Improved Characteristic of Load Current of Cascaded-Flux Compression Generator

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Abstract— **One of the main problem of Cascaded-Helical Magnetic Flux Compression Generators (Cascaded-HFCG) is the returned energy from second stage winding to first stage winding after starting of second stage operation. Since there is no electrical connection between first stage winding and the load of the generator, so a great part of energy doesn't reach to the load and losts. This energy loss cause to decrease in generator efficiency and has a great impact on output characteristic of the generator. In this paper, an approach is proposed to minimize returned energy and to improve the output characteristic of a Cascaded-HFCG. The approach is based on time-varying primary winding of dynamic transformer and addition of a gradually incremental resistance in series with the first stage winding. In order to verificate the ability of the proposed approach, a computer code is programed based on a simple model of the generator and a Cascaded-HFCG is simulated for two cases: first case for the conventional generator and the other for the proposed approach. It is demonstrated that for the proposed approach, the output current has a greater value, consequently the current gain of the generator becomes better. The comparison between output currents for two cases shows that the rise-time of output current becomes smaller for the case of proposed approach.**

Index Terms— **helical magnetic flux compression generator; load characteristic; explosive charge; dynamic transformer; incremental resistance.**

I. Introduction

HELICAL magnetic flux compression generators (HFCG) are widely used to produce very high current pulses in the recent past decades. These generators convert chemical energy of explosive charge into magnetic energy in the form of current pulses. They are used in a variety applications like nuclear research, X-Ray source, high power microwave, high power laser, rail gun and so on [1-4]. Some applications of HFCGs require shorter pulse width (shorter rise time), higher voltage, higher current, higher energy gain and higher instantaneous power delivered to load [5-7]. Several approaches have been proposed in literatures to achieve these requirements. For example, increasing the axial length of winding increases current gain and energy gain of the generator but cause to wider pulse width [8]. Another approach to get the higher current and energy gain is to increase the diameter of armature which cause to increase of cost and explosive pressure [8]. As mentioned, many application require a rise-time of output current pulses in the range of one microsecond or less. In order to achieve shorter pulse width (less rise-time of pulse), in 1979 between more ideas and opinions, Chernyshev proposed dynamic transformer and its combination with Cascaded generator [9]. A Cascaded generator consists of two or more FCGs connected in-series with air transformer or dynamic transformer, where each FCG is the load of the previous generator. A schematic of Cascaded-HFCG is shown in Fig.1. It is composed of two conventional HFCG that coupled magnetically using dynamic transformer.

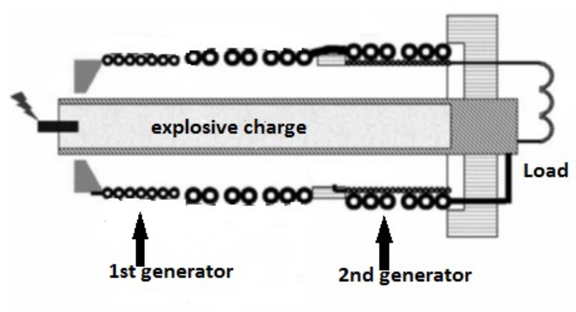

Fig. 1. Schematic of Cascaded Helical Magnetic Flux Compression

The electrical equivalent circuit of Cascaded-HFCG after starting the explosion is shown in Fig.2.

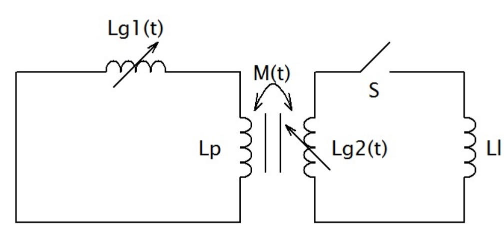

Fig. 2. Electrical Circuit of Cascaded-HFCG

In this circuit, $L_{g1}(t)$ is winding of first stage, L_P is primary winding of dynamic transformer, $L_{g2}(t)$ is winding of second stage (secondary of dynamic transformer) and L_l is load inductance. A seeding system (usually a capacitor bank) introduces an initial magnetic flux into generator by injecting current directly into first stage winding. When the explosion

