Study of Shaft Voltage on Short Circuit Alternator with Static Frequency Converter

Arun Kumar Datta, Manisha Dubey, Shailendra Jain

Abstract—Electric machines are driven nowadays by static system popularly known as soft starter. This paper describes a thyristor based static frequency converter (SFC) to run a large synchronous machine installed at a short circuit test laboratory. Normally a synchronous machine requires prime mover or some other driving mechanism to run. This machine doesn't need a prime mover as it operates in dual mode. In the beginning SFC starts this machine as a motor to achieve the full speed. Thereafter whenever required it can be converted to generator mode. This paper begins with the various starting methodology of synchronous machine. Detailed of SFC with different operational modes have been analyzed. Shaft voltage is a very common phenomenon for the machines with static drives. Various causes of shaft voltages in perspective with this machine are the main attraction of this paper.

Keywords—Capacitive coupling, electric discharge machining, inductive coupling, Shaft voltage, static frequency converter.

I. INTRODUCTION

SHORT circuit alternator is basically a synchronous machine used as a source of energy for short circuit tests on electrical power equipment. Energy requirement during the test is enormously high and equals to the fault level of the apparatus. A robustly designed alternator can only able to supply this energy. Conventional alternators are normally coupled with a turbine as prime mover for the mechanical energy input. But the machine taken up here is without any prime mover. This specially designed synchronous machine is started as synchronous motor. It is well known that synchronous motor is not a self starting machine. Various techniques are applied to start a synchronous motor. These are depicted in Fig. 1.

The conventional methods are less energy efficient and also need a huge investment. After the invention of high rating semiconductor devices, static starting devices are designed to start and run a synchronous motor. The static starting device is commonly known as SFC (Static Frequency Converter) or LCI (Load Commutated Inverter).

Frequency converter converts supply frequency to load requirement frequency. It has a feature of four quadrant operations. Though the concept of frequency converter is very old, but its application has increased in the recent years in the field of aviation industry, computer installations, communications, military installations, motor speed control, ships and power transmission.

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High rating thyristor based SFC is in use worldwide for starting and speed control of AC motors by providing a power supply of variable frequency and voltage simultaneously. It is very much popular in the field of gas turbine base power plant, pump storage power plant and railways [1]-[3]. However, to the authors' best knowledge, SFC technology to start a large synchronous machine in a short circuit testing plant has not been studied yet. The machine discussed in this paper is an alternator of short duration rating: 1500 MVA, 12.5 kV, 69 kA and 3000 rpm. SFC makes this machine to run as a synchronous motor and later on converted to alternator for supplying power during electrical tests. Machine field is supplied through static excitation system [4], [5]. Pictorial view of the short circuit alternator and its single line diagram is shown in Fig. 2.

a. Starting with starter motor
b. Starting with transformer
c. Starting with asynchronous gen.
d. Starting with synchronous aux. machine

T = Turbine
SM = Synchronous machine
M = Starter motor
R = Variable resistor
Tr = Starting transformer
ASG = Asynchronous generator
IM = Induction motor
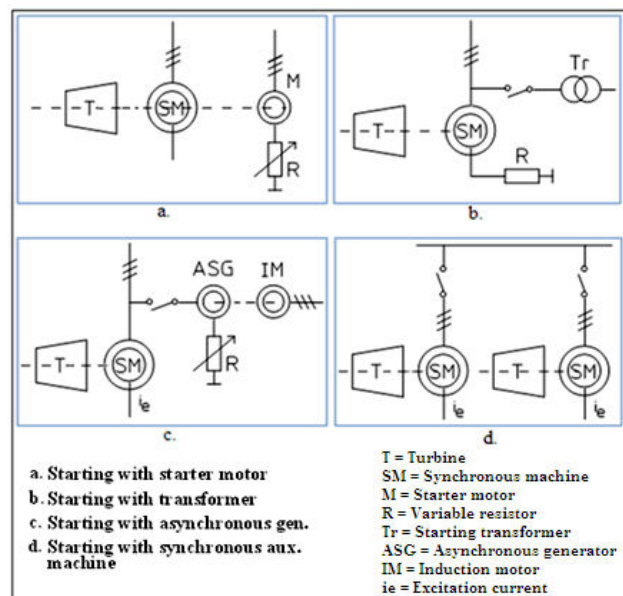ie = Excitation current

Fig. 1 Methods of starting a synchronous machine

Static starting devices has eased the starting process of the ac machine but at the same time it shows the evidence of shaft voltages. Though shaft voltage and bearing current are the very common phenomenon since the invention of electric machines, but they are more predominant in the case of machines with static supplies [6]. More motor bearing cases are reported since the inception of static drives.

