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CURRENT CONTROL OF Z-SOURCE FOUR-LEG INVERTER FOR AUTONOMOUS PHOTOVOLTAIC SYSTEM BASED ON MODEL PREDICTIVE CONTROL

Mohamed T. Boussabeur[1],
boussabeur-mtayeb@univ-eloued.dz

Djaafar Toumi[1],
toumi-djaafar@univ-eloued.dz

Boualaga Rabhi[2],
Boualaga@yahoo.fr

Laid Zellouma[1],
Zellouma13@yahoo.fr

Raef Aboelsaud[3],
rsahmed@eng.zu.edu.eg

Alexander G. Garganeev[4],
Garganeev@rambler.ru

Ahmed Ibrahim[4],
ibragim@tpu.ru

[1] University of El-Oued,
48, El Oued street, El-Oued, 39000, Algeria.

[2] University of Biskra,
145, Shagar street, Biskra, 7044, Algeria.

[3] Zagazig University,
90, University street, Zagazig, 44519, Egypt.

[4] National Research Tomsk Polytechnic University,
30, Lenin avenue, Tomsk, 634050, Russia.

The relevance. *Renewable energy resources for electrical power generation have gained higher interest over the traditional underground fuels due to geo-reasons, such as the low generation cost and clean energy resources. Moreover, renewable energy resources, especially photovoltaic generation system, can efficiently be used as an autonomous power supply for consumers geographically located in remote, inaccessible areas. The performance of autonomous power supply depends mainly on the conversion system and its control technique. Therefore, this paper uses a new and alternative control system based on the finite control set model predictive control strategy to control the load current of the Z-source four-leg inverter employed for the autonomous photovoltaic generation system.*
The main aim *of the research is the development of a control algorithm based on finite control set model predictive control strategy to regulate the load currents of Z-source four-leg inverter for a geographical stand-alone photovoltaic generation system.*
Methods: *mathematical and computer modeling using the MatLab/Simulink software environment.*
Results. *Due to using Z-source four-leg inverter, the power conversion system for the photovoltaic generation systems is reduced to be single-stage, instead of two-stage power conversion. The results show that the proposed control algorithm can effectively regulate load current under balanced/unbalanced issues with high controllability. The proposed control algorithm has excellent steady-state and transient performances.*

Key words:
Renewable energy resources, autonomous photovoltaic systems, model predictive control, four-leg inverter, Z-source inverter.

Introduction

Renewable energy resources (RER), such as photovoltaic, wind, and geothermal power systems have gained higher interest over the traditional underground fuels because these energy resources have low generation cost and no pollution. Due to the fact that the solar energy resource is the most geographically available in the world, the photovoltaic (PV) generation system, can efficiently be used as an autonomous power supply (APS) for consumers geographically located in remote, inaccessible areas. The performance of the stand-alone PV systems depends mainly on the power converter topologies and their control structures [1]. Generally, two-stage power conversion is performed to transfer the electric power from DC PV modules to the AC loads [2–5]. The power converter in the first stage is employed to boost the DC voltage and extract the maximum power from the PV modules [6, 7], while the second conversion stage uses the power DC-AC inverter to convert from DC to AC and to control the load voltage or load current [8, 9]. On the other hand, the Z-source inverter (ZSI) topology is proposed as an alternative power converter topology for PV systems [10–13]. The ZSI can combine the functions of the two-stage conversion system in a one-stage system with a lower number of power electronics switches [14, 15].

The unbalanced loads of the stand-alone power supply system can cause unbalancing and harmonic distortion in the load voltage [8, 16]. The Z-source four-leg inverter (ZSFLI) topology has been proposed to handle this issue. ZSFLI provides a neutral wire for circulating the unbalanced current under unbalanced load conditions [17]. With proper control, the ZSFLI can regulate the load current or voltage in high power quality regardless of the loads unbalancing issues.

The control of the power converter plays a vital role in the stand-alone power supply system [18–20]. In literature, a number of control techniques have been proposed to control the four-leg inverter and the ZSI. Recently, the Finite Control Set Model Predictive Control (FSMPC) has gained high interest in the power electronics sphere due to its features. The FSMPC has provided direct control action to the converter switches without using the modulation stage. Moreover, the FSMPC has a rapid transient response and its algorithm is intuitive and can be easily modified and designed according to the control objective [8, 9].

