Suggesting a DC-DC Buck Converter for Compensating Shaft Induced Voltage and Bearing Current

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Abstract—**This paper proposes a complete distributed model for investigating both the induced shaft voltage and bearing current in turbo generators due to the interaction with their static excitation systems. This affects the insulations gradually, leading to a possible electrical discharge current when the shaft voltage exceeds the dielectric breakdown voltage level of the lubricating grease film in journal bearings. Furthermore, a buck converter is proposed to overcome the stated issue, where simulations confirm the effectiveness of the proposals.**

Keywords-**Bearing current; Buck converter; Motion control; 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) of generator, 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 voltages and bearing currents, developing a circuit model of the system is of special importance. Equivalent circuit models have been proposed for investigation of shaft voltage. In [8], a model is proposed to observe the existence of significant shaft voltages induced by the PWM voltage source inverters in motors. Amman et al. in [3] have proposed a circuit model to investigate shaft voltage in a large turbo generator. Each coil in the circuit 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.

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 of the proposed models in [3] and [8], 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 models. 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. Simulation results of the proposed model verify the existence of the shaft voltage; also, when a buck converter is applied as the compensator, then the bearing voltage is lowered down to a desirable level.

II. Shaft Voltage Analysis

A. Model Of the System

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

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

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6. Brushes

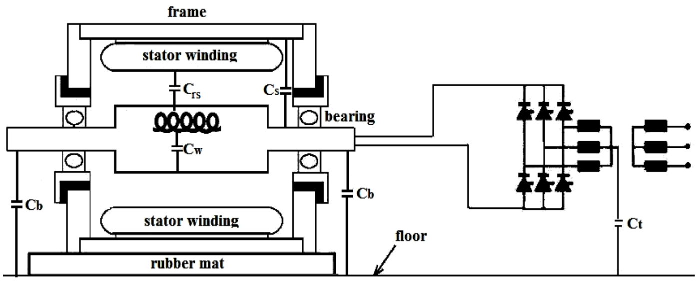

Figure 1. Static excitation system schematic diagram

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

1- Phase voltages, applied to the ac side of rectifier, are three symmetrical sinusoidal waves with the main frequency of 50Hz related to the base frequency of the power system.
2- Rectifier output DC voltage which is produced 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 switch, 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). This voltage contributes to the shaft voltage.

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 [9].

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

$$V_S = \frac{C_W C_t}{C_W C_t + C_S C_t + C_S C_W} V_C \qquad (1)$$

Where C_t is the transformer to ground capacitance [10], C_w is the leakage capacitance between rotor windings and shaft line and C_s is the capacitance between shaft line and the frame [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 [11].

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 equivalent 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 determining the leaking current paths in order to distinguish the stray capacitances. 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 model is connected in series to the model of other half turns. Parasitic capacitances between each turn and the adjacent turns are calculated and applied to the proposed model [12].

Shaft line of generator has been modeled by a passive RL circuit which indeed expresses the frequency-dependent behavior of the shaft line [7]. 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 value between shaft line and the frame and can be calculated by studying bearing dimensions and its lubricating oil material [13].

The other parameter in the proposed scheme of the system is the capacitance C_{rs} which represents couplings 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 of the generator. The values of brush resistance and capacitance are calculated by studying brush material. In this case brushes are made up of graphite. 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 Figure 2.

III. COUNTERMEASURES AGAINST SHAFT VOLTAGE AND BEARING CURRENT

There are possible countermeasures against shaft voltage in turbo sets. For example, the design procedure can be carried out in a way to prevent magnetic asymmetries. Also, all magnetized parts can be demagnetized to prevent axial shaft flux occurrence [3]. Another way could be the connection of the TE of generator to ground using 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 by 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 TE of generator cannot entirely eliminate high frequency peaks of shaft voltage.

Retention of bearing insulation at the 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.