Common mode voltage (CMV), capacitive coupling, and inductive coupling are the main causes by which shaft voltages are generated in a machine with static drive. Various

converter topologies and filtering techniques are suggested in literatures [7]-[10] to get rid of CMV. Variable frequency drives or static drives are getting more popular in spite of its many drawbacks.
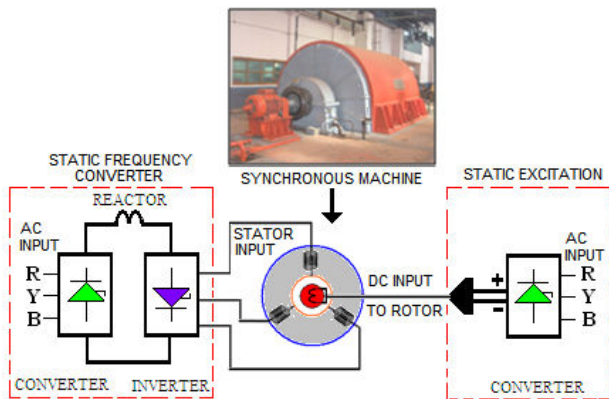

Fig. 2 Synchronous machine with connected systems

This paper gives the detailed analysis of static frequency converter applied on the above synchronous machine. Impact of SFC on shaft voltage and bearing current is the prime feature of this paper.

II. SFC: LAYOUT

Frequency converters are of many types depending on the technology and application. Process of frequency conversion with the static devices is a three stage process. In the first stage, power frequency is converted to dc. The second stage is to filter out the ripples through a smoothing reactor. The filtered dc is inverted to ac at desired frequency in the third stage. The configuration of SFC is a combination of two 6-pulse thyristor bridges (Fig. 3) with an intermediate dc link reactor [11].
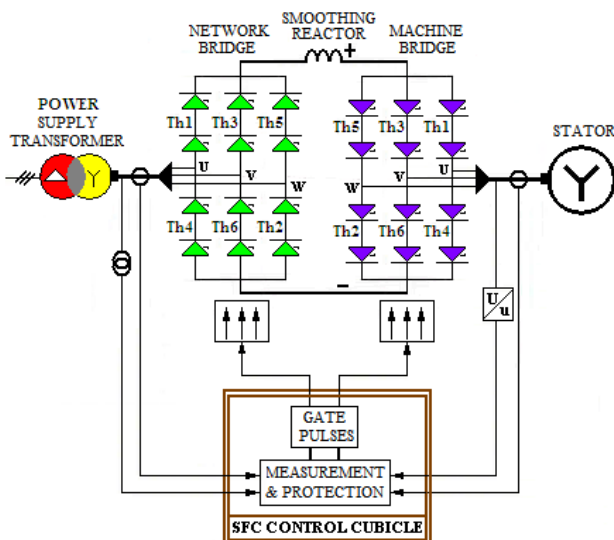

Fig. 3 SFC configuration

The bridge connected with the line supply is known as network bridge (NB). It normally acts as a rectifier. Another bridge feeds the machine stator terminals is called machine bridge (MB). MB operates as an inverter producing three-phase alternating current, the frequency of which is varied from a very low value up to the nominal value [12]. Both these bridges can also be made to operate in vice versa mode depending upon the machine requirements e.g. braking etc. With these SFC features, the machine can operate in dual mode i.e. motor and generator. SFC control cubicle takes care of different parameters and sets the thyristor firing angle accordingly [13]-[15].

III. SFC: FUNCTIONAL DESCRIPTION

The thyristor bridges in SFC are in the form of 6 legs Graetz bridge. Each leg comprises at least one thyristor, but the system under study is having two series thyristors in each leg (Fig. 3) due to voltage limitation. Function of SFC is to start the machine as a motor. To generate the torque in motoring mode two inputs are required. One is from the stator side and another from the rotor side. Rotor in a synchronous machine is always dc which it gets from the static excitation system [16]. The motor can't achieve full speed at once. It is a two step process. Thyristor commutation is different in both the process. These are explained in the next paragraphs.