This paper presents the FSMPC technique for ZSFLI to control the load current of the stand-alone PV system with high performance and quality, and also control the ZS network capacitor voltage. To achieve this goal, an accurate discrete-time model of the stand-alone PV system is derived to allow the FSMPC to perfectly predict and regulate its controllable signal. Simulation results are introduced to assure the effectiveness of the presented technique.

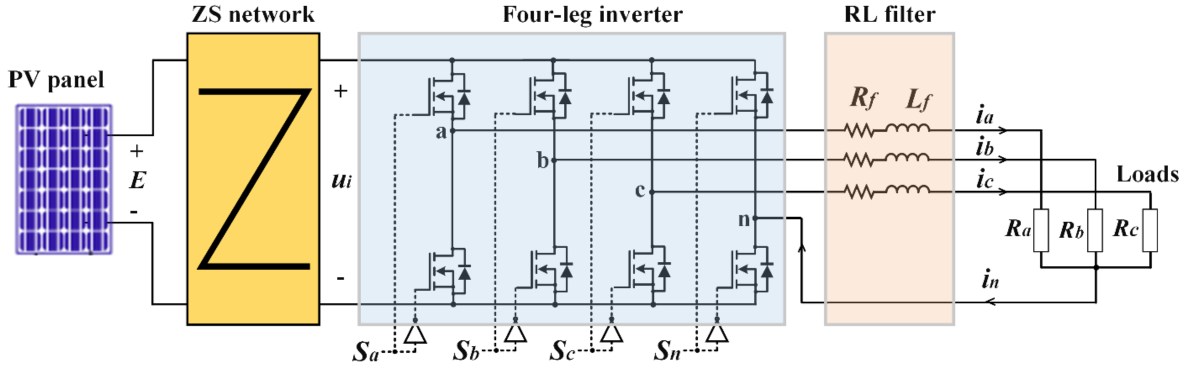

Fig. 1. *Stand-alone PV system with ZSFLI*
Рис. 1. *Автономная фотоэлектрическая система на основе Z-инвертора*

Mathematical model of the stand-alone PV system

The PV system under investigation, consisting of a ZSFLI, an RL-filter, and a load, is shown in Fig. 1. The ZSFLI has the ZS network which can be used instead of the dc-dc converter in traditional two-stage power conversion. The PV module in the PV system can be considered as an ideal source.

Mathematical model of ZS network

The ZS network has two operation states [21]: non-shoot-through state and shoot-through state. The equivalent circuits of the ZS network with its states are shown in Fig. 2. The ZS network contains two inductors (L_1 and L_2) and two capacitors (C_1 and C_2) as it is shown in Fig. 2. For simplification, it can be assumed that two inductors have the same inductance and two capacitors have the same capacitance to make the ZS network symmetrical. This symmetry can be observed in the expression (1):

$$U_{C1}=U_{C2}=U_C;\ u_{L1}=u_{L2}=u_L. \tag{1}$$

In the shoot-through zero state, for the interval (T_0), during the switching cycle (T), two semiconductor switches in the same leg of the inverter are simultaneously closed to create short-circuit across the dc link. During this state, the inverter is modeled as a short circuit for the ZS network as it is shown in Fig. 2, *b*. In this case, energy is transferred in the ZS network from the capacitors to the inductors, resulting in boosting the dc voltage. From the equivalent circuit (Fig. 2, *b*) the inductor voltage (u_L), diode voltage (u_d), DC-link voltage (u_i) are expressed in (2):

$$u_L=U_C;\ u_d=2U_C;\ u_i=0. \tag{2}$$

The other normal states, where the switches of the same leg are not simultaneously closed, are considered as non-shoot-through states. The ZSFLI has 16 normal non-shoot-through states and one shoot-through zero state, while the traditional four-leg inverter has only the normal 16 states. In the non-shoot-through state for the interval (T_0), during the switching cycle (T), the inverter is modeled as a constant current source as depicted in Fig. 2, *c*. From the equivalent circuit, one can obtain expression (3):

$$u_L=E-U_C;\ u_d=E;\ u_i=U_C-u_L=2U_C-E, \tag{3}$$

where E is the DC voltage from the PV panel. The average voltage of the inductors over one switching period ($T=T_0+T_1$) across the inverter should be zero in steady-state, from (2) and (3), one has:

$$U_L=\frac{T_0U_C+T_1(E-U_C)}{T}, \tag{4}$$

$$\frac{U_C}{E}=\frac{T_1}{T_1-T_0}. \tag{5}$$

Similarly, the average dc-link voltage across the inverter bridge can be found in (6):

$$U_{i\_av}=\frac{T_0\times 0+T_1(2U_C-E)}{T}=\frac{T_1}{T_1-T_0}E=U_C. \tag{6}$$

