AUXILIARY POWER SUPPLIES IN LOW POWER INVERTERS FOR THREE PHASE TESLA'S INDUCTION MOTORS

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Abstract

This paper describes and proposes auxiliary power supplies that may be employed to feed control and gate drive circuits in a three phase micro inverter for a three phase Tesla's induction motor. The proposed solutions use bus voltage and output voltage ripple, and the dc link current ripple in the motor converter as primary source of the energy to provide regulated output voltage of approximately 15V at load up to 100mA

I. Introduction

In power converters such as PWM inverters, rectifiers and dc-dc converters, an auxiliary power supply is required to feed analog and digital control circuit, and gate drivers of power switches (usually IGBTs or MOSFETs). The auxiliary output voltage is usually 15 V at load up to 100 mA. There are several possible topologies used of used auxiliary power supplies. The, applied topology depends on conditions, such as input voltage, output voltage, power rating, dynamic and static regulation, ripple and insulated/non-insulated from the main dc bus. Application we would focus in this paper are PWM inverters used to feed a low power three phase Tesla's induction motors. Block diagram of a single phase supplied motor converter is given in Fig 1. The converter consists on the power stage, a control and driving unit, and auxiliary power supply with start up circuit.

A commonly used topology is an insulated fly-back converter, supplied from main dc bus. The input voltage is 300 up to 1200 V [1,2,9].

In some applications where the size and cost of the power supply are critical, a standard power supply is not appropriate solution. The main problem is cost and volume of the power supply. In these applications other type of power supply ahs to be used.

Yakow, Zelster, and Ivensky, analysed and proposed a snubber network employed as a power supply in boost converters [4,5].

An auxiliary power supply used in boost power factor correction (PFC) converters is based on topology with auxiliary inductor coupled with the main boost inductor [7]. This topology may be used in motor drives having input power factor correction circuit.

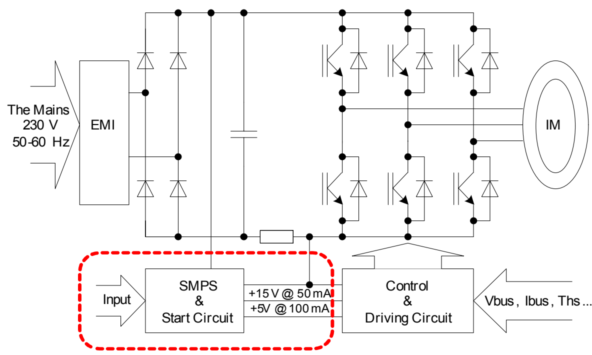

Fig. 1. A block diagram of a typical low power motor converter

Three new power supplies are proposed in this paper. The proposed auxiliary power supplies use a current and voltage ripple that exist as parasitic effects in the power stage of an inverter. A power supply based on the output voltage ripple was tested and applied into a three phase inverter feeds low power Tesla's induction motor in water pump applications.

II. Auxiliary power supply based on current ripple

As it is well known, a PWM motor converter works in switching mode. Therefore, the output current consists on low frequency component due to the modulation and high frequency component due to discontinuous (Pulse With Modulated) output voltage. The dc link current consists on a dc component proportional to the output power, and high frequency due to commutation of the output current between positive and negative rail.

The idea is to extract high frequency component of the output or dc link current, and to use it as primary source of the energy for an auxiliary power supply. The power supply consists on air-gap transformer inserted in the dc link, a diode bridge and an output filter C_2 and a zener diode D_3 as parallel voltage regulator.

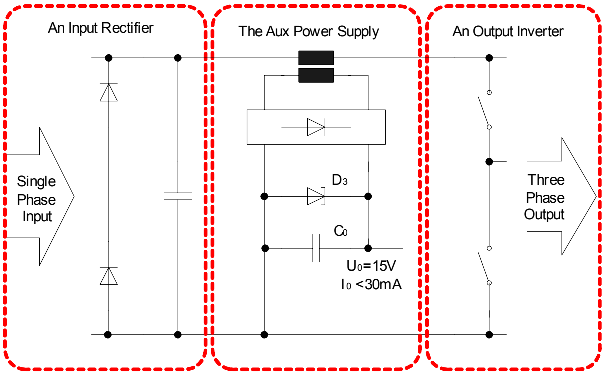

Fig.2 A power supply based on the dc link current ripple.