A. Motoring action: Pulse Link Mode

- NB rectifies the line supply and results a voltage across MB.
- MB thyristors are fired in such a way that only 2 legs conduct at a time. The sequence of firing can be Th1-Th2, Th2-Th3, Th3-Th4, Th4-Th5, Th5-Th6, Th6-Th1 and then again repeated as Th1-Th2, ….so on (Fig. 4).
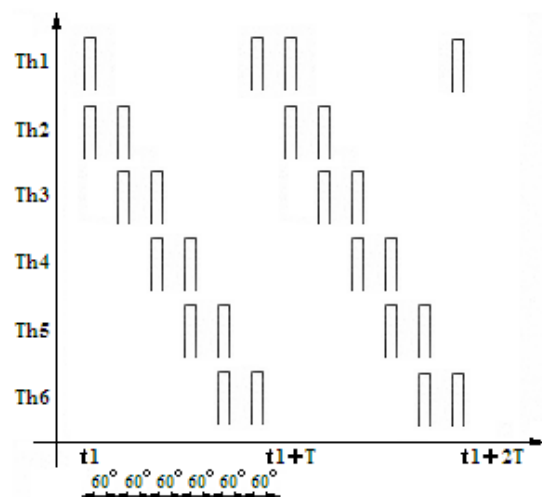

Fig. 4 Thyristor firing sequence

- Each configuration last 60° electrical and repeats periodically after every 360°. Hence individual thyristor leg conducts for 120° out of 360° (1/3 of the time).
- Conduction of two thyristor legs sends low frequency current pulses to the two phases out of three phase stator

winding (Fig. 5). This current is drawn through the smoothing reactor L and a pulsating dc current i_d is established. Current through stator winding produces a resultant magnetic flux Φ_i (Fig. 6).

• Field current in the rotor winding producing another magnetic flux Φ_e (Fig. 6). It turns the rotor by 60°.
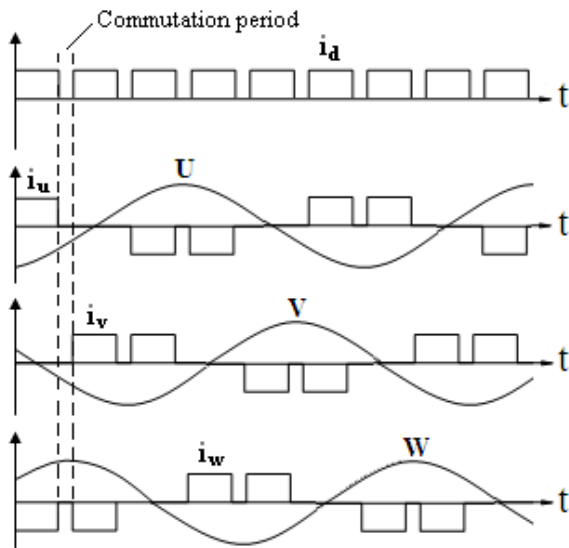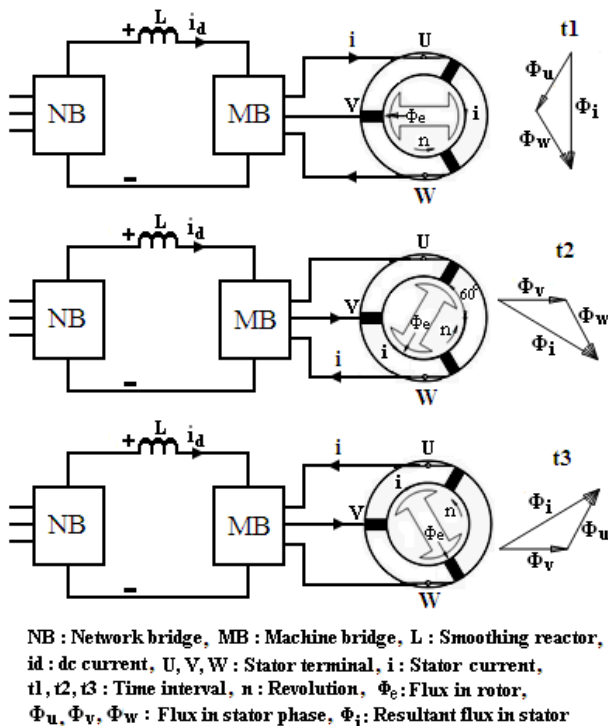

Fig. 5 Stator V & I in pulse link mode

NB : Network bridge, MB : Machine bridge, L : Smoothing reactor,
id : dc current, U, V, W : Stator terminal, i : Stator current,
t1, t2, t3 : Time interval, n : Revolution, Φ_e : Flux in rotor,
Φ_u, Φ_v, Φ_w : Flux in stator phase, Φ_i : Resultant flux in stator

Fig. 6 Stator & rotor flux and torque generation

• Vector Φ_i rotates in steps of 60° according to the sequence of the fired thyristor legs. Rotor also follows the rotation.

• Being connected with the network side, NB thyristors are in self commutating mode.

• Machine terminal voltage (back e.m.f.) is proportional to the speed. At low speed commutation is difficult for MB thyristors due to insufficient voltage. Hence forced commutation technique is adopted in pulse link mode.

