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CONTACT-FREE COMBINED SYNSHRONOUS GENERATORS ROTOR WINDINGS ELECTROMAGNETIC ANALYSIS

Розглянуті схеми-розгортки обмоток ротора безконтактних суміщених синхронних генераторів. На підставі виконаного аналізу електромагнітних показників визначені переваги і недоліки відомих суміщених обмоток, а також переваги нової суміщеної обмотки.

Рассмотрены схемы-развертки обмоток ротора бесконтактных совмещенных синхронных генераторов. На основании выполненного анализа электромагнитных показателей определены достоинства и недостатки известных совмещенных обмоток, а также преимущества новой совмещенной обмотки.

Contact-free combiner synchronous generators rotor windings distribution schemes were reviewed. Merits and demerits of well-known combined windings and advantages of a new combined winding were defined on basis of electromagnetic properties analysis.

Contact-free combined electric machines became widespread nowadays. Compared with electric machines having sliding contacts, contact-free combined electric machines have a number of advantages, e.g.:

- Improved mass and volume characteristics;
- Simple construction that allows simplifying manufacturing technology.
- Windings assembly that provides an efficient use of expensive wires and insulating materials and maintenance efficiency.

As a result of a higher manufacturability level, contact-free combined synchronous implicit-pole generators (CCSG) deserve special attention compared with explicit-pole ones.

Well known CCSG have a similar to each other construction: two synchronous generators are combined in a common magnetic system. One of these generators implements functions of exciter and the other one is main.

Two windings are stacked at CCSG stator:

- Generator anchor winding (GAW) with a p_g pole pares number;
- Exciter excitation winding (EEW) with a p_e pole pares number, fed with direct current from an accumulator or voltage regulator.

Stator can also contain additional excitation windings and it regulation devices.

These elements allow realizing a feedback between generator output voltage and exciter excitation winding voltage.

Generally, rotor contains windings system that creates alternating voltage, main magnetic field of excitation and a rectifying block (RB).

Stator windings assembly, technologic and electromagnetic properties analysis [5, 6] and also CCSG rotor windings assembly variants [3] were overviewed in previous articles however the analysis of rotor windings electromagnetic properties was not fulfilled.

In view of the aforesaid, this work's task is to analyse well-known CCSG rotor windings properties and an efficient winding scheme selection.

CCGS rotor windings construction greatly defines it properties, such as:

- Manufacturability;
- Field of excitation harmonic components.

Manufacturability can be estimated by such factors as:

- Common number of windings layers;
- Number of coils;
- Number of coil groups;
- Number of coil groups types.

It is significant that the number of windings layers is the most important of listed factors, because it increase heightens work content of winding and insulating operations and insulation expenses.

Rotor windings technologic properties analysis can be done analogous to GAW [5] and will not be examined in current work.

Excitation winding active coil parts distribution (ACP) by rotor slots affects harmonic components of an excitation field and therefore it affects the generators output voltage (OV) quality that can be characterized with a sine distortion factor which defines the level of additional harmonics content in OV curve [4].

$$K=\sqrt{\sum_{\nu=2}^{\infty}E_{\nu}^{*2}}\ ,$$

where E_{ν}^{*} is a relative amplitude of generator EMF harmonic component with a serial number ν, that can be found from an expression

$$E_{\nu}=2\sqrt{2}\tau_{\nu}\cdot l\ \cdot w\ \cdot f_{\nu}\cdot k_{W\nu}\cdot B_{m_{\nu}},$$

where $k_{W\nu}$ is a GAW winding factor with serial number ν;

$B_{m_{\nu}}$ is an amplitude value of induction in air gap harmonic component with a serial number ν;

$\tau_{\nu}=\dfrac{\tau_1}{\nu}$ is an electromagnetic force (EMF) harmonic component with a serial number ν pole division;

$f_{\nu}=\nu\cdot f_1$ is an EMF harmonic component with a serial number ν frequency;

w is a GAW coils number;

l is an anchor active length.

Amplitude value of induction in air gap harmonic component with a serial number ν

$$B_{m_{\nu}}\equiv\frac{k_{WE\nu}}{\nu\,p_g},$$

where $k_{WB\nu}$ is a winding factor of a generator excitation winding (GEW) with a serial number ν.

