The College of Engineering
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Wisconsin Electric Machines and Power Electronics Consortium

RESEARCH REPORT
88-14

DESIGN AND PERFORMANCE OF A DIGITALLY BASED VOLTAGE CONTROLLER FOR CORRECTING PHASE UNBALANCE IN INDUCTION MACHINES

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ABSTRACT

The case of unbalanced supply presents a uniquely difficult problem in motor application since its causes are multivaried. In many situations a static starter utilizing back-to-back thyristors in series with the motor lines is already installed for the purpose of soft starting or for power factor improvement. An attractive low cost solution for phase unbalance is to simply modify the control strategy of the static starter by adjusting firing the angles of the three thyristor pairs independently. In this manner the series connected thyristors serve the function of unsymmetrical, variable supply impedances which can be used to balance the voltage across the motor phases. A new digital controller utilizing a static starter for balancing the phase currents of an induction motor operating with unbalanced supply is the topic of this paper. Experimental results show a marked reduction in the current unbalance from approximately 40% to a few per cent and clearly demonstrate the attractiveness of the new phase balancer.

INTRODUCTION

The case of unbalanced supply presents a uniquely difficult problem in motor application since the causes of such unbalanced arise from numerous unsymmetrical conditions. Unsymmetrical transformer windings or transmission line impedance, unbalanced three phase loads or large single phase load, are some typical examples. Causes exist in all stages of the electrical energy transformation from the generation to utilization. However, regardless of the cause, even a small phase unbalance voltage can induce large negative sequence currents, due to the relatively low negative sequence impedance of the connected ac machine. Induction motors are particularly sensitive to unbalanced operation since localized heating can occur in the stator and the life of the machine can be seriously affected with only a few percent voltage unbalance.

Conventional remedies for phase unbalance often involve costly modification of the incoming substation equipment, redesign of the feeder line layout to the various loads, or perhaps, retrofit with an oversized machine. In many situations however, a static starter utilizing back-to-back thyristors in series with the motor lines is already installed for the purpose of soft starting or for power factor improvement. Hence, an attractive low cost solution for correcting the phase unbalance problem would be to simply modify the control strategy of the static starter by adjusting firing the angles of the three thyristor pairs independently[1]. In this manner the series connected thyristors serve the function of unsymmetrical, variable supply impedances which can be used to balance the voltage across the motor phases[2].

A new digital controller utilizing a static starter for balancing the phase currents of an induction motor operating with an unbalanced supply is the topic of this paper. The benefits obtainable by this solution are not only reduction in hot spots inside the machine but also, with drastic reduction of the negative sequence of current and voltage, it is possible to improve also the motor efficiency, to limit the level of the flux saturation inside the machine and also to eliminate acoustic noise and vibration due to torque pulsations.

APPROACH TO ANALYSIS

In order to avoid the unbalanced voltage problem, a system consisting of three back-to-back thyristors pairs in series with the induction machine phases together with a new control strategy that provides different firing angles for each phase has been proposed[2]. The block diagram of the overall system is shown in Fig.1.

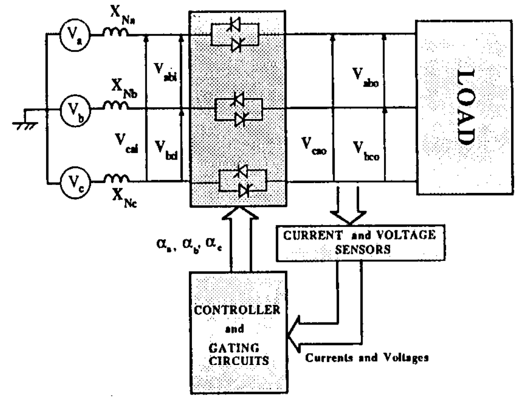

Fig 1: Block diagram of the overall system.

The three phases constituting an unbalanced supply V_{ai}, V_{bi}, V_{ci} are assumed to feed the converter. The induction machine, on the other side of the converter, should be supplied by the balanced three phase voltages V_{ao}, V_{bo}, V_{co} . The unbalanced conditions are counteracted by the controller to produce balanced voltages across the induction machine terminals. Thus the unbalanced parts of the input voltages drop across the SCRs, that can be represented by a variable series reactance for fundamental component analysis[3]. The voltage drops, in each phase, are X_aI_a, X_bI_b and X_cI_c. To illustrate this behavior, the related phasor diagram is shown in Fig. 2. The main objective of the controller is then to equalize the line current and the losses in each phase. Since losses are proportional to the line current squared, the control variables used are the currents.

