DOI: https://doi.org/10.15407/techned2024.06.038

CONTROL OF A CAPACITOR EXCITED ISOLATED INDUCTION GENERATOR ASSISTED BY A MULTI-MODULAR POWER ELECTRONIC CONVERTER

L.I. Mazurenko[1*], O.V. Dzhura[1], M.O. Shykhnenko[1***], S.M. Korotin[2****]**
[1] Institute of Electrodynamics National Academy of Sciences of Ukraine,
Beresteiskyi Ave., 56, Kyiv, 03057, Ukraine. E-mail: 3662491@gmail.com.
[2] Ivan Chernyakhovsky National Defense University of Ukraine,
Povitrianykh Syl Ave., 28, Kyiv, 03049, Ukraine.

The principles of multi-level output voltage control of an autonomous power supply system implemented on the basis of a three-phase constant speed self-excited induction generator with a regulated source of reactive power connected to the stator terminals and containing both a multi-modular electronic power converter and excitation capacitors are proposed. To regulate the voltage of the specified system, a stator voltage oriented vector control algorithm has been developed. Using the developed dynamic simulation model, numerical investigations of electromechanical processes in the system supplying RL-load of the local consumers were carried out to verify the effectiveness of the proposed principles of voltage control and the proposed vector control algorithm of the generator. The main advantages of applying multi-module electronic power converters in autonomous power supply systems using a self-excited induction generator with a short circuited rotor winding and an electronic power converter connected to the stator terminals for reactive power control are noted. References 10, figures 3, table 1.
Keywords: multi-modular power converter, induction generator, multi-level voltage control.

Introduction. Most of the mini- and small hydropower plants (HPPs) built in Ukraine can operate only in grid-tide mode. During the construction of new and modernization of existing small-capacity HPPs, it is often required from the designer to provide the option of autonomous or backup power supply as needed, which is relevant in times of acute shortage of energy resources.

Asynchronous (induction) generators (IGs) with squirrel-cage rotor and wound rotor IGs are used in fixed speed and variable speed wind turbines, in small power (up to 10 MW) HPPs, in development of autonomous electric power sources supplying technological processes, such as welding, etc. [1-5].

Capacitor banks (CBs), synchronous compensators and voltage source (power electronic) converters (VSC, PEC) are used to compensate for the reactive power drawn by IGs. For small and mini hydroelectric power stations with available option of emergency power supply to temporarily de-energized consumers, the presence of CBs, in addition to compensating the reactive power of IGs, is needed to generate voltage waveform with distortion limits acceptable to consumers. The voltage distortion limits are highly affected by the operation of generator-side PECs used for active and reactive power control. In fixed-speed off-grid HPPs, the torque of the IG can be controlled by switched dump loads, if available, or by a VSC with a DC-side resistive dump load.

Currently there is a practice of developing various high power PECs according to a modular structure. This allows to design PECs of different power ratings using identical electronic components [6]. In such PECs, the number of operating modules is determined by the load, which allows them to be operated close to the nominal mode with high efficiency. The failure of a separate module does not lead to a stop in the operation of the entire PEC and due to this an increased operational reliability is achieved. And finally, the production of PECs using a modular structure makes it possible to abandon the parallel connection of power switches and thus escape the problem of uneven current distribution between paralleled elements. It is

ORCID: * https://orcid.org/0000-0002-7059-249X; ** https://orcid.org/0000-0002-0224-3351;
*** https://orcid.org/0000-0003-4012-1731; **** https://orcid.org/0000-0003-2123-6103

advisable to use this approach in the development of both CB and PEC-based combined systems for excitation (CSE) of IGs operating in autonomous low-power HPPs and hydro-wind power systems [7].

The aim of this work is to develop principles of multi-level output voltage control and a control algorithm for an autonomous power supply system implemented on the basis of a three-phase constant speed self-excited induction generator with a regulated source of reactive power connected to the stator terminals and containing both a multi-modular electronic power converter and excitation capacitors.

