LATVIAN JOURNAL OF PHYSICS AND TECHNICAL SCIENCES
2013, N 2

DOI: 10.2478/lpts-2013-0009

UNDERCAR ELECTRICAL GENERATOR FOR RAILWAY PASSENGER CARS: IMPROVEMENT OF EFFICIENCY

N. Levin[1], E. Kamolins[1], A. Gusakov[1], V. Pugachev[2]

[1]Riga Technical University
1 Kalku Str., Riga, LV-1658, LATVIA

[2]Institute of Physical Energetics
21 Aizkraukles Str., Riga, LV-1006, LATVIA
e-mail: edmunds.kamolins@tuv.lv

Passenger cars of the railway transport are being constantly improved, thus becoming ever more comfortable for public conveyance. These cars are fitted with air conditioners, installations for heating and forced ventilation, heaters, refrigerators; lighting, radio and TV sets; communication equipment, etc. All the listed fittings need continuous and secure electricity supply from a primary independent source. The paper considers the possibilities of meeting requirements for particular power supply systems – first of all for undercar generators. At operation of such a high-power generator under rugged conditions it should be highly reliable, possessing a reasonable mass and high efficiency. The existing designs of these generators still do not meet the listed requirements in full measure. To improve the efficiency of the undercar generator it is proposed to integrate its excitation winding into the armature one, thus reducing the copper consumption, losses and mass, while – which is the most important – considerably raising reliability of the generator and its availability factor.

Key words: *inductor generator, passenger car, excitation & armature windings, integration*.

1. INTRODUCTION

A modern passenger car is an autonomous object with normal life conditions provided during a long travel (especially under severe meteorological influence from outside). Electric energy for the car’s functioning is delivered from the primary power supply system including also the undercar electric generator and storage batteries [1]. These latter are needed for supplying the cars with electricity during standing and at low speed. In the main time (i.e. at normal motion) power is supplied from the undercar generator while the storage batteries are charged from this same generator.

The design of generator has been under constant improvement since the middle of the last century. The improvement was keeping pace in the direction of raising the power, reducing the whole mass, reparability, and other qualities – that is, in the direction of efficiency improvement.

The first undercar generators were those working on constant current and having a collector and brushes. These generators turned out to be too massive. At the rated power of 4.5 kW the mass of such a generator was 250 kg at the rotational speed from 650 to 2000 min^{-1}.

The specific electromagnetic moment of such an electric machine was only 0.28 Nm/kg. However, the main drawbacks of the generator were a low operational reliability and a high labour consumption at its making and use. All these drawbacks were mainly associated with collectors and brushes. For example, an undercar generator with collectors and brushes based on the use of transversal magnetic field had even lower specific power (0.22 Nm/kg) [2]. Still, a merit of this generator was that changes in the speed and direction of rotation did not lead to the increase in load and to the change of output voltage polarity. However, the low reliability caused by the presence of collector-brush fittings eventually forced to abandon this design in the time of ever increasing demand for power with simultaneous increase in the comfort of passenger cars. The disadvantages of the collector-brush undercar generators caused the transition to contact-free generators of the inductor type.

A modern two-core generator of this type with a power of 32 kW has at the rotational speed 950 min^{-1} the mass of 750 kg, which provides the specific electromagnetic moment M_{em} = 0.45 Nm/kg – i.e. twice as high as that for the collector-brush designs of the earlier time. However, this does not meet anymore the current demand [3].

Further development of the primary power supply systems would possibly be going three ways as shown in the diagram of Fig. 1.

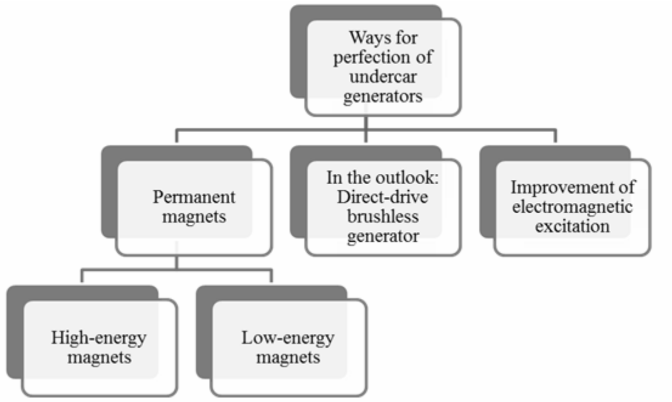

Fig. 1. Ways for perfection of the undercar generator design.