In view of the aforesaid, relative amplitude of generator EMF harmonic component with a serial number ν

$$E_{\nu}^{*}=\frac{E_{\nu}}{E_1}=\left(\frac{k_{W\nu}}{k_{W1}}\right)\left(\frac{1}{\nu}\frac{k_{WB\nu}}{k_{WB1}}\right)=k_{w}^{*}\cdot H_{\nu}. \qquad (1)$$

Lets mark the expression (1) components related to GAW and GEW as k_{w}^{*} & H_{ν}, then

$$E_{\nu}^{*}=\frac{k_{W\nu}}{k_{W1}}\frac{1}{\nu}\frac{k_{WE\nu}}{k_{WE1}}=k_{w}^{*}\cdot H_{\nu}.$$

Since CCSG rotor windings are the objects of current article analysis, the principal factor of OV analysis is the excitation field harmonic components relative amplitude.

$$H_{\nu}=\frac{1}{\nu}\frac{k_{WE\nu}}{k_{WE1}}.$$

The posed problems are being solved with a use of a program named GA [2] that gives an opportunity to perform a harmonic analysis of windings with following results comparison.

Based on this conclusions lets fulfil well-known CCSG rotor windings electromagnetic properties analysis.

The simplest example of CCSG is a generator with separated rotor windings.

A pre-production model of an indicated generator was processed at Odessa national polytechnic university chair of electric machines at the beginning of 90-th years [7]. Rotor of this generator contains GEW and exciter anchor winding (EAW) that are stacked into a single layer at different slots. EAW is connected with a RB supplying GEW with direct current (Fig. 1.).

At fig. 2. and in further text figures of an article following elements are listed: a table of CCSG direct $I_{=}$ and alternating $I_{\sim}$ currents correspondence to rotor slot numbers (Fig 1, *a*), excitation force distribution (Fig 1, *b*) and a rotor winding distribution scheme (Fig 1, *c*).

Arrows at the distribution scheme show conditional direction of direct and alternating currents that flow in windings. Belonging to alternating current phases *A*, *B* and *C* is corresponding signed with one, two or three arrows.

An obvious disadvantage of such generator is an inefficient use of rotor slot space a specially regarding to EAW that occupies little number of slots. This fact makes difficulties in exciter of needed power designing.

Harmonic analysis of GEW, given in the tab. 1, shows that the harmonic with a serial number $\nu=7$ has a biggest relative value