• To achieve forced commutation of MB thyristors, NB thyristors are set in full inverter mode. This reduces the dc current to zero level, subsequently turning off the conducting MB thyristors pair.

• After which the new MB thyristors pair is fired and dc current i_d is established again through the smoothing reactor. Due to the commutation period the i_d current in the dc link is pulsating in nature.

B. Motoring Action: Synchronous Mode

• As the machine develops speed, sufficient voltage is built up in the stator. This voltage helps MB thyristors for self commutation.

• In order to change thyristor configuration from Th1-Th2 to Th2-Th3, the only need is to send a gate pulse to thyristor Th3. When current is built up in Th3, the machine back e.m.f. automatically blocks Th1, hence natural commutation takes place.

• This is called 'Synchronous mode'. MB output frequency is increased gradually to 50Hz, to achieve the machine speed of 3000 rpm.

• The NB, MB voltage & current waveforms and complete speeding up process are shown in Figs. 7 (a), (b), 8 (a), (b), and 9.
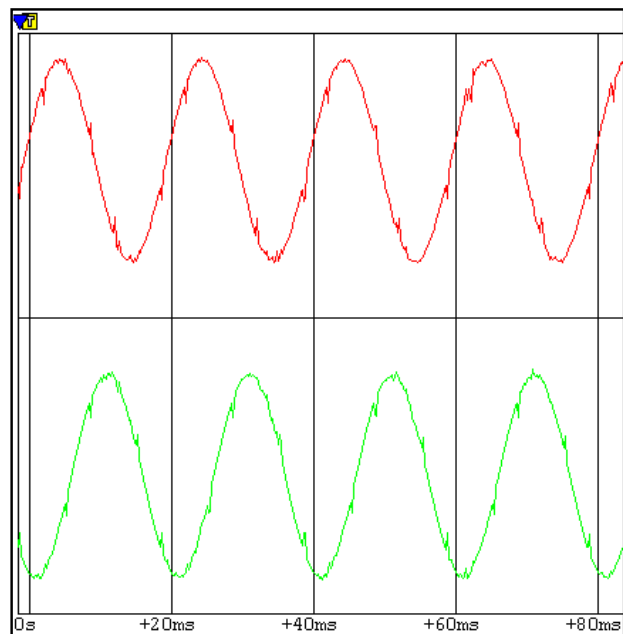

Fig. 7 (a) NB voltage U & W

C. Alternator Mode

Purpose of this machine is not only to run as motor but to get electrical energy from it. This is only possible when the machine acts as an alternator at its rated speed. To convert from motor to alternator, SFC controller blocks gate pulses to all the bridge thyristors. When the thyristors are at idle condition rotor field supply is established. This turns the rotating machine to act as an alternator. The desired stator terminal voltage can be achieved by adjusting the level of rotor field excitation. This voltage is applied on the equipment under short circuit test. Current under the influence of applied voltage is sourced by the machine in alternator mode.

Current and voltage waveforms during a short circuit test are shown in Fig. 10. After one cycle of short circuit test SFC acts back and the machine is converted to motor by releasing the thyristor gate pulses.
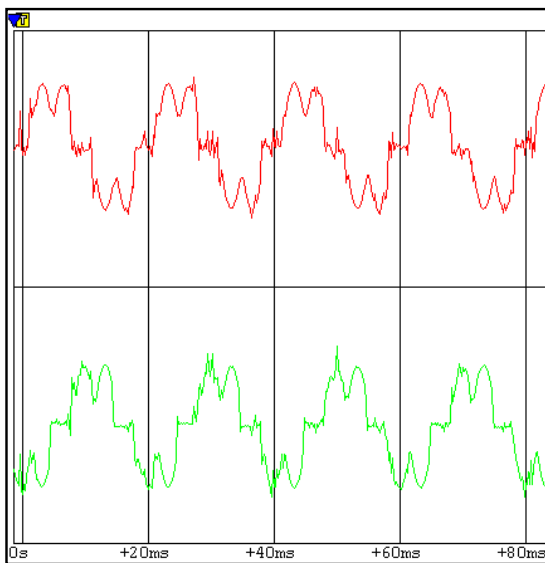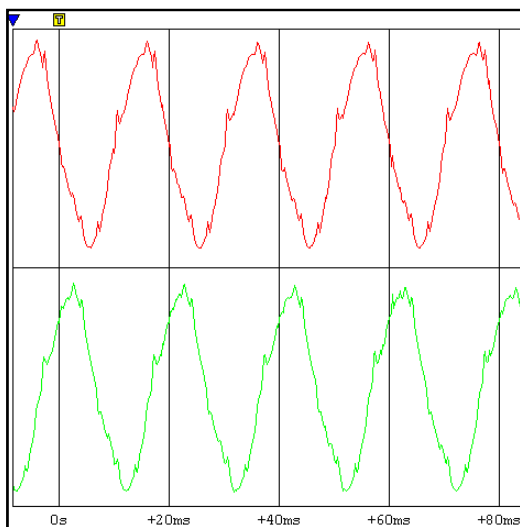