The first way was the combined use of electromagnetic excitation and additional excitation from highly reliable low-energy magnets (Fe–Ba or Fe–Sr) placed in the slots of axial inductor machine [4]. Then an alternate-pole generator followed, with excitation from high-energy (Nd–Fe–B) prismatic magnets [5]. Finally, new designs of electric generators have emerged, with highly efficient use of the armature and excitation windings [2, 6]; also, direct-drive generators find application [3].

One of the operational features of undercar generators is the wide range of rotational speeds (1:4). This feature as well as insufficient resistance of modern high-energy magnetic materials to the temperature and mechanical impacts (shocks) along with high cost made unreasonable their use for these generators. Hence, of particular interest for the authors was the possibility to integrate electrically the excitation and armature windings thus retaining the wide-range control over rotational speeds; in this case it is also possible to reduce the copper consumption and the mass of such an electrical machine [6].

2. ELECTRICALLY INTEGRATED ARMATURE AND EXCITATION WINDINGS: ADVANTAGES AND DISADVANTAGES

To reveal the advantages and disadvantages of the electrical integration of armature and excitation windings we will assume that on the pole horn only one coil with w_c turns is arranged. In Fig. 2 a bridge connection circuit is shown which allows integration of the armature and excitation currents (I_a and I_e, with the current density in the coil being j). Since current I_e is constant and I_a is sinusoidally alternating, the effective value of current in the coil will be:

$$I = \sqrt{I_a^2 + I_e^2}\,. \tag{1}$$

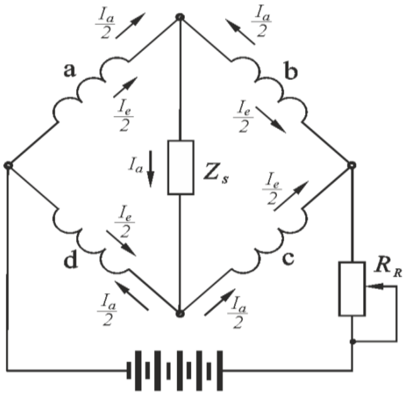

Fig. 2. Bridge connection circuit of the armature winding coils of inductor machine.

The cross-section of the coil wire is:

$$q_k = \frac{I}{j} = \frac{\sqrt{I_a^2 + I_e^2}}{j}, \tag{2}$$

the copper volume will be:

$$V_{\mathrm{Cu}_1} = w_c L q_c = w_c L \frac{\sqrt{I_a^2 + I_e^2}}{j}\,. \tag{3}$$

Now, we will assume that on the pole horn two separate coils with equal number of turns w_c are arranged – one of them for the armature winding and the other for the excitation winding. Then for the respective wire cross-sections we will obtain:

$$q_a = \frac{I_a}{j}; \quad q_e = \frac{I_e}{j}, \tag{4}$$

while the copper volume needed for the coils will be:

$$V_{\mathrm{Cu}_2} = w_c L\left(q_e + q_a\right) = w_c L \frac{I_a + I_e}{j}. \tag{5}$$

It is easy to show that

$$w_c L \frac{\sqrt{I_a^2 + E_e^2}}{J} = V_{\mathrm{Cu}_1} < V_{\mathrm{Cu}_2} = w_c L \frac{I_a + I_e}{J}, \tag{6}$$

which directly evidences that there is a gain in the copper consumption in the case of an integrated winding. The greatest possible gain (≈ 30%) owing to such integration will be at $I_a = I_e$.

In the case when $I_a < I_e$ the losses due to the armature current are essentially retained. An obvious disadvantage of integrating the armature and excitation windings is the stringent relation for the numbers of coil turns to be used in both the windings: these numbers are always equal, which is inconvenient when optimizing the design.

An important condition at designing the generator with electrically integrated windings is to exclude the negative influence of d.c. excitation current on the armature winding and vice versa. Fulfilment of this condition depends on the effectiveness of the technical solutions found in the process of designing the generator.