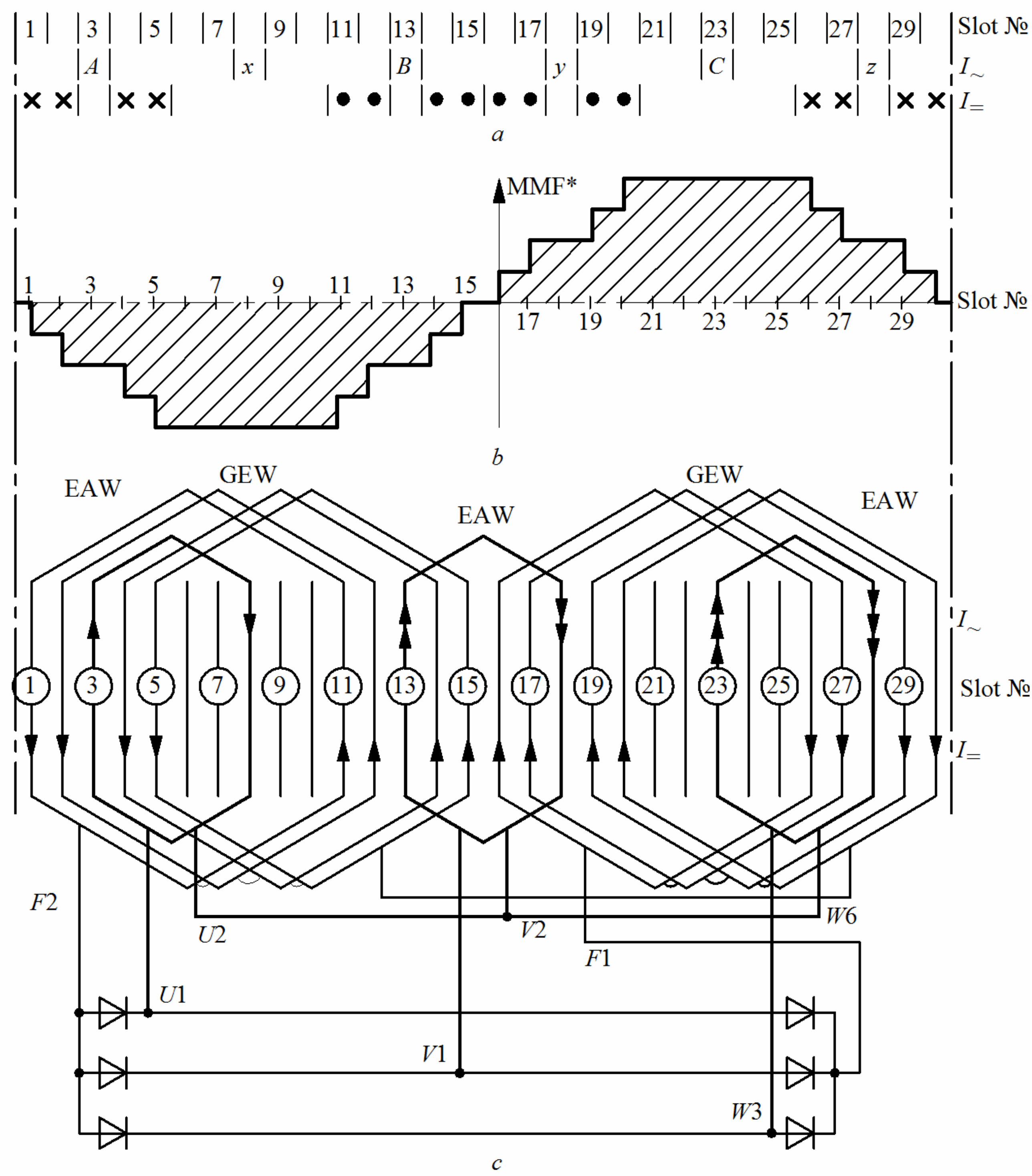

Fig.1. CCSG rotor winding scheme

1. GEW Winding factors

ν	1	7	11	13
k_{WE}	0,819	0,378	0,335	0,106
H_ν	1	0,0659	0,0372	0,00996
ν	17	19	23	29
k_{WE}	0,106	0,335	0,378	0,819
H_ν	0,0076	0,0215	0,02	0,034

Compared with a previously described generator there is a more complicated CCSG. This generator has a periodically changing rotor structure.

This generator rotor was developed by Klementev V.A. and contains an excitation winding that is stacked not all over the rotor circle [9, 10]. A part of rotor stays unwound and combines empty slots into, so called, big jags. Specified winding is made at least from two parts each of which (GEW1 & GEW2) is shown with bold lines at fig.2. Each of GEW parts is closed by a rectifier through an additional winding that is shown at fig.2. with thin lines and is stacked into the slots that are remote from big jags.

Direct current flows at windings' GEW1 & GEW2 wires and creates the main excitation. EMF is induced in these windings. Specified excitation windings create double pole excitation field when diodes are inserted towards each other. Direct current flows in additional excitation winding and creates an additional excitation field. The fact that there are two excitation windings – main and additional causes difficulties during harmonic analysis of MMF curve.

A disadvantage of this winding is the fact that it uses only a part of a rotor winding space, except big jags, that decreases the efficiency of active materials usage. The presence of two excitation windings increases work content of windings manufacturing and stacking.

