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CLOSED LOOP VOLTAGE CONTROL OF BRUSHLESS DC GENERATOR FOR VEHICLE APPLICATION

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ABSTRACT

Brushless DC generator (BLDCG) is one of the most popular machines in variable speed drives. That is due to its numerous advantages which are high efficiency and power density, light weight, compact design and low maintenance. The most common applications, in which BLDCG has been employed, are wind energy and transportation systems. These applications have a main drawback that they are featured by large speed fluctuations accomplished by wind turbines and internal consumption engines. This speed variation results in changes in the BLDCG output voltage. This paper aims to maintain the generator output voltage at a constant level with variation of both load and prime mover speed. This is achieved using a simple closed loop control system including a variable reactor. This study belongs to vehicle application, since it is recommended to replace the brushed claw pole synchronous generator by BLDCG. Throughout the present work, the mathematical model, along with a matlab/simulink program, have been developed and implemented for BLDCG system to predict its operating characteristics. An experimental setup has been built and tested for the sake of comparison. Good agreement between the theoretical and experimental results is obtained. This confirms the validity of the theoretical analysis. Moreover, good performance of the BLDCG with the proposed simple control method is obtainable.

أصبح مولد التيار المستمرعديم الفرش مرشحا جيدا لكثير من التطبيقات التى تتميز بتغير السرعة. ويرجع ذلك لمزاياه العديدة التى جعلته مناسبا لمثل هذه التطبيقات. من هذه المزايا ارتفاع الكفاءة وكثافة الطاقة به ، خفة وزنه وقلة حاجته للصيانة. وتعتبر أنظمة طاقة الرياح و أنظمة النقل من أكثر التطبيقات المرشح فيها إستخدام مولد، التيار المستمرعديم الفرش. وتكمن المشكلة الأساسية فى أن هذه التطبيقات تتسم بتغيرات كبيرة فى سرعة توربينات الرياح و محركات الإحتراق الداخلى، وهذا يؤدى إلى حدوث تغير فى قيمة الجهد المتولد من المولد. ويهدف هذا البحث الى تثبيت هذا الجهد مع تغير السرعة و الحمل باستخدام نظام تحكم مغلق بسيط يشتمل على ممانعة حثية متغيرة. ويرشح استخدام هذا العمل فى السيارات حيث من المقترح استبدال المولد التزامنى الفرشى ذو الأقطاب المخلبية بمولد التيار المستمرعديم الفرش. فقد تم إعداد النموذج الرياضى وبناء عليه نظام المحاكاة الذى يمثل المولد بإستخدام Matlab/Simulink و حساب خواص تشغيل المولد. وتم أيضا إنشاء منظومة إختبار معملية للتحقق من النتائج النظرية. و بمقارنة كل من النتائج النظرية و المعملية تأكدت صلاحية النموذج الرياضى و تأكد أيضا الأداء الجيد لمولد التيار المستمرعديم الفرش مع وسيلة التحكم المقترحة.

Keywords: *Brushless DC Generator* **(***BLDCG*), *Variable reactor, Variable Speed Generator, Wind Energy Generators*.

1. INTRODUCTION

Due to the main drawback of brushed DC machine, which is represented in brushes and commutator segments, the idea of brushless DC machine had started earlier and is still in progress. With the availability of permanent magnet materials and reliable power electronic devices, the full realization of brushless machine became possible in the early of 1980. [1]

Recently, much research work has been paid for brushless DC generator (BLDCG) to exploit its numerous advantages. BLDCG consists of a stator with laminated steel to reduce the eddy current loss and a rotor provided with permanent magnets. Due to the permanent magnets, field windings with attached brushes and commutator segments are not required. As a result, low maintenance and high efficiency are obtained. These advantages make BLDCG the best choice for many applications such as wind energy and transportation systems. These applications are characterized by large speed fluctuations accompanied by wind turbines and internal consumption engines. This leads to large changes in BLDCG output voltage. Some attempts have been reported in literature to overcome this problem [2-11].

A digital control technique for controlling the output voltage of BLDCG against shaft speed variation using three phase controlled bridge has been proposed [2-4]. The switching signals of the bridge devices are established using a digital controller called Field Programmable Gate Array (FPGA). The control technique was implemented using two power electronic control algorithms: hysteresis current control and pulse width modulation (PWM) control. The control concept of both two techniques is based on comparing the actual speed of the prime mover with a reference speed value.

