# Experimental Study on Six-Phase Synchronous Alternator for Stand-Alone Renewable Energy Generation

G. K. Singh and Derminder Singh

*Abstract*—**A purely experimental analysis is presented in this paper to study the performance characteristics of a six-phase synchronous alternator coupled to a hydro turbine for stand-alone energy generation. It is depicted that the alternator is well suited to supply two independent three phase loads. Performance of the machine was observed with resistive load (i) on single winding set and (ii) on both the winding sets for constant field excitation, for constant frequency, and for constant voltage operation. Experimental results were recorded considering independent loading of two three phase stator winding sets with equal and unequal balanced resistive loads. A Fluke 43 Power Quality Analyzer was used for the measurement and recording of different waveforms.**

*Index Terms*—**Energy, hydro power generation, six-phase synchronous alternator, renewable.**

## I. INTRODUCTION

Burning of the fossil fuels causes release of green house gases in the environment. Consequently, it would lead to increase average earth's temperature in the coming years. The climatic change could adversely affect the food and water supply chain. On the other hand, increase in world population and consequently growing demand of energy has encouraged intensive research for efficient, distributed, replenishable and eco-friendly energy resources like: biomass, solar, wind, and small hydro potentials. Thus reliable, efficient and low cost generating systems are preferred to deliver   power either to grid or in remote locations, in conjunction with various types of prime mover.

In 1930's, higher phase order (phases more than three) AC alternators were used to overcome the limitation of current interrupting capacity of the circuit breakers [1]. The steady state investigation was carried out on a double winding alternator using orthogonal transformation. In this study, the effect of damper windings and mutual coupling between the two stator winding sets was not included [2]. For AC and DC power supplies, a six-phase machine is the best fit as they weigh less and are more economical. An analytical study of a six-phase salient pole generator was presented in [3] where effect of winding resistance has not been included. The same work was extended by another author by considering the effect of winding resistances [4, 5].

A mathematical model was presented with AC-DC connections, wherein the steady state performance of

six–phase synchronous machine with harmonic phasor method has been reported considering the effect of mutual coupling between the two three phase stator winding sets [6, 7]. A finite element technique using multi-loop method was presented in [8] by incorporating space harmonics and saturation effects for the study of AC-DC supply system. Very few researchers, in the past, have focused on use of multi-phase AC machine for energy generation [9-13]. In the age of decentralization of power industry, where the interest of large business houses is to provide low cost, reliable and energy efficient systems in a competitive market, the advantages of multi-phase AC machines are yet to be explored for energy generation. Singh [12, 13] presented an analysis of six-phase synchronous generator (SPSG) for stand-alone renewable energy generation in conjunction with hydro power. However, it is worth to mention here that at present, no such solution was considered by the power generation industry.

A detailed experimental analysis has been carried out in the present work to assess the performance of six-phase synchronous alternator to operate as an isolated source of energy generation powered by a hydro power. The experiments were performed on SPSG with (i) constant field excitation (ii) constant frequency (iii) constant voltage. Performance indices were observed with load on (i) one winding set (ii) both the winding sets. It is illustrated that the SPSG can operate with a single three phase winding set, so that the fault at other winding set does not lead to system shutdown. Another advantage is that with SPSG AC and DC power both can be supplied simultaneously with single machine. The comparative study indicates that SPSG is capable to deliver more power in the same frame.

## II. EXPERIMENTAL ANALYSIS

A prototype 3-phase, 5HP, 50Hz, 36 slots, 6-pole synchronous machine with all the coil ends available at the terminal box was used to carry out the investigations. The six-phase, six pole configuration was obtained by phase belt split. The six stator phase has been reconfigured to form two three phase star connected sets ('*abc*' and '*xyz*') in such a way so that the magnetic axis of two three phase stator winding sets were displaced by an angle of 30° electrical from each other. Neutrals of both the winding sets were kept isolated to prevent physical flow of fault current and triplen harmonics from one three phase winding set to other. A semi closed-loop small hydro power test rig was coupled with the six-phase synchronous machine under test, installed at Alternate Hydro Energy Centre, Indian Institute of Technology Roorkee. The detailed experimental

arrangement is given in [11]. For the measurement and recording of various test results, a Fluke power quality analyzer has been used. It is worth mentioning here that the small error in data of the experimental waveforms for the similar configuration is because of the non availability of a coordinated system to record the waveforms simultaneously.

