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OPERATION OF FIVE-PHASE INDUCTION MOTOR WITH THREE-PHASE SUPPLY

DZIAŁANIE PIĘCIOFAZOWEGO SILNIKA INDUKCYJNEGO PRZY ZASILANIU TRÓJFAZOWYM

Abstract: Multiphase induction motors have recently gained attention in many applications where needed is high overall system reliability. Electrical machines with increased number of phases are being used primarily because of their safety and reliability comparing with three-phase induction machines. The additional phases compared to standard three–phase motors allow the creation of a rotating flux even in fault conditions. The control technique in post–fault situation must ensure operation of the induction machine. The paper deals with operation of five-phase induction motor in case three-phase supply.

Streszczenie: Wielofazowe silniki indukcyjne zyskały ostatnio na znaczeniu w wielu zastosowaniach, gdzie potrzebna jest wysoka ogólna niezawodność systemu. Maszyny elektryczne o zwiększonej liczbie faz są używane głównie ze względu na ich bezpieczeństwo i niezawodność w porównaniu z trójfazowymi maszynami indukcyjnymi. Dodatkowe fazy w porównaniu ze standardowymi silnikami trójfazowymi umożliwiają tworzenie wirującego strumienia nawet w warunkach uszkodzenia. Technika sterowania w sytuacji po zwarciu musi zapewniać działanie maszyny indukcyjnej. Artykuł dotyczy działania pięciofazowego silnika indukcyjnego w przypadku zasilania trójfazowego.

Keywords: *multiphase induction motor, five-phase induction motor, three-phase supply*
Słowa kluczowe: *wielofazowy silnik indukcyjny, pięciofazowy silnik indukcyjny, zasilanie trójfazowe*

1. Introduction

Multiphase electrical drives have been recently proposed for variable–speed applications (like electrical vehicles and traction), where some advantages (lower torque pulsations, higher overall system reliability, better power distribution per phase) can be better exploited [1]. Compared to three–phase drives, fault–tolerance may be the most interesting feature of multiphase drives because it allows the drive to operate after a fault occurs. Fault tolerant operation has been reported in squirrel cage induction machines [2 - 5]. An issue is the existence or non-existence of higher order spatial harmonics that lead to non–sinusoidal magneto–motive force in the induction machine air-gap. In concentrated–winding of the induction machine there are higher order spatial harmonics that allow torque enhancement in normal operation [6].

The advantage of the multi-phase motor is the improvement of the torque-speed characteristic by increasing the low speed torque more than 5 times than the three-phase induction motor [7]. Multi-phase motors have advantages such as lower torque pulsation, reduced current per phase without increasing the voltage per phase and reduction in the harmonic current [8 - 12]. Multi-phase induction motors are interesting as viable alternative solutions to a three-phase induction motor system for hybrid electrical vehicles, aircraft and ship propulsion applications [13]. Five-phase is the smallest phase number of multi-phase motor which is commonly used.

2. Mathematical description of 5-phase induction motor

The voltage equations of individual phases (A to E) of five phase induction machine are:

$$\begin{aligned} v_A &= \sqrt{2} \cdot V \cdot cos\left(\omega t\right) \\ v_B &= \sqrt{2} \cdot V \cdot cos\left(\omega t - 2\pi / 5\right) \\ v_C &= \sqrt{2} \cdot V \cdot cos\left(\omega t - 4\pi / 5\right) \\ v_D &= \sqrt{2} \cdot V \cdot cos\left(\omega t + 4\pi / 5\right) \\ v_E &= \sqrt{2} \cdot V \cdot cos\left(\omega t + 2\pi / 5\right) \end{aligned} \qquad (1)$$

where V is rms voltage.

The five-phase induction motor can be represented as a d-q-x-y-0 model [6]. Components d-q are responsible for power, torque and fluxes.

