Journal of Multidisciplinary Engineering Science and Technology (JMEST)
ISSN: 2458-9403
Vol. 11 Issue 2, February - 2024

Slip control, of three phase wound rotor induction electric machines, using rotating electronic devices

Petros Karaisas
Dep. of Electrical & Electronics Engineering
University of West Attica
Athens, Greece
karaisas@uniwa.gr

George Ioannidis
Dep. of Electrical & Electronics Engineering
University of West Attica
Athens, Greece
gioan@uniwa.gr

Avgeris Avgerinos
Dep. of Electrical & Electronics Engineering
University of West Attica
Athens, Greece
aavgerinos@uniwa.gr

Olympiada Syggeridou
Dep. of Electrical & Electronics Engineering
University of West Attica
Athens, Greece
osygger@uniwa.gr

***Abstract*—This manuscript provides an overview of the resent research, concerning rotor embedded electronic devices, as a method of controlling slip, on three phase wound rotor induction machines. Using shaft embedded power electronic devices on wound rotor induction machines, could lead to the elimination of the rings of these machines, providing an improved and maintenance free operation. This could be a major improvement and could be useful in many variable speed applications, such as high starting torque demanding applications, wind generators, electric vehicles, etc.**

Keywords— Induction motors; Electric vehicles; Slip ring motors; Wound rotor motors; Wind turbine generators; Power electronic controllers

I. INTRODUCTION

It is known, that three phase wound rotor induction machines, provide excellent mechanical and electrical characteristics, such as high starting torque, with reasonable low starting current. Besides these, three phase wound rotor induction machines, are quite robust and thus, a good choice for several applications, including automotive industry.

Despite these benefits, three phase wound rotor induction machines are rarely been used and most often they are used as motors, at very high torque demanding applications.

The reason is that these machines need slip rings for their operation, and thus, they need frequent maintenance. Besides this, the use of external resistors and the power loss on them, makes these machines quite inefficient, at low speed or variable speed operation. This problem can be solved, using doubly fed topologies or other slip power recovery topologies, but the main disadvantage of slip rings, still remains.

II. SLIP CONTROL, USING SHAFT EMBEDDED POWER ELECTRONIC DEVICES

Last years, many efforts have been made, for the elimination of the slip rings, of three phase wound rotor induction machines.

Starting from 2002, Avgeris Avgerinos proposed a method [1] for the elimination of the slip rings of the three phase wound rotor motor (3PhWRM). A patent apply was filed at the Hellenic Industrial Property Organization, proposing a 3PhWRM, having a rotating power electronic device mounted at the shaft of the rotor (Fig. 1). The power electronic device (part 4) was designed to be connected through a couple of electrically conductive bearings (parts 5 & 6) with the control device (part 7). These bearings were providing the small electrical power needed by the rotating power electronic device (part 4) and also the control signal for it's operation. The power circuit was only connected to the three phase winding of the rotor, adjusting rotor's current. There was not present any other electrical connection between the power electronic device and the grid, so slip rings were not needed any more.

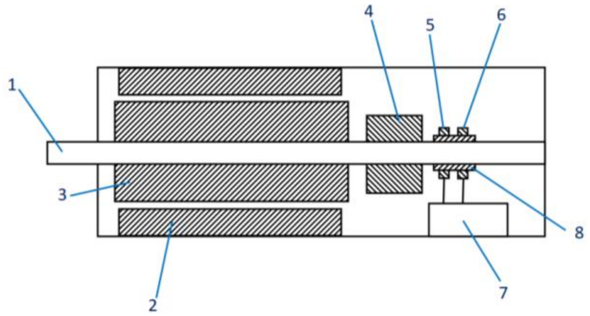

Fig. 1. *Patent apply #20020100420.*

Three different power electronic topologies were proposed for the power circuit, by Avgerinos, having all, advantages and drawbacks. The first one (Fig. 2), has been studied by A. Avgerinos, N. Trogadas and N. Margaris, as part of a research program [2], funded by the Technological Educational Institute of Larisa. This topology, was named “passive inverter topology”, because the inverter circuit was not connected to the grid. When all IGBTs are off, the circuit is behaving as a three phase rectifier bridge and the capacitor is been charged by the rotor’s windings, through the diodes. Once the capacitor is charged (a few hundred milliseconds after powering on motor’s stator), there is no current flow at the rotor, so the motor is not rotating. When the gates of the IGBTs are been driven by a proper SPWM signal, the motor is rotating.