Fig. 8 (b) MB current U & W
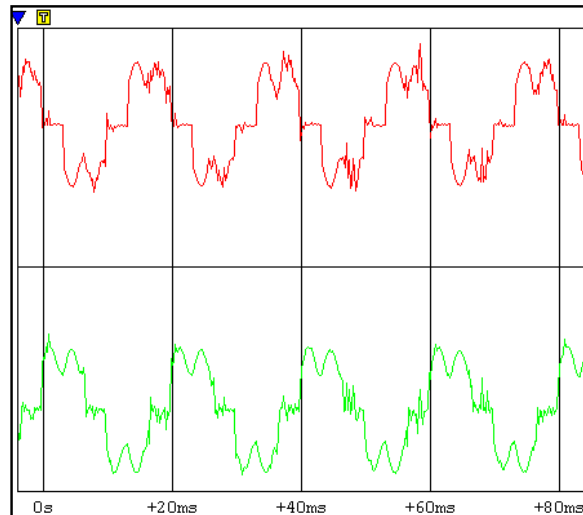

Fig. 7 (b) NB current U & W

Fig. 9 Different modes of operation

n – MACHINE RPM
i_d – DC LINK CURRENT
i_u – STATOR PH. CURRENT

Fig. 8 (a) MB voltage U & W
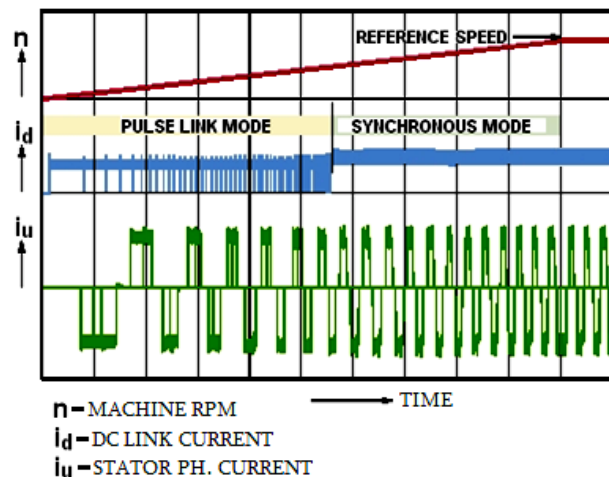
IV. SHAFT VOLTAGE PHENOMENON

Electric sparks have been observed between the shaft and grounding brushes of this machine. It is the indication of the presence of shaft voltage. During machine operation its shaft is charged with significant potential above the ground by some internal or external means. This unwanted voltage named shaft voltage is the cause of flow of bearing current. Bearing current is of two types; circulating [17] or non-circulating.

There are many causes of shaft voltage. Common mode voltage, capacitive and inductive couplings are the major reasons to induce e.m.f. in the shaft of the machine. It mainly depends on the type of source voltage [1]. Shaft voltage is more prominent with non sinusoidal supply. Various causes of shaft voltages in perspective with this machine are discussed hereafter.
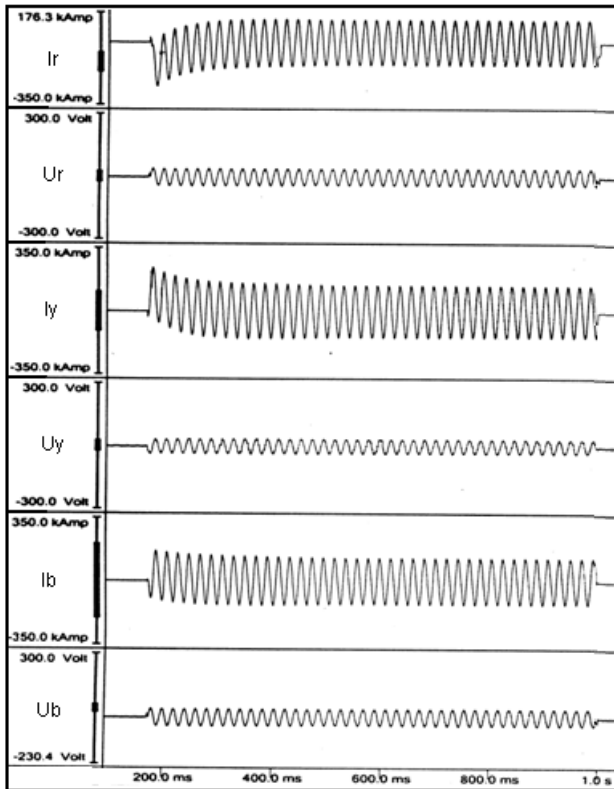
Fig. 10 Current & voltage waveforms during tests on a generator bus duct

