EVALUATION OF A REDUCED SINGLE-PHASE TO THREE-PHASE CONVERTER FOR AC MOTOR DRIVE APPLICATIONS

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Abstract – **In this work the operation of a reduced part single-phase to three-phase converter is evaluated under different start up procedures, with the purpose of establishing the practicability of this topology for AC motor drive applications. Different operating modes (negative and positive sequences) are analyzed while driving a squirrel-cage induction motor with a centrifugal (squared) load torque, and a soft-start procedure is proposed. The analysis is carried out through PSCAD/EMTDC™ simulations, which shows that the proposed starting method is effective for reducing the converter VA ratings. An experimental prototype is developed based on look-up tables, implemented in a low cost digital programmable device (PIC 16F628), for synchronizing the PWM modulating signal.**

Keywords **– AC motor drive, reduced parts converter, single-phase to three-phase converter, look-up table method.**

I. INTRODUCTION

In this paper the performance of a reduced part single-phase to three-phase converter is evaluated, with the purpose of identifying its practicability which can suit AC motor drive applications. It is the most reduced parts topology for single-phase to three-phase conversion, which is composed of a diode leg, an active switch leg and two split capacitors. This circuit was first proposed in [1] and [2] as a low cost motor drive system suitable for the agricultural sector. In [2] two different operating modes were identified and designated as negative and positive sequences. In that work, a soft-start procedure based on the connection of a start-up capacitor was proposed. Also in that work, the drive operation at positive sequence was considered a good approach for high performance. In [3] the operation of this converter was studied, under the negative sequence mode only, with and without a soft-start procedure, which was performed by a ramp function applied to the PWM modulating signal of the active switch leg. It was verified that the starting condition can influence significantly the device ratings and the converter VA ratings as well, in such a way that one can come to different results when compared to those of previous works. In this work, a starting procedure is proposed based on the combination of the start up capacitor and the soft-starting of the PWM modulating signal. The operation of this converter is analyzed under different starting conditions at negative and positive sequences, while a squirrel-cage induction motor is driving a load torque proportional to the square of the speed. The dynamic analysis is carried out through digital simulations with the use of PSCAD/EMTDC™ software, with emphasis on the devices and on the converter input VA ratings. These results are summarized in tables. An experimental prototype is built based on a 1/6 HP squirrel-cage induction motor and on a low cost PIC microcontroller type.

II. SPWM SWITCHING CONTROLLER

Fig.1 shows the schematics of the motor drive system with a block diagram of the SPWM (sinusoidal PWM) strategy that controls the active leg of the power converter. The zero-crossing detector circuit is implemented by means of a voltage resistive divider applied to the source voltage, and it is followed by a comparator and an optocoupler. This zero-crossing signal is the input signal of the PIC A/D converter.

In Figs. 2 and 3 an schematic of the PWM control circuits and the sinusoidal modulating signal are presented, respectively. The output of the zero-crossing detector is connected to the PIC (16F628) A/D converter. The microcontroller synthesizes the modulating signal by means of 30 voltage levels, which are programmed in a look-up table.

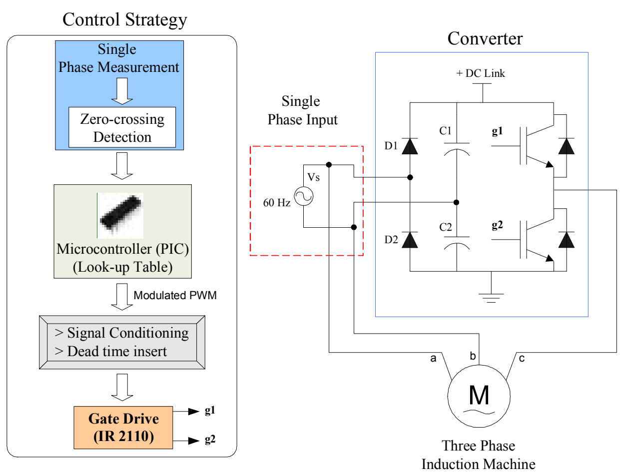


Fig.1: Reduced parts motor drive system.