The results of this study were announced at the day conference of the Technological Educational Institute of Larisa, on 16th of May 2005 [2]. Later experiments, conducted by Avgerinos, showed interesting parameters of the operation of a slip ring induction motor, with this topology, as, very high cosφ (very close to 1) and very stable speed of the motor, independent of load. A more detailed review of these results, is been given in this paper, at chapter III.

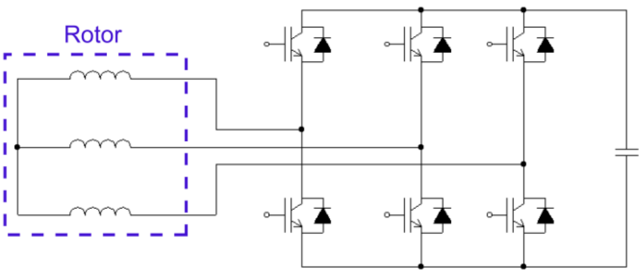

Fig. 2. *Passive inverter topology (A).*

The second proposed power electronic topology (Fig. 3), was consisting of three SCRs and three anti-parallel diodes.

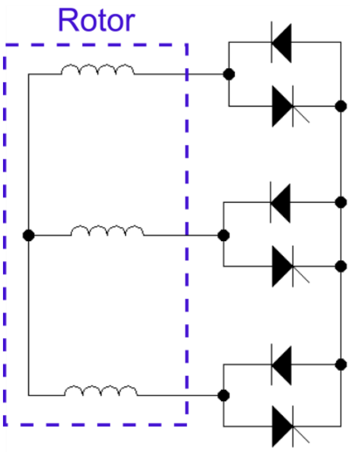

Fig. 3. *SCR & diodes topology (B).*

The third proposed power electronic topology (Fig. 4), was consisting of three TRIACs.

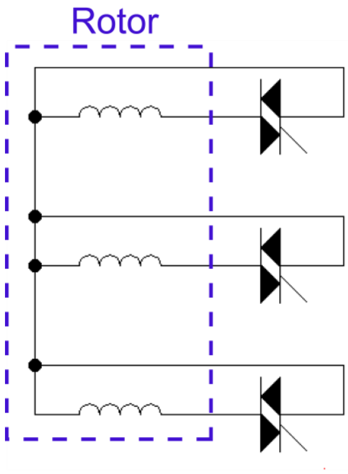

Fig. 4. *TRIAC topology (C).*

Both second and third topology, have the advantage over the first one, of needing no capacitor. This is important, because there is a high mechanical stress at the capacitor, when it is mounted at the rotating shaft. Furthermore, both SCRs and TRIACs are able to handle more power than IGBTs, with less switching losses. It is pointed out, that the third topology needs the star point, of rotor’s star connection windings, to be available.

On 2012, Yongsu Han [3], proposed the “Single External Feeding of Doubly-Fed Induction Generator (SEF-DFIG)”. This configuration was using the same topology as the passive inverter topology (three phase full bridge inverter and a capacitor), but his analysis was covering the operation of the machine at over synchronous speed (as a generator). Yongsu Han, showed, that this configuration could be very useful in wind turbines applications. Considering that adjustable speed wind energy conversion systems, are more efficient than fixed speed systems [4], [5], the above proposed topology could be used in high efficiency wind turbine generators. Yongsu Han also proposed, that part of the power that the capacitor was handling, could be used to supply power to the control circuit of the inverter, eliminating the need of the bearings that Avgerinos had proposed [1], to be used as a power supply of the rotating power electronic device.

On 2013, Yongsu Han [6] gave a more detailed description of the control method of SEF-DFIG. He also proposed a dual inverter topology, where both stator and rotor were been driven by two separate inverter units.

On 2014, he studied the above method in a wound rotor machine, fed by a single phase grid [7].

On 2015, Kahyun Lee proposed a machine, having a single phase stator and a three phase rotor winding [8]. This configuration could be useful in applications where only single phase grid is available [9], [10], due to the high cost of a three phase grid. This is a very common situation at domestic applications [11].

On 2019, Jan Pötter proposed a method [12] for the brushless excitation of the synchronous machine, using a rotating power converter. In this method, the converter was using a single phase full bridge topology, mounted at the shaft of the rotor.