A significant advantage of integrating the armature and excitation windings is lower copper losses and increased efficiency of the machine. Indeed, the copper losses are:

$$P_{\mathrm{Cu}} = \rho V_{\mathrm{Cu}} J^2, \tag{7}$$

where ρ is the specific resistance of copper.

From this equation it is clear that losses are lower at smaller volume of copper.

3. SPECIFIC FEATURES OF A GENERATOR DESIGN WITH ELECTRICALLY INTEGRATED ARMATURE AND EXCITATION WINDINGS

The combination of armature and excitation windings was originally applied in the Beteno machine [6] used as a modulator; then an improved solution arose, when bridge circuits were applied for connection of the armature winding coils of the inductor generator shown in Fig. 2. In the figure, four coils (a, b, c, d) are connected to form a closed quadrangle. In one diagonal of the circuit a d.c. source is connected, and in the other – load resistance Z_S. In such a circuit the a.c. load current does not enter the excitation circuit, while d.c. current I_e – the load circuit. Therefore, neither the currents nor the relevant processes interfere with each other.

At the same time, these widely known circuits are valid for one occasion only, and cannot be employed in designing the high-power generators. The point is that the excitation circuit has two parallel paths, and in the case of three-phase circuits there are up to six parallel paths. This substantially raises the flowing excitation current, while its distribution among the circuits with a low active resistance – due to possible asymmetry – could turn out to be non-uniform. In this case the asymmetry in the magnetic circuit increases, and the operation of the electric machine is disturbed and becomes inefficient.

A better solution was developed at the Institute of Physical Energetics [6]. The solution is as follows.

In a one-core inductor generator (Fig. 3) with the ratio 6:5 for the tooth numbers of stator 1 and rotor 2 there is one armature winding (being simultaneously the excitation winding) consisting of the coils arranged singly on each stator tooth. The coils are series-oppositely connected to form an open polygon. To the ends of the open circuit a d.c. excitation current source is connected, while the vertices of the polygon are connected to the middle points of the arms of bridge rectifier 3.

The number of arms in the rectifier is by one greater than that of the coils (phases) in the generator. To the ends of the open polygon a capacitor is connected – a filter protecting the d.c. source from occasional higher harmonics. Since capacity provides the reactive impedance of the capacitor one order of magnitude smaller than the inductive impedance of the capacitive polygon, this capacity helps to rectify the potentials of the a.c. polygon ends. The difference in the a.c. current potentials can arise only at the presence of higher harmonics and of the magnetic circuit asymmetry.

The generator operates as follows.

When the excitation current is fed to the armature winding, the stator teeth acquire alternate polarity as shown in Fig. 3. The magnetic fluxes of the stator teeth depend not only on the MMF but also on their position with respect to the rotor teeth. The magnetic-flux linkage with the stator coils (phases) at the running rotor is time-varying, and, as a result, in these coils a symmetrically multiphase EMF system is induced.

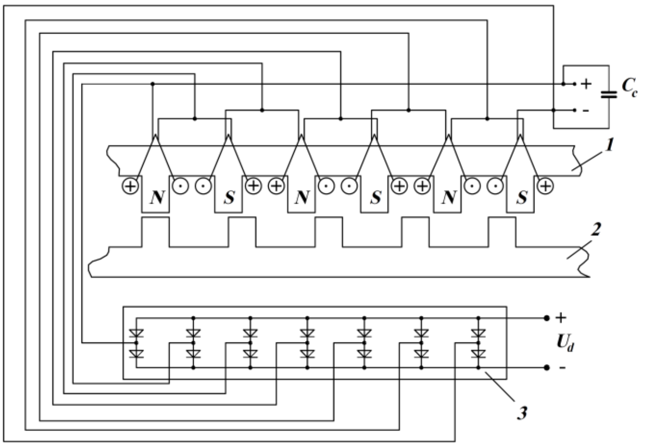

Fig. 3. The design concept of the generator with integrated armature and excitation windings.

The respective fluxes are mutually compensated at the terminals of the excitation current feed, although they manifest themselves in full measure and arrive at the rectifier from each phase; as a result, at its output a rectified voltage appears.