More details and full analysis of the proposed solution was given in [8].

III. Auxiliary power supplies based on the voltage ripple

A. The bus voltage ripple

The dc bus voltage of an inverter consists on a dc component, and ripple as an ac component. The bus voltage ripple consists on low frequency component due to the rectified input mains voltage, and a high frequency component due to commutation of the output current. The first part of the ripple is dominant, especially if a bulky capacitor is used as the dc bus capacitor. This case would be analysed as an example.

The idea is to use this ripple as a source of the energy to feed an auxiliary power supply. The proposed topology is based on high pass filter used to extract ac component of the bus voltage and half wave rectifier with a simple capacitive filter. The circuit diagram is depicted in Fig. 3. The high pass filter consists on the coupling capacitor C1 and resistors *R1* and *R2*. The resistor *R2* plays role of the start up resistor. The extracted ac component is rectified by half wave rectifier which consists on *D1* and *D2*. The output voltage is filtered by capacitor C_0. The zener diode *DZ1* plays role of a parallel voltage regulator.

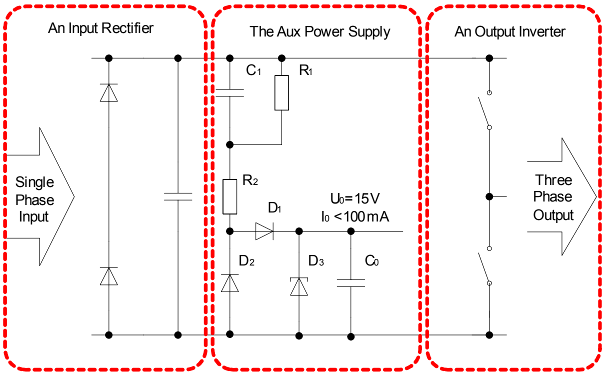

Fig 3. A power supply based on the dc bus voltage ripple.

The coupling capacitor *C1* should be selected to provide requested voltage U_0 at maximum of the load current I_0. Selection of the capacitor C1 is based on the capacitance

$$C_1 \geq 0.71 \frac{I_0}{(\Delta V_{BUS} - U_0) f_0}, \qquad (1)$$

and RMS current

$$I_{C1RMS} = \frac{1.42 \pi I_0}{\sqrt{2}} \cong \pi I_0 . \qquad (2)$$

Where I_0 is load current, U_0 the output voltage (usually 15V), ΔV_{BUS} is ripple of the bus voltage and f_0 is the mains frequency.

The bus voltage ripple is a non-linear function on the drive load and the bus capacitance. In case of using a relatively bulky the bus capacitor, the bus voltage ripple is determined by the following transcendent equation.

$$\frac{4 C_{BUS} f_0 V_{BUS} \Delta V_{BUS} - P_{BUS}}{4 P_{BUS}} = \frac{1}{2\pi} \arcsin\left(1 - \frac{\Delta V_{BUS}}{\sqrt{2} U_{IN}}\right) \qquad (3)$$

Where C_{BUS} is the bus capacitance, V_{BUS} is the dc bus voltage, P_{BUS} is power of the inverter and U_{IN} is the mains voltage.

The power dissipation of the zener diode *D3* is estimated in the worst case as

$$P_{D3} = U_0 (I_0 1.7 - I_{0\min}) . \qquad (4)$$

The rectifier diodes are low voltage low speed diodes. The reverse voltage of the diodes is

$$U_{RD1} = U_0 - 0.7 \quad U_{RD2} = U_0 + 0.7 , \qquad (5)$$

and forward RMS and average current is

$$I_{DAV} = 1.42 I_0 \qquad I_{RMS} \cong \frac{\pi}{2} I_0 . \qquad (6)$$

As it has been seen in the equation 3, the bus voltage ripple strongly depends on the inverter load. In case of unloaded drive, when the inverter does not operate, the bus voltage ripple becomes almost zero. Therefore, the power supply loss the input and the output voltage would drop to zero.