A. Common Mode Voltage (CMV)

Any inverter fed machine is having some potential in its star point. This neutral point voltage is the sum of instantaneous value of inverter output voltages. CMV has amplitude proportional to the inverter DC bus voltage with a frequency of three times of the fundamental. Due to the CMV, common mode current flows between motor windings and ground through parasitic capacitances. These currents pass through machine bearings to ground, thereby eroding the bearing surfaces.

B. Capacitive & Inductive Coupling

Due to thyristor switching, stator voltage and current as shown in Figs. 11 (a), (b), 12 (a), & (b), contain number of high frequency signals. These are applied to the stator windings which cause the flow of high frequency fluxes across the magnetic core. These fluxes induce e.m.f. in long machine shaft and other metallic parts through inductive coupling. A circulating current flows through shaft and bearings due to the inductive coupling. It can be restricted by insulating any one of the two bearing from the ground.

Other than inductive coupling, a capacitive coupling is also formed due to distributed capacitance in the complete alternator system. This parasitic capacitances cause the flow of leakage current from stator winding to the rotor and in this process shaft gets charged. This current is normally non-

circulating or discharge mode current and its effect is more severe than the circulating current.
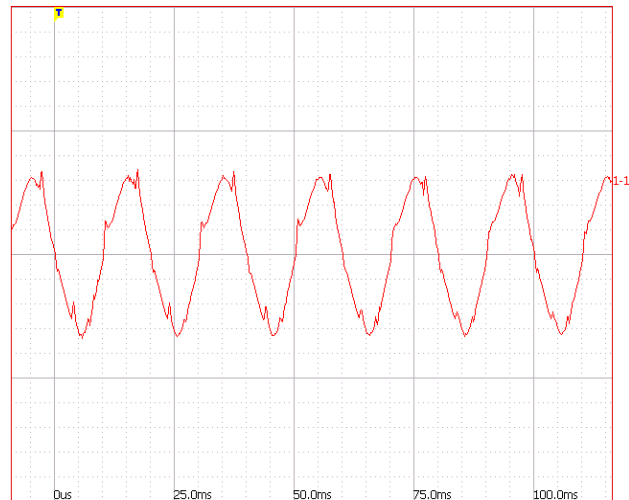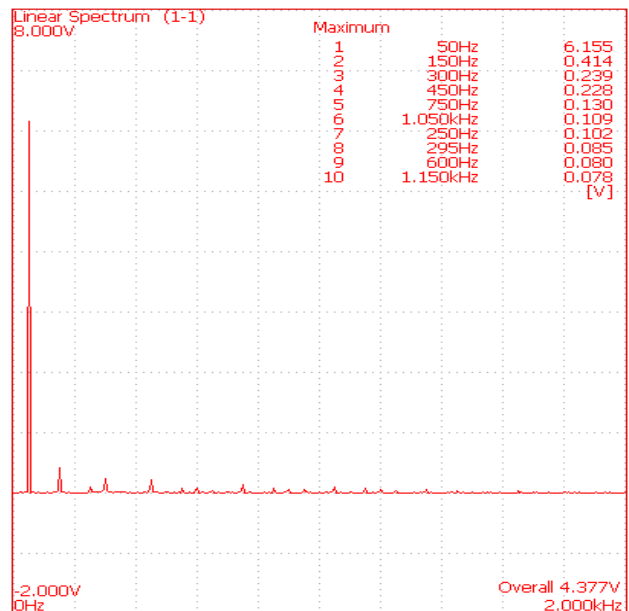

Fig. 11 (a) Stator voltage

Fig. 11 (b) FFT of stator voltage

The short circuit alternator taken here has insulated bearing at the exciter end and opposite end bearing is grounded. Shaft is also grounded through carbon brushes. During rotation the electrically charged shaft is not always at ground potential. When the contact resistance of the grounding brushes is high (due to poor contact or contamination), the dielectric (oil film) breakdown takes place between shaft & bearing due to close proximity. A discharge mode bearing current called electric discharge machining (EDM) in the form of short duration high magnitude impulses take place from the shaft to the grounded bearing. EDM is viewed as electric spark and can be recorded with a storage oscilloscope (Fig. 13). This high energy EDM