The schematic diagram of the autonomous power supply system considered in this article is shown on Fig. 1. The system is built using an IG driven by a regulated hydro turbine (HT), a CB of compensating capacitors and a multi-modular VSC developed with *n* parallel-operated modules VSC1...VSCn. The modules are implemented based on the schematics of autonomous voltage source inverter operated in current source inverter mode. The CB power rating is sufficient for the self-excitation of the generator. The system provides power to the local residential load and an auxiliary equipment of the HPP.

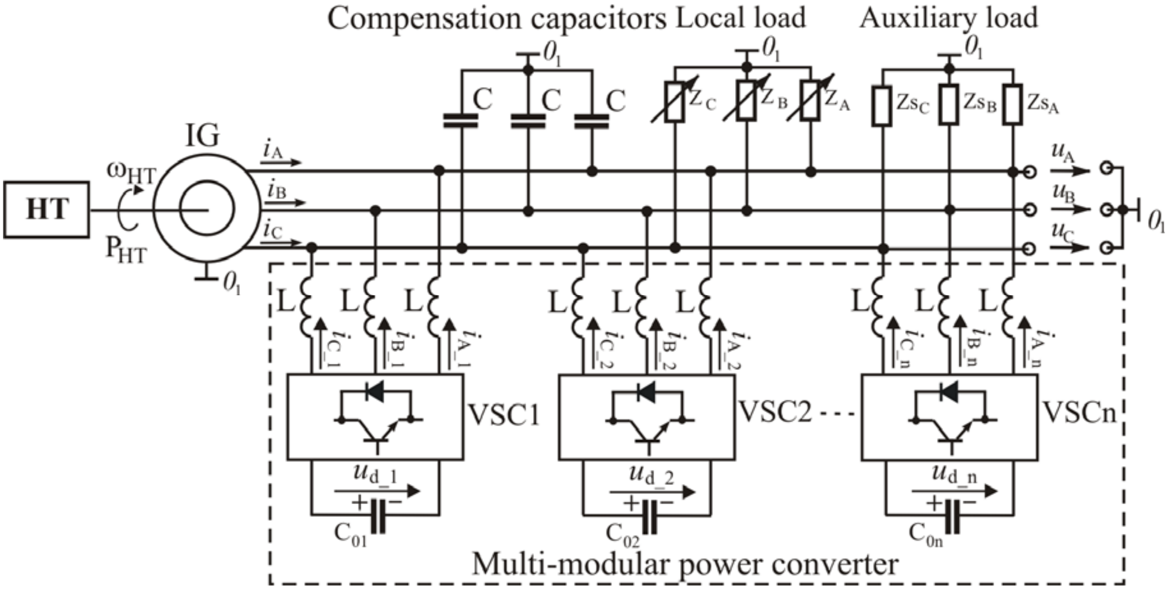

Fig. 1

The following principles of multi-level voltage control of an autonomous fixed speed IG with CSE and multi-modular VSC (Fig. 1) are proposed:

1. The CB power rating must be set to the value providing the IG no load voltage magnitude approximately equal to the voltage reference of the 1st VSC module (VSC1);

2. The first VSC module has the highest voltage reference and can both generate ("capacitor" mode) and consume ("inductance" mode) reactive power;

3. Other modules operate in reactive power generation mode, and their voltage references are decreased as their number increases;

4. Each subsequent module is connected when the previous one enters saturation (reaches its reactive power rating in generation mode) or the system voltage magnitude decreases lower than the voltage reference of this module by a certain value. The order of connection is sequential, in order of increasing module number;

5. Each module, except for the first one, is turned off if the system voltage magnitude increases higher than the voltage reference of this module by a certain value or if its reactive power value decreases to zero. The order of disconnection is sequential, in decreasing order of the module number.

To verify the proposed principles of multi-level voltage control of a self-excited IG, a dynamic simulation model of the Fig. 1 system with the number of VSC modules n=2 was developed. The asynchronous machine was simulated by the 4th order model [8]. The IG fixed speed operation was assumed. The VSC was modeled by idealized switches "transistor-reverse diode" with possibility of current conduction in both directions.

