsional modes. It was considered that the masses M1, M2, M3, M4 and M5 represent the elements of the turbine on which the resultant mechanical torques of the combustion of the gas act. These torques had been distributed in the ratio of 4% (M1), 27% (M2), 27% (M3), 27% (M4) and 15% (M5) of the total mechanical torque. This premise was adopted since no more detailed information was available. Table I presents the date of shaft model used in the simulation. Damping effects were not considered.

C. *Line Reclosing Scheme*

All 230 kV and 500 kV transmission lines of the electric system where Termopernambuco is located make use of tripolar reclosing. The “dead-time”, that is, time interval between the first fault clearance and reclosing, is about 500ms for 500kV lines and varies within the range 1 to 1.5s for the 230 kV lines. Figure 3 presents the sequence of switching for unsuccessful tripolar reclosing cases here analyzed. For all cases the fault was applied (t_F=0.1s) in the line terminal closer to Termopernambuco. It is assumed that first zone protection of both line terminals operates almost simultaneously in 100ms (t_{CF1}=0.2s) tripping the faulted line.

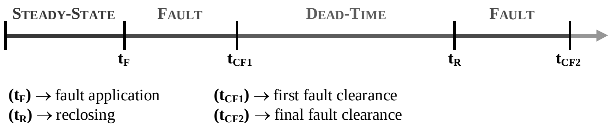

Fig. 3. Definition of switching times of unsuccessful reclosing.

TABLE I
GENERATOR-TURBINES SHAFT DATA

Mass	Identification	Inertia Moment (10^6Kg*m^2)	Spring Constant (10^6N-m/rad)
1	GT (overhang)	0,000021	24,8
2	GT1 (Turbine Region)	0,000111	1109,9
3	GT2 (Turbine Region)	0,000320	1177,6
4	GT3 (Turbine Region)	0,002579	1177,6
5	GT (Marriage Flange Region)	0,000320	1296,0
6	GT-AFT (Compressor)	0,000111	196,8
7	GT1 (Compressor)	0,000119	143,5
8	GT2 (Compressor)	0,000108	171,5
9	GT3 (Compressor)	0,001032	13020,2
10	GT (Foward Compressor)	0,000447	12535,8
11	Load Coupling-GT Overhang	0,001256	11165,2
12	Gen TE Overhang-Load Coup.	0,001392	9415,5
13	Gen - TE Spindle	0,000916	6208,0
14	Gen - TE Body END	0,000970	3818,5
15	Gen - Body	0,003024	7285,0
16	Gen - CE Body End	0,002395	5933,1
17	Gen - CE Spindle	0,000881	218,2
18	Gen - CE Overhang	0,000004	

As mentioned before, the dead time varies for each particular line, so that there is different reclosing time t_R. The second fault elimination is $t_{CF2}=t_R + 0.1s$. It should be observed that the 2^o terminal actually never close in case of unsuccessful reclosing (the fault remain on line) because the 1^o terminal trip again before 2^o terminal attempt to close. In case of successful reclosing, the second terminal close only if some procedures realized by the second terminal protection are checked. These procedures are usually referred to as "check of synchronism" and are usually based on voltage and phase angle verifications.

III. IMPACTS ON TURBINES-GENERATOR SHAFT

A. Machine Initial Condition

The analysis considered the machine operating with rated power. The initial operating point is presented in Table II.

TABLE II
TURBINE-GENERATOR (UNIT 1) INITIAL CONDITION (FULL LOAD)

Quantity	Value	Unit
Active Power (P)	179.9	MW
Reactive Power (Q)	17.0	Mvar
Voltage (V)	18	kV
Generator Electrical Torque (TQ GEN)	0.4722	Million N.m
TOR1	0.0188	Million N.m
TOR2	0.14573	Million N.m
TOR3	0.2726	Million N.m
TOR4	0.39957	Million N.m
TOR5	0.4701	Million N.m
TOR6	0.4701	Million N.m
TOR7	0.4701	Million N.m
TOR8	0.4701	Million N.m
TOR9	0.4701	Million N.m
TOR10	0.4701	Million N.m
TOR11	0.4701	Million N.m
TOR12	0.4701	Million N.m
TOR13	0.4701	Million N.m
TOR14	0.4701	Million N.m

B. Criteria

As indicated in the standard ANSI C50.13-1989 [3] the generators must be capable of withstanding mechanical efforts caused by short circuits on its terminals. It is assumed that this requirement is applied not only to the generator itself, but also for the entire generating turbine set. However, the probability of occurrence of this event is extremely low, so that its incidence is very seldom throughout the useful life of the machine. On the other hand, three-phase faults followed by unsuccessful reclosing in the transmission lines should have certain probability that requires a careful investigation. In principle, maximum torques in the cases of three-phase short circuit in the machine terminals can be taken as reference of maximum values acceptable for the machine.