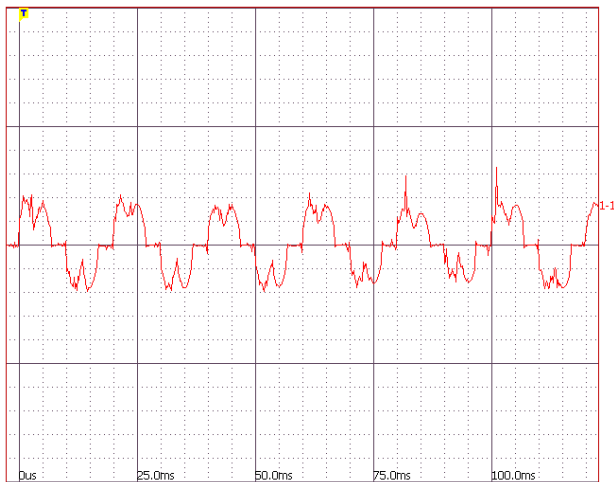can erode the surfaces of bearing, shaft and nearby metal surfaces.
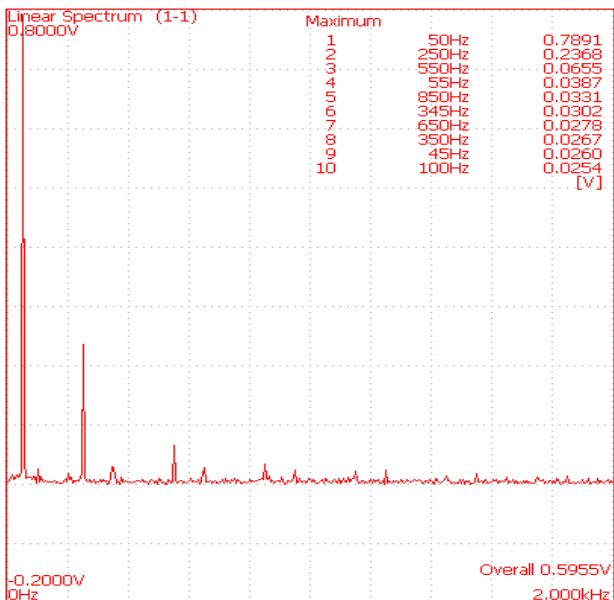

Fig. 12 (a) Stator current

Fig. 12 (b) FFT of stator current

V. CONCLUSION

Statistics say that more number of motor bearing failure cases is being reported after the introduction of static drives. This is because of the flow of bearing currents due to the presence of shaft voltage. To understand the effects of SFC on a large machine, this study is carried out on a short circuit alternator. It is a specially designed machine and similar to the synchronous generator used in a power plant. SFC technology has more operational flexibilities than any other methods. Any large machine can be started softly without much loading the supply source. Speed control, monitoring and troubleshooting are very much user friendly with this technology. A single

machine is feasible to operate in four quadrant mode. This machine can operate as motor or generator. Motor mode operation is divided in two parts; turning gear and synchronous. In generator mode the output power is utilized for electrical testing. The only side effect of SFC technology is the generation of shaft voltage. Switching of thyristors in the converter-inverter bridge is the main reason behind this. Circulating bearing current in this machine is eliminated by the use of insulated bearing at one end. But the presence of non-circulating or discharge mode bearing current is verified with the recorded EDM. Though the study is carried out on a specially designed alternator used for short circuit testing, but the findings are useful to other large machines with static drives.
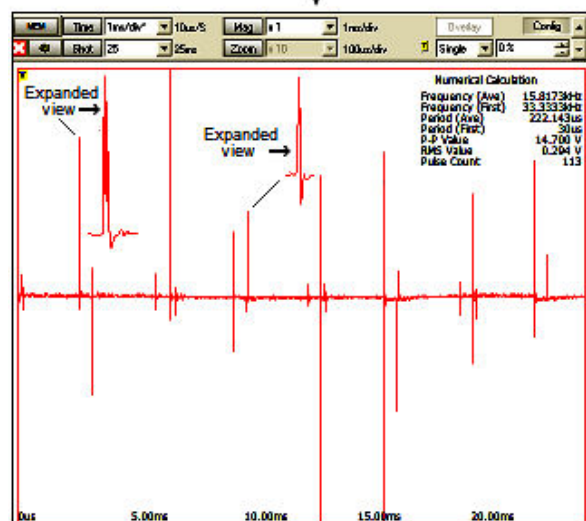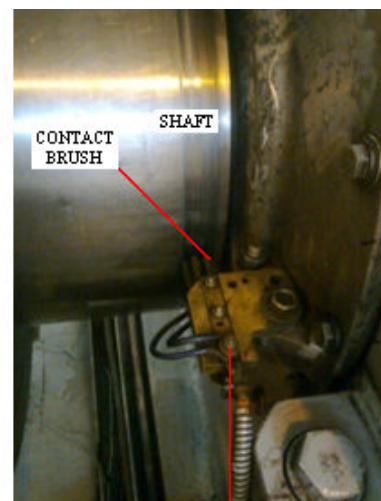