To control the RMS voltage value of the system, an IG stator voltage oriented hysteresis current vector control technique of the IG was developed. The technique provides simultaneous control of the IG stator voltage and DC-side voltage magnitudes of the VSC modules (Fig. 2). The voltage oriented vector control technique has been used heretofore for a single-module converter control [9, 10].

The control signals of electronic switches for *i-th* VSC module are formed by hysteresis controllers as a result of subtraction the instantaneous actual currents $i_{A\_i}, i_{B\_i}, i_{C\_i}$ and phase current references $i^*_{A\_i}$, $i^*_{B\_i}$, $i^*_{C\_i}$ of this module. The voltage vector angle of the system is evaluated by the PLL (phase locked loop) block using instantaneous values of the system phase voltages u_A, u_B, u_C. The operation of each module, except the first one (VSC1), can be blocked if the value of the p.u. system voltage amplitude $u_{mp.u.}$ is higher than the value of the switching threshold of this module, which is equal to $u^*_{m\_1} - \left(u^*_{m\_1} - u^*_{m\_n}\right)(i-1.5)/n$, where $u^*_{m\_1}$, $u^*_{m\_n}$ are the AC system voltage reference amplitudes of the 1st and *n*th module, *i* – module number, *n* – total number of modules. Equations of AC and DC voltage controllers of the modules are of the following form:

$$i^*_{d\_1u} = k_1\tilde{u}_{m\_1} + \int k_2\tilde{u}_{m\_1}dt\,;\; i^*_{d\_1} = sat\Big|_{Id\_1l}^{Id\_1h}\left(i^*_{d\_1u}\right), \quad (1)$$

$$i^*_{q\_iu} = -C_{0i}(k_3\tilde{u}_{d\_i} + \int k_4\tilde{u}_{d\_i}dt)/k_5\,;\; i^*_{q\_i} = sat\Big|_{Iq\_il}^{Iq\_ih}\left(i^*_{q\_iu}\right),\; i=1\ldots n, \quad (2)$$

$$i^*_{d\_iu} = k_1\tilde{u}_{m\_i} + \int k_2\tilde{u}_{m\_i}dt\,;\; i^*_{d\_i} = sat\Big|_{0}^{Id\_ih}\left(i^*_{d\_iu}\right),\; i=2\ldots n, \quad (3)$$

where k_1, k_2, k_3, k_4, k_5 are constants; *sat* is a signal saturation function limiting input signal to lower and upper limit; Id_ih is the upper limit level of the AC voltage controller of the VSC*i* module; $Id\_1l < 0$ is the lower limit level of the AC voltage controller of the VSC1 module; Iq_ih, Iq_il are the upper and lower limit level of the DC voltage controller of the VSC*i* module.