A single stage step up/down AC/DC converter for small wind power BLDC generator has been presented [5]. This converter consists of a three phase diode bridge rectifier and a C'uk converter. C'uk converter steps up and down the output dc voltage to cope with wind speed variation. However, this converter regulates the load voltage over low speed range.

The brushless DC machine is used as an integrated starter–generator–torque-booster (ISGTB) for hybrid electric vehicles [6-8]. It is operated in three modes of operation. Switch mode power converter, which consists of six-pulse inverter and bi-directional buck–boost converter, has supported all operating modes of ISGTB using intelligent control software. In generation mode, the amplitude of the induced EMF is proportional to the speed of internal consumption engine which varies in large rate. This could be overcome by synchronizing the switching signals of the inverter switches with the generator voltage and DC link voltage.

In [9], a predictive control of BLDCG coupled with wind turbine system has been proposed through a theoretical study. This method of control is applied to three phase controlled bridge to obtain a constant value of dc output voltage for connecting with DC grid. This was achieved using a certain control algorithm based on minimization of joule losses and torque ripples.

Variable-speed constant-frequency (VSCF) power converter has been described [10]. This converter consists of a three phase diode bridge rectifier and a three phase thyristor controlled inverter. The output voltage of the BLDCG is rectified by the diode bridge then converted to three phase AC voltage with fixed value and frequency for connecting with the AC grid using the inverter. This was achieved by comparing the actual DC link current, which varies with the prime mover speed, with a reference value of the current then the difference determines the firing angle of the thyristors.

A BLDC machine has been used as a motor and a generator in a light motorcycle powered by fuel cell energy [11]. A typical BLDC motor drive system consists of a BLDC machine, a power inverter and a digital controller. The machine works as a generator during regenerative braking. In this mode of operation, the DC link voltage decreases because of speed slowing down. As a result, boost converter is used to obtain a constant DC link voltage.

The previous attempts to overcome the BLDCG problem are complicated and costly. This paper presents a simple control method to obtain a fixed output DC voltage, from BLDCG, with load and prime mover speed variations.

In this paper a mathematical model for BLDCG with the proposed control method is developed and implemented in a simulation program to predict the machine performance at different operating conditions. An experimental setup is established for the system to check the simulation results. A comparison between the simulation and experimental results is performed and evaluated. The results illustrate the good performance characteristics of BLDCG with the proposed control method.

2. SYSTEM DESCRIBTION

This paper suggests adding a variable reactor in series with each generator phase terminal to keep the output voltage constant at a desired value by its voltage drop which changes with the speed and load variation. The variable reactor used throughout this work is the magnetic amplifier (MA) [12-14] which is a type of magnetically controlled reactors. It consists of two windings on the outer two limbs of a three limb iron core, connected in series with the generator terminals. Auxiliary winding on the middle limb is connected to a controlled DC supply. the current through the auxiliary winding controls the saturation level of the outer limbs iron core. Hence, the inductance of the outer windings is controlled. The controlled current is obtained from the feedback control circuit of the generator output voltage.

Fig.1 shows a schematic diagram of BLDCG closed loop control system, in which, the main windings of magnetic amplifiers are connected in series with the generator terminals. A three phase diode bridge is connected to the generator terminals after the magnetic amplifiers for rectifying the AC voltage. A signal of load voltage is compared with the reference voltage then the error is fed to PI voltage controller as shown in the simple block diagram of Fig.2. The proportional and integral gains of PI controller have been adjusted until suitable values are obtained. The output of PI controller is compared with a saw tooth voltage to determine the duty ratio of the gating signal using PWM technique. This gating signal is transmitted via DSP board, on line, to trigger the main switch of buck converter (IGBT). As a result, the DC current of MA auxiliary winding is controlled resulting in controlling the reactor voltage drop to cope with the speed and load variation. Hence the constant output voltage is obtained. All the closed loop control process has been implemented in real time using DSP controller board (dSPACE1104).