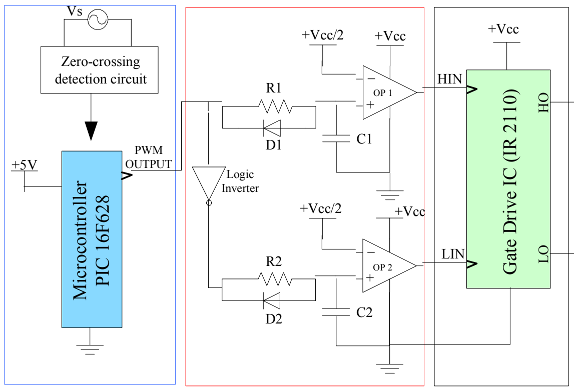


Fig.2: Schematic diagram of the PWM control circuits.

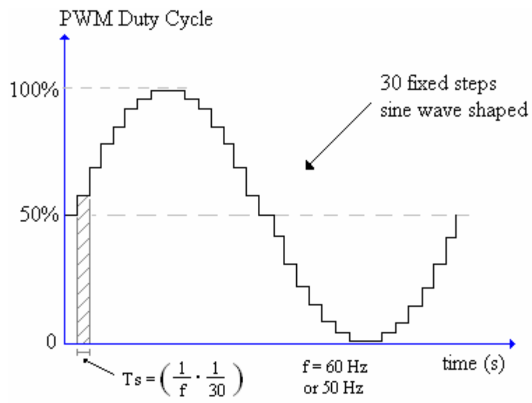


Fig.3: Sinusoidal modulating signal.

As a matter of fact, two phase-shifted look-up tables are programmed: one is 60 degrees lagging and the other is 60 degrees leading the AC input voltage source. They produce the negative and the positive sequences of the motor operation, that correspond to the direction of the motor rotation. These synthesized sinusoids are synchronized with the falling edge of the signal that comes from the zero-crossing detector. It activates an interruption routine (external interruptor RBO) at each cycle of the look-up table. The generation of the dead-time intervals is implemented with the circuitry as shown in Fig. 2, and it is adjusted at 3 μs. It was preferred this way rather than implementing it through programming, due to the limitations of the PIC used in this work.

The synchronization method used here is not sensitive to the amplitude variations of the input AC source voltage. However, the controller can be drifted off synchronization due to variations of the input source frequency. In this work, a frequency margin equal to 1% is considered in the programmed look-up tables.

Different performances are obtained on account of the choice of operation sequence, which will be described in the next sections.

III. EXPERIMENTAL RESULTS

In Fig. 4 a reduced parts power converter is shown, where Ls represents the leakage inductance of a typical single-phase feeder. The motor rated characteristics are: 1/6 HP, 1720 rpm, 220 V line-to-line, 0.891 A per-phase, and power factor equal to 0.62. In the experimental prototype the active switches and the diodes are of type IRG4BC20KD (IGBT) and 1N5408, respectively. In Figs. 5 up to 12 the experimental operation at steady-state is shown, when the input source voltage is 120 Vrms. A load torque of magnetic breaker type is applied to the machine axis, which yields motor phase currents close to rated values. The measured motor speeds at negative and positive sequences are equal to 1526 rpm and 1500 rpm, respectively. Figs. 5(a) and 5(b) show the control signals and the DC bus voltage during positive and negative sequences, respectively. Figs. 6 and 9 show the motor phase currents at negative and positive sequence, respectively. It can be seen that at positive sequence the balance of motor phase currents is better. The corresponding FFT and THD% of motor phase current, *ia*, are calculated by using MATLAB program, and are shown in Figs. 7 and 10. In Figs. 8 and 11 the input source voltage and current at negative sequence and positive sequence operations are respectively shown. The corresponding FFT and THD% of the input current are presented in Fig. 12, where it can be seen that less distortion is obtained at positive sequence. The experimental results confirmed that the positive sequence operation yields better efficiency in the sense that less input power (Sin) is required by the converter in order to drive the motor. Tables 1 and 2 summarize these results, where *Sout* represents the converter power delivered to the motor.

