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Simulation of Static Frequency Converter for Synchronous Machine Operation and Investigation of Shaft Voltage

Arun Kumar Datta, M. A. Ansari, N. R. Mondal, B. V. Raghavaiah, Manisha Dubey, Shailendra Jain

Abstract**—**This study is carried out to understand the effects of Static frequency converter (SFC) on large machine. SFC has a feature of four quadrant operations. By virtue of this it can be implemented to run a synchronous machine either as a motor or alternator. This dual mode operation helps a single machine to start & run as a motor and then it can be converted as an alternator whenever required. One such dual purpose machine is taken here for study. This machine is installed at a laboratory carrying out short circuit test on high power electrical equipment. SFC connected with this machine is broadly described in this paper. The same SFC has been modeled with the MATLAB/Simulink software. The data applied on this virtual model are the actual parameters from SFC and synchronous machine. After running the model, simulated machine voltage and current waveforms are validated with the real measurements. Processing of these waveforms is done through Fast Fourier Transformation (FFT) which reveals that the waveforms are not sinusoidal rather they contain number of harmonics. These harmonics are the major cause of generating shaft voltage. It is known that bearings of electrical machine are vulnerable to current flow through it due to shaft voltage. A general discussion on causes of shaft voltage in perspective with this machine is presented in this paper.

Keywords**—**Alternators, AC-DC power conversion, capacitive coupling, electric discharge machining, frequency converter, Fourier transforms, inductive coupling, simulation, Shaft voltage, synchronous machines, static excitation, thyristor.

I. Introduction

There are various means of starting a synchronous machine from standstill. The old conventional methods (with additional motor) are less energy efficient and also need a huge investment and time. After the invention of high rating semiconductor devices, static starting devices are designed to start and run a large synchronous motor. One of these static starting devices is known as Static Frequency Converter (SFC).

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. Frequency converter converts supply frequency to load requirement frequency. It has a feature of four quadrant operations. High power 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 normally used in gas turbine based power plant, pump storage power plant, railways and large synchronous motor [1]-[4]. SFC technology has also been extended to the field of short circuit alternator [5], [6]. This alternator runs as a synchronous motor and later on converted to generator by virtue of SFC. As a generator it supplies energy to the electrical power equipment during tests. No additional prime mover is required to start and run this machine. Only rotor field power is required which is supplied through a static excitation system (SES) [7]. SES has already been implemented in power generator since beginning of sixties [8], [9]. It is basically a poly-pulse AC-DC power conversion [10] system with different control circuitry. Pictorial view of the short circuit alternator and its single line diagram is shown in Fig. 1.

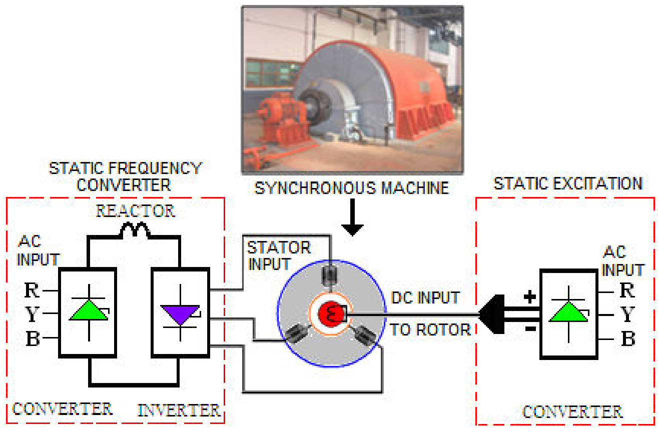

Fig. 1 Short circuit alternator with connected systems

SFC has an edge over the various methods of starting in terms of operation flexibility, quick response, easy monitoring, control and troubleshooting. Being the static source it has only one concern i.e. of shaft voltage. Shaft voltage is a very common phenomenon in large machine [11]-[13].

Bearing current is the ultimate result of shaft voltage. Many papers have been published on the effect shaft voltage on induction motors [14]-[18]. Different solution techniques to eliminate shaft voltage are common mode voltage reduction, inverters topologies and filter circuits (active, passive or

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hybrid) [19]-[26]. This field is still under the scope of research.