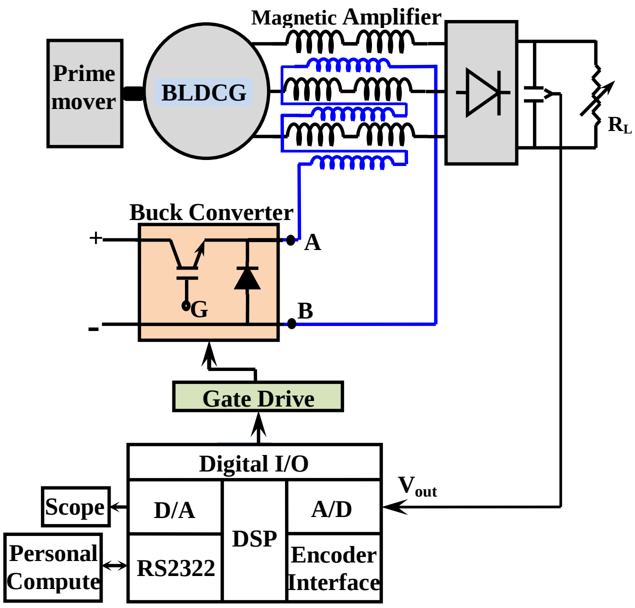

Fig.1 A schematic diagram of BLDCG closed loop control system

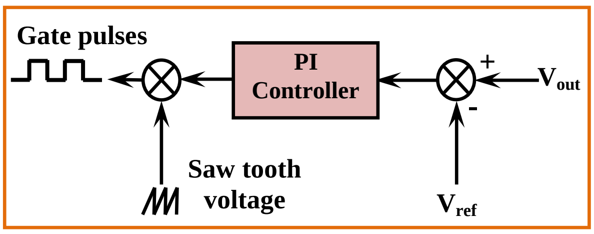

Fig.2 A simple block diagram of control circuit

3. MATHEMATICAL MODEL

The dynamic model of BLDCG is derived according to its equivalent circuit represented by Fig (3). The BLDCG under investigation is a surface mounted permanent magnet type, consequently the air gap is approximately uniform. Thus the variation of self and mutual inductances with rotor angular position can be neglected. Accordingly, the voltage equations are expressed as a set of differential equations [5] as follows:

$$e_a = Ri_a + (L_{aa} + L_{add})\frac{di_a}{dt} + L_{ab}\frac{di_b}{dt} + L_{ac}\frac{di_c}{dt} + v_a \quad (1)$$

$$e_b = Ri_b + (L_{bb} + L_{add})\frac{di_b}{dt} + L_{ba}\frac{di_a}{dt} + L_{bc}\frac{di_c}{dt} + v_b \quad (2)$$

$$e_c = Ri_c + (L_{cc} + L_{add})\frac{di_c}{dt} + L_{ca}\frac{di_a}{dt} + L_{cb}\frac{di_b}{dt} + v_c \quad (3)$$

Where:

e_a, e_b, e_c: Instantaneous stator phases EMF

i_a, i_b, i_c: Instantaneous stator phases current

v_a, v_b, v_c: Instantaneous phases terminal voltage at the bridge input

R : Stator phase winding resistance (0.55 ohm)

$L_{aa}=L_{bb}=L_{cc}=L$: Stator phase winding self inductance =0.0047 H

$L_{ab}=L_{ba}=L_{bc}=L_{cb}=L_{ac}=L_{ca}=L_m$: Mutual inductance

L_{add} : Added reactor inductance (varies automatically with the load and speed variation)

Based on the symmetrical three phase windings of the stator, the mutual voltages cancel each other. As a result, the BLDCG voltage equations become:

$$e_a = Ri_a + (L + L_{add})\frac{di_a}{dt} + v_a \quad (4)$$

$$e_b = Ri_b + (L + L_{add})\frac{di_b}{dt} + v_b \quad (5)$$

$$e_c = Ri_c + (L + L_{add})\frac{di_c}{dt} + v_c \quad (6)$$

Figure(4) shows the typical waveforms of the phases EMF`s (e_a, e_b & e_c) . Each of the phase EMF has a maximum value (e_{max}) which is described as:

$$e_{max} = K_e\omega \quad (7)$$

Where:

K_e: the machine EMF constant incorporating the permanent magnet flux linkage

ω: the electrical frequency

From Fig.4, the induced EMF can be written as a function of time. The EMF of phase (a) is as follows:

$$e_a = \frac{6}{\pi}\left(\omega t - \frac{\pi}{6}\right)e_{max} \quad \text{for } 0 \le \omega t \le \pi/3 \quad (8)$$

$$e_a = e_{max} \quad \text{for } \pi/3 \le \omega t \le \pi \quad (9)$$

$$e_a = -\frac{6}{\pi}\left(\omega t - \frac{7\pi}{6}\right)e_{max} \quad \text{for } \pi \le \omega t \le 4\pi/3 \quad (10)$$

$$e_a = -e_{max} \quad \text{for } 4\pi/3 \le \omega t \le 2\pi \quad (11)$$

While for phases (b) and (c), the EMF is the same as of the phase (a) but a function of $\left(\omega t - \frac{2\pi}{3}\right)$ and $\left(\omega t + \frac{2\pi}{3}\right)$ respectively.