TABLE 1
Power values at negative sequence operation

Input Power (VA)			
Irms (A)		Vrms (V)	S_{in} = Irms*Vrms (VA)
1.88		Vab= 121	227.48
per phase Output Power (VA)			
Irms (A)		V_{LL} (V)	Irms*V_{LL} / √3 (VA)
Ia	0.882	121	61.62
Ib	0.88	114.5	58.17
Ic	0.75	104.5	45.25
S_{out}			165.04
Power ratio (S_{out}/S_{in})			**0.725**

TABLE 2
Power values at positive sequence operation

Input Power (VA)			
Irms (A)		Vrms (V)	S_{in} = Irms*Vrms (VA)
1.41		Vab= 121	170.61
per phase Output Power (VA)			
Irms (A)		V_{LL} (V)	S_{out} = Irms*V_{LL} / √3 (VA)
Ia	0.884	121	61.76
Ib	0.81	114.5	53.55
Ic	0.833	112.5	54.10
S_{out}			169.41
Power ratio ($S_{(out)}$/$S_{(in)}$)			**0.992**

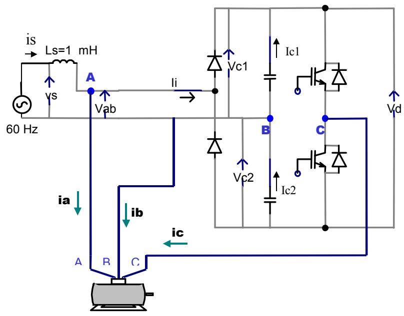
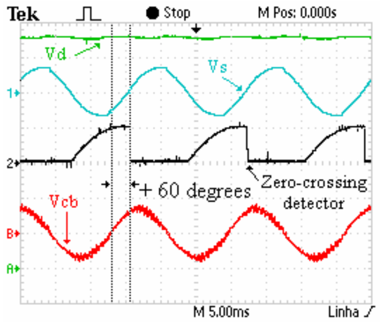


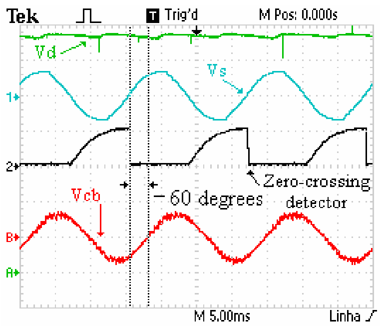
Fig.4: Single-phase to three-phase reduced converter with voltage doubler diode rectifier (each C is equal to 990µF) **[1]-[2].**



Vs = Ch1; Zero-crossing detector = Ch2

Vcb = ChB ; Vd = ChA

a) Positive sequence.



Vs = Ch1; Zero-crossing detector = Ch2

Vcb = ChB ; Vd = ChA

b) Negative sequence.

Fig.5: Input Voltage Vs (200 V/div), Zero-crossing detector output signal (5V/div), fundamental Vcb voltage (200V/div) and DC Bus voltage Vd (50 V/div) at positive and negative sequence operation.

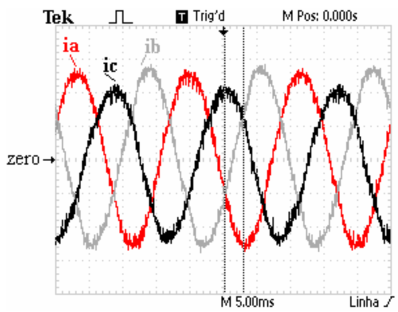


Fig.6: Motor phase currents at negative sequence (0.5 A/div).

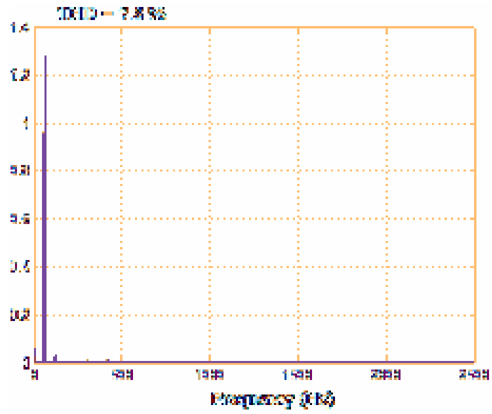


Fig. 7: Peak values of harmonics in the motor phase current (ia=0.91 A rms) and corresponding THD% at negative sequence.