The peak dc-link voltage across the inverter bridge is expressed in (3) and can be rewritten as in (7):

$$U_{i\_peak}=U_C-u_L=2U_C-E=\frac{T}{T_1-T_0}E=BU_C, \tag{7}$$

where

$$B=\frac{T}{T_1-T_0}=\frac{T}{1-2\dfrac{T_0}{T}}\geq 1 \tag{8}$$

is the boosting factor which is caused by the shoot-through zero state.

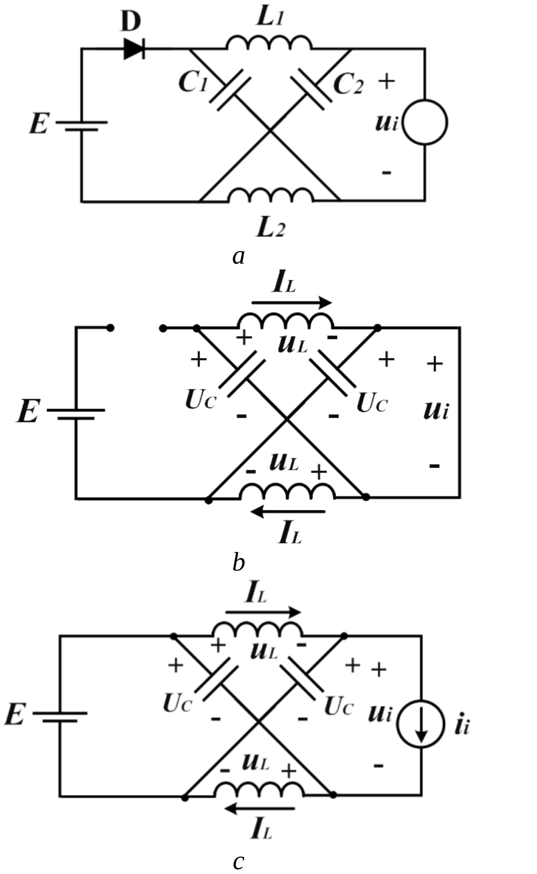

Fig. 2. *a) equivalent circuit of the Z-source inverter; b) in shoot-through zero states; c) in non-shoot-through state*

Рис. 2. *а) эквивалентная схема Z-инвертора при (b) нулевом состоянии переключения и (c) обычном состоянии переключения*

Mathematical model of the four-leg inverter

The four-leg inverter with RL-filter and loads is shown in Fig. 1. The output inverter voltage can be expressed in (9):

$$\left.\begin{aligned} u_{an} &= (S_a - S_n)u_i \\ u_{bn} &= (S_b - S_n)u_i \\ u_{cn} &= (S_c - S_n)u_i \end{aligned}\right\} \qquad (9)$$

by applying the Kirchhoffs voltage law to the output circuit of the inverter, the output inverter voltages can be expressed as in (10):

$$\left.\begin{aligned} u_{an} &= (R_{fa} + R_a)i_a + L_{fa}\frac{di_a}{dt} \\ u_{bn} &= (R_{fb} + R_b)i_b + L_{fb}\frac{di_b}{dt} \\ u_{cn} &= (R_{fc} + R_c)i_c + L_{fc}\frac{di_c}{dt} \end{aligned}\right\}. \qquad (10)$$

This equation can be expressed in (11):

$$u_j = (Rf_j + R_j)i_j + Lf_j\frac{di_j}{dt}, \qquad (11)$$

where j=a, b, c. Neutral current can be expressed as:

$$i_n = i_a + i_b + i_c. \qquad (12)$$

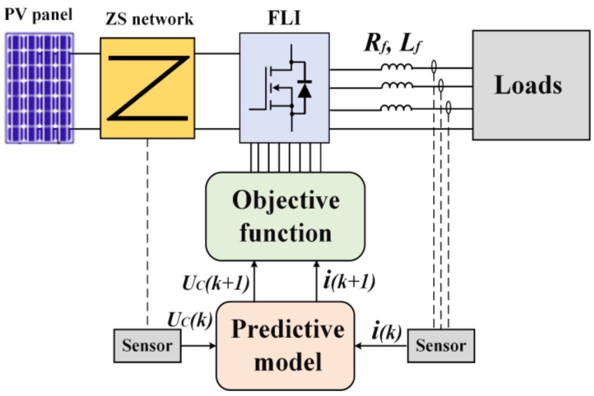

Fig. 3. *Block diagram of the proposed FSMPC for the stand-alone PV system*

Рис. 3. *Топологическая схема автономной фотоэлектрической системы на основе ПУ*

The proposed FSMPC

The block diagram of the proposed FSMPC scheme for the FLZSI is depicted in Fig. 3. This control technique can be considered as a digital control technique because its algorithm uses the discrete model of the system and is repeated for a determined sampling period (Ts). The proposed FSMPC algorithm uses the discrete predictive model of the PV system to predict the load current (i_j) and the voltage (U_C) and current (I_L) of the ZS network for a one-step prediction horizon (k+1), where k – sampling instant. This prediction is performed for each switching state of FLZSI. The objective function is used to select the best switching state that minimizes the error between the predicted currents and voltages values and the reference values. Finally, the selected switching state is applied to the inverter switches. The flow chart of this algorithm is depicted in Fig. 4.

The predictive model of the system

The predictive model is derived in two parts:

1) Predictive Model part (I):

This part is used to predict the load currents. From (11), the derivative value of load currents can be written as it is shown in (13):

$$\frac{di_j}{dt} = \frac{1}{Lf_j}[u_j - (Rf_j + R_j)i_j]. \qquad (13)$$

By using the forward Euler rule [22], the predicted load current for the next sampling instant (k+1) can be expressed as it is shown in (14):

$$i_j(k+1) = \frac{Ts}{L_f + (R_j + R_{fj})Ts}u_j(k+1) + \\ + \frac{Ts}{L_f + (R_j + R_{fj})Ts}i_j(k). \qquad (14)$$

2) Predictive Model part (II):

This part is used to predict the capacitor voltage of the ZS network (U_C). From the equivalent circuit of the ZS network shown Fig. 2, *a*, the ZS capacitor current can be expressed as it is shown in (15):

$$i_C = C\frac{dU_C}{dt}, \qquad (15)$$

where C is the capacitance of the ZS capacitor. From (15), the capacitor voltage can be derived as it is shown in (16):

$$\frac{dU_C}{dt} = \frac{1}{C}i_C. \qquad (16)$$

By using the forward Euler rule, the predicted value of the capacitor voltage for the next sampling instant (k+1) can be obtained as it is shown in (17):

$$U_C(k+1) = U_C(k) + \frac{Ts}{L}i_C(k), \qquad (17)$$

where $i_C(k)$ is ZS capacitor current for the present sampling instant (k) which depends on the states of the ZSFLI topology (non-shoot-through and shoot-through states):

a) for the non-shoot-through state:

$$i_C = I_L - (S_a i_a + S_b i_b + S_c i_c); \qquad (18)$$

b) for the shoot-through state:

$$i_C = -I_L. \qquad (19)$$

Objective function

The proposed FSMPC uses three objective functions combined in one multi-objective function: one objective function for the load current, and two other objective functions for ZS inductor current and capacitor voltage, respectively. The multi-objective function can be expressed as it is shown in (20):

$$g = g_i + \lambda g_C, \qquad (20)$$

where gi is the objective function of the load current and can be written as it is shown in (21):

$$g_i = [i_j^* - i_j(k+1)]^2, \qquad (21)$$

where j=a, b, c; i_j^* is the reference load current; g_C is the objective function of the ZS capacitor voltage and is expressed as it is shown in (23):

$$g_C = [U_C^* - U_C(k+1)]^2, \qquad (23)$$

where U_C^* is the reference ZS capacitor voltage. The weighting factor (λ) was determined by using the objective function classification technique that was is detailed explained in [23].