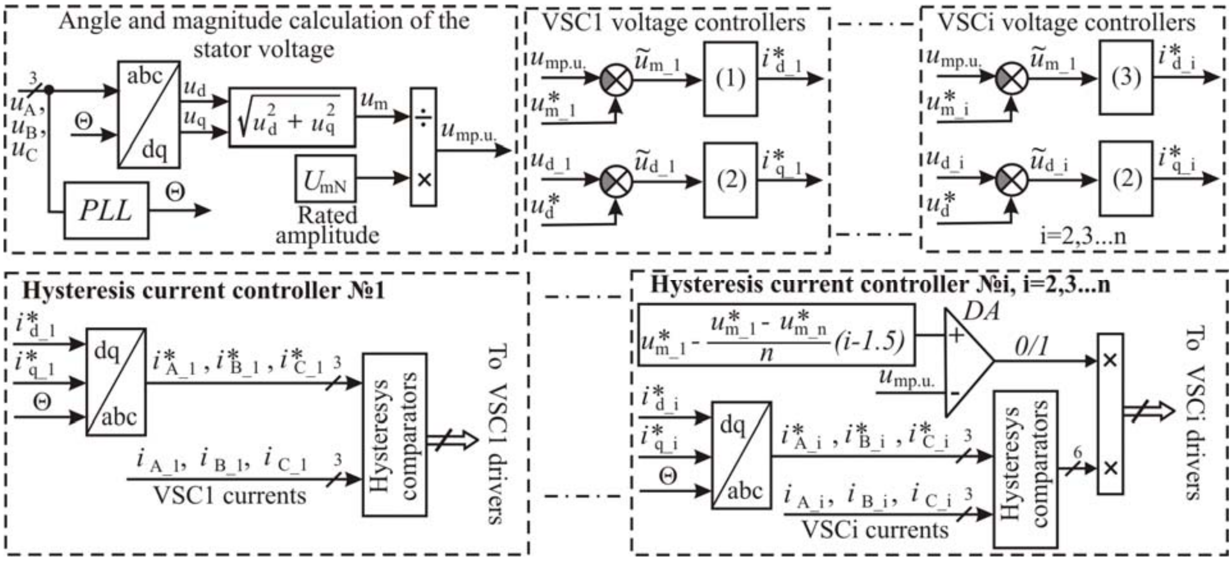

Fig. 2

The main specifications and parameters used in the simulation are as follows.

Induction generator. Pole pairs number – 2; rated power/voltage/frequency (connection): 275 kVA/400 V/50 Hz (Y connected); stator/rotor resistance: 0.016/0.015 p.u.; stator, rotor leakage inductance: 0.06 p.u.; inertia constant (combined IG and WT): 2 s; friction factor: 0 N·m·s/rad. The magnetization characteristic of the IG is given in the table below (397 A = 1 p.u. of phase current; 400 V=1 p.u. of line voltage).

Phase current [p.u.]	0.13	0.25	0.34	0.46	0.7	1.02	1.43	2.03	2.76
Line voltage [p.u.]	0.67	0.86	0.96	1.05	1.15	1.25	1.34	1.44	1.5

AC capacitors. Rated power/voltage (connection): 115 кВА/400В (Y_n connected).

Load. Power factor of the local (main) load: 0.707. Rated power/power factor of the HPP auxiliary load: 2.5 кВт/1.

PEC. Number of modules – 2. Inductance/resistance of inductors: 0.0004 H/0.024 Ω. Capacity of DC side capacitors: $C_{01} = C_{02}$=10 F. Parameters of controllers: k_1=1156, k_2=52000, k_3=20, k_4=100, k_5=1.5, Id_1l=-70 A, Id_1h=70 A, Id_2h=70 A, $u^*_{m\_1}$=1.04 p.u., $u^*_{m\_2}$=1 p.u.

The electromechanical processes shown in Fig. 3 demonstrate the system's response to a step up power demand increase of the local (main) load.