A specific feature of such a generator design and of its armature winding circuit is that when the excitation circuit consists of series-oppositely connected elements (i.e. has no branches) the magnetic system turns out to become symmetrical. Also remarkable is that – with the armature winding being multiphase – the rectified current can exceed the a.c. current several times in each of the phases. The efficiency of such a generator is determined by the choice of its parameters: teeth of stator and rotor, connections of winding coils, numbers of phases, etc. The last named parameter is to be analyzed from the viewpoint of the numbers providing the highest specific power, simple technology of making the generator and its reliability.

4. SUBSTANTIATION OF THE OPTIMAL DESIGN SCHEME FOR A GENERATOR WITH ELECTRICALLY INTEGRATED ARMATURE AND EXCITATION WINDINGS

One of the specific features of the generator under consideration is the elevated excitation current values. Hence, it is necessary to make the armature windings with a small number of turns, using a wire of large cross-section. This makes it problematic to make inter-coil connections, especially if these coils are connected not in succession but “out of continuity” (see the relevant scheme in Fig. 3): 1 → 4 → 2 → 5 → 3 → 6…

Such a connection might in principle exist, but this would extend the inter-coil connections, raise the copper consumption and the armature winding resistance, thus leading to decrease in the efficiency and to technological problems. Therefore, it is reasonable to connect the armature winding coils in the sequence: 1 → 2 → 3 → 4 → 5 → 6 (see Fig. 3).

The sequential coil connection substantially simplifies the technology of making windings and improves the efficiency of the electric machine, and also allows increasing the power at its given sizes

At the same time, a simple technology would lead to increase in the number of phases; besides, the rectifier becomes more complicated. For example, if at six stator teeth and five rotor teeth it is necessary to make the armature winding three-phase, we should combine in the first phase (A) coils 1, 2, in the second phase (B) – 3, 4, and in the third (C) – 5, 6. Such being the case, the winding coefficient will fall to 0.87, while the decrease in power will be 24%.

Therefore, it is necessary to connect the armature winding coils sequentially, with the number of phases equal to that of coils – i.e. to the number of teeth on the stator.

The second in importance parameter to be selected when designing a generator with integrated armature and excitation windings is the ratio of the stator and rotor tooth numbers and their absolute values.

As indicated above, the minimum number of stator teeth is to be six (which corresponds to a six-phase armature winding), with the rotor tooth number being equal to five. Obviously, it is possible to build a generator with four or two teeth on the rotor, but in this case we would have a three-phase machine whose phase angle (i.e. the angle between the adjacent stator teeth) would be 240° or 120°. At such a phase angle the paths of closing the magnetic fluxes are longer, which means decrease in the force of these fluxes, and, consequently, in the EMF and power of the electric machine. In Fig. 4 the picture obtained using the QuickField program is shown for the case of 12 stator teeth, with the number of rotor teeth being 10. At this number being 8 the increase in the phase angle to 240° would reduce the useful magnetic flux and raise the number of saturated sections of the magnetic core.