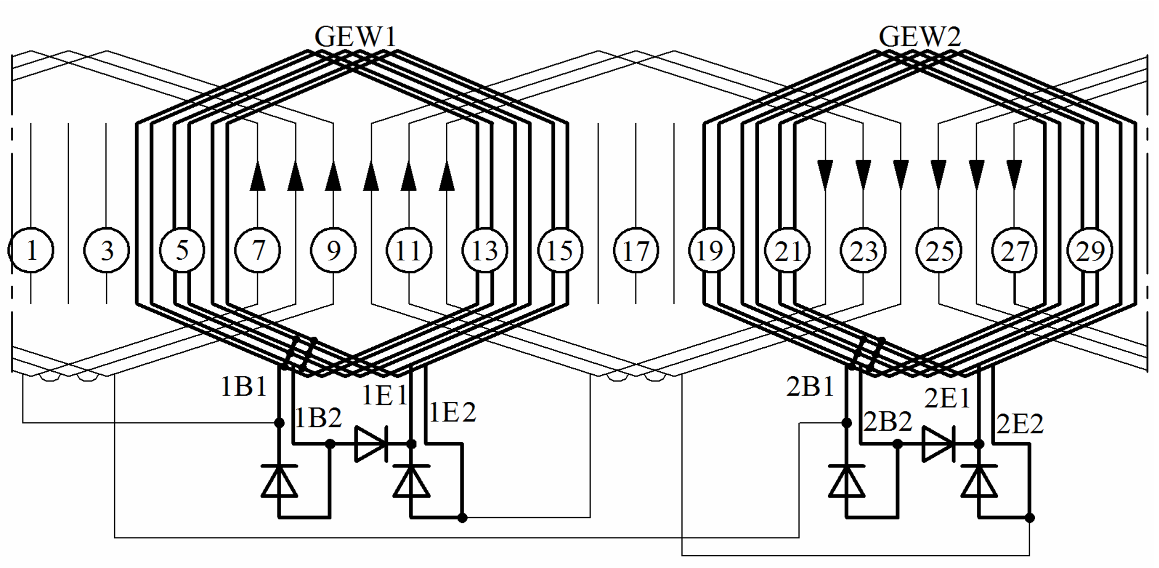

Fig.2. Winding with a periodically changing rotor structure distribution scheme

There is a well-known generator with an excitation winding that consists of three parts.

This generator was worked out by Karavaev V.T. [1, 8]. Rotor of this generator contains electrically combined winding (CW) that realises functions of EAW and generator excitation winding (GEW1) and two equal parts of generator excitation winding GEW2 & GEW3. Each of winding parts is connected consecutive with RB and as a whole creates GEW.

Generator excitation MMF is created by ACP of concentric windings GEW1 & GEW2 that lay in slots number 3, 4, 5, 6, 7, 8, and by ACP that lay in slots number 12, 13, 14, 15, 16, 17 and are inserted towards each other (Fig.3.).

An additional generator excitation MMF is caused by ACP of an equal-coil double-layered CW, that lay in slots with numbers 4, 5, 6, 7, and with ACP that are switched towards to them and lay in the slots numbers 13, 14, 15, 16.

The same direct current flows in all listed ACP that's why the resulting generators excitation MMF is equal to the sum of main and additional MMF and depends on a coil number ratio w^* in ACP of main winding w_{GEW} and combined winding w_{CW}.

$$w^* = \frac{w_{\text{GEW}}}{w_{\text{CW}}}.$$

Direct currents distribution can be represented at a vector diagram (Fig. 4.).

At the diagram, that is shown at fig. 4, continuous vectors with radius $R = 1$ and displaced one after another at an angle $\alpha = 20^{\circ}$ of minimal displacement in magnetic field show MMF caused by GEW2 & GEW3 active coil parts.

Dotted vectors with radius $R = 1 + w^*$ and displaced one after another at an angle $\alpha = 20^{\circ}$ of minimal displacement in magnetic field show MMF caused by CW active coil parts.