III. Slip control, using passive inverter, connected at the rotor

The passive inverter topology (Fig. 2) has been studied, with encouraging results. A three phase, four pole wound rotor machine was used for the experiments, supplied by a three phase, 50Hz, 380V AC line voltage power input. The passive inverter was connected to the rotor of the machine, through slip rings (Fig. 5). Experiments showed, that the wound rotor induction machine performed well, at both sub synchronous and over synchronous speeds. This means, that the machine could function both as motor and as generator too. The experiments at sub synchronous speed (function as motor), showed that the three phase wound rotor induction machine was behaving as a three phase synchronous machine. The speed was not affected by the loading torque and the power factor was very close to one in most cases. The machine had inductive, resistive, or even capacitive behavior.

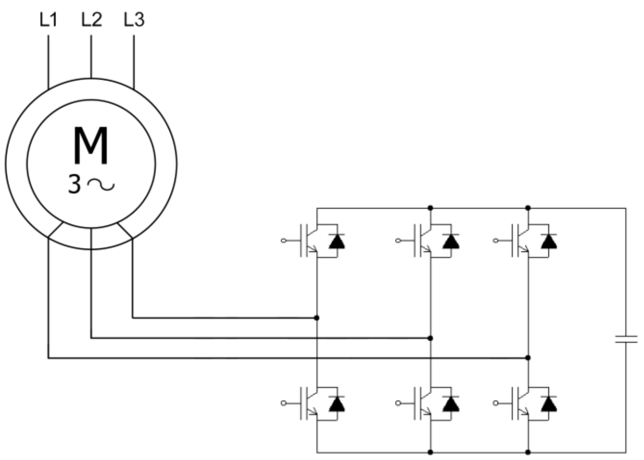

Fig. 5. *Passive inverter connected to the rotor.*

Several measuring sets at several speeds and loading conditions, showed that the machine's stator current was less with the passive inverter topology, than with the resistors. At Table I and Table II, are shown some parameters of the operation of the machine (at 1246 RPM), with the passive inverter topology and with the resistors, accordingly.

TABLE I. OPERATION WITH PASSIVE INVERTER TOPOLOGY.

Speed (RPM)	*I_1(A)*	*cosφ*	*Torque (Nm)*
1246	1.1	0.8i	2
1246	1.2	0.98i	4
1246	1.6	1	6
1246	2.1	0.99c	8
1246	2.8	0.99c	10
1246	3.4	0.99c	12

TABLE II. OPERATION WITH RESISTORS.

Speed (RPM)	*I_1(A)*	*cosφ*	*Torque (Nm)*
1246	2.1	0.4i [1]	2
1246	2.3	0.58i	4
1246	2.7	0.7i	6
1246	3	0.75i	8
1246	3.5	0.8i	10
1246	3.9	0.83i	12

[1] *cos meter out of range.*

I_1 is stator's line current (Ampere).

The speed was stable and independent from load, when the rotor was connected to the passive inverter, but when the rotor was connected to the resistors, the resistance had to be adjusted to maintain a stable speed at various loading conditions.

It is pointed out, that the machine's cosφ was increased and was near to 1 with the passive inverter topology, in contrast with the resistors (Fig. 6). Also, at the same speed and load, the machine's line current was less with the passive inverter topology than with the resistors (Fig. 7). The better power factor of the passive inverter topology, could be the main reason for this.