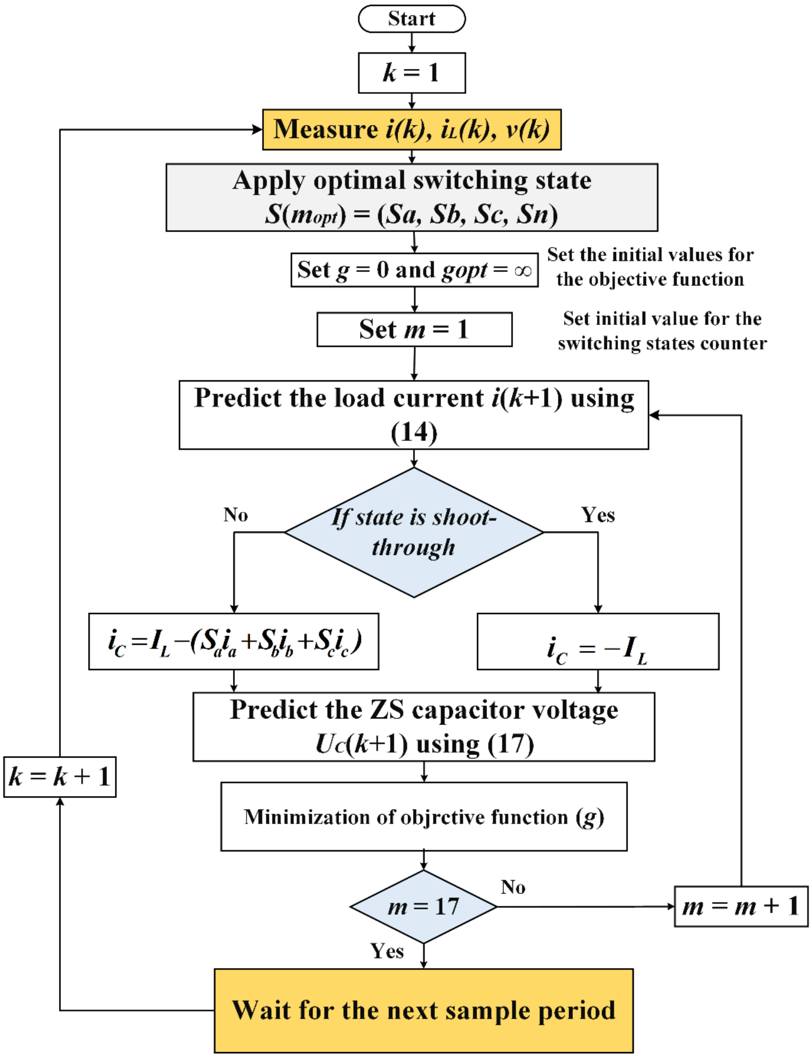

Fig. 4. Flowchart of the proposed FSMPC algorithm for FLZSI

Рис. 4. Блок-схема алгоритма прогнозирующего управления Z-инвертором

Proposed FSMPC algorithm

The flowchart for the proposed FSMPC algorithm is given in Fig. 4. The algorithm of the FSMPC can be summarized as follows:

- Measure the load currents, ZS inductor current, and ZS capacitor voltage.
- By using the predictive model, for each switching state, predict the load currents, ZS inductor current, and ZS capacitor voltage.
- For each switching state, evaluate the objective function (g).
- Select the best switching state that gives the minimum value for the objective function (g).
- Apply the switching state to the ZSFLI switches.

Results and discussion

To verify the theoretical analysis and confirm the proposed FSMPC technique of ZSFLI, simulation has been conducted with the configuration shown in Fig. 1 in Matlab/Simulink. The system parameters are given in Table.

Table. *System parameters*
Таблица. *Параметры системы*

Parameters/Параметры	Values/Значения
Output voltage of PV panel Выходное напряжение фотоэлектрической панели	V_{dc}=150–250 V
Reference capacitor voltage Эталонное напряжение конденсатора	U_C=635 V
ZS inductances Индуктивность индукторов Z-инвертора	L_1=L_2=L=1,5 mH
ZS capacitances Юмкость конденсатора	C_1=C_2=C=470 μF
Load resistance Сопротивление нагрузки	R=5–10 Ω
Filter parameters Параметры RL-фильтра	L_f=10 mH, R_f=0,05 Ω
Nominal frequency Номинальная частота	F=50 Hz
Sampling time Время выборки	T_s=20 μs

Three case studies are performed, two cases in the steady-state mode, and one case in the transient mode. In steady-state mode, the proposed FSMPC is used to control the ZSFLI with unbalanced references load currents (i_a^*=15 A, i_b^*=5 A, and i_c^*=15 A) in one case, and balanced references load currents (i_a^*=i_b^*=i_c^*=20 A) in another case, while the loads are unbalanced (Ra=5 Ω, Rb=10 Ω, and Rc=10 Ω) in the two cases. The results with balanced and unbalanced references load currents are shown in Fig. 5, *a*, *b*, respectively. From the results, it can be observed that the proposed FSMPC algorithm can regulate each phase current independently while the dc-link voltages are kept unchanged. The neutral current flows through the neutral wire when the load currents are unbalanced.