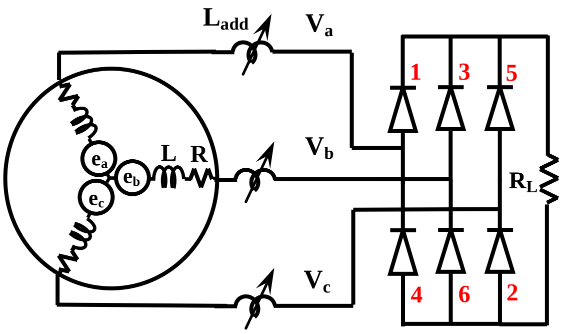

Fig.3 Equivalent circuit for BLDCG system

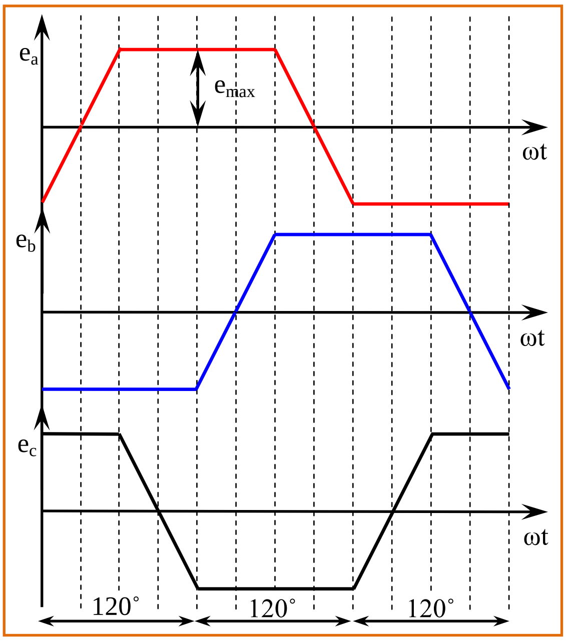

Fig.4 Typical waveforms of the generated EMF of BLDCG

4. SIMULATION RESULTS AND DISCUSSION

A simulation program has been built, in Matlab/Simulink environment, based on the previous mathematical model and implemented to study the operating characteristics of BLDCG. The simulation results are divided into two groups. The first group is predicted at constant load resistance (R_L) with speed variation. While the second group is calculated at constant speed with load variation. As stated before in section 1, the BLDCG studied throughout this work, is recommended to be an alternative to the claw pole synchronous generator in vehicles. The generator in vehicle is used to charge a battery of 12V, therefore the suitable voltage for charging is 14V. As a result, the generator characteristics are studied for load voltage of 14V weather with the load or speed variation.

The first group of results includes the speed, load voltage, reactor voltage and generator voltage during step change of speed reference as shown in Figs (5-8) respectively. These curves are taken at constant load resistance (R_L=6.8Ω). Fig.5 shows the step variation of speed at levels (588, 833, 1160 and 1500) rpm. The constant load voltage (14V), during this speed variation is obtained as shown in Fig.6. This is achieved by controlling the reactor voltage to vary in proportional to the speed variation as illustrated by Fig 7. This is occurred in spite of the proportional variation of the generator voltage with speed as evident in Fig 8.

The second group of the results is recorded at constant speed of 1000 rpm during the load variation. In spite of reducing the load current gradually as shown in Fig.9, the load voltage is maintained constant at the desired value (14V) as illustrated in Fig 10. It is noticed from Figs(11&12) that the load current has low influence on both of the reactor and generator voltage respectively. Where reducing the load current results in decreasing the line current which, in turn, increases the reactor inductance and the reactor voltage seems to be constant as shown in Fig.11. Also, the generator voltage is almost constant as evident by Fig.12 because of the constant speed.