The proposed solution may be used in some specific applications, such as "capacitor less" converters. A film capacitor is used as dc bus capacitor instead of a bulky electrolytic capacitor. In this case, the dc bus voltage ripple consists on significant high frequency component that may be used to feed the auxiliary power supply. Typical applications of this kind of the inverter are washing machines, air-conditioning and specific pumps.

B. The inverter output voltage ripple

The second possibility to provide an auxiliary power supply is to use an output voltage of the inverter as the source of energy for the auxiliary power supply. The voltage between an output of the inverter and the minus rail consists on a dc component of $V_{BUS}/2$, low frequency component due to the modulation, and high frequency component due to the commutation.

$$u_A = \frac{V_{BUS}}{2} + \frac{V_{BUS}}{2} M \sin \omega_M t + u_{Asw} \qquad (7)$$

Where V_{BUS} is the dc bus voltage, M is modulation index and u_{ASW} is ac component due to the inverter switching [11].

Amplitude of the low frequency component of the output voltage strongly depends on modulation index of the inverter. Therefore, it may not be used to feed the auxiliary power supply [8]. The high frequency component in the output voltage is caused by switching of the inverter switches. Amplitude of this component slightly depends on the modulation index. Therefore, the high frequency component may be used as an input voltage of the auxiliary power supply.

The proposed power supply is based on circuit diagram given in Fig 4. The proposed power supply consists on a *LC* circuit connected on an output of the inverter, a half wave rectifier *D1, D2,* output filter C_0 and zener diode *D3*. A load of the power supply is designated as current source I_0. The zener diode *D3* is used as parallel voltage regulator to regulate the output voltage U_0.

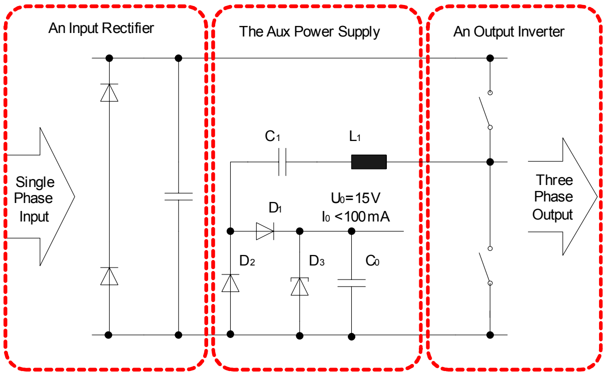

Fig 4. A power supply based on the output voltage ripple.

Voltage between an output phase of the inverter and the minus dc bus has discrete value depends on modulation index and switching frequency.

$$u_A = \begin{cases} V_{BUS} \ldots\ldots\ldots\ldots 0 \le t \le t_{on} \\ 0 \ldots\ldots\ldots\ldots t_{on} \langle t \le T_{SW} \end{cases} \qquad (8)$$

The analysis is based on a simplified circuit given in the Fig 5.

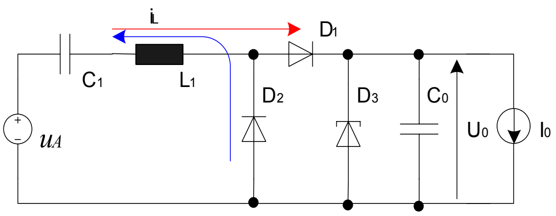

Fig. 5. Simplified circuit diagram of the power supply based on the inverter voltage ripple.

Each rising and falling edge of the voltage u_A excites LC circuit. Current of the *LC* circuit with positive direction flows through diode *D1* and charges the filter capacitor C_0. The current with negative direction flows through the diode *D2* and discharges the capacitor C. Since the total resistance in the circuit is very low, the oscillations are slightly damped. However, the amplitude of the current linearly decreases due to the asymmetric rectifier *D1* and *D2.* It was detailed and explained in [8], [10].