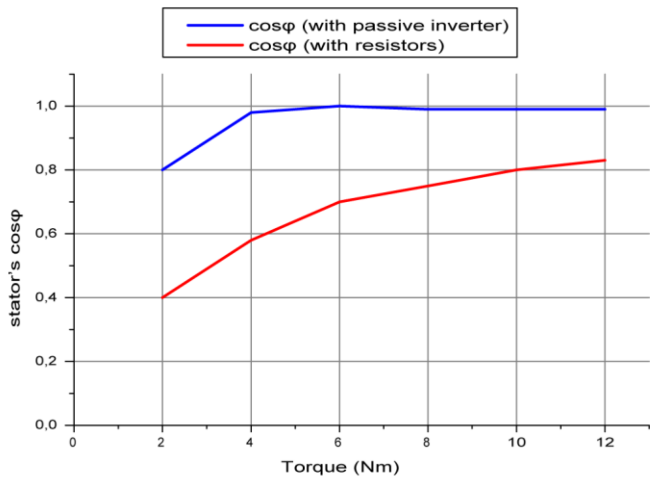

Fig. 6. *Stator's cosφ vs torque.*

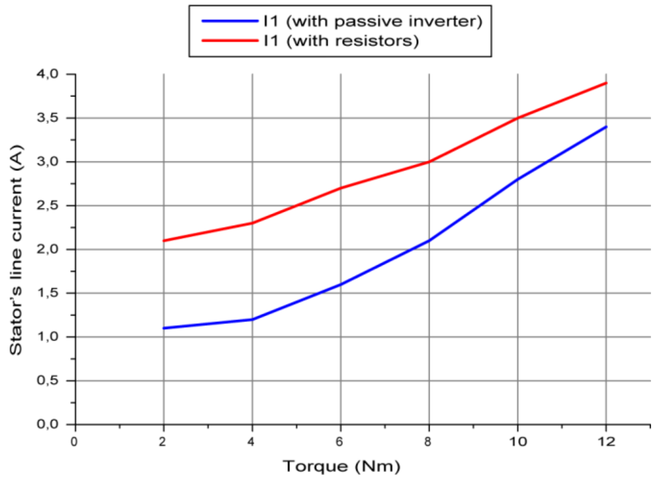

Fig. 7. *Stator's line current vs torque.*

It is mentioned, that at the operation of the machine with the passive inverter topology, the speed was very stable and independent from load. Also, machine's cosφ was capacitive in some cases, so, the machine was behaving much like a synchronous motor.

The speed of the motor (in RPM), with the passive inverter topology, is:

$$V = V_S \cdot \left(1 - \frac{F_m}{F_n}\right) \quad (1)$$

Where VS is the synchronous speed (in RPM), F_m is the modulated frequency of the SPWM signal (first harmonic) and F_n is network's frequency.

For a 4 pole machine, connected at a 50Hz network, the speed is:

$$V = 1500 \cdot \left(1 - \frac{F_m}{50}\right) = 1500 - 30 \cdot F_m \quad (2)$$

All the above measuring sets, have been taken with a unipolar SPWM signal, modulated with a modulation factor of 1. The switching frequency was 3 KHz. Further research has to be made, to study the effect of changing the modulation factor, on machine's efficiency.

IV. Comparison between topologies

In this chapter, the three above mentioned topologies (A,B,C), (Fig. 2, Fig. 3, Fig. 4) will be compared to each other. The cons and the pros of each topology will be referred in short.

A. *Passive inverter topology (Fig. 2)*

Benefits:

- Rotor's and stator's current can have a very low harmonic distortion if the switching frequency of the SPWM signal is high enough (Fig. 8).
- Motor's speed is stable and independent of the load.
- Motor's power can be inductive, resistive or even capacitive (as in synchronous motors).
- The control circuit can be an open loop system, without motor's position feedback.

Drawbacks:

- IGBTs have greater switching losses than SCRs or TRIACS and can handle less current.
- A capacitor has to be used, which has to be capable to handle high current and mechanical stress, due to high speed rotation.
- A full IGBT bridge with anti-parallel diodes and capacitor, consumes much more space than three SCRs with anti-parallel diodes (topology B) or three TRIACs (to-pology C).

B. *SCRs with antiparallel diodes topology (Fig. 3)*

Benefits:

- SCRs and diodes can handle more power and larger currents than IGBTs and TRI-ACS.
- Much less switching losses than topology A.
- Less switching losses than topology B.
- Consumes less space than topology A.
- In contrast to topology A, there is no need for a capacitor, capable to handle high current and mechanical stress.
- Simpler gate driver circuit, compared to topology A, because only one power supply is needed, versus four flying power sources for topology A.

Drawbacks:

- Greater current's harmonic distortion, compared to topology C.
- Much greater current's harmonic distortion, compared to topology A.
- Asymmetry of rotor's current, especially at high conduction angles (Fig. 9, Fig. 10).
- In contrast to topology A, a more complicated control circuit, including a position feedback circuit may be needed.

C. *TRIACs topology (Fig. 4)*

Benefits:

- TRIACSs can handle more power and larger current than IGBTs at topology A.
- Much less switching losses than topology A.
- Consumes less space than topology B.
- Consumes much less space than topology A.
- In contrast to topology A, there is no need for a capacitor, capable to handle high current and mechanical stress.
- Simpler gate driver circuit, compared to topology A, because only one power supply is needed, versus four flying power sources for topology A.

- Smaller current's harmonic distortion, compared to topology B (Fig. 11).
- Symmetrical current, in contrast to topology B.

