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Comparative Analysis of Voltage Regulators Based on Thyristors and IGBT Switches Applied to AC Machines Jorge Lara

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Keywords

Voltage Regulator, Induction Machines, IGBTs Switches, Thyristors.

Abstract

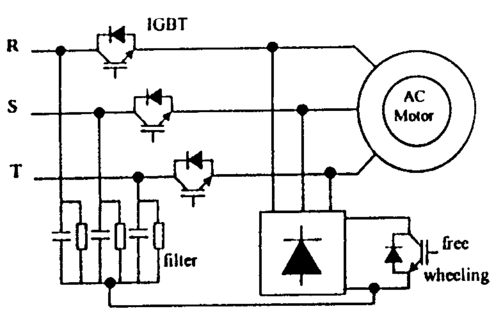
This work presents a comparative analysis of two AC voltage control techniques for induction machines, one using antiparalled thyristor switches and the other one based on IGBT switches. This study defines the conditions to apply each technique. Complete system performance is considered, including the AC machine, the electronic switches, and the electric power system. From the machine point of view, the analysis is focused on current harmonic content, harmonic torque effects, efficiency, speed control, soft start capability and power factor control. The electronic switches are studied analyzing topologies, cost, reliability and controllability. The amount of harmonic pollution injected on the power system is also considered. The results point out that the controlled-switched scheme with IGBTs appears as an effective, efficient and cost competitive alternative to the voltage regulation for AC machines.

Introduction

Soft starters for induction machines have been widely used for many years, since thyristors reached general use in the 60's. When the mechanical load is a direct function of the speed, these systems offer a controlled start-up that increases the service life of the electric machine. However, the phase control technique used by these controllers increases the harmonic content injected both to the supply system [1] and to the induction machine. In addition, the input power factor at the supply bar is notably reduced. The development of IGBT transistors allows the construction of voltage controllers having multiple commutations per supply cycle, providing supply line current harmonic control and significantly increasing the overall power factor.

Figures 1 and 2 show the experimental setup required for the two proposed control voltage strategies. In the SCR Circuit Configuration, the SCRs are naturally commutated and there is only one control variable: the turn-on delay. The delay sets both the rms value and the shape of the voltage waveform applied to the load, hence the voltage harmonic spectrum applied to the machine is fixed for each voltage/load combination (i.e. there is not control over the harmonic spectrum).

On the other hand, since the IGBT Circuit Configuration uses multiple commutations per cycle in a PWM strategy [2,3], independent amplitude control can be performed over a number of voltage harmonics, usually the fundamental and the lower order ones. The soft start function is performed controlling the fundamental rms value, and the voltage waveform is modified in order to increase the overall machine efficiency, reducing the harmonic torque and the harmonic current filtering requirements [4,5].



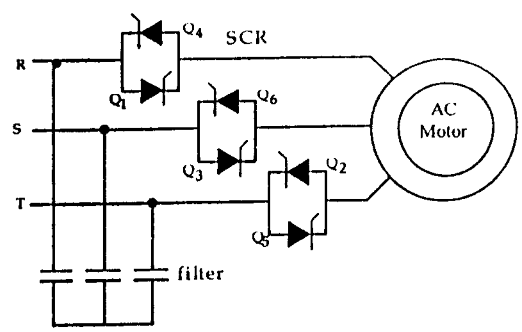


Fig. 1: IGBT Circuit Configuration Fig. 2: SCR Circuit Configuration

However, the fast commutations associated with PWM voltage controllers based on IGBTs transistors generate sharp voltage fronts (high dv/dt transients) that raise the stress applied to the electrical machine isolation, reducing its useful life and reliability. These detrimental effects must be compensated for by using a more robust (and hence more expensive) machine. Both equipment costs and system efficiency should be considered when choosing among these techniques. This article presents a practical method to establish quantitative and qualitative comparisons between these two configurations [6].

Comparative Analysis

The comparison between both Circuit Configurations is based on the analysis of the three subsystems that compose it:

-The electrical network.
-The electronic converter.
-The induction machine.

There are legal regulations limiting the maximum harmonic distortion than can be injected into the mains, therefore the electrical Supply Company can penalize the reactive consumption with a higher bill. The selection of a given converter type can affect the equipment cost, its efficiency, the harmonic injection, and the reliability. The current and voltage harmonics affect the electrical machine, increasing the losses and the thermal protection requirements, producing transient torques in the mechanical shaft and reducing the windings electrical isolation due to the very sharp voltage fronts.