Average value of the *D1* current is

$$I_{AV}^{o} = \frac{T_0}{T_k}\frac{1}{\omega_0 L\pi}\left\{\begin{matrix} V_{BUS}(k_{ON}+k_{OFF}) \\ -U_0\begin{pmatrix} k_{ON}(1+k_{ON}) \\ +k_{OFF}(2+k_{OFF}) \end{pmatrix}\end{matrix}\right\}. \quad (9)$$

Where k_{ON} and k_{OFF} are total numbers of the oscillations into one switching cycle, and ω_0 is natural ringing frequency of the LC circuit.

The resonant *LC* circuit is the key element of the power supply. Therefore, the capacitance and inductance of the resonant circuit must be selected to provide the constant output voltage U_0 in the worst case, such as minimum of the input voltage and maximum of the load. The required parameters of the *LC* circuit can easily be defined by the energy storage analysis.

$$W_{OFF} \cong W_{ON} \cong \frac{C}{2}\left(V_{BUS}-U_0\right)^2 \quad (10)$$

$$C = \frac{T_{SW}U_0}{\left(V_{BUS\,\min}-U_0\right)^2} I_{0\max} \quad (11)$$

$$L = \frac{1}{C}\left(\frac{T_0}{2\pi}\right)^2 \quad (12)$$

Selection of the filter capacitor C_0 is based on the voltage ripple and RMS current requirement. The worst case is operation under over-modulation of the output inverter. In that case there is a long period with no commutation of the IGBTs. During that period the capacitor is discharged into the load and the output voltage U_0 decreases. The required capacitance is

$$C_0 \geq \frac{10^{-2} I_0}{6\pi\Delta u_0}. \quad (13)$$

Where Δu_0 is the output voltage ripple.

The zener diode *D3* used as a parallel voltage regulator has to be selected for the worst case of the power dissipation. The worst operational condition for the diode *D3* is the maximum of the bus voltage and minimum of the load current I_0.

$$P_{D3} = U_0\left(\left(\frac{V_{BUS\,\max}-U_0}{V_{BUS\,\min}-U_0}\right)^2 I_{0\max} - I_{0\min}\right) \quad (14)$$

The rectifier diodes are low voltage fast diodes having reverse voltage

$$U_{RD1} = U_0 - 0.7 \quad U_{RD2} = U_0 + 0.7\,. \quad (15)$$

The average and peak current of the diodes is

$$I_{DAV} = I_{0\max} \qquad I_{peak} \cong 2\frac{V_{BUS}-U_0}{\omega_0 L}\,. \quad (16)$$

IV. Experimental results

An auxiliary power supply based on an inverter output voltage was designed and tested in the Laboratory for Digital Control of Power Converters at School of Electrical Engineering at Belgrade's University. The auxiliary power supply has been used to feed a microprocessor control unit and gate drivers in a motor converter ***TRISTALAN150.*** The converter has been used as a drive of a three phase Tesla's induction motor *150W 3x200V* employed in industrial water pumps.

The auxiliary power supply requirements:

Input voltage	***- V_{BUS}=150 to 350V_{DC},***
Output voltage	***- U_0=+15V, U_1=+5V,***
Load current	***- I_0=30mA, I_1=20mA,***
Voltage ripple	***-Δu_0=200mV_{pp}, Δu_1=50mV_{pp}***

The tests were preformed in several different conditions. Some waveforms were recorder on a digital storage oscilloscope. The waveforms are depicted in the following Figs.

Waveforms of the voltage and current of the resonant capacitor *C* is depicted in the Fig below. The waveforms were recorded at nominal bus voltage, nominal load I_0 and at output frequency of *15Hz*. The high amplitude spikes seen on the upper diagram are measurement noise due to inappropriate connection of the oscilloscope probes. As it was explained in the previous analysis, the transient process is lightly damped. However, due to asymmetric rectifier *D1* and *D2*, the amplitude of the current and capacitor voltage is decreased cycle by cycle. It is seen in the recorded waveforms.