Drawbacks:

- Greater current's harmonic distortion, compared to topology A.
- In contrast to topology A, a more complicated control circuit, including a position feedback circuit may be needed.
- The star point, of rotor's star connection windings, has to be available, because it has to be connected to the power circuit of the electronic power controller.

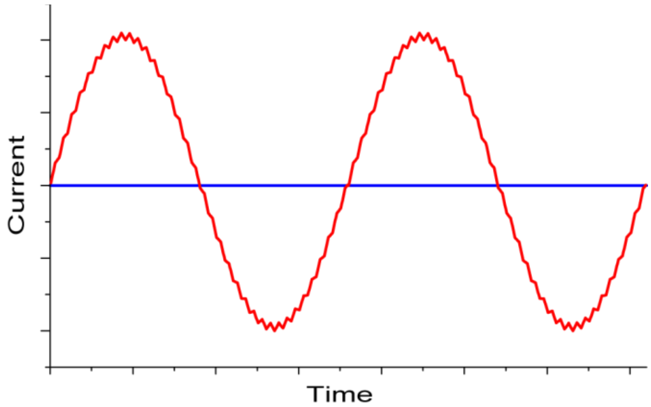

Fig. 8. *Estimated rotor's line current, with passive inverter topology (A).*

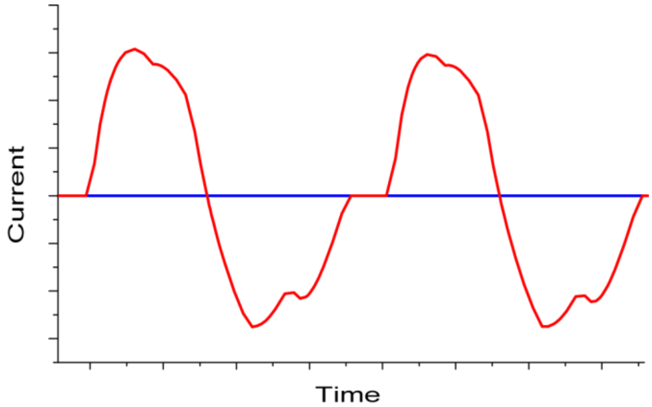

Fig. 9. *Estimated rotor's line current, with SCRs & diodes topology (B), at high conducting angle.*

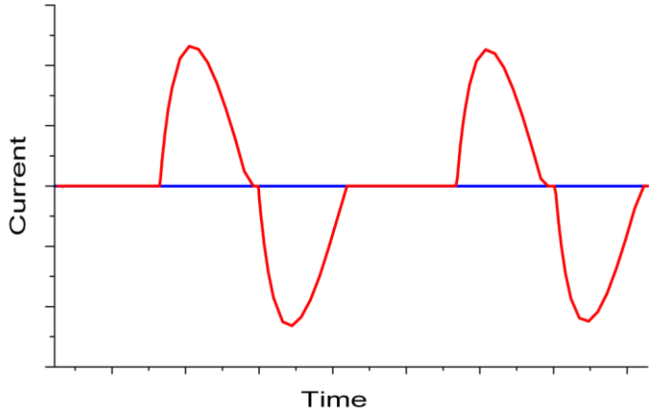

Fig. 10. *Estimated rotor's line current, with SCRs & diodes topology (B), at low conducting angle.*

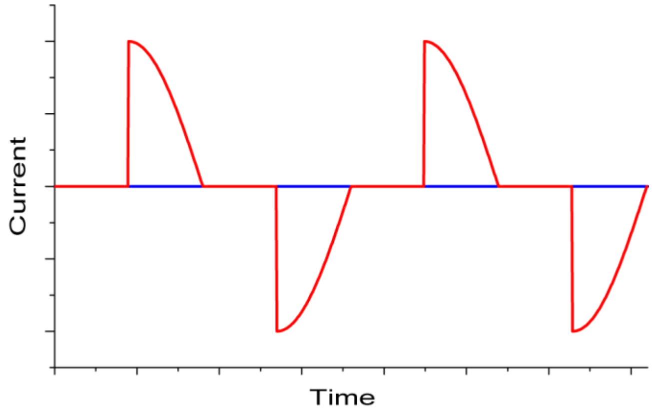

Fig. 11. *Estimated rotor's line current, with TRIACs topology (C).*

V. Slip control, using topologies B and C

Future experiments are planned, to study the behavior of the machine, with topologies B and C. Using SCRs or TRIACs, is expected to increase machine's line current harmonic distortion, compared to topology A, but the reduced size of these topologies, and the fact that a capacitor is not needed, makes them worthy of study. For this purpose, an experimental setup has been developed (Fig. 12), consisting of a pair of a three phase, four pole, slip ring induction motor and an independent excitation DC machine. To control SCRs and TRIACs, a trigger circuit has also been developed (Fig. 13). The PCB of this circuit, is shown in (Fig. 14). The first topology that is planned to be studied, is the SCRs with anti-parallel diodes topology (B) (Fig. 15).