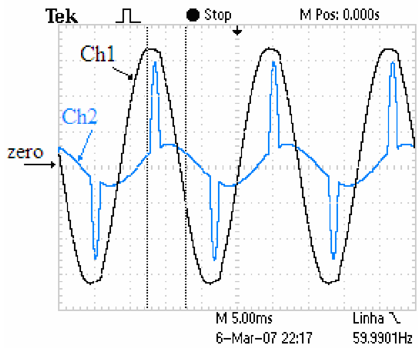


Fig.8: Input source voltage and current at negative sequence operation. (Ch1 = 50V/div ; Ch2 = 2 A/div).

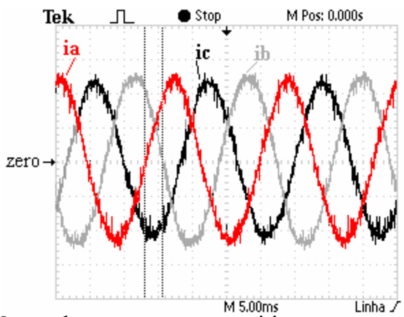


Fig.9: Motor phase currents at positive sequence (0.5 A/div).

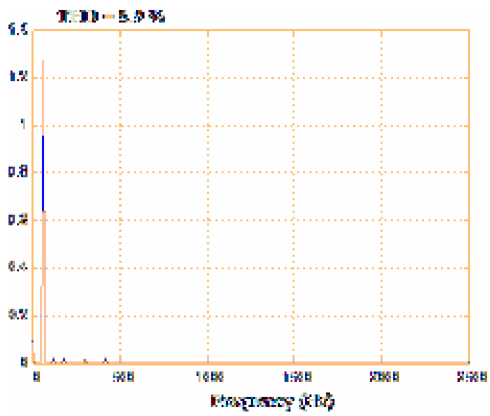


Fig.10 : Peak values of harmonics in the motor phase current (ia=0.9 A rms) and corresponding THD% at positive sequence.

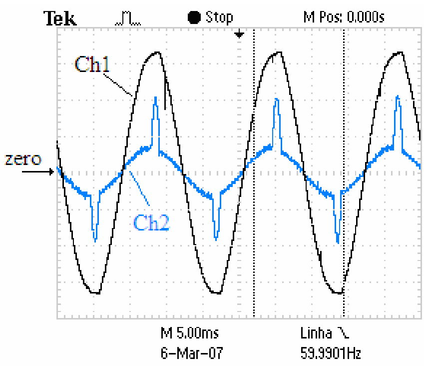


Fig.11: Input Source Voltage and current at Positive Sequence (Ch1 = 50V/div ; Ch2 = 2 A/div).

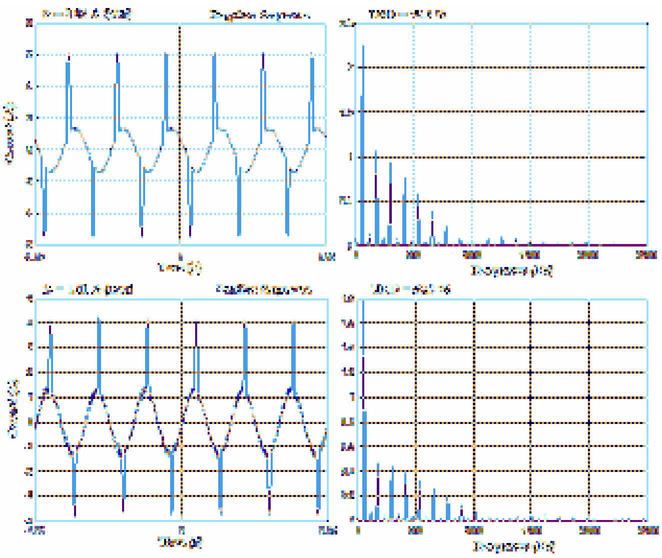


Fig. 12: Peak values of harmonics and THD% of experimental input source current at negative (top) and positive (bottom) sequences.

