A Complete Excitation-Shaft-Bearing Model to Overcome The Shaft Induced Voltage And Bearing Current

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Abstract—**This paper proposes a complete distributed model for investigating the induced shaft voltage and bearing current in turbo generators due to the interaction with the static excitation systems. This undesirable voltage affects the insulations gradually, lowering the life expectancy of the whole system. If the shaft voltage exceeds the dielectric breakdown voltage level of the lubricating grease film in journal bearings, an electrical discharge current flows through the bearings. In order to inspect the shaft voltage, a passive filter is proposed to overcome the stated issue. Both the proposed model and the passive filtering technique are simulated with SIMULINK, and discussed in detail to confirm the presence of the bearing current and shaft voltage.**

Keywords-bearing current; breakdown voltage; passive filter; shaft voltage; static excitation system

I. INTRODUCTION

Shaft voltages have become a serious problem in large turbo generators. There are four potential sources of shaft voltages in rotating machinery: Magnetic dissymmetry, axial shaft flux, electrostatic charge and external voltages supplied to the rotor windings [1]-[4]. The mechanism of occurrence and transmission of the first three types of shaft voltages are relatively well known and are not discussed here. External voltages supplied to the rotor windings are primarily related to the electrical machines excitation system [1]. Static excitation systems are source of shaft voltages with considerable magnitudes. The output voltage of the rectifier, however, contains harmonics in addition to the desired DC-voltage [5]. When shaft voltage with respect to the frame exceeds the dielectric breakdown of thin lubricating grease in two metal bearings on the exciter end (EE) or turbine end (TE), an electrical discharge machining (EDM) current flows through the bearings [6]. By occurrence of the dielectric breakdown, a high current impulse is created. These current pulses result in the appearance of pits and transverse flutes burnt into the bearing race [7].

In order to predict the problems related to shaft voltage and bearing current, developing a circuit model of the system is necessary. Equivalent circuit models have been proposed for

investigation of shaft voltage. Amman et al. in [3] have proposed a circuit model in which each coil was lumped and

modeled by one inductance and two capacitances and then these circuit models were connected in series with each other. The proposed model in [3] represents transmission from excitation winding to the shaft line in the frequency range of 50Hz to 1MHz. Also in their paper a passive RC filter has been proposed for reduction of shaft voltage and bearing current to a harmless value.

This paper deals with the shaft voltages arising from static excitation systems. A complete distributed circuit model of parasitic couplings between adjacent windings, between windings and rotor shaft and also between windings and the stator is proposed. The aim of this approach is investigating shaft voltage and bearing current in a typical 200MVA Ansaldo turbo generator. In this procedure, in addition to the characteristics mentioned about the proposed model in [3], each turn is modeled individually, skin effect of conductors in high frequencies and also the value of the parasitic capacitances between each turn and its adjacent turns are calculated and finally, the equivalent circuits are connected in series with each other and in parallel with the shaft line and bearing equivalent circuit to form the model. In order to reduce shaft voltage and bearing current, some countermeasures have been investigated and compared in this paper. Among the solutions, one of them is described in detail and applied to the proposed model. Unlike the solution mentioned in [3], the proposed filter in this paper is applicable on DC-side of rectifier in a static excitation system and is not connected directly to the shaft line. Simulation results of the proposed model verify reduction of shaft voltage to the desired value in the case of applying RC filter.

II. Shaft Voltage Analysis

A. Model Of the System

A scheme of the system to be investigated is depicted in Fig .1. The elements are as follows:

1. Excitation transformer
2. Rectifier (static excitation system)
3. Excitation winding
4. Journal bearings
5. Shaft line
6. Brushes

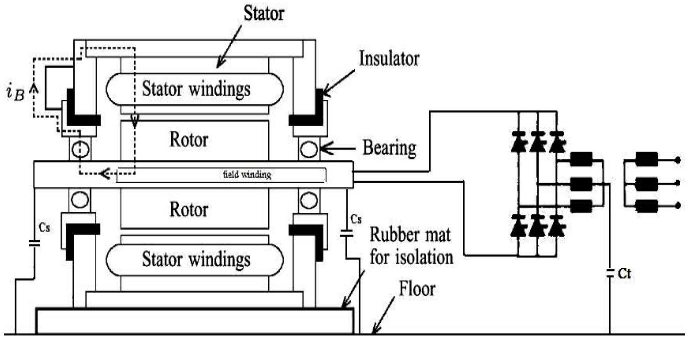

Fig .1: Static excitation system

Voltages in the system can be divided into three main parts:

1- Phase voltages which are injected to the ac side of rectifier are three symmetrical sinusoidal waves with the base frequency of 50Hz related to the base frequency of the power system. These voltages are applied to the excitation system.
2- Rectifier output DC voltage which is created between positive and negative terminals on the DC-side of rectifier. This voltage includes six saw tooth peaks per period, so its main frequency is six times the main frequency of the system. As this voltage is produced by switching of rectifier, there are some high frequency peaks superimposed on it.
3- Common mode voltage which is created as a result of rectifier switching includes three saw tooth peaks per period with the frequency of 150Hz (three times the main frequency of the system)

Under symmetrical conditions only common mode voltage contributes to the shaft voltage but under asymmetrical conditions, additionally, the saw tooth-like DC voltage superimposes on the common mode voltage and both of them contribute to the shaft voltage [8].

When shaft line is non-grounded, shaft voltage in low frequencies would be dependent on the common mode voltage. The relation is shown in (1).

$$V_{shaft} = \frac{C_w C_t}{C_w C_t + C_s C_t + C_s C_w} \qquad (1)$$

Where C_t is the transformer to ground capacitance [9], C_w is the leakage capacitance between windings and shaft line and C_s is the capacitance between shaft line and the frame which is mainly comprised of the journal bearing capacitances [3].

B. Model Developement

The proposed model in this paper is appropriate for the numerical simulations of shaft voltage, field winding and shaft line of a 200MVA Ansaldo turbo generator. Each turn of field winding is modeled with an equivalent RL circuit. The main methodology to model the contributions of skin effect is to consider a conductor to be made up of concentric shells. By increasing the frequency, resistance value will increase and on the other side, inductance value will decrease. This fact can be achieved by parallel combination of impedance branches. The values of resistance and inductance can be calculated according to the desired frequency range [10].

According to the proposed model for our investigations, another parameter which should be determined is the parasitic capacitance of conductors. As in this case high frequency switching power converters are used, an accurate prediction of conductors' response in high frequencies is important for design of high-frequency power circuits. Parasitic capacitances are as follows:

1. Turn-to-turn capacitances between adjacent turns
2. Turn-to-core capacitance and turn-to-frame capacitance

Parasitic capacitances are distributed along the turns. The value of these capacitances can be calculated by determination of capacitive paths for stray currents. In the proposed model, these capacitances are modeled by two lumped values connected to the ends of each half turn. Each half turn equivalent circuit is connected in series to the other half turns. Parasitic capacitances between each turn and the adjacent turns are calculated and applied in the proposed model.

Shaft line of generator has been modeled by a passive RL circuit which indeed expresses the frequency-dependent behavior of the shaft line. Bearings in this case are journal type ones with an oil lubricant film which are connected between shaft and the housing as shown in Fig .1. As a thin layer of lubricant film exists in contact regions, the bearing impedance becomes capacitive. C_s represents bearing capacitance between shaft line and the frame and can be calculated by studying bearing dimensions and its lubricating oil material.

The other parameter in the proposed scheme of the system is the capacitance C_{rs} which represents coupling capacitance between rotor and stator. This parameter has been modeled by two lumped values connected to each end of the shaft line. Brush impedance is represented by a parallel RC circuit which is connected to the exciter end (EE) of the generator. The values of brush resistance and capacitance are calculated by investigating brush material and its dimensions. In this case brushes are made up of graphite [11].

By calculation of the parameters described above, complete model of field winding and shaft line of the 200MVA Ansaldo turbo generator can be derived as Fig .2.