The comparison was accomplished by numerical simulations and experimental measurements performed on two prototypes, one based on IGBT and the other in SCR technology. The experimental circuits were similar to those illustrated in Figures 1 and 2 respectively. Table I presents the most relevant data for these controllers. Table II shows the machine parameters and characteristics. The power source characteristics are presented in Table III.

Power Supply

In Figures 3 and 4 the instant currents injected for each converter in the secondary of the transformer are showed, when these controllers are delivering 80% of the rated voltage to the electrical machine. In Figures 5 and 6, the harmonic spectra of these two signals are compared. As can be observed, the PWM modulation used in the IGBT Circuit Configuration significantly reduces the low order harmonics present in the SCR Circuit Configuration, but it also introduces higher harmonics in the current spectrum. The total harmonic distortion (THD) values are very similar, the value measured in the IGBT Circuit Configuration is 61.7%, and in the SCR Circuit Configuration is 62.7%. Since higher harmonics are predominant in the IGBT Circuit Configuration, the filter needs are reduced, because harmonic elimination using a passive low-pass LC filter is simpler, and the filter components are smaller and therefore less expensive than those required to produce the same filtering effect when the SCR Circuit Configuration is used. If no additional filtering is introduced to reduce the harmonic content, the IGBT Circuit Configuration may be at a disadvantage, since the high frequency components may cause damaging resonances in other circuit elements.

From the power factor point of view, SCR Circuit Configuration is at a disadvantage during the star-up period, since voltage control is achieved by reducing the conduction angle, delaying the current waveform. The power factor is at a minimum at very low speed, and rises with the applied voltage until the nominal working level is reached. In the IGBT Circuit Configuration, voltage control is achieved by PWM modulation; conduction and non-conduction intervals are evenly spread in the supply cycle, hence no phase shift between the current and voltage waveforms is generated, and the power factor is not affected by the voltage control. If the SCR Circuit Configuration is properly rated, and nominal voltage is reached with zero delay, no power factor reduction will be introduced by the regulator when the machine is working at its nominal speed; then the measured power factor will be the same for both configurations (the AC motor rated power factor at nominal load, as shown in table I).

Table I: Voltage controller characteristics

Properties	IGBT	SCR
Number of power elec. elements	10	6
Rated voltage	208V	208V
Rated Current	17A	10A
Efficiency at rated load	97.7 %	98.2 %
Maximum frequency	20KHz	400Hz
Power factor at rated load	0.86	0.86
Filter's reactive power	163 VAR	255 VAR

Table II: Electric machine characteristics

Properties	Value
Rated power (Shaft)	373 W
Rated voltage (line-line)	208 V
Rated current	1.8 A
Rated speed	1720 rpm
Rated frequency	60 Hz
Rated power factor at nominal load	86 %
Rated efficiency	82 %
Connection	Y
Isolation class	B
Stator resistance	0.051 pu
Rotor resistance	0.04 pu
Magnetization reactance	2.2 pu
Total leakage reactance	0.31 pu

Table III: Power system characteristics

Properties	Value
Short circuit capacity	36 kVA
Rated primary voltage (line-line)	208 V
Rated secondary voltage (line-line)	208 V
Transformer Power	3.6 kVA
Rated frequency	60 Hz
Rated efficiency	97 %
Connection	Y-Y
Isolation class	B

Table IV shows the power factor and the total current harmonic distortion in both controllers for several operation conditions with a mechanical torque in the machine shaft that varies with the square of the angular speed.

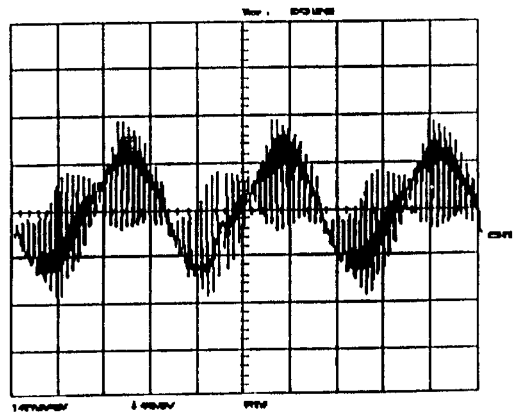


Fig. 3: IGBT Circuit Configuration current injected in the secondary transformer winding when the converter is operating at 80% of the rated voltage.