Effect of static power supplies on large synchronous machine has broadly discussed in paper nos. [27] & [28]. This paper begins with the details of SFC circuitries and its functions. Thereafter a MATLAB/Simulink model [29] of SFC is prepared with circuit parameters. The model is run and the waveforms are viewed in scope and plot windows. These results are validated with the waveforms recorded from the actual bridge with a high speed recorder. All the waveforms are process through FFT analysis tool. Fourier transformation shows the presence of number of harmonics in the waveforms. A discussion on the shaft voltage is brought out on the basis of these results.

II. SFC: Configuration

SFC is a combination of two 6-pulse thyristor bridges (Fig. 2) with an intermediate dc link reactor [30]. The first bridge named as network bridge (NB) connected with a source transformer. Second bridge is called machine bridge (MB) that connects the machine stator terminals. Both these bridges can be operated either as rectifier or inverter depending upon the machine requirements as motor or generator. In normal mode NB acts as rectifier and power frequency supply is converted to DC. This DC contains ripples which are filtered by the link reactor. 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. Thyristor firing angle in the NB & MB are set by a controller [31], [32] with various feedback loops.

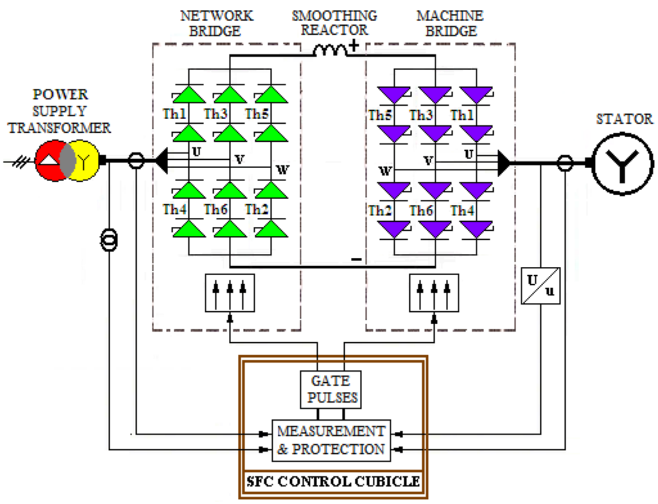

Fig. 2 SFC configuration

SFC panel is divided in two main parts (Fig. 3). One is power cubicle, consisting of thyristors and snubber circuits. The second part is the CPU with other electronic control circuitry and feedback circuits. It is named as power electronic controller (PEC) and acts very fast in a µsec range during short circuit test sequence [33]. A human machine interface (HMI) fitted on the controller visualises all fault and abnormality records in the SFC.

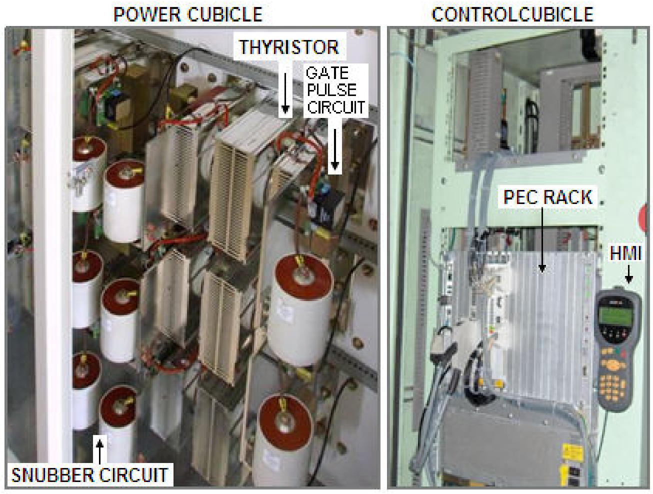

Fig. 3 Static frequency converter for 1500MVA short circuit alternator

III. Motor Operation with SFC

SFC feeds variable frequency supply to the machine through a cable. It starts the machine as a motor from standstill to the rated rpm value (Fig. 4). The acceleration is kept low to maintain the synchronism at all speed. Another benefit of low acceleration is less loading on the source.

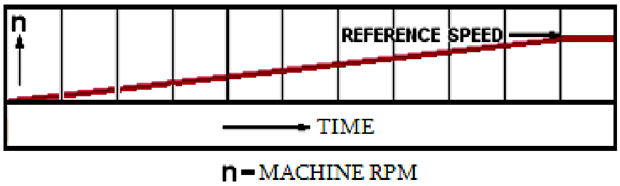

Fig. 4 Synchronous motor speed

At rated speed motor voltage and current are measured with a high speed waveform recorder. For voltage measurement Hall effect transducer is connected across the motor terminals. Current is measured by a specially designed variable frequency CT through which motor cable is passed. Motor voltage & current waveforms are displayed in Figs. 5 & 6. As the waveforms are not purely sinusoidal their fast Fourier transformation are carried out to view the harmonics content. FFT analysis of motor voltage and current are shown in Figs. 7 & 8.