III. COUNTERMEASURES AGAINST SHAFT VOLTAGE AND BEARING CURRENT

There are possible countermeasures against shaft voltage in turbo sets. For example all kinds of asymmetries can be avoided in designment procedure in order to prevent magnetic dissymetries and also all magnetized parts can be demagnetized to prevent axial shaft flux occurrence [3]. Another way is grounding turbine end (TE) of generator with specific grounding brushes. Of course this procedure has some problems. As grounding of shaft line is done in some specific points, it cannot entirely remove shaft voltage and on the other hand with increasing the points that are grounded in the shaft line, grounding currents flow through the points which indeed cause additional damage to the shaft. Grounding system on the turbine end of generator cannot entirely eliminate high frequency shaft voltage peaks.

Retention of bearing insulation at the exciter end (EE) is an effective protection against currents from induced shaft voltages. Also insertion of insulating layers in all possible short circuit loops can prevent occurrence of large currents.

More than the solutions described above, like what mentioned in [3], connection of a passive RC circuit through a grounding brush to the exciter end (EE) of generator can decrease shaft voltages to a harmless value. Direct installation of the passive filters to the rotor shaft is a milestone procedure and can be interrupted during shaft rotation. On the other hand, mechanical parts need maintenance during long term application. Connection of a passive filter to the shaft in one point, decreases shaft voltage locally but as the shaft line is long, this procedure cannot entirely reduce shaft voltage. Calculation of resistance and capacitance values is done according to the cut-off frequency. There are some restrictions in choosing the appropriate value of resistance and capacitance. Resistance value should be high enough to minimize currents to some few amps and on the other hand it should be low enough to prevent generating DC-voltage in the case of no grounding brush or its malfunction [3].

Another solution to the shaft voltage is applying symmetrical filters on DC-side of the rectifier in order to eliminate high frequency peaks in rectifier output voltage and prevent them entering to the field winding. By this procedure a applied to the field winding and shaft voltage reduces to a harmless value. This passive filter is connected symmetrically to both terminals on DC-side of rectifier. The appropriate values of resistance and capacitance chosen for the passive filter are 10 ohms and 2μF. These values insure damping high frequency peaks of voltage and prevent them entering to the field winding. This procedure results in reduction of shaft voltage. Connection of the designed passive filter to the system is depicted in Fig .3.

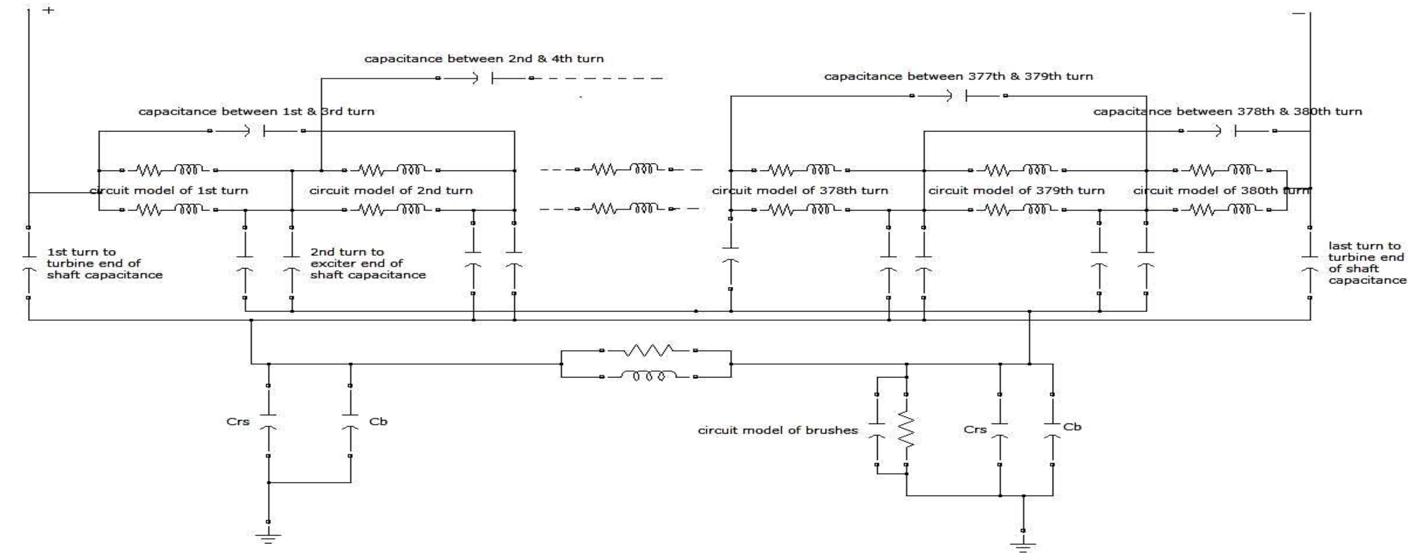

Fig .2: Model of excitation winding and turbo shaft for ANSALDO 200MVA turbo generator