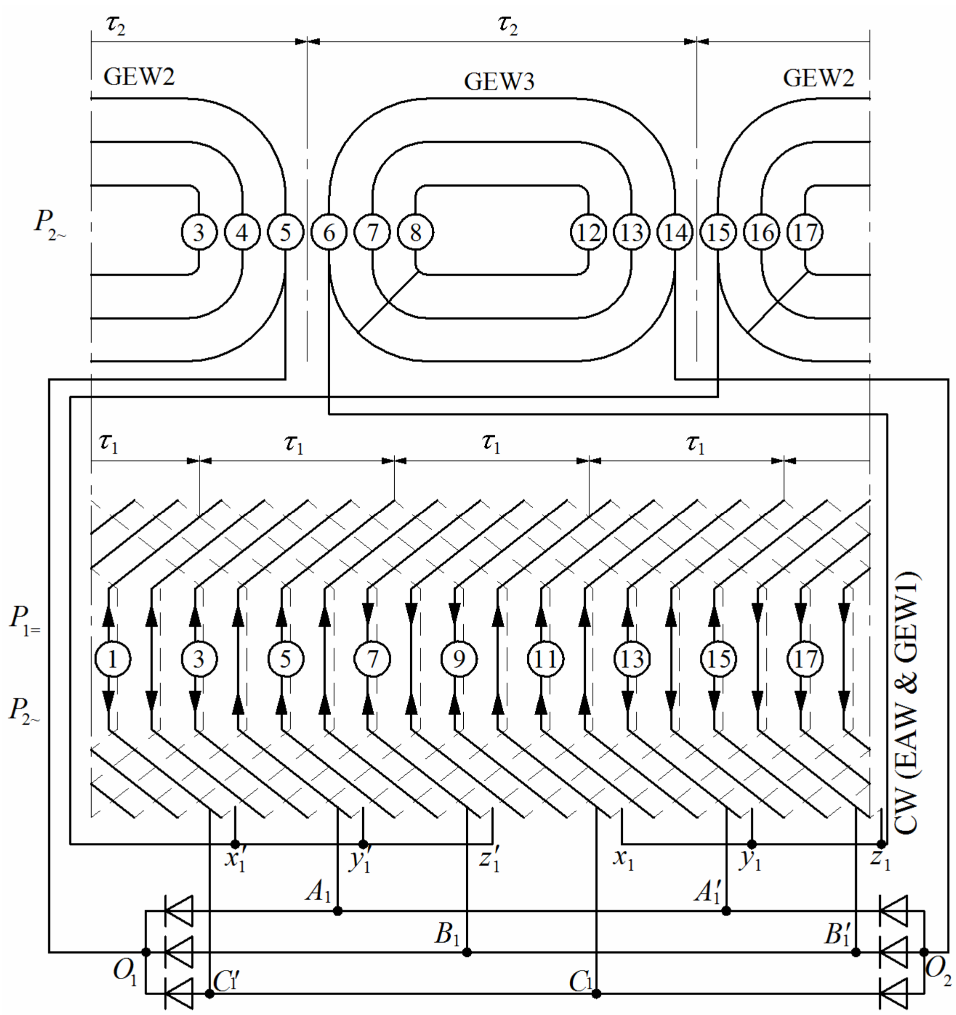

Fig. 3. Karavaev V.T. CCSG rotor combined winding distribution scheme

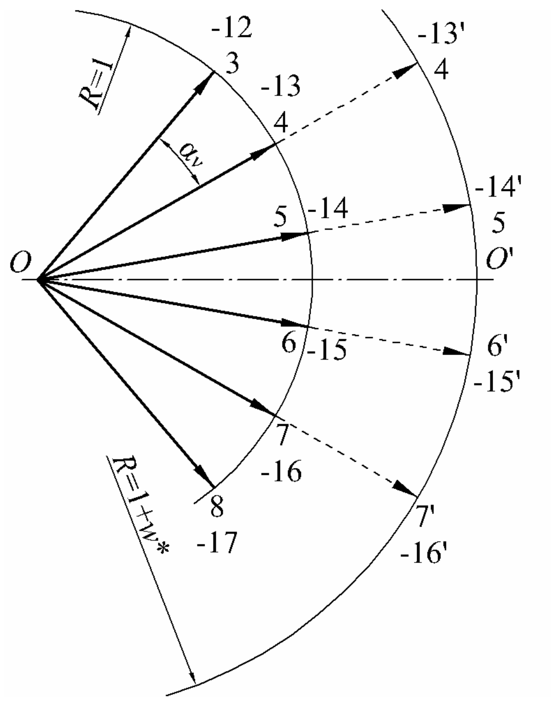

Fig. 4. Vector diagram of CW currents

Using fig. 4 an expression for a winding factor of an arbitrary harmonic component calculation can be written as follows

$$k_{\mathrm{WE}\nu}=\frac{(1+w*)\left[\cos\left(\frac{\pi\nu}{Z}\right)+\cos\left(\frac{3\pi\nu}{Z}\right)\right]+\cos\left(\frac{5\pi\nu}{Z}\right)}{3+2w*}. \quad (2)$$