Components x-y cause losses in the machine. The zero component is only used to show machine as a power invariant after transformation. The transformation matrix (2) for stator is:

$$A_s=\sqrt{\frac{2}{5}}\cdot\begin{vmatrix} cos(\theta_s) & cos(\theta_s-\alpha) & cos(\theta_s-2\alpha) & cos(\theta_s+2\alpha) & cos(\theta_s+\alpha) \\ -sin(\theta_s) & -sin(\theta_s-\alpha) & -sin(\theta_s-2\alpha) & -sin(\theta_s+2\alpha) & -sin(\theta_s+\alpha) \\ 1 & cos(2\alpha) & cos(4\alpha) & cos(4\alpha) & cos(2\alpha) \\ 0 & sin(2\alpha) & sin(4\alpha) & -sin(4\alpha) & -sin(2\alpha) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{vmatrix} \quad (2)$$

where θ_s is the instantaneous angular position of the d-axis of the common reference frame with respect to the phase „A" magnetic axis of the stator and $\alpha = 2\pi / 5$.

The transformation of rotor variables (3) is performed using the same transformation expression, where θ_s is replaced with β:

$$A_R=\sqrt{\frac{2}{5}}\cdot\begin{vmatrix} cos(\beta) & cos(\beta-\alpha) & cos(\beta-2\alpha) & cos(\beta+2\alpha) & cos(\beta+\alpha) \\ -sin(\beta) & -sin(\beta-\alpha) & -sin(\beta-2\alpha) & -sin(\beta+2\alpha) & -sin(\beta+\alpha) \\ 1 & cos(2\alpha) & cos(4\alpha) & cos(4\alpha) & cos(2\alpha) \\ 0 & sin(2\alpha) & sin(4\alpha) & -sin(4\alpha) & -sin(2\alpha) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{vmatrix} \quad (3)$$

where β is the instantaneous angular position of the d-axis of the common reference frame with respect to phase „A" magnetic axis of the rotor.
The angles of transformation for stator and rotor quantities are related to the arbitrary speed of the selected common reference frame through

$$\theta_s = \int \omega_a \cdot dt \quad (4)$$

$$\beta = \theta_s - \theta = \int (\omega_a - \omega) \cdot dt \quad (5)$$

where ω is the instantaneous electrical angular speed of rotor rotation.
Provided that the machine equations are transformed into frame of references rotating at angular speed ω_a, the model of five phase induction machine with Stator side voltage equations in d- and q- reference frame are given as:

$$\begin{aligned} v_{ds} &= R_s \cdot i_{ds} - \omega_a \cdot \psi_{qs} + p \cdot \psi_{ds} \\ v_{qs} &= R_s \cdot i_{qs} + \omega_a \cdot \psi_{ds} + p \cdot \psi_{qs} \\ v_{xs} &= R_s \cdot i_{xs} + p \cdot \psi_{xs} \\ v_{ys} &= R_s \cdot i_{ys} + p \cdot \psi_{ys} \\ v_{0s} &= R_s \cdot i_{0s} + p \cdot \psi_{0s} \end{aligned} \quad (6)$$

Rotor side voltage equations in d- and q- reference frame are given as:

$$\begin{aligned} v_{dr} &= R_r \cdot i_{dr} - (\omega_a - \omega) \cdot \psi_{qr} + p \cdot \psi_{dr} \\ v_{qr} &= R_r \cdot i_{qr} + (\omega_a - \omega) \cdot \psi_{dr} + p \cdot \psi_{qr} \\ v_{xr} &= R_r \cdot i_{xr} + p \cdot \psi_{xr} \\ v_{yr} &= R_r \cdot i_{yr} + p \cdot \psi_{yr} \\ v_{0r} &= R_r \cdot i_{0r} + p \cdot \psi_{0r} \end{aligned} \quad (7)$$

Flux equations of stator side are given as:

$$\begin{aligned} \psi_{ds} &= (L_{1s} + L_m) \cdot i_{ds} + L_m \cdot i_{dr} \\ \psi_{qs} &= (L_{1s} + L_m) \cdot i_{qs} + L_m \cdot i_{qr} \\ \psi_{xs} &= L_{1s} \cdot i_{xs} \\ \psi_{ys} &= L_{1s} \cdot i_{ys} \\ \psi_{0s} &= L_{1s} \cdot i_{0s} \end{aligned} \quad (8)$$