C. Three phase short circuit

Simulation of three-phase short circuit in the terminals of the machine G1 has been performed (200 statistical cases) with the model of statistic switch available in ATP. Appropriate Gaussian distribution parameters for switch closing time were employed according to recommendation of Brazilian Grid Code. The simulation cases that resulted in maximum torque for the 10 sections of the shaft are shown in Table III. The electromagnetic transient torque of G1 for three-phase short circuit in the machine terminals is shown in figure 4 that indicate a 60Hz oscillation associated with a DC component of the stator current during the fault. The transient torque in section 14 is also shown in figure 5.

TABLE III
MAXIMUM TORQUES FOR THREE-PHASE SHORT CIRCUIT IN THE G1 MACHINE TERMINALS

Torque	Maximum Value Million (N.m)	Maximum Value (pu)	Simulation case
TOR1	2,308E-2	1,228	13
TOR2	1,688E-2	0,1158	13
TOR3	3,492E-1	1,280	145
TOR4	8,624E-1	2,1587	13
TOR5	9,759E-1	2,076	13
TOR6	9,871E-1	2,100	13
TOR7	9,707E-1	2,06	13
TOR8	9,413E-1	2,00	13
TOR9	1,1567	2,460	145
TOR10	1,3759	2,927	145
TOR11	1,9148	4,069	145
TOR12	2,4044	5,1146	13
TOR13	2,7195	5,7849	13
TOR14	2,9612	6,299	13

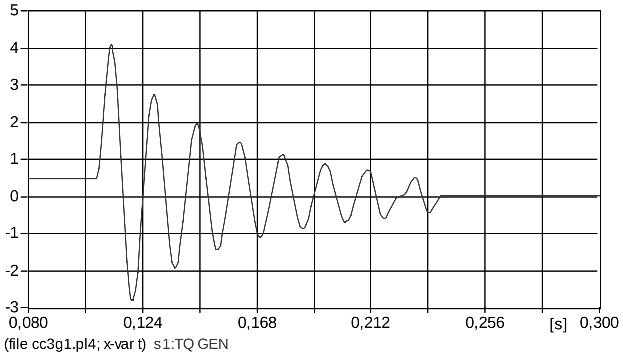

Fig. 4 Electromagnetic torque for a three-phase short circuit in G1 terminals.

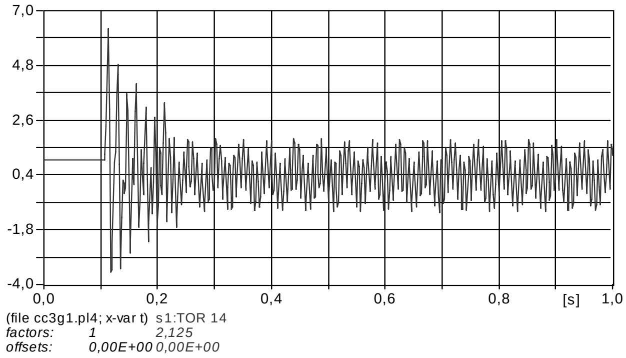

Fig. 5. Transient Torque in the section 14 of the set generator turbine

D. *Single phase short circuit*

The electromagnetic torque for a single-phase short circuit in the terminals of machine G1 is shown in figure 6. Besides the oscillatory component of 60Hz associated to DC component of the stator current, it is also observed a 120Hz component associated to negative sequence of the stator current. Although single-phase short circuits in the terminals of the machine can also represent impact of certain severity, the unsuccessful single pole reclosing produce inferior impacts when compared with tripolar ones. Thus, the single pole reclosing is not of major concern and usually does not demand further evaluations neither result in operative restrictions.