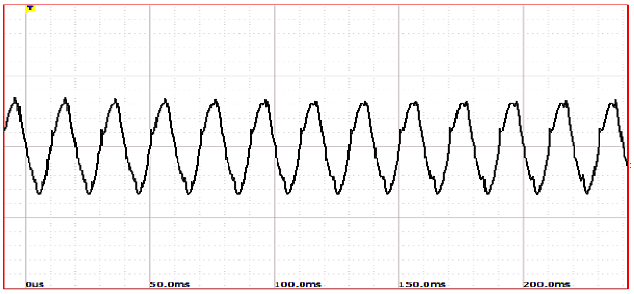

Fig. 5 Synchronous motor phase voltage

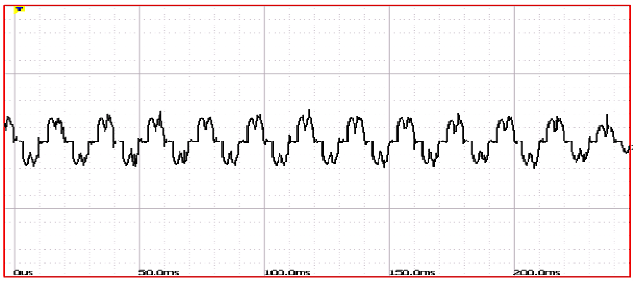

Fig. 6 Synchronous motor line current

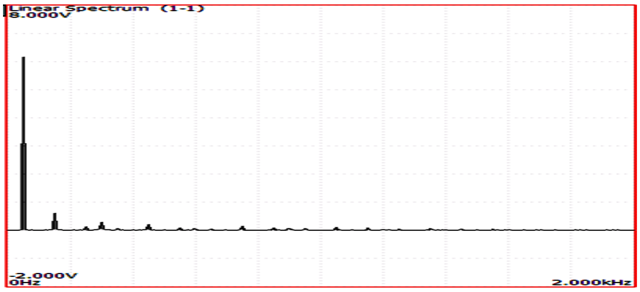

Fig. 7 FFT of motor voltage

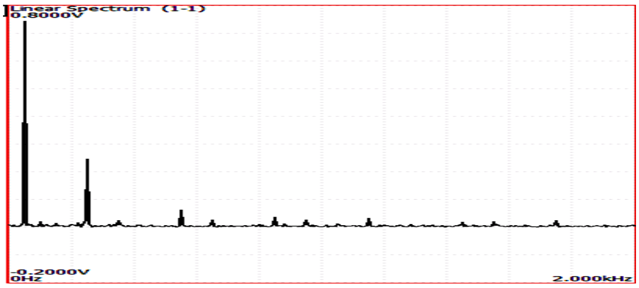

Fig. 8 FFT of MB current

IV. SFC: Simulink Model

Modelling of SFC is done to understand its intricacies in a simple manner. Simulink platform of MATLAB is used to model the SFC system (Fig. 9).

One source transformer, two thyristor converter bridges, pulse generators and control circuitries are taken to create the model. Following parameters are taken from the actual SFC configuration working for the short circuit alternator:

TABLE I
SFC Model Parameter Values

Parameter	Value
Input source	33kV, three phase
Transformer nominal power	3.5 MVA
Transformer primary input, Delta winding	33KV, 50Hz
Transformer secondary output, Star winding	1.72KV
Thyristor bridge	3 arms
Snubber resistance	2000 Ω
Snubber capacitance	0.1 µF
Link reactor	4.8mH
Base voltage	12kV
X/R ratio	7
Motor voltage	1.72kV
Motor RPM	3000