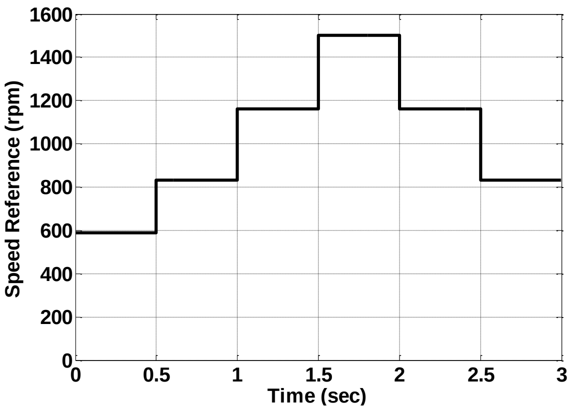

Fig.5 Step variation of speed reference at R_L=6.8Ω

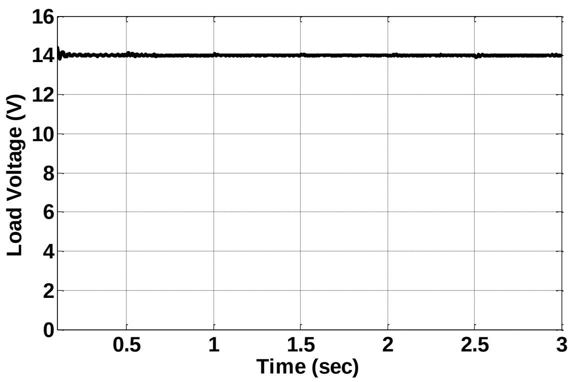

Fig.6 Load voltage at R_L=6.8Ω

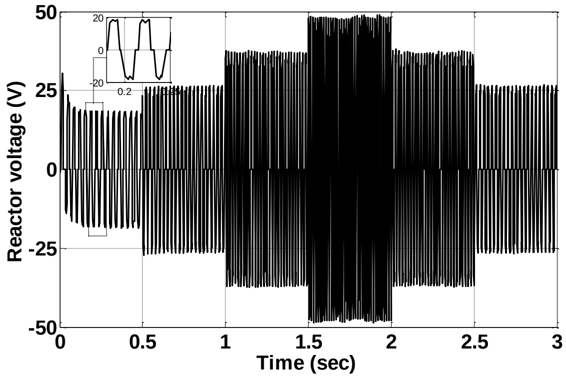

Fig.7 Reactor voltage at R_L=6.8Ω

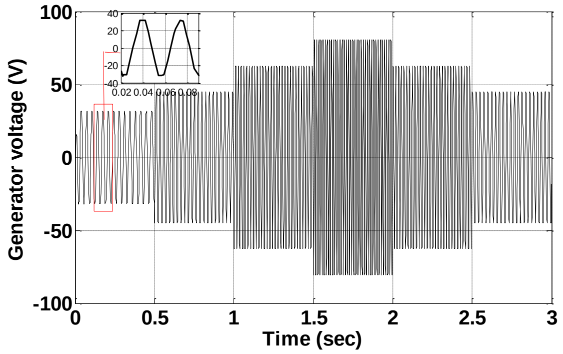

Fig.8 Line to line generator voltage at R_L=6.8Ω

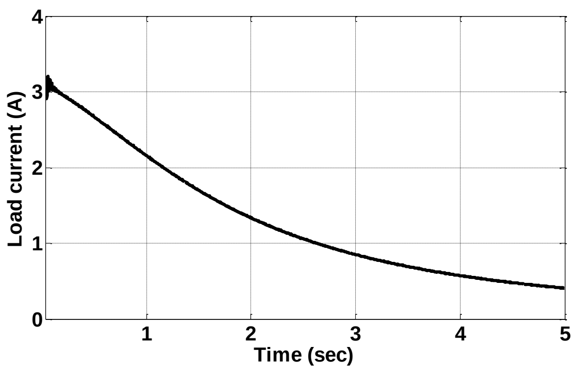

Fig.9 Variation of load current at speed=1000rpm

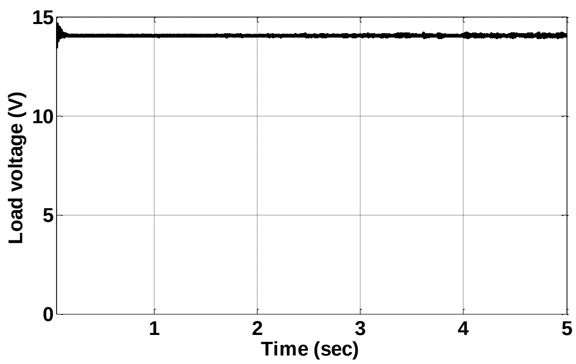

Fig.10 Load voltage during load changes

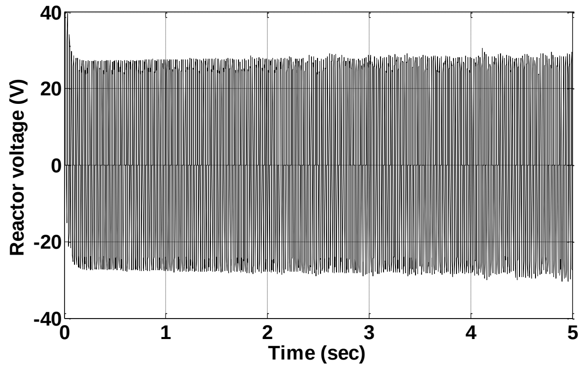

Fig.11 Reactor voltage during load changes

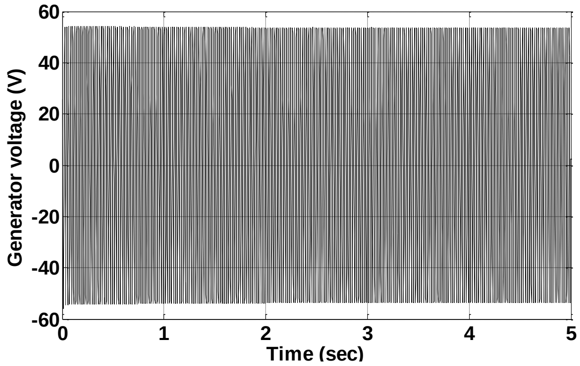

Fig.12 Generator voltage during load changes

5. EXPERIMENTAL RESULTS

The experimental setup has been established for BLDCG closed loop control system, shown in Fig.13, to verify the simulation results. Most of the system components are labeled and listed in table 1. The setup consists of the generator under test (BLDCG) of rating (0.185kw, 10.8A, 14V, 3900rpm), an induction motor of rating (1hp, 380V, 1425rpm) as a prime mover, three magnetic amplifiers (MA) each of which is connected in series with each of the generator phase winding and a tacho generator (TG) for detecting the generator speed as shown in Fig.14. The setup also comprises the buck converter illustrated by Fig.15, which is mainly consists of an Isolated Gate Bipolar Transistor (IGBT) [type: CM50DY-24H]. The output voltage of the converter is filtered out by a capacitor bank filter consisting of four parallel capacitors (each of 470μF, 400V). A fast recovery diode of type (TO-247AD) is connected in parallel across the MA auxiliary winding to recover the load stored energy while IGBT is switched off. The main components of buck converter are labeled and listed in table 2. All the closed loop control process has been implemented in real time using DSP controller board (dSPACE1104) along with its attachments which has the labels (I, H, PC).The experimental results are recorded at the reference voltage 14V and presented as follows:

Table 1

Label	Component
I	DSP Interface circuit
H	Voltage and current transducers
PC	Personal computer
P	AC power supply
G	Gate Drive Circuit
C	Digital inverter
R	Variable resistive load
B	Buck Converter