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starts, the armature is expanded and the injected flux is compressed. During the operation of first stage, no current passes through second stage and load, so ohmic losses of second stage and load become zero and generator efficiency increases. At the end of first stage operation, switch S is closed and magnetic flux is trapped by $L_{g2}(t)$ using dynamic transformer.At the same time, load current appears and increases rapidly to form a current pulse. The rise-time of load current is smaller than first stage current due to less axial length of $L_{g2}(t)$ compared to $L_{g1}(t)$.

In this paper some problems of the Cascaded-HFCG are described and an approach is proposed to improve the output characteristic of the generator. This paper is organized as follows: it will be briefly reviewed a main problem of Cascaded-HFCG in section 2. In section 3 a new approach is proposed to overcome the described problem of Cascaded-HFCG in section 2 using theoritical analysis. In section 4 validation of the proposed approach is examined using simulation results and some conclusions will be described in the last section.

II. DESCRIPTION OF THE PROBLEMS OF CASCADED-HFCG

Actually, a Cascaded-HFCG is composed of two conventional HFCGs which connected in series and coupled magnetically, so it is expected that its efficiency be a number close to the product of efficiency of each individual HFCG. But experimental results show that efficiency of Cascaded-HFCG is about 30% less than the expected value [8]. One of the reasons of this less efficiency is magnetic flux losses at the moment of flux trapping by second stage (this moment is named crowbar time). High enough mutual inductance between dynamic transformer windings can decrease flux losses and consequently increase the generator efficiency. There are many factors to maximize mutual inductance between two windings such as: turns number of windings, pitch of winding, axial length of windings and so on [10]. Although, high mutual inductance decreases magnetic flux losses, but it can cause to increase transferred energy between two windings. As we know, in Cascaded-HFCGs, after starting second stage operation, the first stage current is still ongoing. Given that two stages are magnetically coupled through dynamic transformer, so a part of energy returned back to first stage. Since there is no electrical connection between load and first stage winding, so the returned back energy leads to increase in current of first stage winding instead of reaching to load.

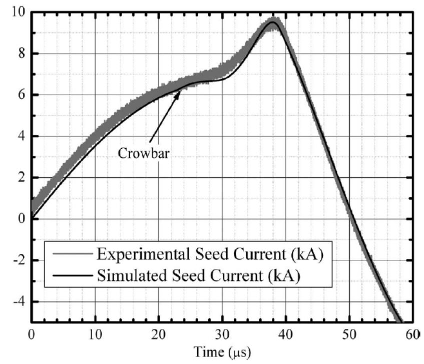

Fig. 3. Filed winding current of flux trapping HFCG from [11]

In [11], a flux-trapping HFCG is considered, which is structurally similar to Cascaded-HFCGs. Simulation and experimental results show that after starting operation, once the currents begin to diverge, mutual inductance between the main winding (which is similar to second-stage winding in Cascaded-HFCG) and field winding (which is similar to first-stage winding in Cascaded-HFCG) is high enough for a great amount of energy to return to the field-winding circuit. The returned energy causes an increase in the current of field winding more than usual (see Fig.3). As we can see, after starting of generator operation, the current of field winding increases simultaneously with the current of main winding due to the returned backed energy.

It should be noted that in the described flux-trapping HFCG, the field winding only covers the first 50% of the main winding, which helps to decrease the coupling between the two windings before an appreciable amount of energy is transferred to the field-winding circuit. In [12], a Cascaded-HFCG is considered, in which primary winding of the dynamic transformer covers 100% of the second-stage winding. Simulation results show that due to the high amount of energy returned to the first-stage winding, its current increases irrationally (Fig. 4).