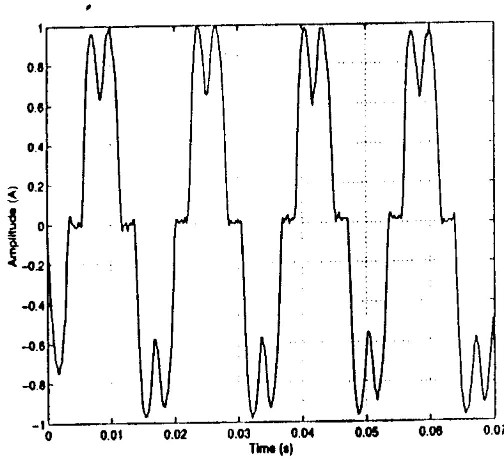


Fig. 4: SCR Circuit Configuration current injected in the secondary transformer winding when the converter is operating at 80% of the rated voltage

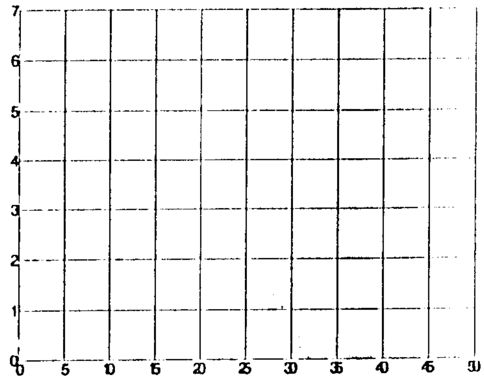


Fig. 5: IGBT Circuit Configuration spectrum of the current injected in the secundary transformer winding when the converter is operating at 80% of the rated voltage

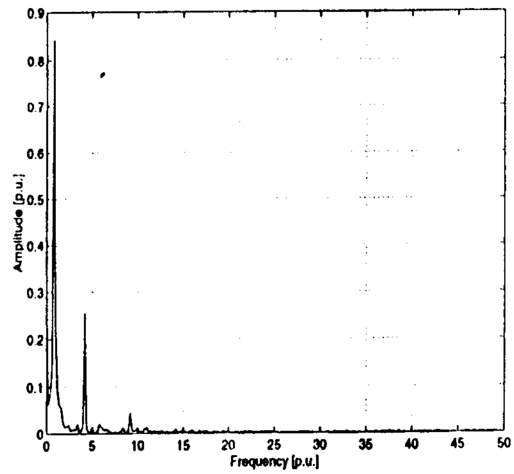


Fig. 6: SCR Circuit Configuration spectrum of the current injected in the secondary transformer winding when the converter is operating at 80% of the rated voltage

Table IV: Power Factor and Current Harmonic Distortion for both Controllers

Converter type	V=20%	V=40%	V=60%	V=80%	V=100%
IGBT power factor	37.7 %	49.6 %	62 %	76.8 %	80 %
SCR power factor	23.7 %	31.3 %	54.8 %	75.7 %	80 %
IGBT harmonic distortion	140 %	102 %	81.5 %	61.7 %	0 %
SCR harmonic distortion	254 %	182 %	106 %	62.7 %	0 %

Electronic Converter

The IGBT Circuit Configuration is a cost-effective alternative for the power range below 30 kW due to the reduced number of active components, a simpler (on-off) control strategy and the possibility to switch at any time. The disadvantages of this scheme are the higher losses and the overvoltage increase due to high frequency operation. A careful design of the drivers is required to prevent undesirable switching of the devices due to electromagnetic interference (EMI), hence the system reliability is lower, and needs to be quantified. The driver stage requirements are somewhat simpler in the SCR Circuit Configuration, mainly because the more robust SRC does not require a fast acting overcurrent protection function integrated into its gate controller. Otherwise complexity and hence cost can be similar in both alternatives. Table V shows a qualitative and quantitative comparison between these alternatives. These characteristics include the estimated reliability for both configurations [7].

Table V: Voltage controllers comparison

Properties	IGBT	SCR
Cost in US$ (May 1998)	325.5	187.5
Losses at 80% of rated voltage	27.3 W	17.6 W
Estimated Reliability	99.77 %	99.95 %
Total voltage distortion at 80% of rated voltage	81 %	83 %
Maximum dv/dt	600 V/μs	50 V/μs
Number of commutations by cycle	30	2

Electric Machine

From the machine point of view, the SCR Circuit Configuration injects low order harmonic current components, while the IGBT Circuit Configuration injects high order harmonic current components. Since the machine behaves as a low pass filter, the second method reduces the harmonic torque and increases the effective electric torque and efficiency. On the other hand, the dielectric stress on the machine insulation is increased due to the high frequency voltage switching, accelerating the aging of the windings.