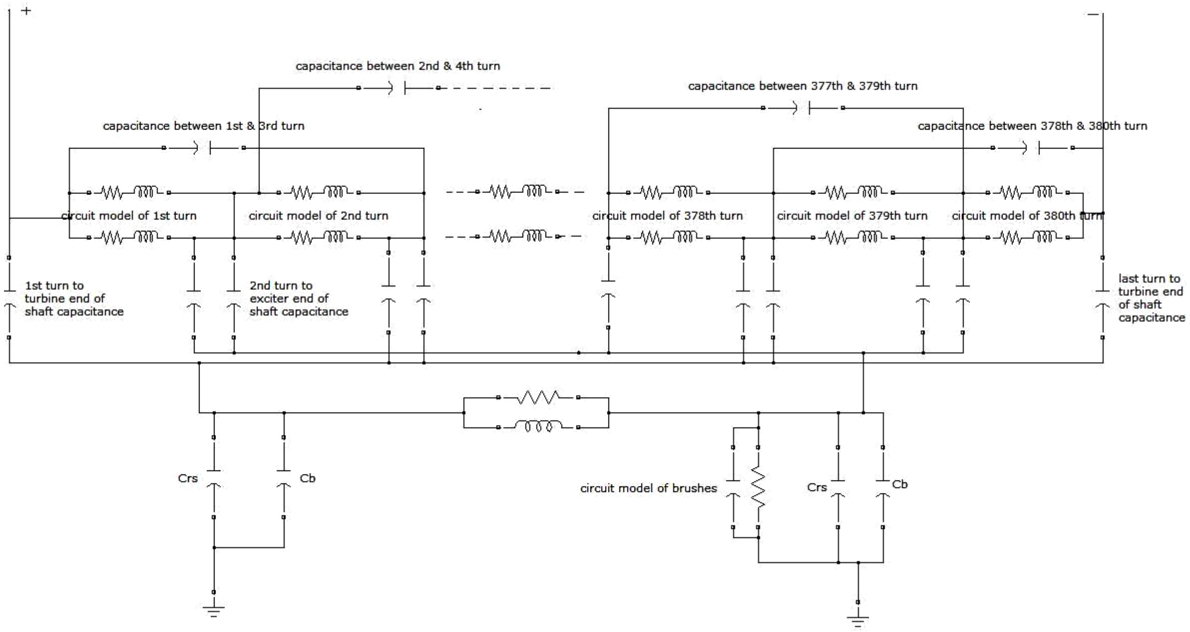

Figure 2. Model of excitation winding and turbo shaft for ANSALDO 200MVA turbo generator

More than the solutions described above, like what mentioned in [3], installation of a passive RC circuit through a grounding brush to the exciter end 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 restrict currents to some few amps and on the other hand low enough to prevent producing DC-voltage when there is no grounding brush.

The other solution which is going to be discussed here is applying a DC-DC buck converter to the DC-side of the rectifier. DC-DC buck converter is a well-known switched-mode converter that can reach the desired value of DC-voltage ripple on its output terminals by adjusting the value of its parameters. In this case the converter is located between the output terminals of the rectifier and the input terminals of generator field winding. The procedure is as follows. Output voltage of the converter is compared with the desired value and the difference is applied to a PI controller. This controller produces the signals to be applied to the PWM pulse generator. PWM pulse generator changes the duty cycle of the switch in the converter and hence the desired value of voltage would be applied to the field winding. Scheme of buck converter is depicted in Figure 3.