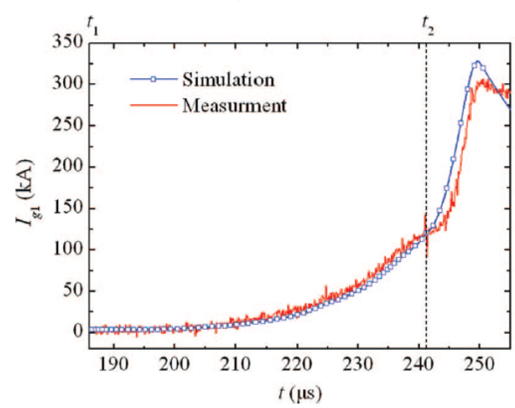

Fig. 4. First stage current of Cascaded-HFCG from [12]

III. THEORITICAL ANALYSIS OF CASCADED-HFCG

It can be concluded from the previous section discussion that one of the main issue about less efficiency of Cascaded-HFCG is increasing of first stage current more than common value after crowbar instance and increasing of ohmic losses. In order to minimize the returned energy to first stage, mutual inductance between two windings of dynamic transformer should tend to a very small value after starting the second stage operation. In conventional Cascaded-HFCG, two windings of dynamic transformer don't essentially decoupled during generator run time. If each turns of primary winding of dynamic transformer wipes out simultaneously with turns of second stage winding and armature expansion, so two windings can decoupled more quickly and returned energy decreases in significant amount. Actually the primary winding of dynamic transformer should have time-varying behavior like as the other windings of generator ($L_P \to 0$). Since in the case of time-varying L_P, the self-inductance of first stage winding reaches to zero at the end of generator operation (at the conventional Cascaded-HFCG the self-inductance of L_P gets a non-zero value) so the maximum value of the current of first stage winding increases too. To prevent the unusual increasing in the first stage current, a gradually incremental resistance should be introduced in-series with L_P. Added resistance restricts the maximum value of first stage current which this causes to increase load current.

The advantage of added resistance explained analytically in the following. According to the proposed model in [12], operation of Cascaded-HFCG can be divided in two distinct phases. Corresponding equivalent electrical circuit of generator is shown in Fig.2. The first phase of operation begins by starting explosion. The Kirchhoff's voltage equation for the loop containing first stage winding can be written as:

$$[L_{g1}(t)+L_p]\frac{dI_{g1}(t)}{dt} + [R_{g1}(t)+\alpha_1\frac{d(L_{g1}(t)+L_p)}{dt}]I_{g1}(t)=0 \quad (1)$$

In this equation α_1 is flux conservation coefficient accounting for intrinsic flux losses of first stage. Second phase begins after closure of switch S and lasts until the end of generator operation. The Kirchhoff's voltage equation for the each loop results these equations:

$$[L_{g1}(t)+L_p]\frac{dI_{g1}(t)}{dt}+[R_{g1}(t)+\alpha_1\frac{d(L_{g1}(t)+L_p)}{dt}]I_{g1}(t) + M(t)\frac{dI_{g2}(t)}{dt}+I_{g2}(t)\frac{dM(t)}{dt}=0 \quad (2a)$$

$$[L_{g2}(t)+L_l]\frac{dI_{g2}(t)}{dt}+[R_{g2}(t)+R_l+\alpha_2\frac{dL_{g2}(t)}{dt}]I_{g2}(t) + M(t)\frac{dI_{g1}(t)}{dt}+I_{g1}(t)\frac{dM(t)}{dt}=0 \quad (2b)$$

In equation (2b), α_2 is flux conservation coefficient accounting for intrinsic flux losses of second stage. Let rearrange the equation (2b) as:

$$[L_{g2}(t)+L_l]\frac{dI_{g2}(t)}{dt}+[R_{g2}(t)+R_l+\alpha_2\frac{dL_{g2}(t)}{dt}]I_{g2}(t) = -M(t)\frac{dI_{g1}(t)}{dt}-I_{g1}(t)\frac{dM(t)}{dt} \quad (3)$$