Flux equations of the rotor side are given as:

$$\begin{aligned} \psi_{dr} &= (L_{1r} + L_m) \cdot i_{dr} + L_m \cdot i_{ds} \\ \psi_{qr} &= (L_{1r} + L_m) \cdot i_{qr} + L_m \cdot i_{qs} \\ \psi_{xr} &= L_{1r} \cdot i_{xr} \\ \psi_{yr} &= L_{1r} \cdot i_{yr} \\ \psi_{0r} &= L_{1r} \cdot i_{0r} \end{aligned} \quad (9)$$

In equations *(6) - (9)* the indices *s* and *r* identify stator and rotor variables/parameters. Symbols *R* and *L* stand for resistance and inductance, and symbols *v*, *i* and ψ denote voltage, current and flux.
In equations *(8)* and *(9)* $L_m=(5/2)M$ and *M* is the maximum value of the stator to rotor mutual inductance in the model of motor.
From the above equations *(6) - (9)* determined can be the torque and rotor speed as:

$$T_e = \frac{5}{2} \cdot \frac{P}{2} \cdot (\psi_{ds} \cdot i_{qs} + \psi_{qs} \cdot i_{ds}) \quad (8)$$

$$T_e = \frac{5}{2} \cdot P \cdot M \cdot (i_{dr} \cdot i_{qs} + i_{ds} \cdot i_{qr}) \quad (9)$$

$$\omega = \frac{P}{2 \cdot J} \cdot \int (T_e - T_L) \quad (10)$$

where *P* is the number of poles, *J* is the moment of inertia, T_L is load torque, T_e is electro-mechanical torque and ω is the rotor speed.
The d-q-0 model of five-phase induction motor in arbitrary reference frame is shown in Fig. 1.

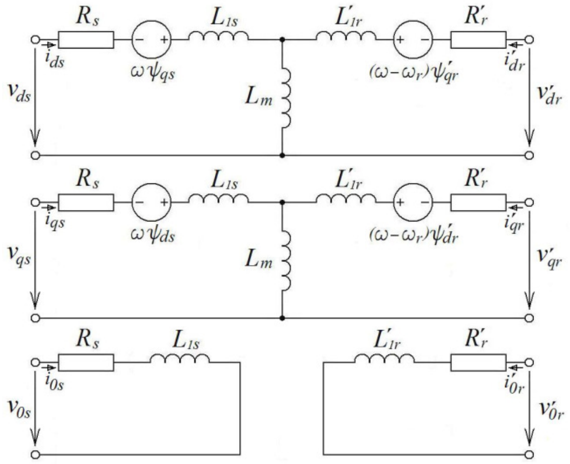

Fig. 1. An equivalent circuit of five phase Induction machine in d-q-0 axis

The steady state model and equivalent circuit of five-phase induction motor are useful for modeling the performance of the machine in steady state.

3. The drive with five-phase induction motor

The five-phase drive system consists of five-phase induction machine, five-phase inverter and a controller used to generate PWM. The three phase AC voltage is converted to DC either by uncontrolled or controlled rectifier. The ripple in the DC voltage is removed by using a LC filter in input of the DC-AC inverter. The inverter output voltage supply the five-phase induction machine. Complete arrangement of the block diagram is shown in Fig. 2.

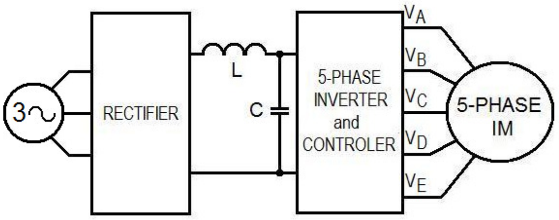

Fig. 2. Block diagram of five-phase induction motor drive

Windings of the five-phase induction motor housed in the stator are excited by five-phase inverter.

4. Electromagnetic and construction design of the five-phase induction motor

Similar to three-phase induction motor, five-phase induction motor works, when five-phase AC supply is given to the stator winding that are spatially and time displaced by 72°. The rotating magnetic field rotates at synchronous speed. In rotor (squirrel cage) an EMF is induced and due to this, current starts flowing in the rotor conductor and sets up its own magnetic field. Due to interaction of these two magnetic fields, a torque is produced [12].

Stator winding of a five-phase machine is designed in such a way that the spatial displacement between any two consecutive stator phases is 72 degrees (in this case a symmetrical machine results) as shown in Fig. 3 [6].