Fig. 13 Machine shaft, grounding brush and recorded EDM

REFERENCES

[1] A. Hisanori Taguchi, et al., "APS Control Method for Gas Turbine Startup by SFC", International Power Electronics Conference, pp.264-269 IEEE, 2010.

[2] Zhang Yu-zhi, "Study of Process of Starting Pumped Storage Machines by Static Frequency Converter with Field Current Controlled", International Conference on Signal Processing Systems, pp. V1-224 – V1-227, IEEE2010.

[3] Robert B., Fisher, P.E., "Introduction of Static Frequency Converters on SEPTA's 25Hz Commuter Rail System", pp.149-155, IEEE.

[4] L. J. Lane, D. F. Rogers, P. A. Vance, "Design and Tests of a Static Excitation System for Industrial and Utility Steam Turbine-Generators", pp.1077-1085, A.I.E.E., 1962.

[5] R.C. Schaefer, "Applying Static Excitation Systems", pp. 41-49, IEEE Industry Application Magazine Nov/Dec1998.

[6] Datta Arun Kumar, Dubey Manisha, Jain Shailendra, "Study of shaft voltage & bearing currents in electrical machines," IEEE Students' Conference on Electrical, Electronics and Computer Science (SCEECS), pp.1-4, 1-2 March 2012.

[7] Zhu, N.; Xu, D.; Wu, B.; Zargari, N. R.; Kazerani, M.; Liu, F.; , "Common mode voltage reduction methods for current-source converters in medium-voltage drives,", IEEE Transactions on Power Electronics, vol.28, no.2, pp.995-1006, Feb. 2013.

[8] R. S. Kanchan, P. N. Tekwani, and K. Gopakumar, "Three-level inverter scheme with common mode voltage elimination and DC link capacitor voltage balancing for an open-end winding induction motor drive," IEEE Transactions on Power Electronics, vol. 21, pp. 1676-1683, 2006.

[9] Yuen, K. K.-F.; Chung, H. S.-H.; Cheung, V. S.-P.; , "An active low-loss motor terminal filter for overvoltage suppression and common-mode current reduction" IEEE Transactions on Power Electronics, vol.27, no.7, pp.3158-3172, July 2012.

[10] Akagi, H.; Isozaki, K., "A hybrid active filter for a three-phase 12-pulse diode rectifier used as the front end of a medium-voltage motor drive", IEEE Transactions on Power Electronics, vol.27, no.1, pp.69-77, Jan. 2012.

[11] Tore Peterson, Kjell Frank, "Starting of large synchronous motor using static frequency converter", paper 71 TP 519-PWR for IEEE International Symposium on High Power Testing, Portland, Ore., pp.172-179, July 18-23, 1971.

[12] Tsorng-Juu Liang, et al, "Analysis of 12 Pulse Phase Control AC/DC Converter", IEEE 1999 International Conference on Power Electronics and Drive Systems, PEDS'99, pp.779-783, July 1999, Hong Kong.

[13] Tian Hua Liu, et al.,"Modeling and Harmonic Elimination for a Static Frequency Converter Driving a 300 MVA Synchronous Machine", pp.602-607, IEEE, 1996.

[14] Ho-Seon Ryu, et al "A Study of Synchronous Motor Drive using Static Frequency Converter" EPE-PEMC, pp.1496-1499, 2006, IEEE.

[15] Datta Arun Kumar, Ansari M. A., Mondal N. R., Raghavaiah B. V. "A Novel Use of Power Electronics: Prime Mover-less Alternator with Static Drive & Excitation System" International Journal of Electronics & Communication Technology, Vol. 3, Issue 1, pp. 472-475, January - March 2012.

[16] Datta Arun Kumar, Dubey Manisha, Jain Shailendra, "Investigation of Bearing Currents in Dual Mode Operation of Synchronous Machine with Static Excitation System", pp.45-53, Electrical and Electronics Engineering: An International Journal (ELELIJ), Wireilla Scientific Publications, Australia.

[17] Muetze A. and Binder A., "Calculation of circulating bearing currents in machines of inverter-based drive systems", IEEE Transactions on Industrial Electronics, vol. 54, no. 2, pp. 932-938, April 2007.

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