### A. Constant field Excitation Operation

For this mode of operation, six-phase synchronous alternator was driven at rated speed with constant field excitation:

Case 1: A resistive balanced variable three phase star connected load was connected to one of the three phase stator winding sets (i.e. abc) keeping the other set open. The no load terminal voltage across 'abc' and 'xyz' winding sets were found to be 192.1 and 190.6 V. The drop in terminal voltage ($V_{an}$, single) with increase in load current is illustrated in Fig. 1. It was observed that the alternator is able to deliver a power of 2.3 kW within safe current limit. A speed drop of 8.2% and voltage regulation of 7.49 % has been observed.

Case 2: Two separate balanced variables three phase star connected resistive loads were switched on to the two stator winding sets for equal loading conditions. The voltage and speed regulation were calculated as 9.38% and 6% respectively. Under full load, power delivered by the alternator was found to be 6.4 kW. Fig.1 depicts the reduction in terminal voltage of 'abc' winding set ($V_{an}$, both). The response of the terminal voltage of the other set 'xyz' was similar to 'abc' winding set.

Case 3: Test was also carried out for a three phase, 6-pole alternator for comparative performance study. Voltage and speed regulation was found to be 15.17% and 9.8% respectively.
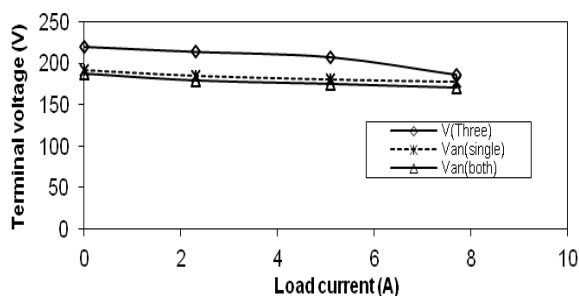


Fig. 1. Terminal voltage verses load current for various configurations of six-phase and three phase synchronous alternator.

### B. Constant Frequency Operation

In this operation, the alternator speed was kept constant by adjusting the head and discharge of input water to the hydro turbine from no load to full load. The behavior for the alternator was observed with resistive (i) balanced load on single winding set (ii) balanced load on both the winding sets and (iii) unbalanced load on both the winding sets. 7.8% and 9.5% drop in terminal voltage has been recorded for single winding and both the winding loading conditions respectively. Experiments were also conducted when both the stator winding sets of a six-phase alternator were connected to separate three phase unbalanced load for equal loading conditions (phase 'c' of 'abc' set and phase 'z' of 'xyz' set were at different resistive load where as other

phases were at the equal resistive load). Fig. 2 shows the drop in terminal voltage as 3.8% and 5.2% across phase 'a' and 'c' at a load of 2.6A and 3.8A respectively. A percentage error of 3% has been found in the measurement of frequency.
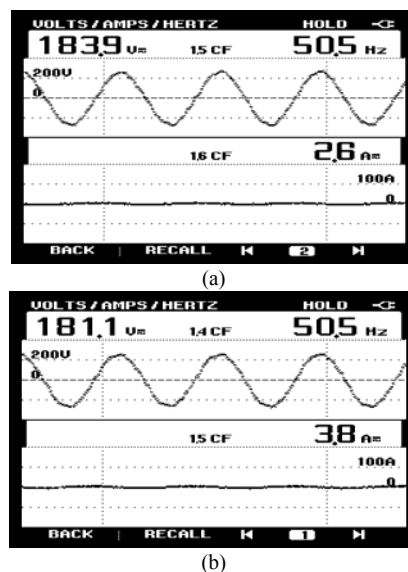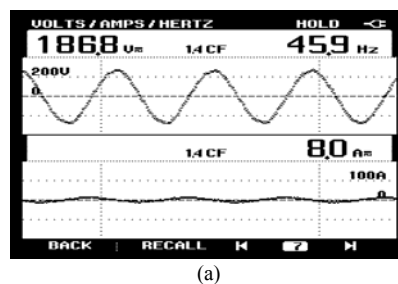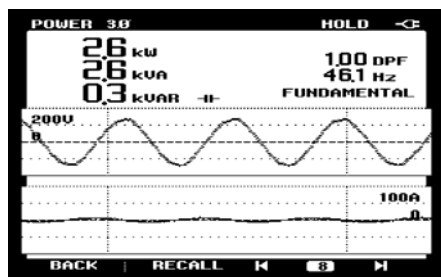


(a)



(b)

Fig. 2. Steady state waveform when both the winding sets are at unequal resistive load for constant frequency operation (a) voltage and current waveform of phase 'a' (b) voltage and current waveform of phase 'c'.