IV. PSCAD SIMULATION RESULTS

A set of PSCAD simulation results is presented in Figs. 13 up to 20, in order to evaluate the impact of different start up strategies in the converter power ratings. In these simulations the motor is started up at t= 0.2s and runs at rated values.. Simple start up, capacitor assisted start up, soft-starting, and capacitor assisted soft-starting are considered. The DC bus capacitors are pre-charged through the rectifier diodes, so that the motor start up is enabled. The motor starts running with rated centrifugal (squared) load torque. When the capacitor assisted start up is applied, a capacitor is connected between terminals A and B (Fig. 4) for both negative and positive sequences of operation. This capacitor was calculated according to the information provided by reference [2]. Its calculation takes into account the motor rated current and line-to-line voltage, as well as its power factor during starting. Thence, a start-up capacitor equal to 10 μF is used in the PSCAD model, based on the nameplate motor ratings. The soft-starting procedure is implemented by means of a ramp function applied to the amplitude of the PWM modulating signal of the active switch leg. The time interval of the ramp function was adjusted so that the starting current in the input AC source is as low as possible, therefore the converter kVA ratings are reduced. Neither sampling, nor dead-time effects are considered in the results displayed here.

1) Negative Sequence Operation

In Figs. 13 and 14, the input source voltage and current, and the motor phase currents are presented respectively. The input source voltage is re-scaled just for improving the graph presentation. It can be seen that similar wave shapes are obtained when compared to the corresponding experimental ones in Figs. 8 and 6. In Fig. 15(a) the input source and motor phase currents, ia and ic, are shown during motor start up when simple starting procedure is applied. And in Fig. 15(b) they are shown when soft-starting is used. In this case, it can be seen that the input current is by half reduced. Figs. 16(a) and (b) show the corresponding motor starting process, when it is introduced a 10 μF start up capacitor into terminals A and B of the converter (Fig. 4) between instants of time equal to 0.2s and 2.0s. In Fig. 16(b) the soft-starting procedure is also applied between these same time intervals. It is shown that the use of start up capacitor and of start up capacitor assisted soft-starting reduce the input current by 0.56 pu and 4.0 pu, respectively, when compared to simple starting. A summary of these results is provided by Table 3, where one can see their impact on the VA ratings of the converter. The per unit values are obtained by taking the motor rated power as the base. They show the maximum ratings that normally happen during the starting process.
In Fig. 17(a) the torque-speed profile is presented at simple start up and the corresponding profile at start up capacitor assisted soft-starting is shown in Fig. 17(b).

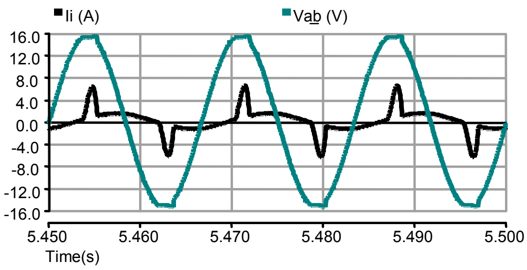


Fig.13: Input source voltage (re-scaled) and current at negative sequence and rated torque proportional to the square of the speed.

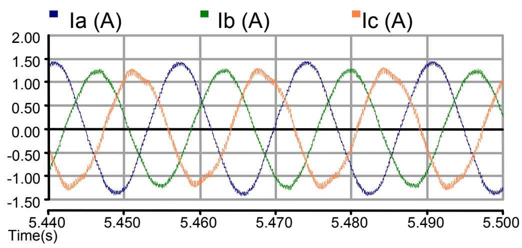


Fig.14: Motor phase currents at negative sequence and rated load torque proportional to the square of the speed.

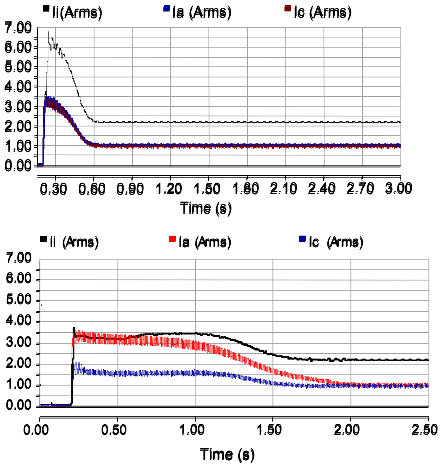


Fig. 15: Input source and motor phase currents at negative sequence (a) with simple start-up, and (b) with soft-starting.