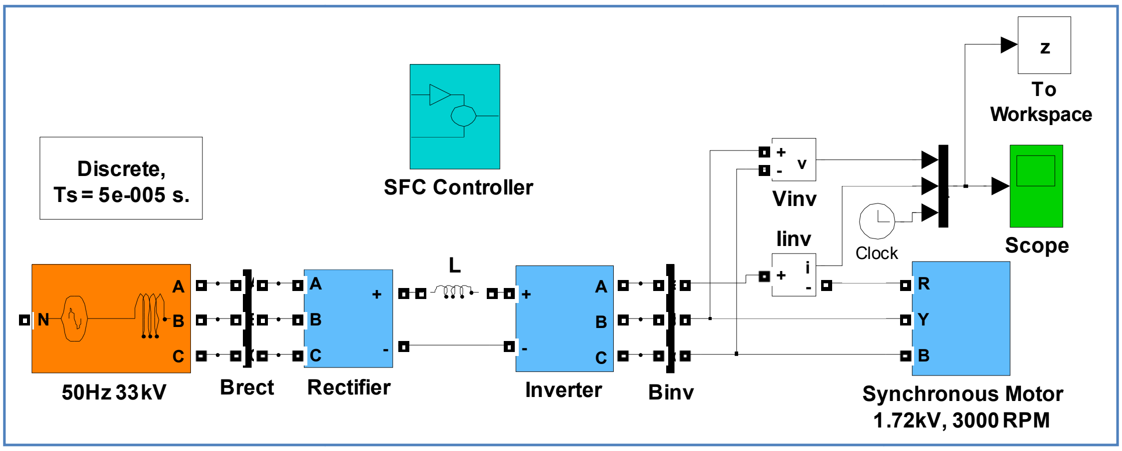

Fig. 9 Simulink model of SFC

V. Simulation Results

The simulated model is run and waveforms are viewed on the scope window (Fig. 10). For better representation of motor voltage and current they are plotted again with the help of MATLAB Script file (Figs. 11 & 12). Further the FFT analysis is done on these waveforms to find out the level of harmonics (Figs. 13 & 14).