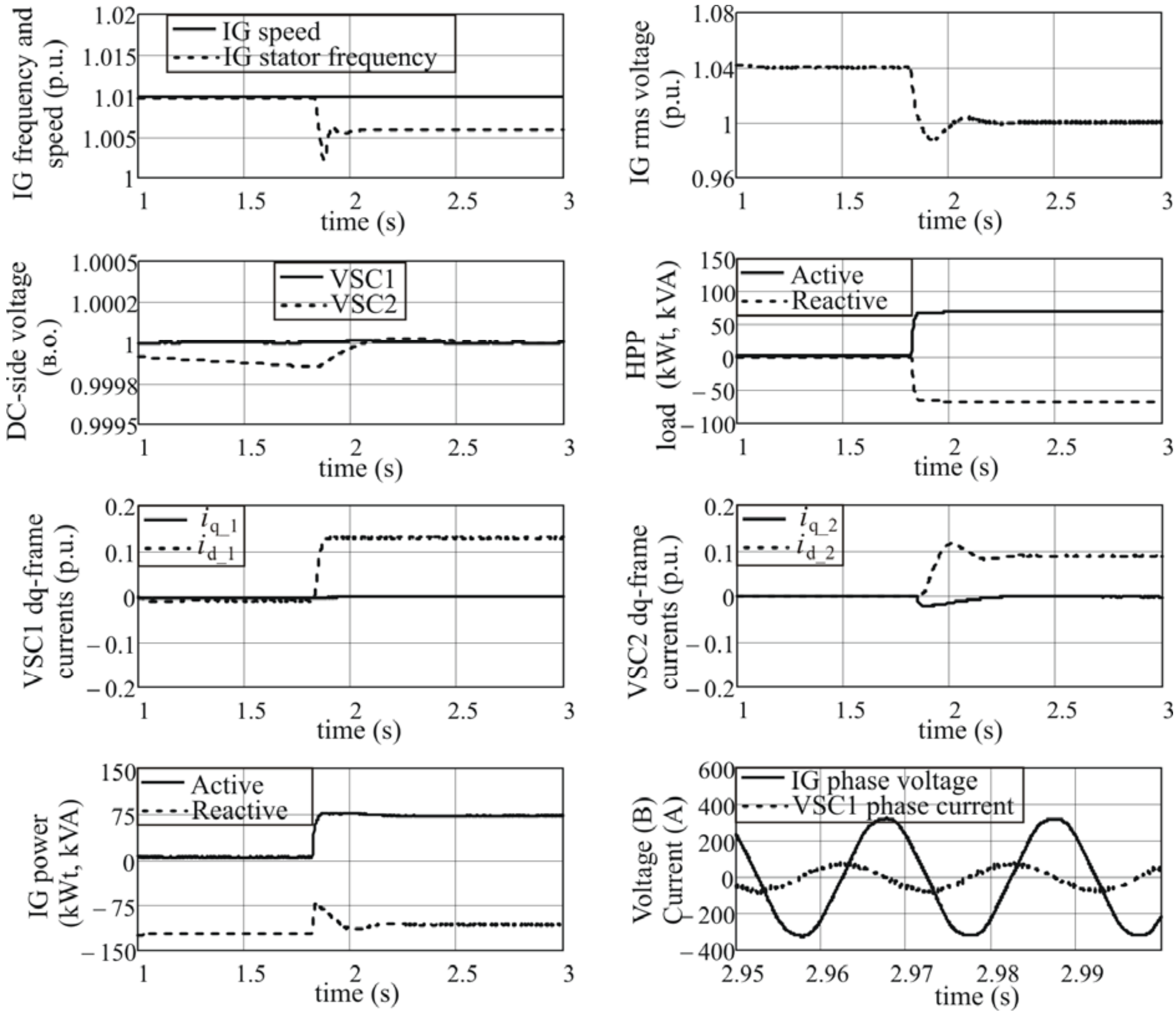

Fig. 3

Until the moment of time 1.82 s, the HPP supplied electric energy to the auxiliary load of 2.5 kW power rating, and total power of the main load was close to zero value. Accordingly, the value of the p.u. electrical frequency of the system was somewhat lower (by 0.03%) than the p.u. value of the IG rotor speed (1.01 p.u.). The value of the RMS voltage of the system was equal to $u^*_{m\_1}$=1.04 p.u. with no steady state error observed. The operation of the VSC2 module was stopped due to the value of the current i_{d_1}= -0.01 p.u. being lower than the Id_1h value. As the VSC2 switches were turned off, the VSC2 DC side voltage magnitude was a bit lower that the VSC1 DC side voltage magnitude.

At the time of 1.82 s, the active and reactive power consumption by the local (main) load was increased by 67.5 kW and 67.5 kVA, respectively. As a result, the IG active power value increased and a decrease in both the frequency and voltage magnitude of the system was observed. The i_{d_1} current component value reached the upper limit level of 0.129 p.u.=70 A, however, since the nominal value of the VSC1 reactive power was not enough to compensate for the reactive power demand of the load, the system voltage fell below of the 1.02 p.u. value. This, in turn, caused the start of the operation of the second PEC module (VSC2). Upon the transient time due to the increase in the i_{d_2} current component to 0.09 p.u. value, the RMS voltage in the system settled at the 1 p.u. value, and the electric frequency – at the value of 1.0058 p.u. The VSC1 and VSC2 DC voltage magnitudes settled at the 1 p.u. value. On Fig. 3 oscillograms, 1 p.u. of speed = 157.08 rad/s; 1 p.u. of electrical frequency = 314.16 rad/s; 1 p.u. of the IG phase RMS voltage = $400/\sqrt{3}$ V; 1 p.u. of DC side voltage=770 V; 1 p.u. of the VSC1 and VSC2 current components=543 A.