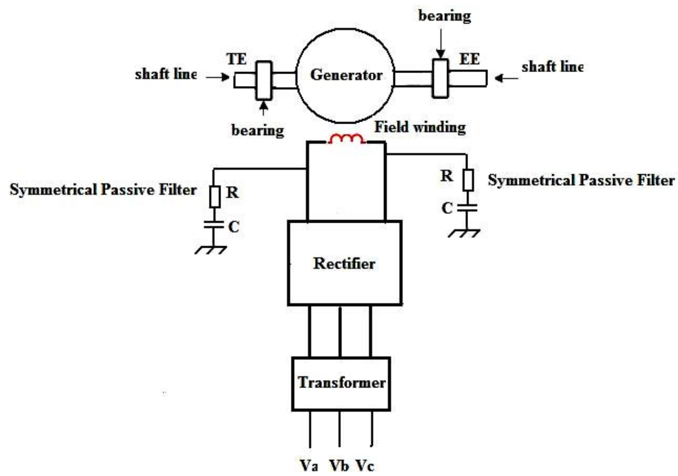

Fig .3: Connection of the passive filter to the DC side of rectifier

IV. SIMULATION RESULTS

According to the simulation results, it can be concluded that under symmetrical conditions and without any grounding brush, only common mode voltage contributes to the shaft voltage. The voltage applied to the field winding is a saw-tooth voltage with the base frequency of six times the base frequency of the system. This voltage is the DC output voltage of rectifier and is depicted in Fig .4.

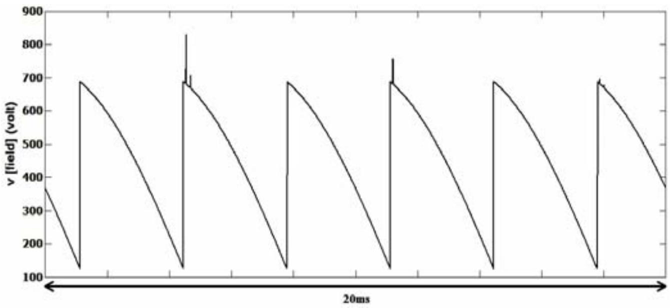

Fig .4: Voltage applied to the field winding of the proposed model

As depicted in Fig. 5, shaft voltage measured on exciter end (EE) and turbine end (TE) of generator is a periodic wave form with the base frequency of 150Hz. High frequency peaks, created by switching of rectifier, are also superimposed on the shaft voltage

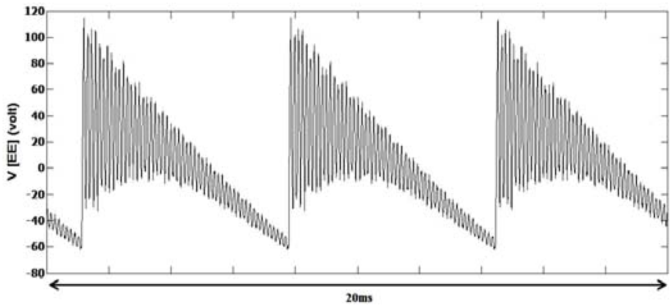

Fig .5: Shaft to ground voltage on (EE) without applying any solution

Simulation results in the case of applying the proposed passive filter to the derived model of the system is shown in Fig .6, 7. Fig .6 shows the voltage applied to the field winding. This voltage does not have high frequency peaks which existed in the previous section.