Electromagnetic design of five-phase induction motor was calculated and optimized in ANSYS/RMxprt program. Based on required electrical parameters designed in ANSYS/Maxwell program has been a 3D model of electromagnetic circuit of the motor.

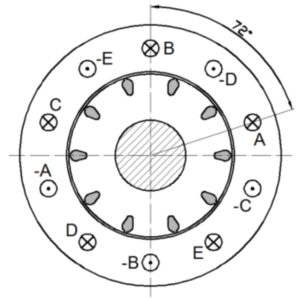

Fig. 3. Five-phase concentrated-winding induction motor

The construction and dimensions of the electromagnetic circuit of the five-phase induction motor are designed so that the electromagnetic circuit can be easily positioned and mounted onto a standard induction motor frame.

The main rated parameters of the five-phase induction motor are shown in Table 1.

Table 1. Main parameters of five-phase induction motor

Parameter	Value
Rated power	1500 W
Phase voltage	230 V
Rated current	6.2 A
Rated torque	5.0 N.m
Rated speed	2860 rpm
Number of poles	2

Based on structural design of the five-phase induction motor devised was the functional prototype as shown in Fig. 4 and Fig. 5.

The stator with windings of the five-phase induction motor is shown in Fig. 6 and the rotor is shown in Fig. 7.

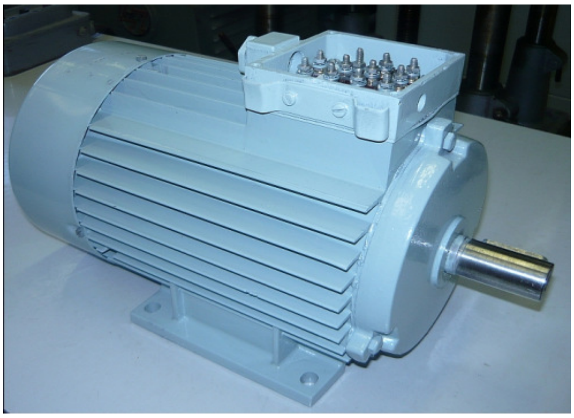

Fig. 4. The Five-phase induction motor prototype

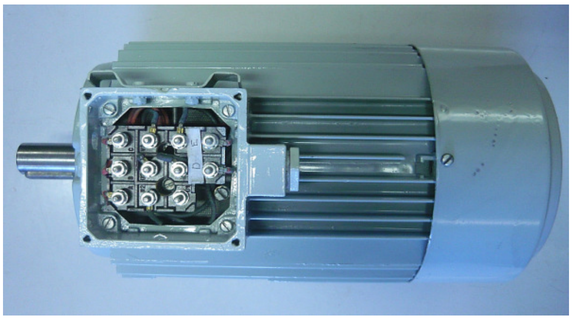

Fig. 5. The Five-phase induction motor prototype

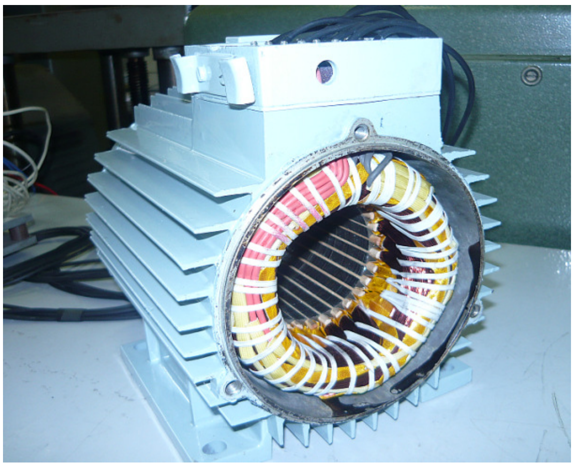

Fig. 6. The stator of five-phase induction motor prototype

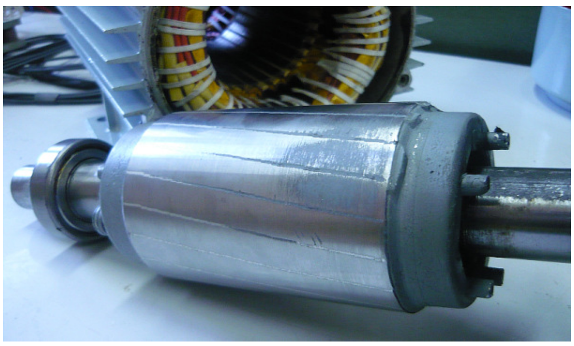

Fig. 7. The rotor of five-phase induction motor prototype

The parameters of five-phase induction motor are shown in Table 2.