In (3), $I_{g1}(t)$ has positive sign and dM(t)/dt is negative during the generator operation, so, $-I_{g1}(t)(dM(t)/dt)$ (for convenience is shown as term A) is a positive quantity for all the time of generator operation. In return, $-M(t)(dI_{g1}(t)/dt)$ (is shown as term B) can be considered in two cases as follow:

a) In conventional Cascaded-HFCG (with no added series resistance), $I_{g1}(t)$ increases during all the time of generator operation, so $dI_{g1}(t)/dt$ has positive sign. On the other hand M(t) is positive too, so sign of term B becomes negative. At this condition, the right side of equation (3) is equal to A-B.

b) Adding resistance in series with L_P cause to current becomes descending and $dI_{g1}(t)/dt$ gets negative sign in this case, so the sign of term B becomes positive and the right side of equation (3) be equal to A+B.

It is obvious that for the case (b), the right term of (3) has a greater value than the case (a), so load current becomes greater.

Another advantage of added incremental resistance is decreasing in rise-time of load current. ohmic resistance of load and second stage can be negligible, so (3) can be written as:

$$\frac{dI_{g2}(t)}{dt} = \frac{-M(t)\frac{dI_{g1}(t)}{dt}-I_{g1}(t)\frac{dM(t)}{dt}-I_{g2}(t)\frac{dL_{g2}(t)}{dt}}{L_{g2}(t)+L_l} \quad (4)$$

With the same analysis before, If dIg1(t)/dt be a negative quantity then the numerator of (4) becomes larger and this means smaller rise-time of current.

IV. Simulation Results and Discussion

In order to validate the above performed analysis, a computer code is programmed based on the model demonstrated in equation (2) and electrical equivalent circuit of Fig.2. Self-inductance and mutual inductance profiles of the modeled generator have been calculated using formulas described in [13]. A brief description of Cascaded-HFCG which is modeled is necessary here. The first stage winding is a single-pitch winding composed of 42 turns and has 300mm length. Primary winding of dynamic transformer has 4 turns and 120mm length. The inner diameter of first stage winding is 115mm and aluminum armature placed inside winding has an outer diameter of 50mm. armature wall thickness is 3.8mm. The second stage winding has 30 turns and 120mm length which located under first stage winding and ends at the same location as the ending of primary winding of dynamic transformer. The initial current of first stage winding is supplied by a 6μF energy storage capacitor charged about 20KV. The load inductance is 25nH. Detonation velocity is 6400m/s. the practical construction of the modeled Cascaded-HFCG has been done by Chen in [9].

Figure 5 shows the simulation results obtained from computer code for conventional Cascaded-HFCG.

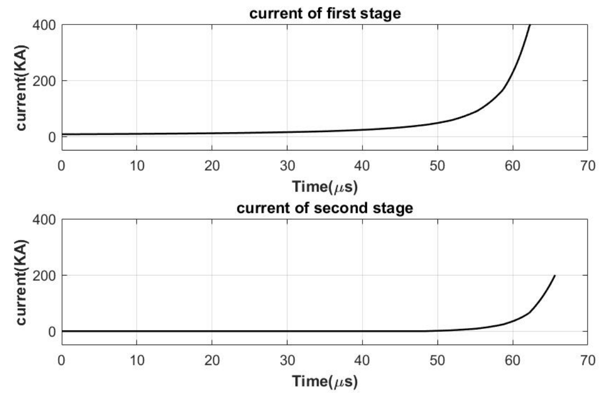

Fig. 5. Current of first stage and second stage windings of Cascaded-HFCG

As we can see, current of first stage reaches a maximum value about 400KA with rise time of current close to 65µs whereas maximum value of load current is 200KA with rise time of current smaller than 15µs. It is obvious that after starting second stage operation (about 50µs) current of first stage rises sharply and reaches an extremely high value. The reason for this excessive current is high mutual inductance between two windings and returned energy to L_P which previously discussed in detail.