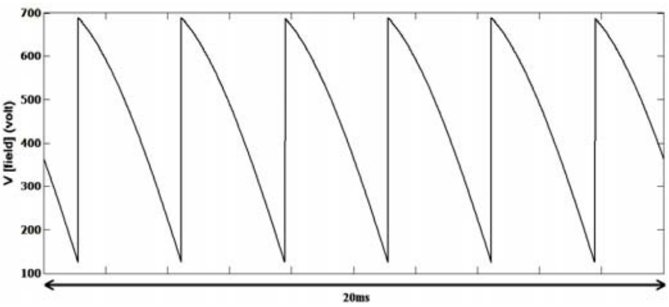

Fig .6: Field winding voltage in the case of applying the proposed passive filter

Shaft voltage on exciter end (EE) of generator is shown in Fig .7. It is significant that in the case of applying the passive RC filter to the DC side of the rectifier in the static excitation system, peaks of shaft voltage reduced from 115 volts, in the simple model, to 30 volts.

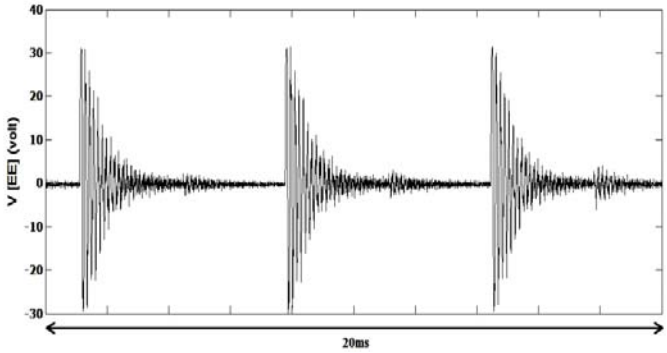

Fig .7: Shaft to ground voltage on (EE) in the case of applying the proposed passive filter

According to the simulation results it can be concluded that applying passive RC filter on DC side of the rectifier reduced high-frequency peaks of field voltage and hence reduced shaft voltage to a harmless value. RMS values of shaft voltage on exciter end of generator (EE) in simple model of the system and in the model with passive RC circuit are depicted in Fig. 8, 9. It can be concluded that applying passive RC filter to the input of field winding reduced RMS value of shaft voltage from 37.3 volts to a value beneath 6 volts and of course this value is low enough to ensure that bearing currents do not damage the journal bearings.

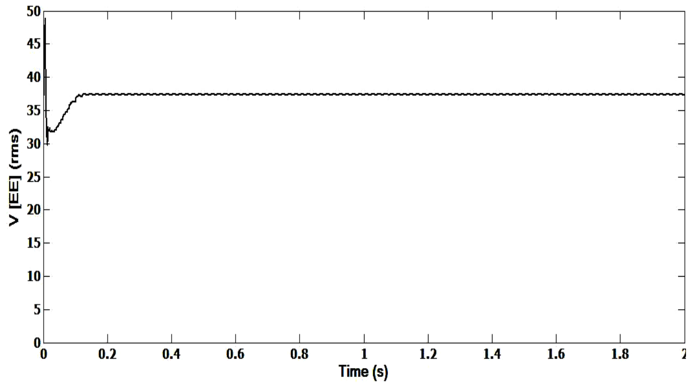

Fig .8: RMS value of shaft to ground voltage on the exciter end of generator

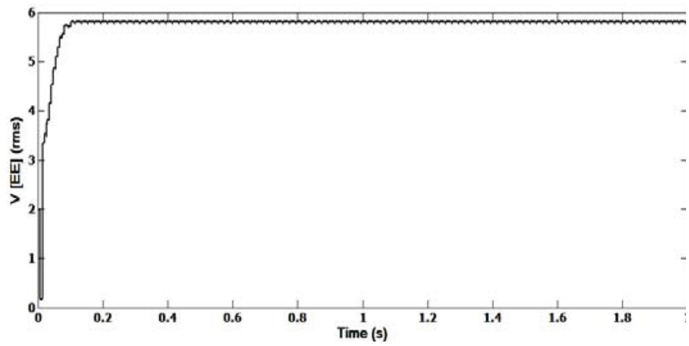

Fig .9: RMS value of shaft to ground voltage on the exciter end of generator in the case of applying passive filter

V. CONCLUSION

Static excitation systems are a source of shaft voltages. They cause wave forms with frequency of three times the fundamental frequency of the system with high-frequency peaks superimposed on them. In order to investigate shaft voltage and bearing current, an accurate equivalent model of the system should be derived and the studies should be applied on that.