Table 2. Main motor parameters

Parameter	Value
Stator resistance (R_s)	8.76 Ω
Rotor resistance (R_r)	0.1426 mΩ
Stator inductance (L_{1s})	39.8 mH
Rotor inductance (L_{1r})	54.2 mH
Magnetizing inductance (L_m)	142.9 mH

5. Measurement of Five-phase induction motor prototype in case of three-phase supply

When measuring five-phase induction machine in no-load condition the motor is connected to a three-phase symmetrical supply voltage of 100 V (RMS), with phase shift 120° and frequency of 50Hz.
The five-phase machine adopts stator winding connections in star, as shown in Fig. 8.

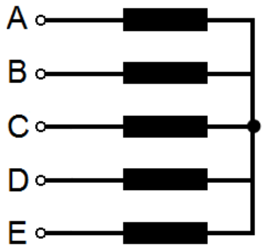

Fig. 8. The stator winding connection

In measurement with three-phase supply voltage (e.g. supply phases A, C and D) the five-phase induction machine operates as an unbalanced three-phase induction machine, where two adjacent phases are out of phase by 72° and the remaining phase is shifted from them by 144° electrical (Fig. 9).

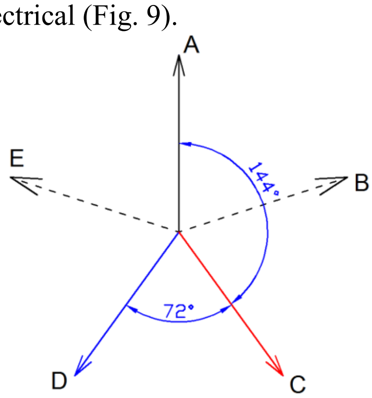

Fig. 9. The three-phase supply of five-phase induction machine (phases A, C and D)

Measured motor quantities (voltages, currents and power factors of individual phases) are shown in Table 3.

Table 3. Measured motor quantities

Phase	Voltage [V]	Current [A]	Power factor
A	100.4	2.319	0.423
C	101.6	3.729	0.469
D	100.5	2.395	0.719

Figure 10 show waveforms of voltages and currents in the individual phases of the five-phase induction machine for the rotation speed of 1004.8 rpm. When the five-phase induction machine is connected to a three-phase symmetrical supply voltage, the rotation speed is lowering (compared to five-phase supply, see [14]).

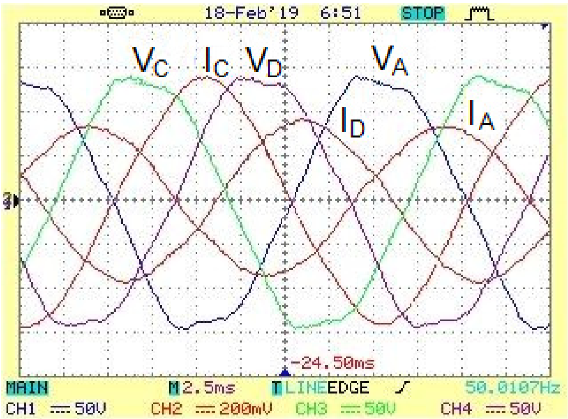

Fig. 10. Measured waveforms of voltages and currents

Frequency analysis of phase voltages is shown in Table 4.

Table 4. Frequency analysis of phase voltages (U_A, U_C, U_D)

Order	U_A [%H01]	U_C [%H01]	U_D [%H01]
3	3.4	3.2	3.2
5	3.9	3.4	3.9
7	0.9	1.1	0.8
9	0.2	0.3	0.3

Frequency analysis of phase current is shown in Table 5.