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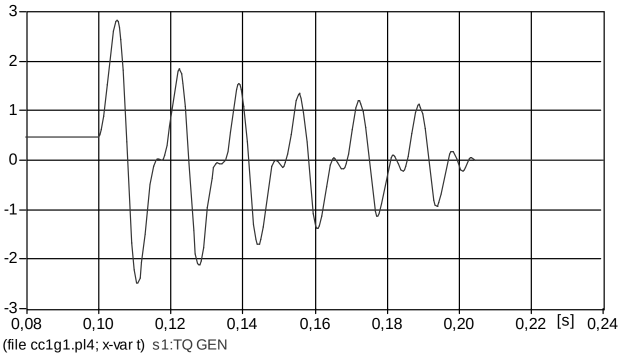

Fig. 6 Electromagnetic torque for a single-phase short circuit in G1 the terminals.

E. *Line Reclosing*

Evaluation of torsional efforts on sections of the generating shaft of the gas turbine G1 were performed for unsuccessful three phase reclosing of 230kV lines on the Termopernambuco vicinity. Considering that the values of transient torques are very sensible to the instant of reclosing, 200 simulations through a statistics ATP switch has been done for each transmission line [4-5]. This procedure is capable of determining most severe transient torques for each section of the shaft of the set turbine-generator. The more significant transient torques have been obtained for the 230kV transmission line Termopernambuco (UTE – PE) – Pirapama as shown in figure 1. The maximum values of torque are shown in Table IV. It is observed that the maximum values occur between the corresponding sections TOR11, TOR12, TOR13 and TOR14.

TABLE IV
MAXIMUM VALUES OF TORQUE FOR LINE RECLOSING

TL Termopernambuco – Pirapama 230kV with reclosing in Termopernambuco 230kV		
Maximum Torque (pu)		Simulation Case
TOR 1	1,18	107
TOR 2	1,14	145
TOR 3	1,25	145
TOR 4	1,83	182
TOR 5	1,74	30
TOR 6	1,75	186
TOR 7	1,73	186
TOR 8	1,68	186
TOR 9	2,19	79
TOR 10	2,45	79
TOR 11	3,04	79
TOR 12	3,47	79
TOR 13	3,71	186
TOR 14	3,93	186

The case of maximum transient torque for the section 14 is shown in figure 7, where an amplification of the torque at the moment of the unsuccessful reclosing is verified.

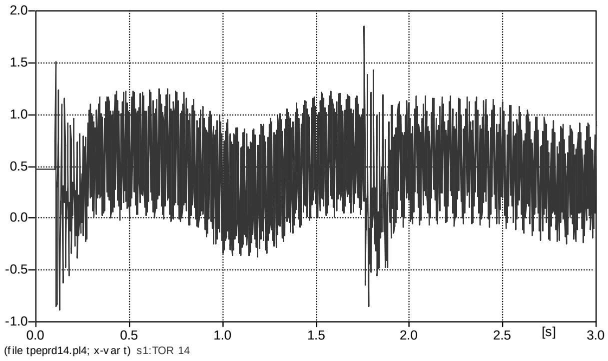

Fig. 7. Section 14 transient torque in (Million N.m) resulting of unsuccessful three phase reclosing of Termopernambuco Pirapama 230kV transmission line.

IV. ALTERNATIVES OF SHAFT DUTY MITIGATION

A. *General Comments*

The simulations of unsuccessful tripolar reclosing were based on machine and shaft model provided by the manufacturer, detailed network representation and realistic reclosing scheme. The stress on shaft sections were evaluated for expected most severe situations.

However, some questions of main concern still need a clear answer:

a) Can machine withstand such duty without risk of damage?
b) How these shaft duties contribute for material fatigue and premature machine loss of life?
c) How much detailed must be the shaft model to give reliable results or, in others words, how many masses are necessary to appropriate representation of shaft torsional dynamics?

Machine shaft is a complex mechanical system composed of several parts tied together. The evaluation of how the transient torques will impact the different parts of the shaft, demand a strongly detailed representation of machine shaft. This is certainly a task to be carried out by the manufacturer. Besides such technical complexity, the commercial aspects associated with machine guarantees also give rise to difficulties to the management of this problem.