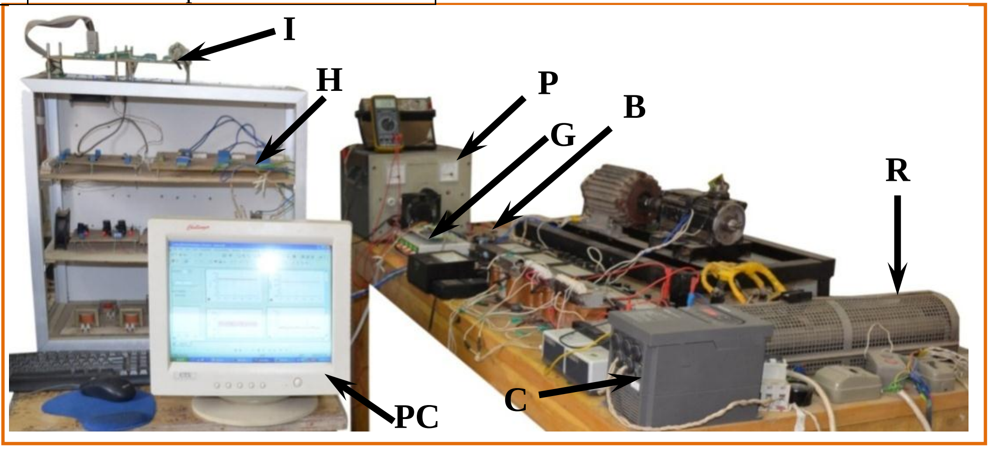

Fig.13 A photo picture of BLDCG closed loop system

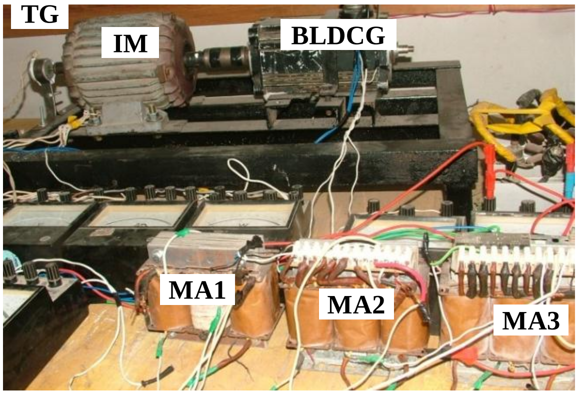

Fig.14 Main parts of BLDCG experimental setup

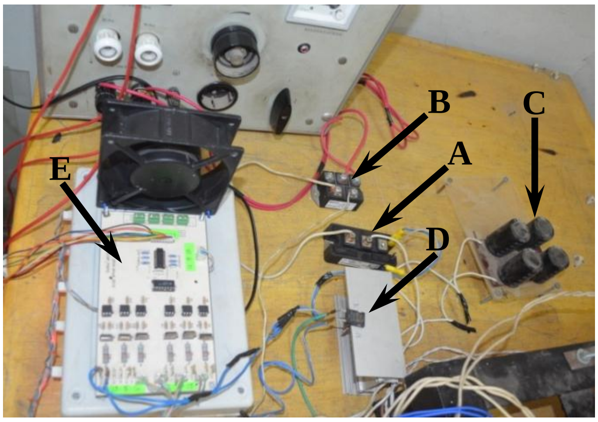

Fig.15 Buck converter along with gate drive circuit

Table 2

Label	Component
A	IGBT (50A)
B	Bridge Rectifier
C	Capacitor
D	Fast Recovery Diode
E	Gate Drive Circuit

As in the simulation results, the load, reactor and generator voltages are recorded during the step change of speed reference at constant load resistance (R_L=6.8Ω). The step change of speed reference is performed at levels (588, 833, 1160 and 1500) rpm as in the simulation results as shown in Fig.16. The desired load voltage (14V), during that speed variation is obtained as in Fig.17. This constant voltage is obtained by changing the reactor inductance with speed variation through the variation of magnetic amplifier controlled current. This is achieved automatically through the closed loop control system explained previously. As a result, the reactor voltage is varied by the manner shown in Fig.18. Figure(19) illustrates the variation of line to line generator voltage during the speed step variation.

When the speed is maintained constant at 1000 rpm and the load resistance is changed, the load current decreases gradually as shown in Fig.20. While the load voltage is constant at the reference value (14V) as illustrated in Fig.21. This is due to the reactor voltage variation demonstrated in Fig.22.

It is observed that the shapes of these figures, obtained experimentally, are close to the relevant shapes of the previous simulation. This confirms the validity of the proposed simulation.