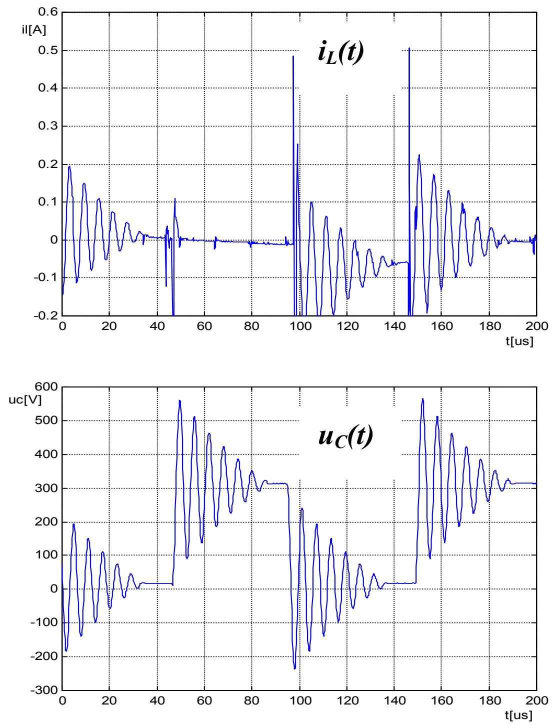

Fig. 6. Voltage and current of the resonant capacitor C. The inverter output frequency is $f_m=15Hz$.

The proposed auxiliary power supply requires a start up circuit. Before the inverter starts to operate, the control and gate driver unit needs the supply. This must be provided by a start up circuit. After the start up sequence, the inverter operates and the auxiliary power supply starts to work and feeds the control and gate driving circuits of the inverter.

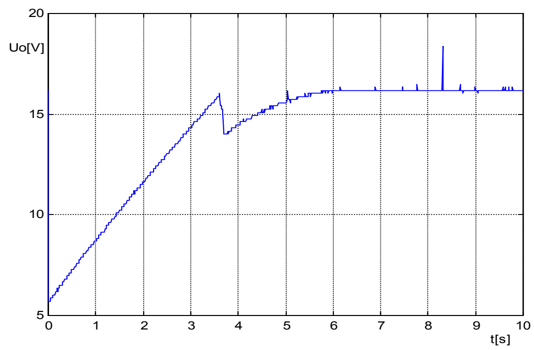

Fig. 7. The output voltage at start up of the drive.

The output voltage U0 during start up of the drive was recorded and the waveform is given in Fig below. The start up time is measured as approximately 5s. This time depends on the filter capacitor C_0 and start up resistor. In applications which request faster start up, an active start up resistor has to be used in order to reduce power losses on the start up circuit.

Output voltage ripple was measured at three different output frequencies and full load. The waveforms are depicted in the Fig 8 below. The upper and middle Figs are focused on high frequency ripple. The lower fig focuses on low frequency ripple due to over-modulation of the inverter. As it is seen from the waveforms, the ripple is below requirement of 200mV.