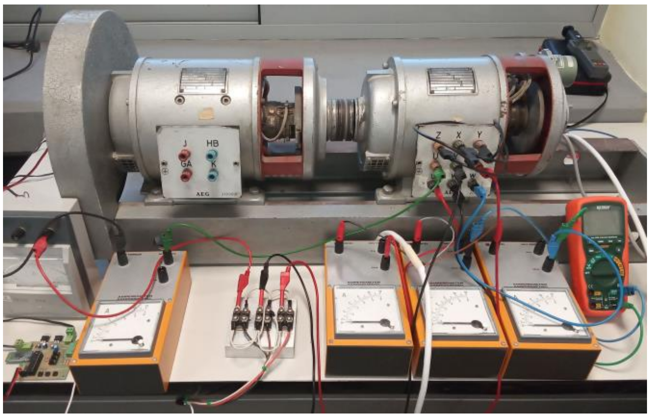

Fig. 12. *Proposed experimental setup.*

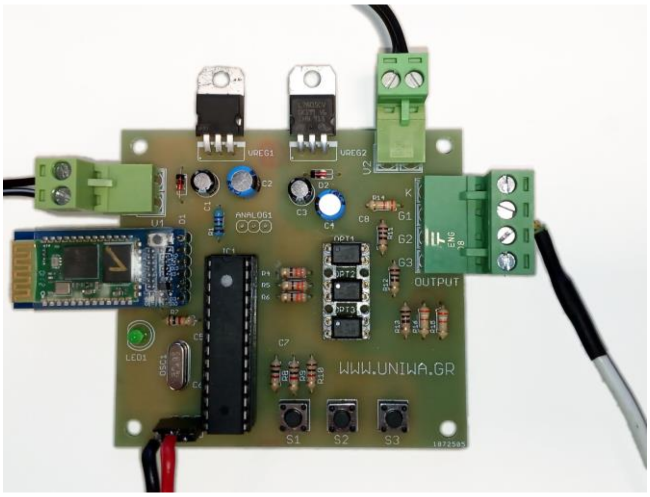

Fig. 13. SCR and TRIAC gate driver.

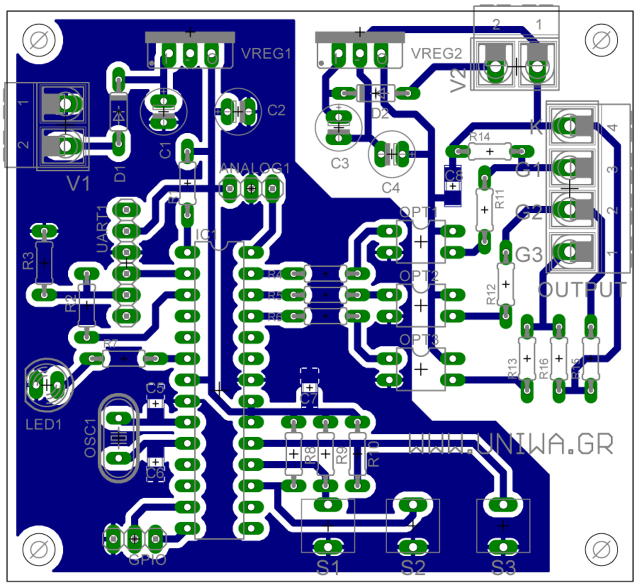

Fig. 14. SCR and TRIAC gate driver PCB.