In transient mode, a step change is carried out for the reference load currents from 0 to 20 A. For this test, reference load currents and loads are balanced (Ra=Rb=Rc=10 Ω). From the results shown in Fig. 6, it can be observed that the FSMPC control technique has a very rapid transient reaction with a small overshoot. In this test, the neutral current is zero because the load current is balanced.

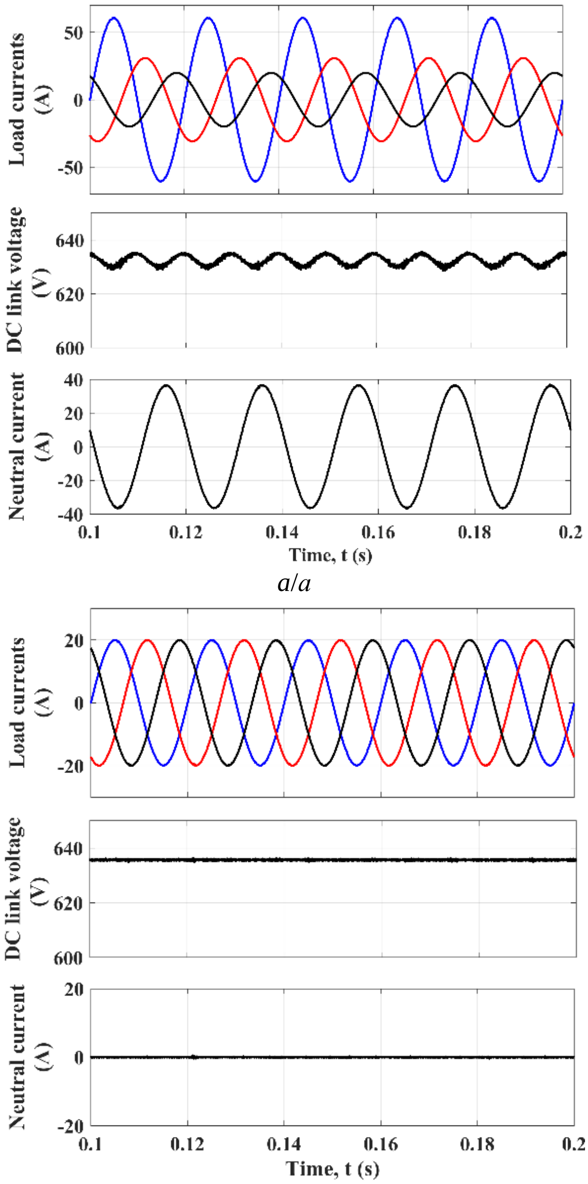

Fig. 5. *Steady state results with (a) unbalanced references of load current (b) balanced references of load current*

Рис. 5. *Результаты при статическом режиме (а) несбалансированными эталонами тока нагрузки (б) сбалансированными эталонами тока нагрузки*

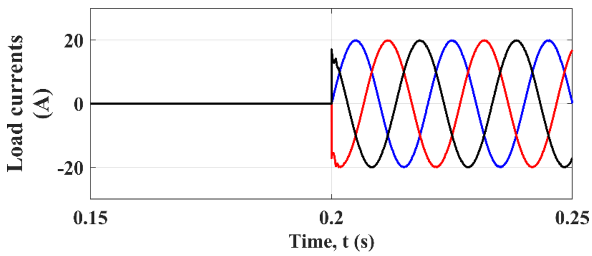

Fig. 6. *Load currents in transient mode*

Рис. 6. *Токи нагрузки при динамическом режиме*

Conclusion

This paper presents the FSMPC algorithm for current control of ZSFLI in the PV system. The main advantage of using ZSFLI is to achieve single-stage power conversion for PV generation systems with handling unbalanced issues with high controllability. The proposed FSMPC is used to regulate the load currents and the capacitor voltage of the ZS network. Case studies were performed to verify the performance of the ZS inverter topology of the proposed control strategy. The results show that the proposed technique has excellent steady-state and transient performances.