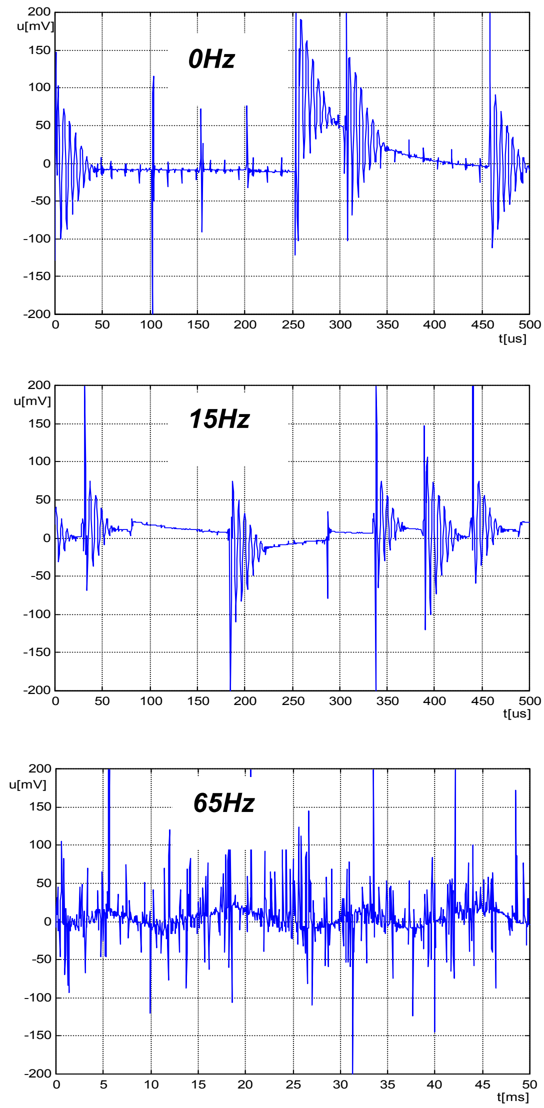

Fig. 8. Output voltage ripple. The inverter output frequency is $f_m=0Hz$, $15Hz$ and $65Hz$.

V. Conclusions

The paper described some new possibility to provide low power auxiliary power supply may be used in low power motor converters. Three possible topologies have been analysed and proposed. A power supply based on output voltage ripple and half wave resonant rectifier was experimentally tested and verified. The results were presented in the paper.

The proposed power supply provides an output voltage of approximately 16V at 30mA load. The power supply feeds control unit of a low power motor drives.

The power supply provides the following features compared to conventional techniques:

- Cost effective and simple power supply in applications where light load and low performance power supply is needed,
- Robust power supply without any active voltage feedback,
- It is not sensitive on electromagnetic noise, and
- The power supply does not require a high voltage active switch such as MOSFET and fast rectifier diodes. The solution uses main inverter's IGBTs and low voltage schottky rectifier diodes.

The proposed solution can be used is micro inverter integrated into the housing of a three phase Tesla's induction motor employed as mechanical actuator in fans, pumps and another similar industrial applications. The proposed solution has been tested on a micro inverter *TRISTALAN150* that was developed in Laboratory for Microprocessors Control of Power Converters and Drives at Department of Electrical Engineering, University of Belgrade.

REFERENCES

[1] Keith H. Billings, "Switch Mode Power Supply Handbook," McGraw-Hill, 1989.

[2] Ned Mohan, "Power Electronics, Converters, Applications and Design," USA, 1995.

[3] Slobodan N. Vukosavic. "Controlled Electrical Drives-Status of Technology," Conference of Power Electronics, Novi Sad, 1999.

[4] Sam Ben-Yakov, IliyZelster, and Gregory Ivensky, "A Resonant Local power Supply with Turn off Snubbing Features," *Proceedings* APEC'99, pp.1093-1097.

[5] Sam Ben-Yakov, IliyZelster, and Gregory Ivensky, "New snubbers with Energy Recovery into a Local Power Supply," *Proceedings* PESC'03, pp. 1327-1332.

[6] International Rectifier," The Complete Power Conversion Design Tool," CD, 2002.

[7] UNITRODE, "Product and Applications Handbook," CD, 1988.

[8] Petar J. Grbovic, "Design of Mini-Inverter for a Three Phase Tesla's Induction Motor, " Master Thesis, 2004, Belgrade.

[9] Lothar Heinmann, Jochen Mast, Guntram Scheible, Thomas Heinzel, Thomas Zuellig," Power Supply for Very High Insulation Requirements in IGBT Gate-Drives," Proceedings IAS Annual Meeting, 1998, pp.1562-1566.

[10] Petar J. Grbovic and Slobodan N. Vukosavic, " An Auxiliary Power Supply Based on The Phase Voltage Ripple Employed in a Micro Inverter for Feeding Three Phase Tesla Induction Motor " *Proceedings* EPE'05, pp. Dresden, 2005.

[11] D. Grahame Holms and Thomas A. Lipo, "Pulse Width Modulation For Power Converters, " IEEE Press, A John Wiley & Sons, Inc. , Publication , 2003.