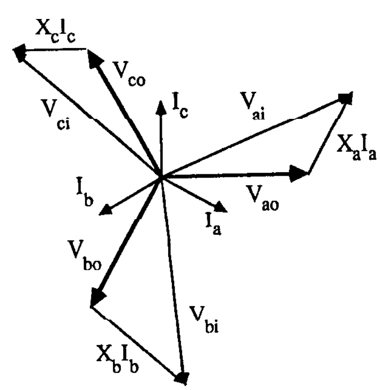

Fig. 2: Phasor diagram of the back-to-back thyristor converter

In the plane of a triangle ABC, as shown in Fig. 3, the control algorithm can be depicted by a geometrical analogy. The triangle angles are defined as α, β, γ and S_α, S_β, S_γ are the corresponding opposite sides.

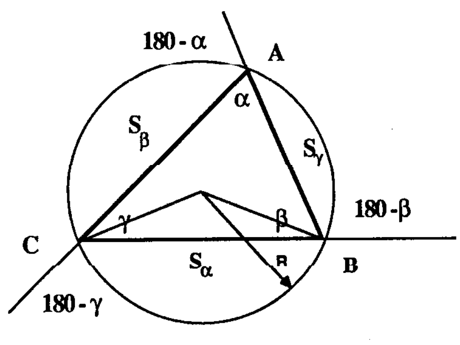

Fig. 3: Triangle plane: control strategy geometrical analogy.

The relations among the angles and sides for the triangle can be written as follows:

$$\frac{|S_\alpha|}{\sin\alpha} = \frac{|S_\beta|}{\sin\beta} = \frac{|S_\gamma|}{\sin\gamma} = 2R \qquad (1)$$

where: R = radius of circumscribed circle.

For any operating condition the following equation can be written for the triangle.

$$\vec{S_\alpha} + \vec{S_\beta} + \vec{S_\gamma} = 0 \qquad (2)$$

If it is possible to adjust the amplitude of S_α, S_β, S_γ independently, and, to make them three equal, then the triangle will then form an equilateral triangle with the following characteristics :

$$|S_\alpha| = |S_\beta| = |S_\gamma| \qquad (3)$$

$$\alpha = \beta = \gamma = 60^0 \qquad (4)$$

$$R = \frac{1}{3}|S_\alpha|\sqrt{3} \qquad (5)$$

The above equations for the triangle can be correlated with a three phase balanced wye connected induction machine, as shown in Fig. 4.

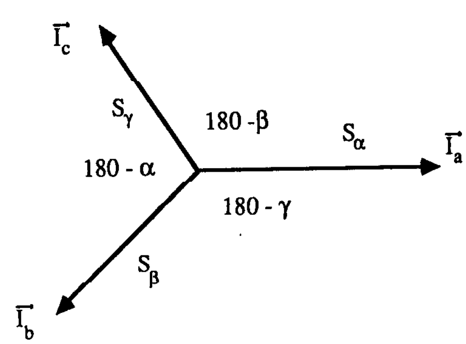

Fig. 4: Asymmetrical currents in the triangle plane.

The three phase line currents for any condition can be written as follows:

$$\vec{I_a} + \vec{I_b} + \vec{I_c} = 0 \qquad (6)$$

For balanced conditions, the line currents (in the time domain) are displaced each from the other by 120 degrees. By analogy with the triangle, if the amplitude of the three line currents can be maintained equal, the line currents are balanced. Thus, in practice, the controller must maintain the amplitudes of the three line currents equal and, consequently, the phase angles of the three phases as well. This is accomplished through control the converter by adjusting the firing angles independently in each phase. The "current balancing loops" of Fig. 5 perform this controller function.

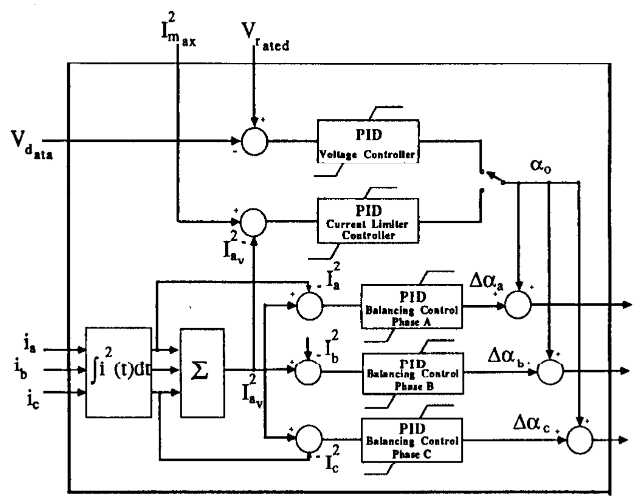

Fig. 5: Block diagram of the control loops

In addition, to keep the induction machine operating at the same condition as before the unbalanced condition occurred, the voltage across the phases must be kept constant at the rated condition. In effect, the machine excitation level must be kept constant and the amplitudes of the balanced currents must return to their original values. This is a further constraint for the system and it defines the necessary steady state operating point.