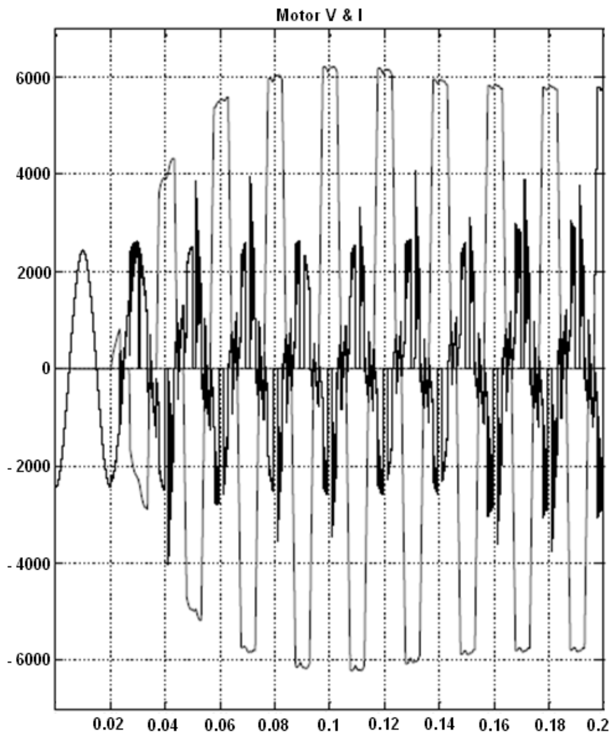

Fig. 10 Scope view of simulated motor voltage and current

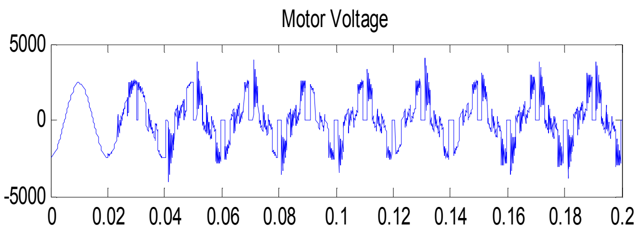

Fig. 11 Simulated motor voltage in plot window

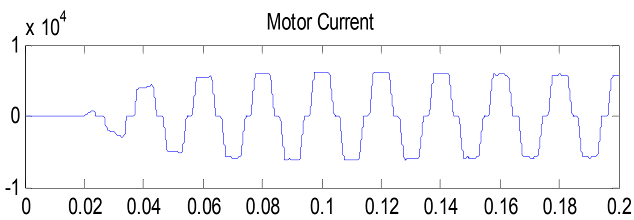

Fig. 12 Simulated motor current in plot window

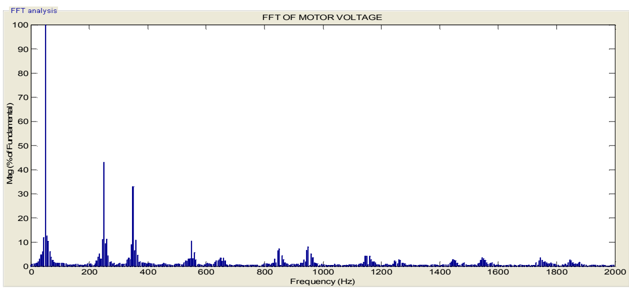

Fig. 13 FFT for simulated motor voltage

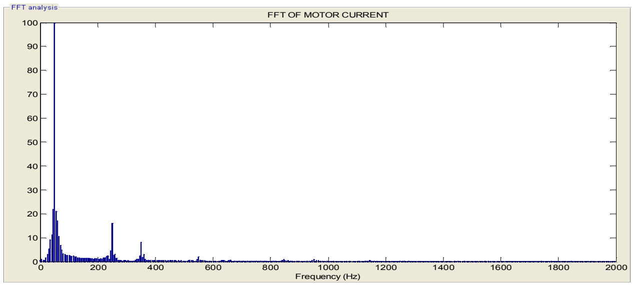

Fig. 14 FFT for simulated motor current

VI. Discussion

The simulated traces and actual waveforms of motor voltage and current are compared and found similar in nature. FFT analyses of simulated and actual waveforms are also matching. Strong presence of harmonics and switching surges are confirmed by FFT. Capacitive and inductive couplings in the complete alternator system are the results of harmonics and other high frequency signals. Winding insulation, air and lubricating oil work as dielectric medium for forming the distributed capacitance in the machine. This capacitance (also called parasitic capacitance) form between stator to ground, stator to rotor, stator to shaft, rotor to shaft, bearing to ground, cable to ground and also supply source to ground. **P**arasitic capacitance is responsible for flow of leakage current all along the stator and rotor windings which generates high frequency flux. Flux is also generated due to harmonics and switching surges. All these fluxes link with winding, core, frame, shaft, and other metallic parts and form inductive coupling. Capacitive and inductive couplings together give an additive effect for shaft voltage generation in a machine.

Shaft voltage creates electrostatic discharges to the ground in the form of small duration high current pulses and contain huge amount of energy (Fig. 15). This energy is the prime cause of bearing erosion which is commonly known as fluting or electric discharge machining (EDM).

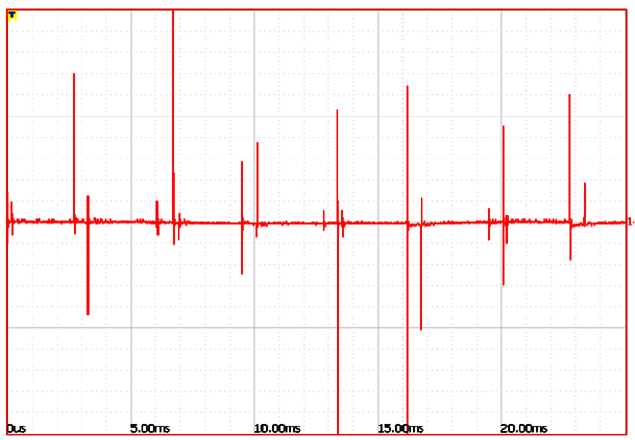

Fig. 15 Electrostatic discharges from the machine shaft

VII. Conclusion

SFC is the first choice of the designers for starting and speed control of large machines. It doesn't need additional rotating device to start and run a synchronous machine. Machine can be started softly without much loading the supply source. Other than starting, SFC can also be used for braking and reversal operation of the machine. By virtue of MATLAB/Simulink software, SFC is modeled from the actual parameters. Simulation results are validated with the waveforms drawn from the real bridge in SFC.

Like other static sources the SFC has also one negative aspect i.e. generation of shaft voltage. Reasons behind this unwanted voltage are capacitive and inductive coupling. High level of harmonics in motor voltage & current waveforms cause capacitive and inductive couplings. FFT analyses on simulated and actual measurements show that the waveforms contain high percentage of harmonics.

Flow of current due to the presence of shaft voltage can damage bearing, shaft and other nearby metal parts of any machine. Large machine requires sufficient time and money to repair the damaged part. Hence to increase the machine life shaft voltage needs to be properly minimized. Though this study is carried out on a specially designed alternator used for short circuit testing, but the findings are useful to other large machines connected with static drives.

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