The ANSI C50.13-1989 [2] establishes that the generator must withstand three-phase fault at its terminal. This is a standard for generators and it is not clear if it also covers the complete machine including shaft parts and turbines. If it is applicable to complete machine, the shaft duty verified due machine terminal three-phase fault could be used as a reference limit. For a three-phase fault at Termopernambuco machine terminals, a maximum torque of 6.299pu was obtained for TOR14 (generator/gear). This would be considered the limit of torque that machine withstand without risk of failure.

Our experience to date indicates that the machine manufacture hesitate to have a clear position about above issues leading the machine owner to an uncomfortable position of assuming the risks of eventual unsuccessful tripolar reclosing. On the other hand, the System Operator refuses to eliminate tripolar reclosing without a consistent evaluation of machine risk.

B. Increasing Reclosing Dead-Time

It is interest of machine owner to reduce as much as possible the shaft stress due transmission lines reclosing. When the dead time is enough larger to assure that torsional transient is finished, the tripolar unsuccessful reclosing represent only a new simple three-phase fault. Given that damping parameters are seldom available in torsional models, it is not possible to determine adequate and safety dead time for line reclosing by means of simulations.

C. Sequential Reclosing

This is means that the 1^0 terminal to reclosing is remote from the power plant. Only after the “check of synchronism” be performed, to assure that the fault was eliminated, the plant end breaker (2^0 terminal) is allowed to close.

Unfortunately, for our present system, the effectiveness of sequential reclosing is low for 230 kV lines due the existence of several others short lines in the region making the remote terminal electrically close to the plant. Sequential reclosing is used for the 500 kV lines (Figure 1).

D. Selective Reclosing

The selective reclosing needs a mean of distinguishing the type of fault and permit line reclosing only for single phase and phase-to-phase faults. This needs line protection schemes capable of identifying fault type.

There is the risk that the fault initiates as phase to phase and become three-phase during dead time period. This may be likely to occur in cases of fire under or close to transmission lines. Farmers sometimes make use of this practice to clean up plantation areas.

V. FINAL REMARKS

Three-phase reclosing of lines in the vicinity of thermal units should not be a practice without a careful analysis of machine torsional stress levels. The possibility of unsuccessful reclosure may lead to torsional stresses that exceed machine limits. In Brazil tripolar reclosing is a normal practice but this has not been a problem so far because almost generations were hydro.

The installation of thermal unit in Brazilian system demands detailed analysis of machine shaft transient torques. These studies have to be carried out with appropriate modeling of electric system and machine with realist parameters.

As long as the authors are acquainted, there are no standards or technical guidelines establishing shaft torsional stress levels that machine should withstand. Machine manufacturer should be requested to provide this information so that plant owner can preserve machine guarantees and avoid risk of damages or premature loss of life.

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VII. BIOGRAPHIES

Wellington Santos Mota (M'76–SM'02) was born in João Pessoa, Brazil, 1946. He received the B.Sc. and M.Sc. in Electrical Engineering from Federal University of Paraiba (UFPB), Brazil, in 1970 and 1972, respectively. He got the Electrical Engineering Ph.D. from Waterloo, University of Waterloo, Canada, in 1981. He has been with the Department of Electrical Engineering, Federal University of Campina Grande (UFCG), where currently is a full Professor. From 1973 to 1977 he worked at the Sao Francisco River Hydro (CHESF) in power system planning. His research interests include Power System Control and Stability, including wind farms. He is a Senior Member of IEEE.

Alvaro J. P. Ramos was born in Recife, Brazil, on 1951. He graduated from the Federal University of Pernambuco in 1973 and received the MSc degree from Federal Engineering School of Itajubá in 1975. In 1974 he joined CHESF where he was engaged on electric studies up to 1998. In 1998 he founded ANDESA a consulting company that provides electric studies for many utilities in Brazil. Since 1977 he is part time professor at Escola Politécnica of Pernambuco University. He is a Senior Member of IEEE.

Sydney Y. Dantas was born in Caicó, Brazil, on 1949 He received the B.Sc. in Electrical Engineering from Federal University of Paraiba (UFPB), Brazil, in 1973 and made specialization in Power System at the Federal Engineering School of Itajubá in 1979. In 1975 he joined CHESF where he was engaged on electric studies up to 1995. In 1998 he founded ANDESA a consulting company that provides electric studies for many utilities in Brazil.