It is useful to again consider the circumscribed circle of Fig. 3. Three conditions might occur during the adjustment of the current amplitudes I_a, I_b, I_c:

a) the radius of the circle is kept constant and equal to R_0. The summation of the line currents amplitudes is the same as before the unbalanced condition were occurred.

b) the radius of the circle is larger than the original and equal to R_2. The amplitude of one or more line currents is larger than the original ones.

c) the radius of the circle is smaller than the original and equal to R_1. The amplitude of one or more line currents is smaller than the original ones. For all three conditions to apply the controller must be capable of adjusting the three line currents back to the original amplitude. Hence the controller must be able to increase or to decrease the applied voltage to the induction machine terminals. A balanced condition is reached when the circumscribed circle of the line currents return to the original condition (radius equal to R_0). This feature is corresponds to the "voltage loop" in Fig. 5.

Finally, since the nature of the SCRs controller is to adjust the voltage applied to the phases winding by modifying the firing angles, the voltage applied at the induction machine terminals is always smaller than the input voltage of the SCRs converter for any value of firing angle except zero. Therefore, to keep the rated voltage at the terminal input of the induction machine, the incoming voltage to the SCRs converter must be larger than the rated voltage of the induction machine. Thus under the normal balanced condition, the firing angles must be slightly greater than zero to reduce the incoming voltage (i.e. to match the induction machine voltage). This condition enables the controller not only to reduce but also increase the voltage across the induction machine terminals.

CONTROL STRATEGY

The system proposed in this paper consists of three pairs of identical thyristors, connected back-to-back in series with a three phase wye (or delta) connected induction machine. In general, the stator voltage control is accomplished by adjusting the hold off angle γ which corresponds to the time the thyristor remains open after current reaches zero in a given phase. The aim of the controller is to compensate the unbalanced voltage supply by controlling each pair of thyristor distinctly with an unsymmetrical firing angle such that different values of γ occur in each phase.

Some of the central functions implemented with the digital controller are shown in the block diagram of Fig. 5. The complete control consists of three main loops: a "current limiter loop", a "voltage loop" and, finally, a "balancing current loop". Each loop contributes to the calculation of the phase angle α_i separately for each phase with i=a, b, c.

The "current limiter loop" is a protection control loop and mainly operates during the starting of the machine as well as during overload conditions (transient operations). Such a loop limits the average current in the three phases to the value imposed by the reference value I_{max}. The current limit value can easily set, consistent with the load demands and the connected network characteristics. The "voltage loop", on the other hand, is the control loop for the normal balanced condition (steady state operation). The voltage loop keeps the voltage at the motor terminals at the rated value.

The two previous loops operate alternatively rather than simultaneously. The output of either loop contributes to the average phase angle command α_o which is nominally equal for the three phases. In addition to the voltage and current limiter loops, the "balancing current loops", one for each phase, operate both in steady state and during transient conditions and control each phase current in order to maintain each of them equal to the average value of the three phases. The outputs of the three loops can be different for each phase, related to the unbalanced voltage of each phase and are expressed by the angles: $\Delta\alpha_a$, $\Delta\alpha_b$, $\Delta\alpha_c$. A pictorial representation of the overall phase balancing strategy is shown in Fig. 6.

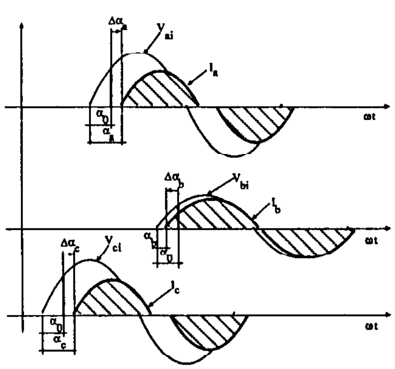

Fig. 6: Current balancing control strategy.