2. GEW winding factors

ν	w*=0	w*=0,2	w*=0,4	w*=0,6	w*=0,8	w*=1
1	0,831	0,842	0,851	0,858	0,864	0,869
3	0,000	0,051	0,091	0,124	0,151	0,173
5	0,188	0,179	0,172	0,166	0,162	0,158
7	0,154	0,105	0,066	0,035	0,009	0,013
9	0,000	0,000	0,000	0,000	0,000	0,000
11	0,154	0,105	0,066	0,035	0,009	0,013
13	0,188	0,179	0,172	0,166	0,162	0,158
15	0,000	0,051	0,091	0,124	0,151	0,173
17	0,831	0,842	0,851	0,858	0,864	0,869

Table 2 shows the results of CW harmonic analysis in case of changing w^* from 0 to 1 calculated with a use of an expression (2). Given results show that a MMF curve includes harmonic with a serial numbers (v=3), which winding factor can reach 17% when w^*=1.

Disadvantages of an examined winding:

– MMF distribution curve contains harmonics that have serial number divisible by 3, caused by additional winding. These harmonics presence increase sine distortion factor of generators phase output voltage;

–Windings of two types presence: equal-coil double-layer GEW1 and concentric single-layer GEW2 & GEW3 increases coil number up to 24 at every 18 slots, increases work content of windings manufacturing caused by a need to create two different types of templates. The winding distribution scheme shows that there are triple-layer parts of a winding and this fact complicates coils stacking and commutation and increases interlayer insulation consumption;

– In ACP that are stacked in slots number 1, 2, 3, 8, 9, 10, 11, 12, CW excitation direct currents in upper and lower layers are directed towards each other, therefore they do not create an MMF, but only increase losses in the winding and it temperature. So the examined winding wire is used inefficiently, and the increase of it temperature reduces generator reliability.

Weaknesses of examined CCSG windings prove that it must be designed a CW which construction and distribution would allow to attain following results:

- Reduction of manufacturing and stacking work content;

- Reduction of generators OV sine distortion factor;

- Improvement of wire usage and generator reliability.

In Odessa national polytechnic university at a chair of electric machines was processed generator [11] which rotor winding was stacked disrupted and has a list of advantages compared with winding patterns that were listed above.

Rotor of a processed pre-production model contains EAW combined with GEW and the alternating current outlets (U1, V1, W1) and zero outlets. EAW is closed by RB through a direct current circuit (F1, F2) (Fig. 5.). Current CW is single layered and contains 18 coil groups with number 1, 2…18.

Figure 5 shows that direct currents flowing in a winding are distributed symmetrically and occupy 2/3 of winding space. That fact provides a field of generator excitation with $2p_g = 2$ pole number. Alternating current phase distribution corresponds to a symmetric three-phase winding that occupies all of rotor slots and easies EAW designing.

Part of rotor slots are flown both by direct and alternating current that has to be accounted while choosing a CW current density. GEW harmonic analysis results are listed in tab.3.

3. Suggested pre-production model GEW MMF harmonic analysis results

ν	$k_{WE\nu}$	H_ν
1	0,828	1,000
5	0,171	0,041
7	0,126	0,022
11	0,088	0,010
13	0,080	0,007
17	0,072	0,005
19	0,072	0,005
23	0,080	0,004
25	0,088	0,004
29	0,126	0,005
31	0,171	0,041
35	0,828	1,000

This CCSG CW has following advantages compared with the windings that were examined below:

1) All of rotor slots are filled with CW ACP, that allows using winding space rationally.

2) CW manufacturing work content decreased due to equal coil-groups number decrease and their stacking into a single layer.

3) Use of a winding that was stacked disrupted allows decreasing it average step that must cause a decrease of insulation and wires consumption.