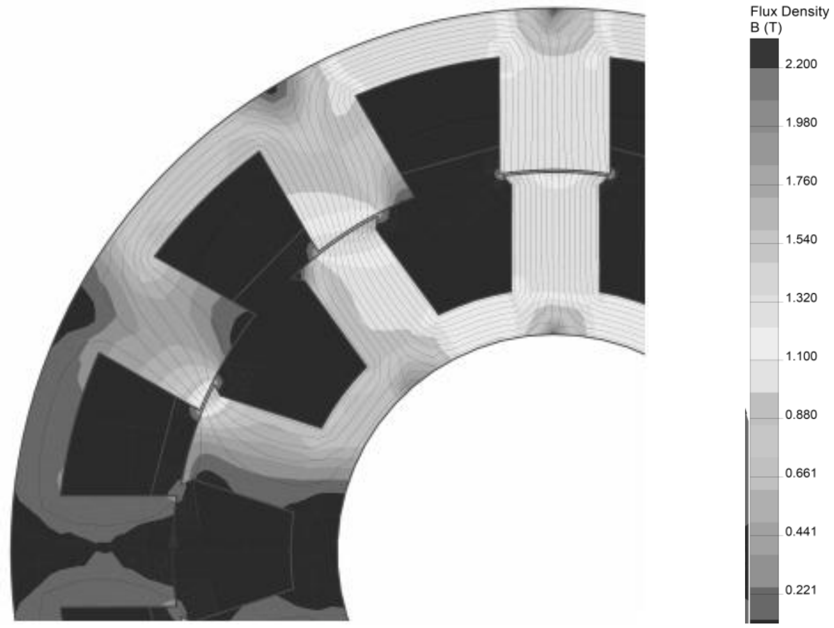

Fig. 4. Magnetic field of the generator with $Z_S = 12$; $Z_R = 10$ ($\Phi_{max} - \Phi_{min} = 0.0471 - 0.00323 = 0.04387$ Wb).

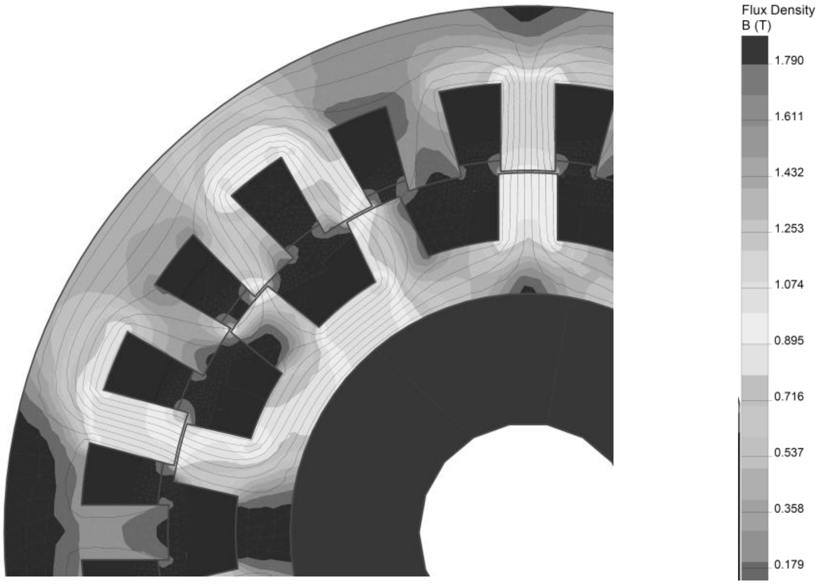

Fig. 5. Magnetic field of the generator with $Z_S = 12$; $Z_R = 14$ ($\Phi_{max} - \Phi_{min} = 0.02362 - 0.001699 = 0.021921$ Wb).

Obviously enough, we might reduce the phase angle between the adjacent stator teeth to 30°, but it would lead to the uneven number of rotor teeth and possible asymmetry of the magnetic circuit.

Therefore, the optimal numbers of stator Z_S and rotor Z_R teeth are to be:

$$Z_S = 6k; \quad Z_R = Z_S - k, \tag{8}$$

where $k = 2$ is an even integer defining the number of elementary hexagons in the configuration of armature windings.

Note that number Z_R should be less than Z_S by *k*. In the case when $Z_R > Z_S$ there will be a decrease in the magnitude of the variable component of phase-linked magnetic flux, and, consequently, in the power, while the losses will be greater (Fig. 5).

The next important parameter to be optimized in the generator with integrated armature and excitation windings is integer, i.e. the number of elementary hexagons in the armature winding – in other words the number of stator teeth. To find the optimum, an experiment was carried out on a physical model (Fig. 6).

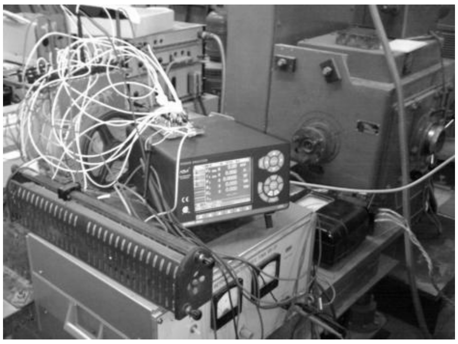

Fig. 6. A physical model of the generator.