Figure 6 shows the simulation results of generator with added gradually incremental resistance in-series with L_P. In this case a resistance which increases linearly from zero to 50mΩ is added in-series to gradually decrease the current of L_P. On the other hand L_P winding supposed to be time varying that means inductance of L_P tend to zero simultaneously with other windings. It is clear that, after adding the resistance to the circuit, current of first stage follows a decreasing trend and causes to increase in load current. Its maximum is 310KA that is 100KA greater than previous case. Current of first stage is limited to 310KA due to added resistance in-series with first stage winding. On the other hand because of destructive behavior of L_P in this case and minimization of returned energy, the generator efficiency becomes greater.

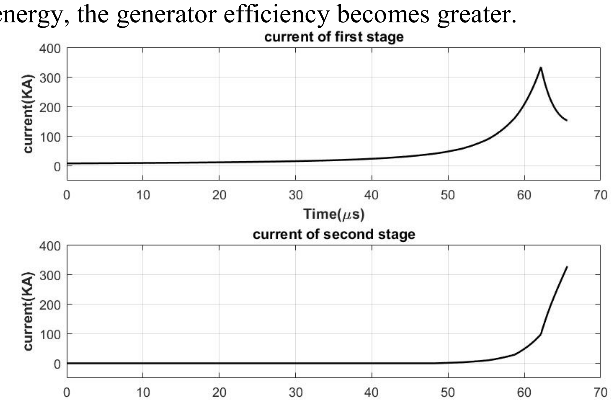

Fig. 6. Current of first stage and second stage winding of Cascaded-HFCG with additive resistance

In order to compare the rise-time of load current for the above two considered case, currents are shown in Fig.7 simultaneously.

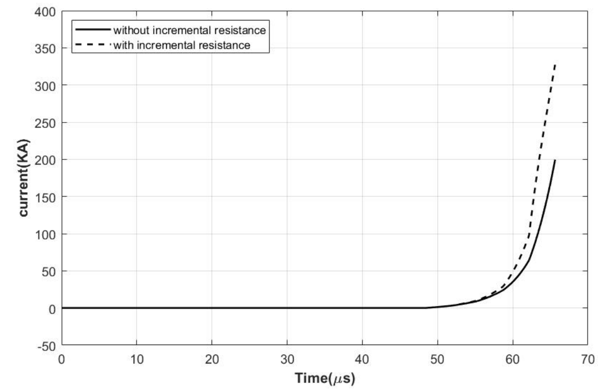

Fig. 7. load current for conventional generator and additive resistance in generator

As it can be seen, there is a considerable improvement in the di/dt and the rise time of the load current in the case of time varying L_P and added incremental resistance in comparison to the conventional Cascaded-HFCG construction.

Practical implement of the above mentioned idea to increase in resistance of first stage winding of Cascaded-HFCG and time varying L_P is proposed in [14].

V. Conclusions

According to the experimental results demonstrated in previous researches, a great part of energy loss in a Cascaded-HFCG is occured after starting of the second stage operation due to the returned energy to the first stage winding. The returned energy causes to increase in the first stage current, and consequently the energy loss increases because the current no reaches to load and only passes through the return conductor and armature. In this paper, a new approach has been proposed to improve the performance of Cascaded-HFCG. According to the proposed approach, each turns of primary winding of dynamic transformer should wiped out simultaneously with armature expansion after second stage operation starting. This causes to decouple primary winding from secondary winding which minimizes returned energy to primary winding. On the other hand, a gradually incremental resistance should be added in-series with primary winding of dynamic transformer. Added resistance restricts increasing of current in primary winding which causes to fewer energy loss and greater load current and shorter pulse width of current. The verification of the proposed method is validated using theoretical analysis and simulation results. As it is demonstrated, the output current amplitude becomes greater, so the current gain of the generator becomes greater too. On the other hand the rise-time of output current becomes smaller that is one of the goal of flux compession generator optimization procedure.

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