Tests were also carried out to study the performance of SPSG with mixed AC and DC stator connections. For this mode of operation, one of the stator winding sets 'abc' was connected to AC resistive load whereas the other set 'xyz' has been loaded with a resistive load through a DC rectifier. Various waveforms have been recorded (though the waveforms are shown due page limitation) at the terminals of the alternator by varying the load current. Total harmonic distortion across phase 'a' was 10.1% when the power delivered by other set was 2 kW.

### C. Constant Voltage Operation

For this purpose, synchronous alternator was driven at rated speed and the terminal voltage was kept constant from no load to full load by adjusting the field excitation current. Performance of the machine was observed with resistive load (i) on single winding set and (ii) on both the winding sets. In single winding loading conditions, the power delivered was found to be 70% (2.6 kW) of the rated power of three phase synchronous machine. The speed regulation was 8.2% at full load. When a three phase balanced load was connected to both the winding for equal conditions, the alternator was able to deliver power of 6.4 kW (173% of the rated power of three phase alternator) and speed regulation is found to be of 6%. The voltage, current and power waveforms are shown in Fig. 3a and 3b.



(a)

Fig. 3. Steady state waveform when single winding set was subjected to resistive load for constant voltage operation (a) voltage and current waveform of phase 'a' (b) power waveform of phase 'a'.

## III. COMPARATIVE PERFORMANCE

Table I and II, shows the experimental comparative performance evaluation of six-phase synchronous alternator for different configurations with pure resistive load (i) on single three phase winding set 'abc', (ii) on both the winding sets for constant field excitation and constant frequency operation. The balanced load current has been varied from no load to full load rating of the machine within the safe current limits. The result given in Tables I and II; clearly indicates that the six-phase alternator has better voltage regulation, frequency regulation when compared to its counterpart three phase alternator. It is worth to mention here that a six-phase alternator delivers high power in the same frame.

TABLE I: COMPARATIVE PERFORMANCE OF SIX-PHASE ALTERNATOR IN DIFFERENT MODES FOR CONSTANT EXCITATION OPERATION

| Configuration | Variation in Terminal Voltage ($V_{an}$) from no load to full load | Regulation at full load | |
| --- | --- | --- | --- |
| | | Voltage | Frequency |
| Six-phase configuration with one winding set at balance three phase pure resistive load (Single) | 192.1-177.7 | 7.49% | 8.2% |
| Six-phase configuration both winding sets at balance three phase pure resistive load (Both) | 187.5-169.9 | 9.38% | 6.0% |
| Three phase configuration at balanced three phase pure resistive load (Three) | 220.1-186.7 | 15.17% | 9.8% |

TABLE II: COMPARATIVE PERFORMANCE OF SIX-PHASE ALTERNATOR IN DIFFERENT MODES FOR CONSTANT FREQUENCY OPERATION

| Configuration | Variation in Terminal Voltage ($V_{an}$) from no load to full load | Voltage Regulation at full load | Output power (KW) |
| --- | --- | --- | --- |
| Six-phase configuration with one winding set at balance three phase pure resistive load (Single) | 192-177 | 7.80% | 2.3 |
| Six-phase configuration both winding sets at balance three phase pure resistive load (Both) | 188-170 | 9.5% | 4.4 |
| Three phase configuration at balanced three phase pure resistive load (Three) | 220.1-187 | 15.% | 2.6 |

## IV. CONCLUSIONS

The experimental result presented in the paper illustrates the utility of six-phase synchronous alternator for energy generation in various modes of operation. The main focus is placed to explore the possibility of supplying two separate three phase loads, which has the added advantage that the fault on one of the two stator winding sets does not lead to complete shutdown, as long as the other sets is healthy. Hence six-phase alternator provides higher reliability and may be used to feed to independent loads. It is worth to mention here that there is an interaction between the two sets as the load on one set changes the working conditions of the other set.

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