Table 5. Frequency analysis of phase currents (I_A, I_C, I_D)

Order	I_A [%H01]	I_C [%H01]	I_D [%H01]
3	2.0	3.2	1.9
5	2.0	1.3	2.0
7	0.2	0.3	-

In measurement with three-phase supply voltage of phases A, B and C the five-phase induction machine operates as an unbalanced three-phase induction machine, where three adjacent phases are shifted by 72° electrical (Fig. 11). For this three-phase power supply (phases A, B and C) the five-phase induction machine changes the direction of rotation. The rotation speed is 990.6 rpm.

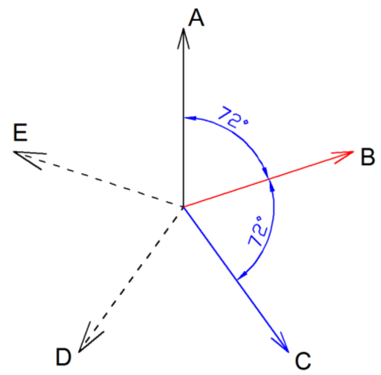

Fig. 11 The three-phase supply of five-phase induction machine (phases A, B and C)

Measured motor quantities (voltages, currents and power factors of individual phases A, B and C) are shown in Table.

Table 6. Measured motor quantities of individual phases A, B and C

Phase	Voltage [V]	Current [A]	Power factor
A	100.3	2.934	0.375
B	101.3	2.703	0.391
C	100.8	2.101	0.588

Figure 12 shows waveforms of voltages and currents in the individual phases of the five-phase induction machine for the supplied phases A, B and C.

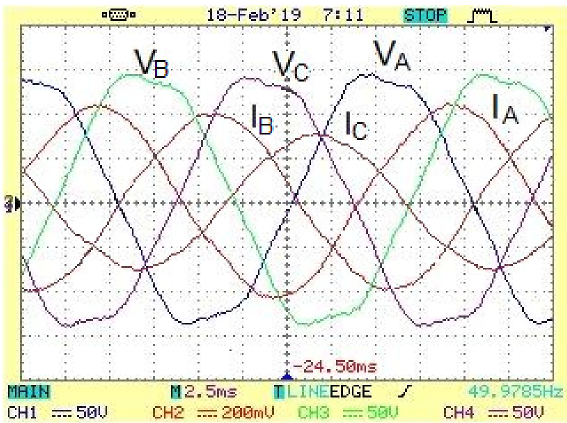

Fig. 12 Measured waveforms of voltages and currents for phases A, B and C

Frequency analysis of phase voltages is shown in Table 7 and frequency analysis of phase current is shown in Table 8.

Table 7. Frequency analysis of phase voltages (U_A, U_B, U_C)

Order	U_A [%H01]	U_B [%H01]	U_C [%H01]
3	3.7	3.6	0.3
5	4.1	1.4	-
7	0.8	0.2	-

Table 8. Frequency analysis of phase currents (I_A, I_B, I_C)

Order	I_A [%H01]	I_B [%H01]	I_C [%H01]
3	3.5	2.0	1.5
5	1.4	1.4	2.3
7	0.2	0.3	-

6. Conclusions

The advantages and drawbacks of the five-phase motor drive are as follow:

- The main advantages of using a five-phase motor drive are found in its reliability to operate properly also in faulty conditions. The five-phase induction machine can operate with one or two open circuited phases giving the drive a high tolerance to faults. In these cases are disconnected the faulty phases only, while other phases remain operating as in the normal working conditions.
- In all faulty cases, a proper current control strategy is required so as to limit the torque ripple, and this could be a mandatory requirement in several applications.
- To control the motor needed is a five-phase converter.

The five-phase induction machine has their uses in safety critical applications that require wide fault tolerant capabilities and higher system reliability such as, electric ships, hybrid vehicle, pumps, compressors, electric aircrafts. In naval applications high availability is a must [15]. With the higher number of phases the motor power is split across the phases, thus reducing the per-phase converter ratings, a highly desirable feature in medium-voltage applica-tions [16].

After a brief introduction and mathematical description this paper presents electro-magnetic and construction design of the five-phase induction machine with a single layer winding. The paper deals with initial measurement of five-phase induction machine in case of three-phase supply at reduced phases voltages. The further measurements (in no-load and load condition of motor) will be implemented upon completion of the manufacture of the five-phases inverter.

7. Acknowledgment

The financial support of the Slovak Research and Development Agency under the contract No. APVV-16-0270 is acknowledged.

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