It can be seen from the Fig. 3 that at the end of the simulation time, a 90° positive phase shift between the VSC1 phase current curve and the IG phase voltage curve is settled in agreement to the theory of electromechanical systems.

Conclusions. The results of numerical investigations confirmed the effectiveness of the proposed principles of multi-level voltage control of the autonomous power supply system developed using a three-phase fixed speed IG, a CB and a multi-modular VSC connected the IG stator winding. The proposed algorithm of stator voltage oriented hysteresis current vector control of IG connected to multi-modular VSC provides a multi-stage drooping external characteristic of IG with no static error within every load range with a fixed number of operating modules. The main advantages of using multi-modular VSCs and the proposed principles of multi-level voltage control of autonomous IG are as follows:

1. The possibility of using converters of standard power ratings;
2. Due to the different voltage references, there is no coupling (disrupting interactions) between voltage controllers of VSC modules and a highly effective generator voltage control is achieved;
3. Due to the variable number of functioning modules, their life time is extended.

Роботу виконано за держбюджетною темою "Розвиток теоретичних засад створення та розроблення засобів підвищення енергоефективності та надійності комбінованих систем електроживлення з різними типами генераторів при роботі в автономному режимі і на мережу» («Енергосист-3», державний реєстраційний номер 0121U100509, КПКВК 6541030).

1. Hernández-Mayoral E., Dueñas-Reyes E., Iracheta-Cortez R., Campos-Mercado E., Torres-García V., Uriza-Gosebruch R. Modeling and Validation of the Switching Techniques Applied to Back-to-Back Power Converter Connected to a DFIG-Based Wind Turbine for Harmonic Analysis. *Electronics*. 2021. Vol. 10(23). Article no 3046. Pp. 1-29. DOI: https://doi.org/10.3390/electronics10233046.

2. Shapoval I.A., Mykhalskyi V.M., Artemenko M.Y., Chopyk V.V., Polishchuk S.Y. Compensation of Current Harmonics by Means of Grid-Side Converter in Doubly-Fed Induction Generator Based Wind Energy System. IEEE 6th International Conference on *Energy Smart Systems (ESS)*, Kyiv, Ukraine, 17-19 April 2019. Pp. 227-232. DOI: https://doi.org/10.1109/ESS.2019.8764226.

3. Goel P.K., Singh B., Murthy S.S., Kishore N. Isolated Wind–Hydro Hybrid System Using Cage Generators and Battery Storage. *IEEE Transactions on Industrial Electronics*. 2011. Vol. 58. No 4. Pp. 1141-1153. DOI: https://doi.org/10.1109/TIE.2009.2037646.

4. Shurub Y., Morozov-Leonov O. Determination of Admissible Power and Digital Filtering Algorithm Development of Discretely Regulated Autonomous Induction Generators. IEEE 4th KhPI Week on *Advanced Technology (KhPIWeek)*, Kharkiv, Ukraine, 02-06 October 2023. Pp. 1-5. DOI: https://doi.org/10.1109/KhPIWeek61412.2023.10312955.