From this figure, the firing angles for the a, b, c phases can be written:

$$\alpha_a = \alpha_o + \Delta\alpha_a$$
$$\alpha_b = \alpha_o + \Delta\alpha_b \qquad (7)$$
$$\alpha_c = \alpha_o + \Delta\alpha_c$$

where $\Delta\alpha_a$, $\Delta\alpha_b$, $\Delta\alpha_c$ can be positive or negative. For steady state balanced conditions the three "balancing current loop" outputs are equal to zero. This mode of operation can be termed the "Voltage Mode" because the phase angles are controlled. In addition, a second mode of operation, a so called "Current Mode", is possible in which the hold off angle γ is controlled. Both control schemes have been tested, but the best results have been obtained by the first mode. Hence, in this paper the results are always related to the "Voltage Mode".

SYSTEM DESIGN

In order to obtain the performances above described, the analog controller of a commercial static starter drive has been substituted with a new digital controller. Fig. 7 shows a simplified block diagram of the overall implementation with the independent firing angles for the three phases, using currents and voltage as feedback signals.

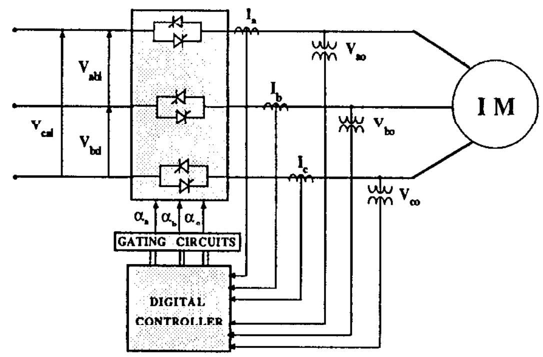

Fig. 7: Overall system with the digital controller.

The controller has been implemented digitally in an INTEL 8088 low cost single board computer. The CPU runs at 5 Mhz clock and, as shown in Fig.8 on the board there is an 8Kb EPROM, an 8 Kb RAM, a serial port 8251, interruption controller 8259, parallel I/O controller 8255 and a 8253 counter [4].

In addition two interface boards have been designed. The first board has a PLL (Phase Locked Loop) for detecting the system frequency and synchronizing the control functions and a D/A converter for detecting currents or voltages as selected by software. The second board is the I/O board with four A/D converters for the three currents and the voltage feedback and a counter for the gate pulse generator.

The serial interface is the communication link between the single board computer and the IBM/AT used as development system. The IBM/AT is also utilized as an input/output terminal for updating the control parameters and checking some control internal variables as the firing angles for each phase. The serial interface has been chosen because it is much more robust than other communication interfaces from the noise point of view since it uses the +15V/-15V as signal level and the parity bit to detect signal errors.

The 8 Kb EPROM is prepared with a basic software that is called a "Mini Monitor" and mainly consists of a debugger, which is compatible with MS-DOS debugger except for assembly and disassembly commands. In addition, some general use subroutines, particularly useful in the stage of the software development, are resident in the EPROM. The 8Kb RAM is the memory for the applicative software. The software has been written in Assembler language and consists of a "main loop" and five levels of "interruption loops". The "main loop" analyzes the keyboard commands and sets and updates the control parameters as the proportional, the derivative and the integral gains for each loop and the references for the "voltage loop" and for the "current limiter loop". In addition, the "main loop" takes care to store important internal variables: such as currents, voltages and balancing angles. Finally the previous variables can be displayed on the screen, selectable by keyboard. Figure 9 shows a simple flow chart of the "main loop".

On the other hand, the "interruption loops" calculate the RMS values for each current and the output of each PID control loop. The first level of the "interruption loop" (INT0) occurs 32 times in each period and calculates I_a^2, I_b^2 and I_c^2. It detects the zero points for the three voltages and in the "Voltage Mode" sets the three counters and calculates the PID outputs.

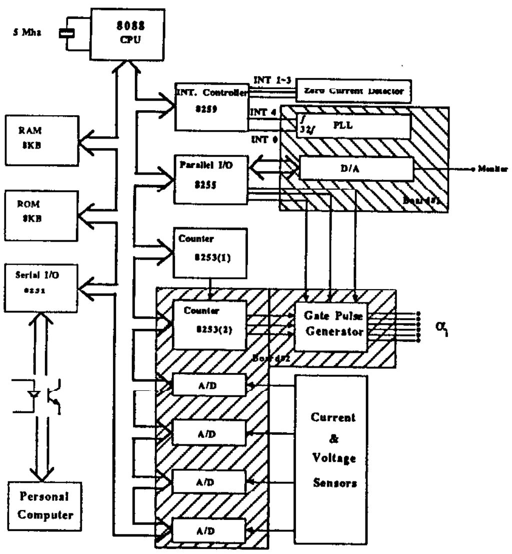

Fig. 8: Hardware configuration of the digital controller.