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Information about the authors

Mohamed T. Boussabeur, postgraduate student, University of El-Oued.
Boualaga Rabhi, Dr. Sc., professor, University of Biskra.
Raef Aboelsaud, Cand. Sc., associate professor, Zagazig University.
Ahmed Ibrahim, Cand. Sc., associate professor, Zagazig University.
Djaafar Toumi, postgraduate student, University of El-Qued.
Laid Zellouma, Dr. Sc., associate professor, University of El-Oued.
Alexander G. Garganeev, Dr. Sc., professor, National Research Tomsk Polytechnic University.

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УПРАВЛЕНИЕ ТОКОМ Z-ИНВЕРТОРА С ЧЕТВЕРТОЙ СТОЙКОЙ ДЛЯ АВТОНОМНОЙ ФОТОЭЛЕКТРИЧЕСКОЙ СИСТЕМЫ НА ОСНОВЕ ПРОГНОЗИРУЮЩЕГО УПРАВЛЕНИЯ

Мохамед Т. Буссабер[1],
boussabeur-mtayeb@univ-eloued.dz

Буалага Рабхи[2],
Boualaga@yahoo.fr

Раиф Абуэлсауд[3],
rsahmed@eng.zu.edu.eg

Ахмед Ибрагим[3],
ibragim@tpu.ru

Джаафар Туми[1],
toumi-djaafar@univ-eloued.dz

Лейд Зеллума[1],
Zellouma13@yahoo.fr

Гарганеев Александр Георгиевич[4],
Garganeev@rambler.ru

[1] Университет Эль-Куэд,
Алжир, 39000, Эль-Куэд, ул. Эль-Куэд, 48.

[2] Университет Бискры,
Алжир, 7044, Бискра, улица Шагар, 145.

[3] Загазигский университет,
Египет, 44519, Загазиг, пр. Университета, 90.

[4] Национальный исследовательский Томский политехнический университет,
Россия, 634050, г. Томск, пр. Ленина, 30.

Возобновляемые источники для производства электроэнергии вызывают больший интерес у учёных и исследователей по сравнению с традиционными источниками, работающими на основе использования углеводородного топлива. Одним из типов возобновляемых источников энергии, отвечающих реализации концепции «зеленая энергетика», являются фотоэлектрические системы, способные эффективно использоваться в качестве автономной системы электроснабжения для потребителей, географически расположенных в отдаленных, труднодоступных районах. Производительность автономной системы электроснабжения во многом определяется системой преобразования и ее алгоритмами управления. В статье рассмотрена новая и альтернативная система управления автономных фотоэлектрических станций, основанная на стратегии прогнозирующего управления напряжением и током нагрузки Z-инвертора с четвертой стойкой.

Цель: *разработка алгоритма, основанного на стратегии прогнозирующего управления, для регулирования токов нагрузки автономной фотоэлектрической системы электроснабжения.*

Методы: *математическое и компьютерное моделирование с использованием программной среды MatLab/Simulink.*

Результаты. *Благодаря использованию Z-инвертора система преобразования энергии для фотоэлектрических систем генерации сокращается до одноступенчатой структуры. Результаты показывают, что предложенный алгоритм управления может эффективно регулировать ток нагрузки при сбалансированных и несбалансированных нагрузках с высокой эффективностью управления. Предлагаемый алгоритм управления имеет отличные характеристики в установившихся и переходных режимах.*

Ключевые слова: *Возобновляемые источники энергии, автономные фотоэлектрические системы, управление с прогнозированием модели, инвертор с четвертой стойкой, Z- инвертор.*

Информация об авторах

Мохамед Т. Буссабер, аспирант кафедры электротехники лаборатории LEVRES, Университет Эль-Куэд.

Буалага Рабхи, доктор технических наук, профессор кафедры электротехники лаборатории LMSE, Университет Бискры.

Раиф Абуэлсауд, кандидат технических наук, доцент, кафедра электроэнергетики, Загазигский университет.

Ахмед Ибрагим, кандидат технических наук, доцент, кафедра электроэнергетики, Загазигский университет.

Джаафар Туми, аспирант, Исследовательская лаборатория VTRS, Университет Эль-Куэд.

Лейд Зеллума, доктор технических наук, доцент, кафедра электротехники, лаборатории LEVRES, Университет Эль-Куэд.

Гарганеев А.Г., доктор технических наук, профессор отделения электроэнергетики и электротехники Инженерной школы энергетики Национального исследовательского Томского политехнического университета.

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