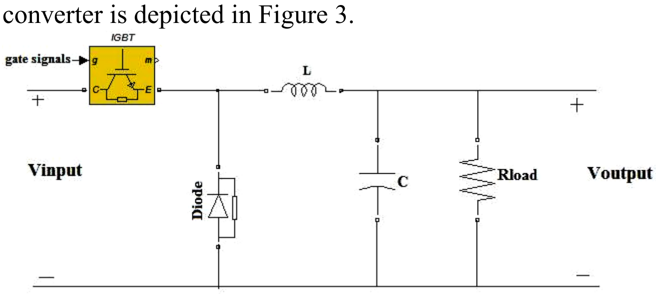

Figure 3. DC-DC buck converter

The value of the capacitance and the inductance in the converter should be calculated. The expression which is used to calculate the appropriate value of the capacitor is a function of the duty cycle and is mentioned in (2), Where V is the DC output voltage which is applied to the load, D stands for duty cycle, T_s is the period of switching and R represents load resistance [14].

$$\Delta V = \frac{V}{2RC} DT_S \tag{2}$$

Switching frequency of IGBT in the buck converter is considered 40 KHz. Another expression used to calculate the appropriate value of inductance L is mentioned in (3). The dimensionless parameter K is a measure of the converter tendency to operate in discontinuous conduction mode. If K is greater than one, then converter operates in the continuous conduction mode for all duty cycles [14].

$$K = \frac{2L}{RT_S} \tag{3}$$

According (3), value of the converter inductance L with respect to the switching frequency is 2.5μH.

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 main frequency of the system. This voltage is the DC output voltage of rectifier and is depicted in Figure 4.

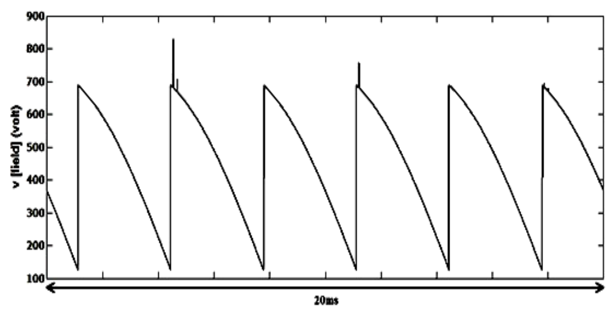

Figure 4. Voltage applied to the field winding of the proposed model

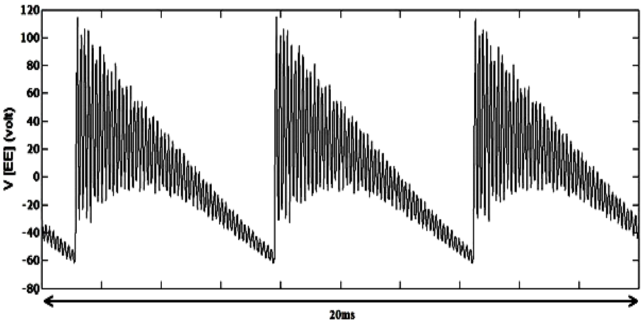

Figure 5. Shaft to ground voltage on (EE) without applying any solution

As depicted in Figure 5, shaft voltage measured on EE and the 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.

Simulation results in the case of applying the proposed DC-DC buck converter to the derived model of the system is shown in Figures 6, 7. Figure 6 shows the voltage applied to the field winding. Field voltage ripple has been decreased to one percent. This voltage does not have high frequency peaks which existed in the previous section.

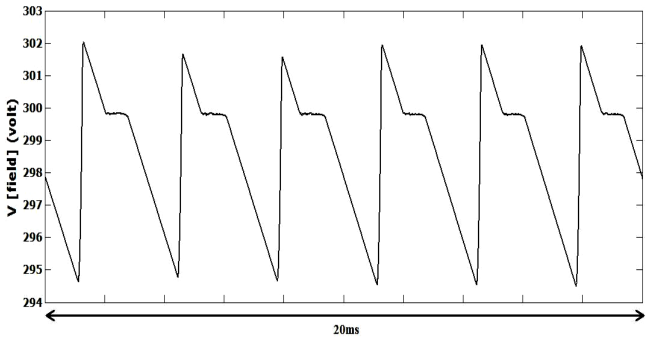

Figure 6. Voltage applied to the field winding in case of applying DC-DC buck converter

Shaft voltage on EE of generator is shown in Figure 7. It is significant that in the case of applying buck converter to the DC side of rectifier in the static excitation system, peaks of shaft voltage reduced from 115 volts, in the simple model, to 30 volts. This shows that shaft voltages have reached to the harmless values.