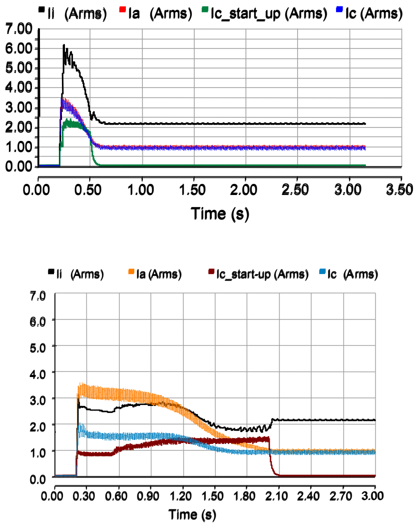


Fig.16: Input source, start-up capacitor and motor phase currents (a) with simple start-up procedure and (b) with soft-starting.

2) Positive Sequence Operation

Figs. 18 up to 22 show the positive sequence results correspondingly to Figs. 13 up to 17. Also here, the wave shapes of the input source current and motor phase currents (Figs. 18 and 19) are similar to those obtained in the experiments (Figs. 11 and 9). It is verified that the motor phase currents are better balanced at positive sequence. In Figs. 20 and 21, when the start-up capacitor is used, it is also connected between terminals A and B, and the time intervals are 0.2s and 1.0s. Same time intervals are considered in the ramp function of the soft-starting method. It can be seen in Fig. 20 that simple starting already provides around half of the input current when compared to the negative sequence operation. The methods based on start up capacitor and on soft-starting have not provided significant improvements in the VA ratings. However, by combining the start up capacitor with the soft-starting, a 0.56 pu reduction in the input current is obtained when compared to simple starting. The torque-speed profile is shown in Fig. 22 with the proposed starting method. This profile with simple starting is the same as the one obtained at negative sequence.

A summary of the results are provided in Table 4. By looking at Tables 3 and 4, one can see that nearly same total VA ratings are obtained with the proposed starting procedure, for both negative and positive sequences.

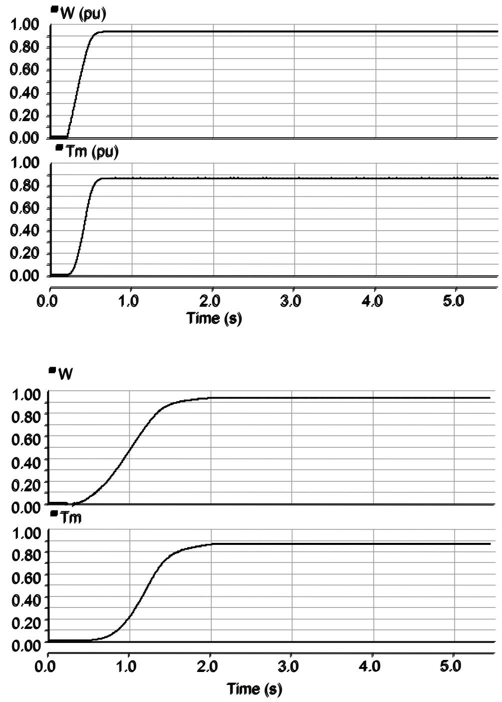


Fig. 17: Angular speed (W) and mechanical torque, in per unit (pu), at negative sequence (a) with simple start up, and (b) with start up capacitor assisted soft-starting at 0.2 s and 2.0s.

TABLE 3

VA RATINGS OF COMPONENTS AT NEGATIVE SEQUENCE

Starting Procedures at Neg. Sequence	C Vrms Irms VI (pu)	Diode Rectifier Vrms Irms VI (pu)	IGBT Vrms Irms VI (pu)	Converter Input Ratings Vrms Irms VI (pu)
Simple Start-up	300 V 4A **9.7 pu**	400V 4A **13.0 pu**	450 V 2A **7.3 pu**	220 V 6.5 A **11.5 pu**
Start-up Capacitor (10 µF)	300 V 4A **9.7 pu**	400V 4A **13.0 pu**	450 V 0.8 A **2.9 pu**	220 V 6.0 A **10.6 pu**
Soft-starting	300 V 1.5 A **3.6 pu**	400 V 1.5 A **4.8 pu**	450 V 1.5 A **5.4 pu**	220 V 3.5 A **6.2 pu**
Soft-starting and Start-up Capacitor	300 V 1.5 A **3.6 pu**	400 V 1.5 A **4.8 pu**	450 V 1.5 A **5.4 pu**	220 V 3.0 A **5.3 pu**

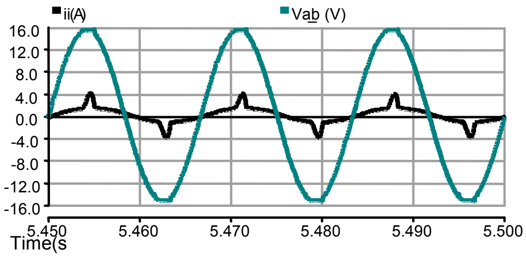


Fig. 18: Input source voltage (re-scaled) and current at positive sequence and rated torque proportional to the square of the speed.