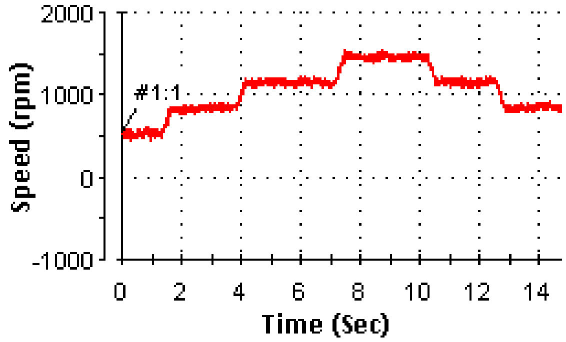

Fig.16 Step variation of speed reference at constant load resistance

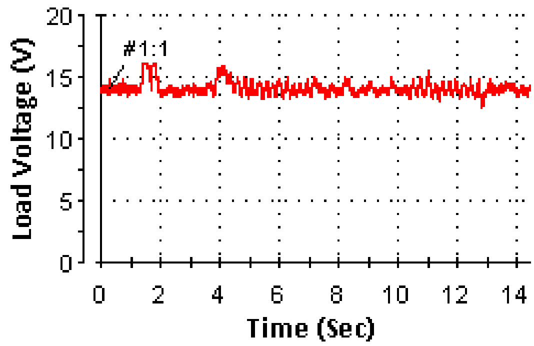

Fig.17 Load voltage at constant load resistance

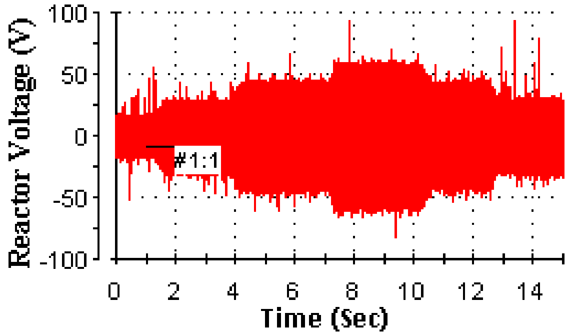

Fig.18 Reactor voltage at constant load resistance

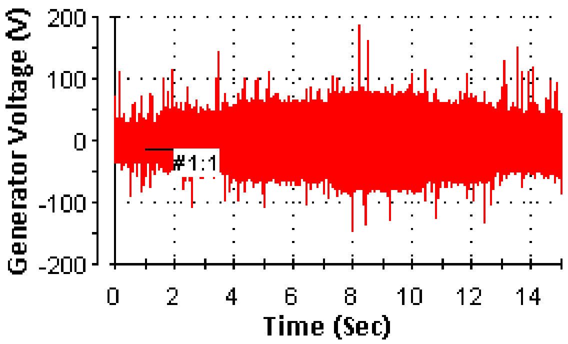

Fig.19 Line to line generator voltage at constant load resistance

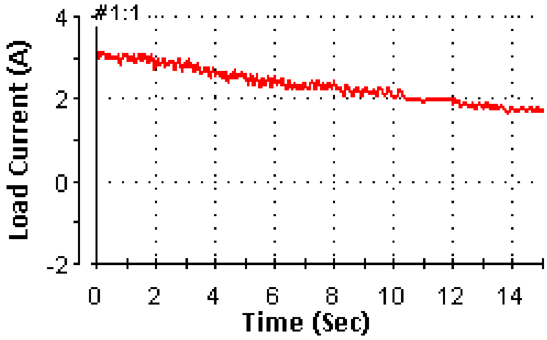

Fig.20 Variation of load current due to load changes

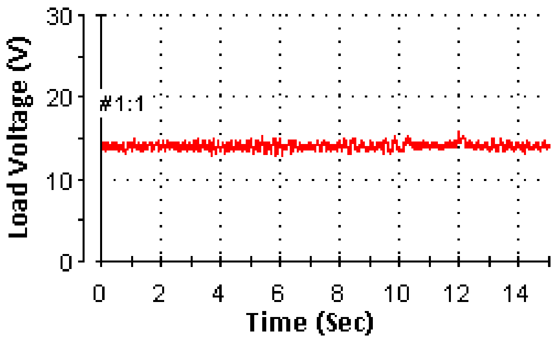

Fig.21 Load voltage during load changes

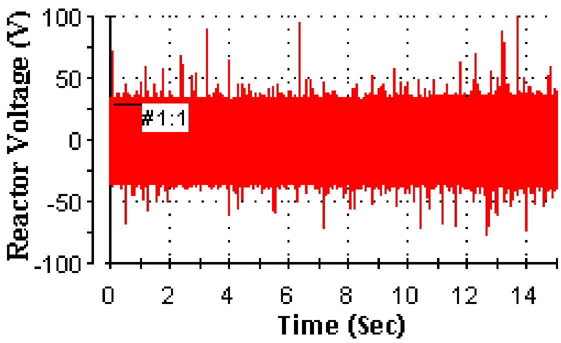

Fig.22 Reactor voltage during load changes

6. CONCLUSION

A BLDC generator has been proposed as an alternative to the claw pole synchronous generator in vehicles. A variable reactor is connected in series with each generator phase winding for suppressing the variation of output voltage with load and prime mover speed variations. This is achieved, automatically, by controlling the reactor voltage drop throughout a closed loop control system via a PI voltage controller. All the closed loop control process is implemented in real time using a DSP of type dSPACE1104. Good agreement is obtained by comparing the theoretical and experimental results. This emphasizes the validity of theoretical analysis.

With the proposed control system a constant value of load voltage is obtained in spite of the variation of either the load or the speed.

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