In this paper a complete model of field winding, shaft line and static excitation system for numerical simulations has been proposed. All parasitic capacitances have been taken into account and their circuit model has been added to the model. Shaft voltage and bearing current are investigated in the proposed model. In order to protect turbo generators from shaft voltage and bearing current, reduction of shaft voltage to a harmless value is necessary and this is accomplished by several countermeasures discussed in the paper. Both the proposed model and the passive filtering technique were simulated with SIMULINK.

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REFERENCES

[1] Michael J. Costello, "Shaft Voltages and Rotating Machinery", IEEE Transactions on Industry Applications,Vol. 29, No. 2, March/April 1993

[2] Jean-Eric Torlay, Chantal Corenwinder, Alain Audoli, Joel Herigault, Albert Foggia, "Analysis of Shaft Voltages in Large Synchronous Generators", International Conference IEMD, PP. 607-609, 1999

[3] C.Amman, K.Reichert, R.Joho, Z.Posedel, "Shaft Voltages in Generators with Static Excitation Systems- Problems and Solution", IEEE Transactions on Energy Conversion, Vol. 3, No. 2, June 1988

[4] Paul I. Nippes, Elizabeth S. Galano, "Understanding Shaft Voltage and Grounding Currents of Turbine Generators", Magnetic Products and Services, Inc, Holmdel

[5] Toshihico Tanaka, Shinji Fujikawa, Shigeyuki Funabiki, "A New Method of Damping Harmonic Resonance at the DC Link in Large-Capacity Rectifier-Inverter Systems Using a Novel Regenerating Scheme", IEEE Transactions on Industry Applications, Vol. 38, No. 4, July/August 2002

[6] Hirofumi Akagi, Shunsuke Tamura, "A Passive EMI Filter for Eliminating Both Bearing Current and Ground Leakage Current From an Inverter-Driven Motor", IEEE Transactions on Power Electronics, Vol. 21, No. 5, September 2006

[7] Rajendra Naik, Thomas A. Nondahl, Michael J. Melfi, Rich Schiferl, Jian-She Wang, "Circuit Model for Shaft Voltage Prediction in Induction Motors Fed By PWM-Based AC D rives", IEEE Transactions on Industry Applications, Vol. 39, No. 5, September/October 2003

[8] H. Valizadeh, M. Tavakoli Bina, "Complete Harmonic Domain Modeling and An Optimal PWM Modulated Statcom in A Realistic Distribution Network", PRZEGLAD ELECTROTECHNICZNY, Vol. 85, PP. 156-161

[9] Hai Yan Lu, Jian Guo Zhu, S. Y. Ron Hui, "Experimental Determination of Capacitances in High Frequency Transformers ", IEEE Transactions on Power Electronics, Vol. 18, No. 5, September 2003

[10] Bidyut K. Sen et al, "Skin Effects Models for Transmission line Structure Using Generic Spice Simulations ", Electerical Performance of Electronic Packaging, PP. 128-131, 1998

[11] David K. Cheng, The Technical Writer's Handbook. Mill Valley, CA: University Science, 1989

[12] H. Y. Lu, J. G. Zhu, V. S. Ramson, S. Y. R. Hui, "Measurement and Modeling of Stray Capacitances in High Frequency Transformers", Power Electronics Specialists Conference, Vol. 2, PP. 763-768, 1999

[13] Juan M. Martinez-Tarifa, Hortensia Amaris-Duarte, Javier Sanz-Feito, "Frequency-Domain Model for Calculation of Voltage Distribution Through Random Wound Coils and Its Interaction With Stray Capacitances", IEEE Transactions on Energy Conversion, Vol. 23, No. 3, September 2008

[14] Hirofumi Akagi, Talkafumi Doumoto, "An Approach to Eliminating High-Frequency Shaft Voltage and Ground Leakage Current From an Inverter-Driven Motor", IEEE Transactions on Industry Applications, Vol. 40, No. 4, July/August 2004