5. Mazurenko L.I., Dzhura O.V., Romanenko V.I., Bilyk O.A. Numerical investigation of induction generators with two stator windings in welding complexes with pwm current regulators. *Tekhnichna Elektrodynamika.* 2012. No 3. Pp. 83-84. (Ukr)

6. Toledo S., Rivera M., Maqueda E., Ayala M., Pacher J., Romero C., Gregor R., Dragicevic T., Wheeler P. Multi-modular scalable DC-AC power converter for current injection to the grid based on predictive voltage control. IEEE 15th *Brazilian Power Electronics* Conference and 5th IEEE *Southern Power Electronics* Conference *(COBEP/SPEC)*, Santos, Brazil, 01-04 December 2019. Pp. 1-6. DOI: https://doi.org/10.1109/COBEP/SPEC44138.2019.9065887.

7. Mazurenko L.I., Dzhura O.V., Kotsiuruba A.V., Shykhnenko M.O. A Wind-Hydro Power System Using a Back-to-Back PWM Converter and Parallel Operated Induction Generators. *IEEE Problems of Automated Electrodrive. Theory and Practice (PAEP)*, Kremenchuk, Ukraine, 21-25 September 2020. Pp. 1-5. DOI: https://doi.org/10.1109/PAEP49887.2020.9240777.

8. Paul C. Krause, Oleg Wasynczuk, Scott D. Sudhoff. Analysis of Electric Machinery and Drive Systems. Wiley-IEEE Press, 2002. 632 p. DOI: https://doi.org/10.1109/9780470544167.

9. Juan juan Sun, Yongdong Li. Voltage-oriented vector control of induction motor: principle and performance improvement. Proceedings of the *Power Conversion* Conference-*Osaka 2002 (Cat. No.02TH8579)*, Osaka, Japan, 02-05 April 2002. Vol. 3. Pp. 1340-1345. DOI: https://doi.org/10.1109/PCC.2002.998168.

10. Shibani Prasad Mohapatra, Pradipta Kishore Dash. A novel control strategy of a variable-speed doubly-fed-induction-generator-based wind energy conversion system. *Clean Energy.* 2024. Vol. 8. Issue 1. Pp. 153-170. DOI: https://doi.org/10.1093/ce/zkad074.

УДК 621.313.332

КЕРУВАННЯ АВТОНОМНИМ АСИНХРОННИМ ГЕНЕРАТОРОМ З ВЕНТИЛЬНО-КОНДЕНСАТОРНОЮ СИСТЕМОЮ РЕГУЛЮВАННЯ РЕАКТИВНОЇ ПОТУЖНОСТІ НА ОСНОВІ БАГАТОМОДУЛЬНОГО ПЕРЕТВОРЮВАЧА

Л.І. Мазуренко[1], докт. техн. наук, **О.В. Джура[1]**, канд. техн. наук, **М.О. Шихненко[1]**, канд. техн. наук, **С.М. Коротін[2]**, канд. техн. наук
[1] Інститут електродинаміки НАН України,
просп. Берестейський, 56, Київ, 03057, Україна. **E-mail: 3662491@gmail.com.**
[2] Національний університет оборони імені Івана Черняховського,
просп. Повітряних Сил, 28, Київ, 03049, Україна.

Запропоновано принципи багаторівневої стабілізації напруги автономної системи електроживлення, реалізованої на основі трифазного асинхронного генератора стабілізованої частоти обертання з вентильно-конденсаторним регульованим джерелом реактивної потужності в колах статора, що містить багатомодульний вентильний перетворювач і батарею конденсаторів. Для регулювання напруги зазначеної системи розроблено алгоритм векторного керування по результуючому вектору напруги статора генератора. З використанням розробленої імітаційної динамічної моделі для верифікації ефективності запропонованих принципів стабілізації напруги та векторного алгоритму регулювання генератора проведено чисельні дослідження електромеханічних процесів в системі за активно-індуктивного характеру навантаження. Відзначено основні переваги застосування багатомодульних вентильних перетворювачів в автономних системах електроживлення? побудованих на основі асинхронного генератора з к.з. ротором і вентильно-конденсаторною системою регулювання реактивної потужності в колах статора. Бібл. 10, рис. 3, табл. 1.

Ключові слова: багатомодульний перетворювач, асинхронний генератор, багаторівнева стабілізація напруги.