Software Block Diagram (1)

■ Main Loop

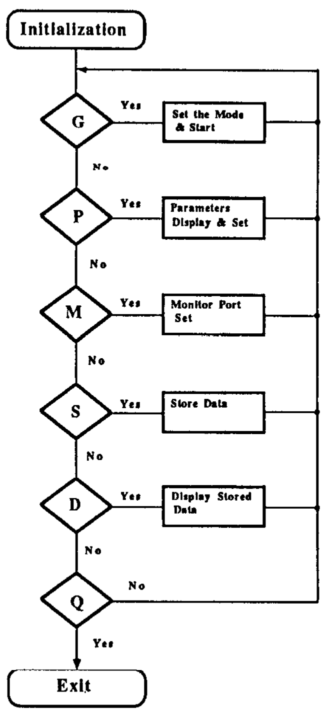

Fig. 9: Flow chart of the "main loop".

Figure 10 shows a simplified flow chart of the loop INT0 and some details about the integration procedure.

The fifth level of interruption (INT4) occurs once in a cycle and resets the angle counter for the voltage in INT0. Finally INT1~3 occur, once in each semiperiod for each phase and these signals come from the zero current detectors. In the "Current Mode", they set the three counters, one for each phase and calculate the PID outputs.

Software Block Diagram (2)

■ Interruption Loop (INT0)

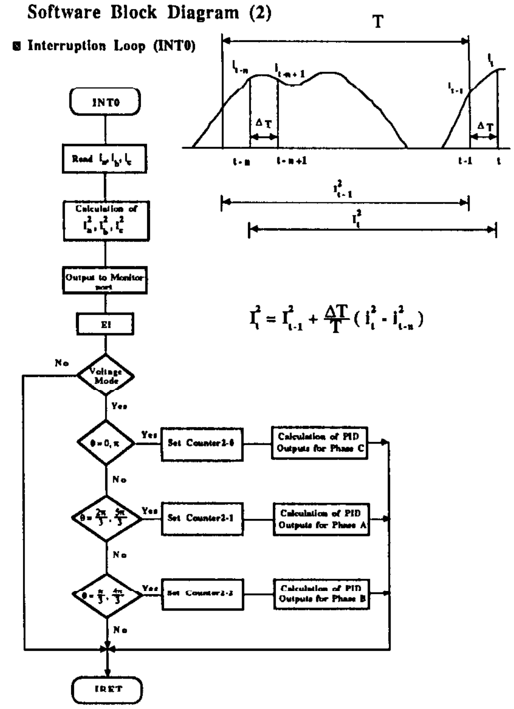

Fig. 10: Flow chart of the interruption loop (INT0).

EXPERIMENTAL RESULTS

Since the causes of unbalanced supply voltages arise from many sources it was necessary to decide how the unbalances were to be simulated in our laboratory. A .75 HP, 4 poles, 60 Hz, 220 V, three phase squirrel cage induction motor has been utilized, supplied by a static starter which employs six thyristors as its power switching devices. Two different causes of unbalance have been selected and realized. In the first simulation three voltages with different amplitudes for supply the back-to-back thyristor converter. Figure 11 shows the simplified schematic employing one 3Φ autotransformer with an additional single phase transformer for obtaining the unbalanced voltage. The percentage of unbalanced voltage can be defined by the following expression:

$$V_{unb} = \frac{V_{abi} - V_{cai}}{V_{cai}} * 100 \qquad (8)$$

where the symbols are illustrated in Fig. 11.

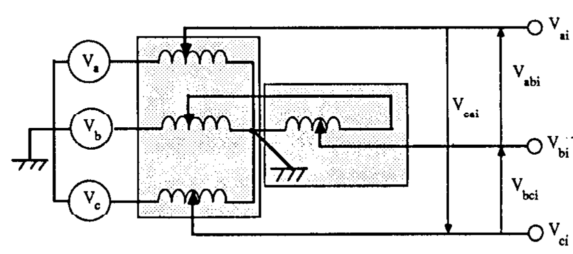

Fig. 11: System for realizing the unbalanced power supply.

The second simulation of unbalance has been set by using different line impedance in series with the three phases. Since the results obtained by the two experiments are comparable, the results reported in this paper are related to the first set of experiments.