Table VI compares the machine losses for different operation voltages. Table VII shows the electrical harmonic torque obtained in these alternatives, for the 80% and 100% voltage operating conditions.

When the SCR Circuit Configuration is used, the supply current harmonics are the same than the machine current harmonics due to the circuit topology and the SCR operation. However, this is not the case when the IGBT Circuit Configuration is used. Figure 7 presents the motor current for the IGBT Circuit Configuration when the converter is operating at 80% of the rated voltage and Figure 8 shows the corresponding harmonic spectrum. Figures 4 and 6 present the same data for the SCR Circuit Configuration. The THD for the IGBT Circuit Configuration is 92,9%. This result shows that the IGBT Circuit Configuration can improve the steady state system power factor for loads under the nominal value using the Voltage Harmonic Elimination (VHE) technique to produce the PWM waveform. This is one of the most significant results obtained from the comparison between both configurations, and it may, by itself be important enough to justify the choice of the IGBT Circuit Configuration for systems where operation over long periods at low load are usual.

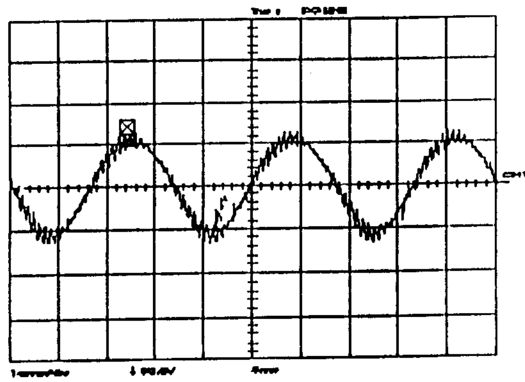


Fig. 7: IGBT Circuit Configuration current injected in the motor when the converter is operating at 80% of the rated voltage.

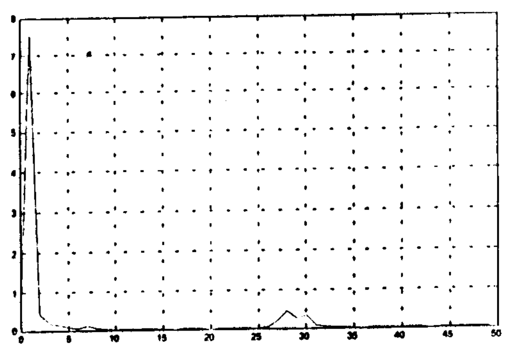


Fig. 8: IGBT Circuit Configuration spectrum of the current injected in the motor when the converter is operating at 80% of the rated voltage.

Table VI: Losses in the induction machine for both alternatives

Converter type	V=80%
IGBT	58 W
SCR	75 W

Table VII: Electric torque in the induction machine for both alternatives

Voltage condition	V=80 %			V=100 %		
Harmonic torque	1st	5th	7th	1st	5th	7th
IGBT	0.93 pu	0.045 pu	0.017 pu	1 pu	0 pu	0 u
SCR	0.89 pu	0.15 pu	0.096 pu	1 pu	0 pu	0 pu

Conclusions

The simulated results and experimental measurements obtained from the analysis of two AC voltage control techniques for induction machines, one using the SCR Circuit Configuration and the other using the IGBT Circuit Configuration have been presented. As result of this work, the controlled-switched scheme with IGBTs appears as an effective, efficient and cost competitive alternative to the voltage regulation for AC machines.

The main advantages of this controller scheme are two:

1. Its intrinsic reduction of the total harmonic distortion in the line current and its filtering requirements reduction. This enables its application on weak power distribution systems. However, at present the schemes by phase control have a wider application spectrum by its cost, efficiency, and reliability.

2. Power factor correction is possible when the AC motor operates for long periods at low load. No power factor degradation is introduced by the power controller during the star-up at any load level.

Due to these advantages the IGBT Circuit Configuration is the best choice for applications working on weak power distribution systems, or where the AC machine will operate at reduced load for long intervals.

Care should be taken when upgrading existing schemes, presently working either with SCR or with electromechanical starters to avoid problems in the AC machine isolation caused by the multiple sharp voltage fronts generated by the IGBT Circuit Configuration.

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