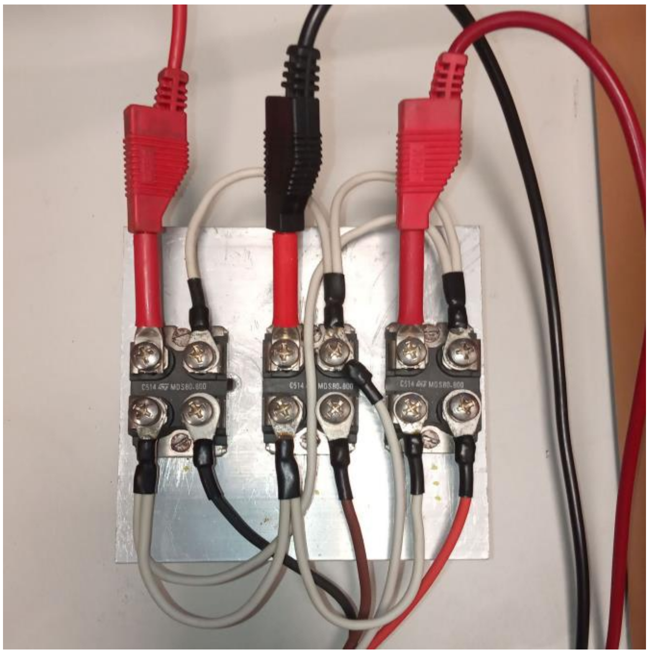

Fig. 15. *SCRs with anti-parallel diodes (topology B).*

VI. Conclusions

In this paper, several methods and topologies, from several researchers, have been mentioned, concerning the elimination of slip rings, of wound rotor induction machines. The elimination of the slip rings, of wound rotor induction machines, would be a major improvement of this kind of machine, because slip rings need frequent maintenance. Also, slip rings increase rotor's electric resistance. This leads to a higher slip and lower machine's efficiency.

Wound rotor induction machines, without slip rings, could be useful in many ap-plications, such as wind generators, high starting torque industry applications, electric vehicles and many more.

All proposed methods and topologies should be studied further, in order for the optimal to be found.

Acknowledgment

The funding of this paper has been covered by the University of West Attica.

References

[1] EDBI, Hellenic Industrial Property Organization. EDBI April 2004, pp. 12.

[2] Avgerinos, A., Trogadas, N. and Margaris, N., “Slip ring induction motor electronic controller.” In Proceedings of the Technological Educational Institute of Larisa Conference, Larisa, Greece, 16 May 2005.

[3] Han, Y., Lee, W.J. and Ha, J.I. “Single grid connection of doubly-fed induction generator for wind turbines.” IEEE Power Electronics and Machines in Wind Applications 2012.

[4] Brune C.S., Spee R. and Wallace A.K. “Experimental evaluation of a variable-speed, doubly-

fed wind-power generation system." IEEE Transactions on Industry Applications 1994, 30.

[5] Helle, L., and Munk-Nielsen S. "Comparison of converter efficiency in large variable speed wind turbines." Sixteenth Annual IEEE Applied Power Electronics Conference and Exposition 2001.

[6] Han, Y., and Ha J.I. "Single External Source Control of Doubly-Fed Induction Machine Using Dual Inverter." IEEE Energy Conversion Congress and Exposition 2013.

[7] Han, Y. and Ha, J.I. "Wound Rotor Machine Fed by a Single-Phase Grid and Controlled by an Isolated Inverter." IEEE Transactions on Power Electronics 2012, 29.

[8] Lee K., Han, Y., Lee, W.J. and Ha, J.I. "Wound Rotor Machine With Single-Phase Stator and Three-Phase Rotor Windings Controlled by Isolated Three-Phase Inverter." IEEE Transactions on Energy Conversion 2015, 30.

[9] Abu-Elhaija, W.S. and Muetze A. "Effect of the Variation of the Rotor Impedance With Slip on the Performance of Single-Phase Excited Three-Phase Induction Motors." IEEE Transactions on Energy Conversion 2010, 25.

[10] Chan T.F. and Lai L.L. "Single-phase operation of a three-phase induction generator with the Smith connection." IEEE Power Engineering Society Winter Meeting. Conference Proceedings 2002.

[11] Mademlis C., Theodoulidis, T. and Kioskeridis I. "Optimization of single-phase induction motors-part II: magnetic and torque performance under optimal control." IEEE Transactions on Energy Conversion 2005, 20.

[12] Pötter J, Pfost M and Schullerus G. "A Novel Brushless Excitation System for Synchronous Machines with a Rotating Power Converter." In Proceedings of the IEEE 13th International Conference on Compatibility, Power Electronics and Power Engi-neering, Sonderborg, Denmark, 23-25 April 2019.