4) CW simple construction gives an opportunity to analyze it harmonic contents easily;

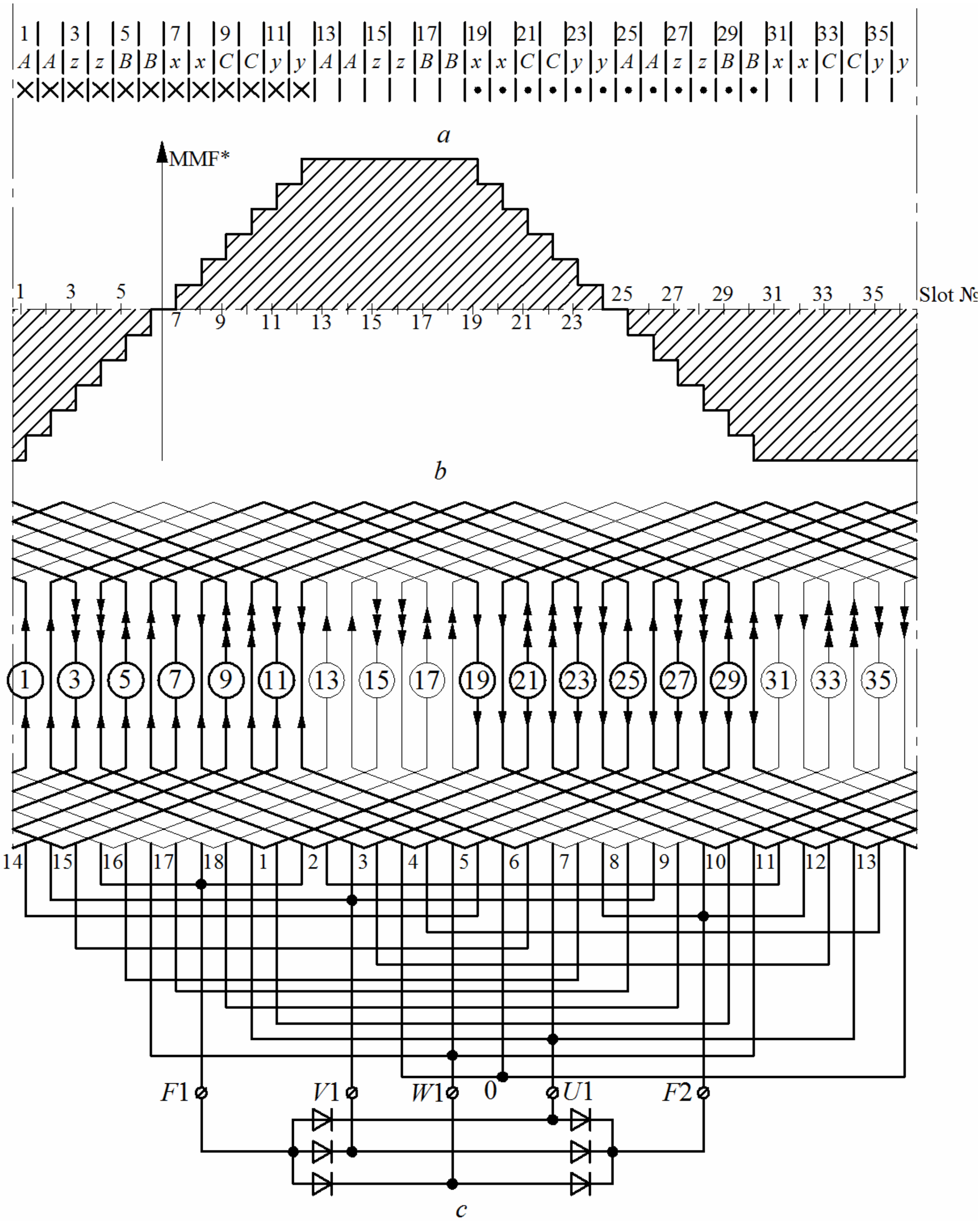

Fig. 5. Suggested CW

a – Direct and alternating currents distribution;
b – Excitation field MMF distribution
c – Distribution scheme of a suggested winding

5) Suggested CW harmonic analysis results show that the excitation MMF curve contains no harmonics divisible by 3 and, harmonics number 5 & 7 level is less than the same harmonics level of examined below CCSG windings.

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