1. Hernández-Mayoral E., Dueñas-Reyes E., Iracheta-Cortez R., Campos-Mercado E., Torres-García V., Uriza-Gosebruch R. Modeling and Validation of the Switching Techniques Applied to Back-to-Back Power Converter Connected to a DFIG-Based Wind Turbine for Harmonic Analysis. *Electronics*. 2021. Vol. 10(23). Article no 3046. Pp. 1-29. DOI: https://doi.org/10.3390/electronics10233046.
2. Shapoval I.A., Mykhalskyi V.M., Artemenko M.Y., Chopyk V.V., Polishchuk S.Y. Compensation of Current Harmonics by Means of Grid-Side Converter in Doubly-Fed Induction Generator Based Wind Energy System. IEEE 6th International Conference on *Energy Smart Systems (ESS)*, Kyiv, Ukraine, 17-19 April 2019. Pp. 227-232. DOI: https://doi.org/10.1109/ESS.2019.8764226.
3. Goel P.K., Singh B., Murthy S.S., Kishore N. Isolated Wind–Hydro Hybrid System Using Cage Generators and Battery Storage. *IEEE Transactions on Industrial Electronics*. 2011. Vol. 58. No 4. Pp. 1141-1153. DOI: https://doi.org/10.1109/TIE.2009.2037646.
4. Shurub Y., Morozov-Leonov O. Determination of Admissible Power and Digital Filtering Algorithm Development of Discretely Regulated Autonomous Induction Generators. IEEE 4th KhPI Week on *Advanced Technology (KhPIWeek)*, Kharkiv, Ukraine, 02-06 October 2023. Pp. 1-5. DOI: https://doi.org/10.1109/KhPIWeek61412.2023.10312955.
5. Мазуренко Л.І., Джура О.В., Романенко В.І., Білик О.А. Розрахункове дослідження асинхронних генераторів з двома статорними обмотками в складі зварювальних комплексів з широтно-імпульсними регуляторами струму. *Технічна електродинаміка*. 2012. № 3. С. 83–84.
6. Toledo S., Rivera M., Maqueda E., Ayala M., Pacher J., Romero C., Gregor R., Dragicevic T., Wheeler P. Multi-modular scalable DC-AC power converter for current injection to the grid based on predictive voltage control. IEEE 15th *Brazilian Power Electronics* Conference and 5th IEEE *Southern Power Electronics* Conference *(COBEP/SPEC)*, Santos, Brazil, 01-04 December 2019. Pp. 1-6. DOI: https://doi.org/10.1109/COBEP/SPEC44138.2019.9065887.
7. Mazurenko L.I., Dzhura O.V., Kotsiuruba A.V., Shykhnenko M.O. A Wind-Hydro Power System Using a Back-to-Back PWM Converter and Parallel Operated Induction Generators. *IEEE Problems of Automated Electrodrive. Theory and Practice (PAEP)*, Kremenchuk, Ukraine, 21-25 September 2020. Pp. 1-5. DOI: https://doi.org/10.1109/PAEP49887.2020.9240777.
8. Paul C. Krause, Oleg Wasynczuk, Scott D. Sudhoff. Analysis of Electric Machinery and Drive Systems. Wiley-IEEE Press, 2002. 632 p. DOI: https://doi.org/10.1109/9780470544167.
9. Juan juan Sun, Yongdong Li. Voltage-oriented vector control of induction motor: principle and performance improvement. Proceedings of the *Power Conversion* Conference-*Osaka 2002 (Cat. No.02TH8579)*, Osaka, Japan, 02-05 April 2002. Vol. 3. Pp. 1340-1345. DOI: https://doi.org/10.1109/PCC.2002.998168.
10. Shibani Prasad Mohapatra, Pradipta Kishore Dash. A novel control strategy of a variable-speed doubly-fed-induction-generator-based wind energy conversion system. *Clean Energy.* 2024. Vol. 8. Issue 1. Pp. 153-170. DOI: https://doi.org/10.1093/ce/zkad074.

Надійшла 15.05.2024
Остаточний варіант 04.07.2024