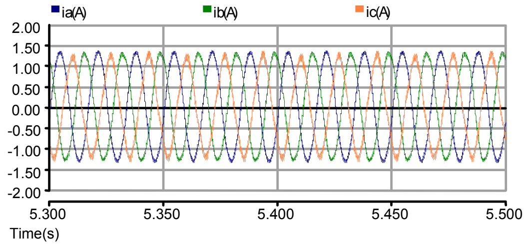


Fig. 19: Motor phase currents at positive sequence

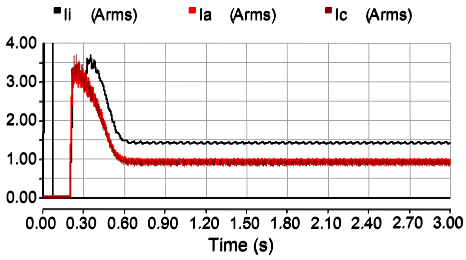


Fig. 20: Input source and motor phase currents at positive sequence and simple start-up.

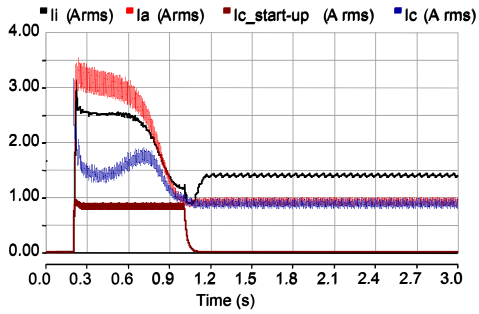


Fig. 21: Input source (Ii) and motor phase currents (Ia, Ic), and start-up capacitor current at positive sequence operation with soft-start procedure.

V. CONCLUSION

In this paper the operation of a reduced parts single-phase to three-phase converter under negative and positive sequences, and different starting conditions is analyzed, while driving a fractional horse-power induction motor with a load torque proportional to the square of the speed. A starting method is proposed and the simulation results show that it can reduce significantly the VA ratings of the converter when compared to the operation at simple starting. An experimental prototype is developed based on programmed look up tables that perform the modulating signals for negative and positive sequences. The experimental results confirmed the digital simulated operation. It is believed that, as far as the converter VA ratings are concerned, this work provides some insight to the converter design guidelines and to its practicability for AC motor drive applications.

TABLE 4
VA ratings of components at positive sequence

Starting Procedures at Pos. Sequence	C Vrms Irms VI (pu)	Diode Rectifier Vrms Irms VI (pu)	IGBT Vrms Irms VI (pu)	Converter Input Ratings Vrms Irms VI (pu)
Simple Start-up	300 V 2.5 A **6.0 pu**	400V 1 A **3.2 pu**	450 V 2.5 A **9.0 pu**	220 V 3.5 A **6.2 pu**
Soft-starting and Start-up Capacitor	350 V 1.3 A **3.7 pu**	400 V 0.8 A **2.6 pu**	500 V 1.3 A **5.2 pu**	220 V 3.0 A **5.3 pu**

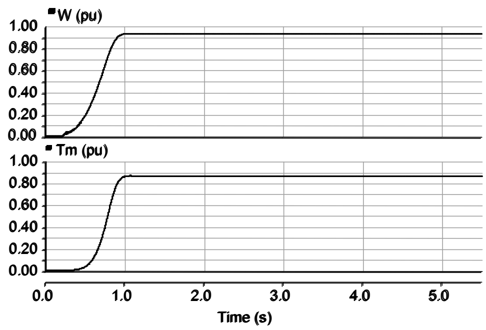


Fig. 22: Angular speed (W) and mechanical torque, in per unit (pu), with start up capacitor assisted soft-starting between 0.2 s and 1.0s.

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