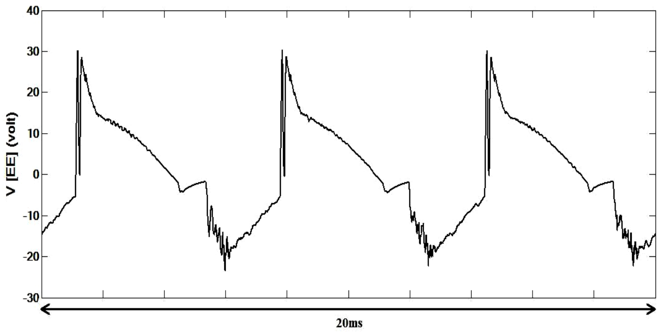

Figure 7. Shaft to ground voltage on (EE) in the case of applying DC-DC buck converter

According to the simulation results it can be concluded that applying buck converter to DC side of the rectifier reduced high-frequency peaks of field voltage; hence reduced shaft voltage to harmless values. RMS values of shaft voltage on exciter end of generator in simple model of the system and in the model with the proposed DC-DC buck converter are depicted in Figures 8, 9. It is significant that RMS value of shaft voltage from 37.3 volts to a value beneath 13 volts in the case of applying proposed DC-DC buck. These values of shaft voltage are low enough to ensure that bearing currents created by them do not damage journal bearings.

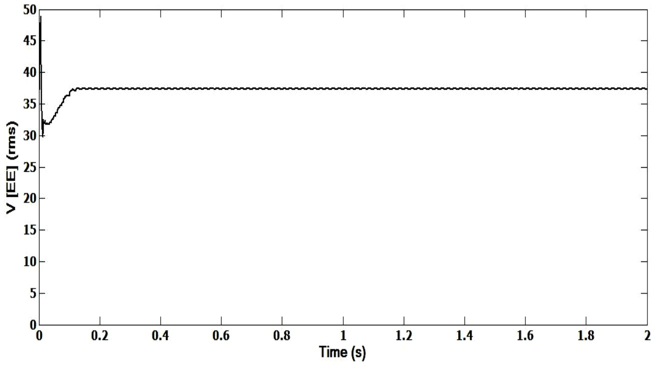

Figure 8. RMS value of shaft to ground voltage on the EE of generator

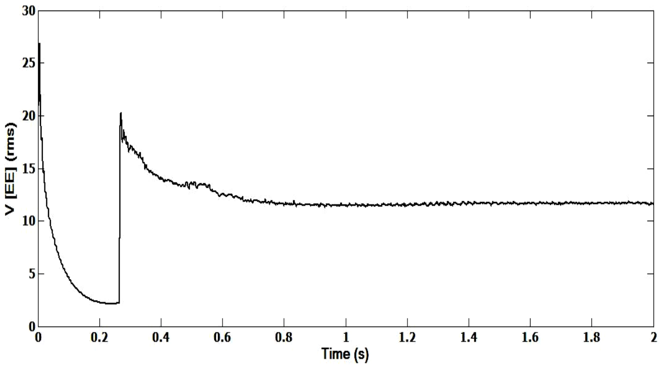

Figure 9. RMS value of shaft to ground voltage on the EE of generator in the case of applying DC-DC buck converter

V. EFFICIENCY

The proposed converter can be compared in terms of the dissipated power (DP) on the bearings, working out based on the monitored voltage and current of the bearings. The complemented model of turbo-generator is considered excluding any compensators, giving the total dissipated power (DP) about 2250 W. The calculated DP for the buck converter case equals to 400 W. A comparison between the DP of two studied cases show that the buck converter results in much lower dissipated energy.

VI. 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.

By this procedure, 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 suggested buck converter technique were simulated with SIMULINK, showing the usefulness of the proposed filter.

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