The physical model presents a low-power inductor generator with conductors taken from an inductor generator. On the doubled stator of the generator there are arranged 24 pole horns embraced with two coils: one of the armature and the other of the excitation winding. The ends of coils were taken out to the commutation panel, which allows assembling practically any scheme of the armature winding with the phase number from 3 to 24.

The results of physical modelling are represented in Table 1 by the generator parameters for rated power P_d.

As follows from the table, the best characteristics of the generator are ensured at the six-phase performance. However, this version is undesirable taking into account an axial asymmetry of the magnetic core that could arise at an uneven number of rotor teeth (e.g. 5). Therefore, still the 12-phase (2×6) version should be chosen, at which the main indices remain practically the same as in the 6-phase version while the current (voltage) transfer ratio is greater. This latter is very important at designing the generator with a wide range of rotational frequencies (rpm) and high-speed operation.

Table 1

The main generator parameters obtained by physical modelling

No.	Parameters	Number of phases (pole horns)			
		3	6	12	24
1.	Output power P_d , W	38.4	40.9	38	30
2.	Phase current I_f, A	0.25	0.23	0.16	0.12
3.	Phase voltage U_f, V	53.3	50.2	19.6	10.4
4.	Rectified current I_d, A	0.56	0.62	0.6	0.55
5.	Rectified voltage U_d, V	68.6	66	69.2	54.5
6.	Current conversion coefficient k_I	2.2	2.45	3.77	4.6
7.	Voltage conversion coefficient k_U	1.35	2.45	3.18	5.24
8.	Excitation loss ΔP_e, W	50	51.6	56	70

5. CONCLUSIONS

The generator for independent power supply of passenger cars should possess high reliability, acceptable sizes and mass, high efficiency, and be easy to operate. In the paper it is shown that the inductor generator with electrically integrated armature and excitation windings possesses all the mentioned indices.

The 12-phase design of such a generator provides the best performance; a 12-phase rectifier is more reliable and easy to operate than the existing axial inductor generators in the two-core version. The achievable mass of the proposed generator is 40% smaller than that of existing designs due to the absence of heavy housing and bushings. The copper amount required for windings is practically half as much compared with existing generators.

Further improvement of the undercar generator can be achieved at its direct-drive design, without intermediate belts and gimbal gears. These latter hamper handling the primary power supply systems for the passenger railway cars and reduce the reliability of their functioning.

ACKNOWLEDGEMENT

This work was supported in part by the ERAF project No. 2010/0291/2DP/2.1.1.1.0/10/APIA/VIAA/055, "Improvement of the effectiveness and competitiveness of the power supply systems for railway passenger cars".

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DZELZCEĻA PASAŽIERU ZEMVAGONA ELEKTRISKĀ ĢENERATORA EFEKTIVITĀTES UZLABOŠANA

N. Levins, E. Kamoliņš, A. Gusakovs, V. Pugačevs

Kopsavilkums

Dzelzceļa transporta pasažieru vilcienu vagoni nepārtraukti tiek pilnveidoti ar mērķi paaugstināt pasažieru komforta līmeni pārvadājumu laikā. Šādi pasažieru vagoni aprīkoti ar gaisa kondicionēšanas, apsildes, ventilācijas, ūdens uzsildīšanas, saldēšanas, apgaismes, radio, televīzijas, sakaru u.c. iekārtām. Visām pieminētajām iekārtām to darbības laikā ir nepieciešama nepārtraukta un droša elektroenerģijas apgāde no primāra neatkarīga avota. Darbā tiek izskatīta elektroapgādes sistēma, kura spētu nodrošināt izvirzītās prasības. Pie šīs sistēmas, pirmkārt, pieder zemvagona ģenerators. Tam ir jābūt paaugstinātas jaudas, smagos darba apstākļos jānodrošina augsts drošums, ar pieņemamu masu un augstu lietderības koeficientu. Šādu ģeneratoru esošās konstrukcijas pilnā mērā nespēj nodrošināt iepriekš minētās prasības. Lai paaugstinātu zemvagona ģeneratora efektivitāti, tiek piedāvāts elektriski integrēt tā ierosmes tinumu enkura tinumā, turklāt samazinot izmantojamā vara apjomu, zudumus, masu, bet, galvenais, būtiski paaugstinot drošumu un gatavības koeficientu.

12.02.2013.