In order to evaluate the performance of the prototype, the same motor has been supplied by two different methods. First, the unbalanced voltage supply, above mentioned, has been connected directly to the motor and different percentages of unbalanced voltage have been supplied to the load (EXPER.1). The test has been repeated employing the static starter prototype supplied by the unbalanced voltage supplier (EXPER.2).

In Fig. 12 is shown the currents in phase b and c when the motor is supplied by a sinusoidal waveform (EXPER.1) with V_{unb} = + 8% and when the machine is operating under a full load condition. It is interesting to note that the currents become nonsinusoidal even for the sinusoidal supply due to the flux level in the machine. The average current in the three phases is 1.95 A rms.

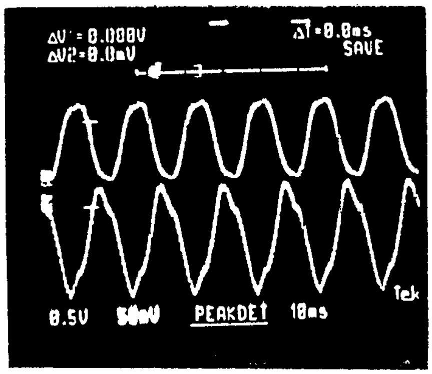

Fig. 12: Motor supplied by sinusoidal supply (EXPER.1).
Top: Current phase C (1.608 A rms)
Bottom: Current phase B (2.515 A rms)
Time scale: 10 ms / div.

Figure 13 shows the results for EXPER.2 for the same conditions. The distinct advantages of operation of solid state voltage controller is clearly shown.

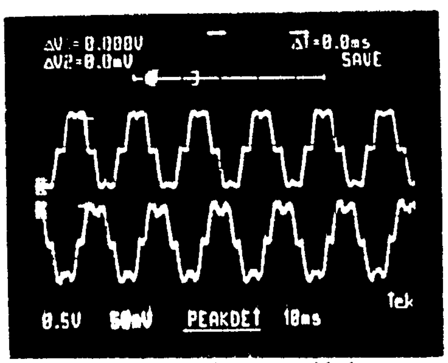

Fig. 13: Motor supplied by static starter with the new controller (EXPER.2).
Top: Current phase A (1.921 A rms)
Bottom: Current phase B (1.917 A rms)
Time scale: 10 ms / div.

In the next series of tests the motor was subjected to a different percentage of voltage unbalance from +10% to -10% and the motor was operated under both no load and full load conditions. In Fig. 14 the experimental results for EXPER.1 for the no load case are shown. On the vertical axis the currents in the three phases are expressed as the percentage of the average current. Figure 15 shows the results for the EXPER.2 for the same conditions. The results indicate the excellent capability of the new controller for balancing motor currents when subjected to an unbalanced supply. It can be noted however, for negative percentage of unbalanced voltage supply greater than -5%, the new controller loses control capability because the "balancing current loops" outputs $\Delta\alpha_a$, $\Delta\alpha_b$, $\Delta\alpha_c$ have the constraint that $(\alpha_0 + \Delta\alpha_i) > 0$, with i = a, b, c. To increase the controllability range (maximum negative $\Delta\alpha_i$), it is clear that the supply voltage must be increased. Thus to obtain rated voltage at the machine terminals α_0 (always positive) must be increased and, hence, the controllability range increases. However, this increase in α_0 also increases the motor losses so that a practical limit is reached wherein the losses become intolerable. This study has established, however, that a ± 10% unbalanced can be corrected with tolerable additional motor losses.

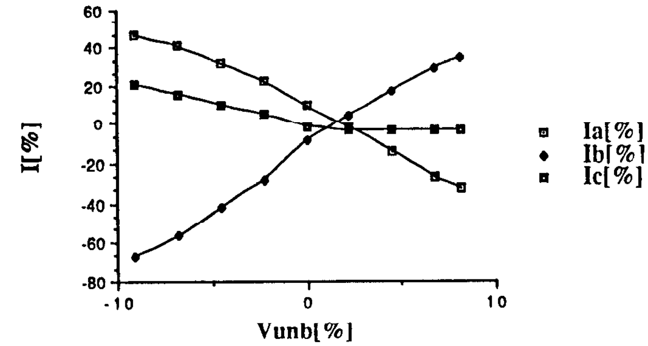

Fig. 14: Currents in each phase versus the percentage of unbalanced voltage (EXPER.1) (no load condition).

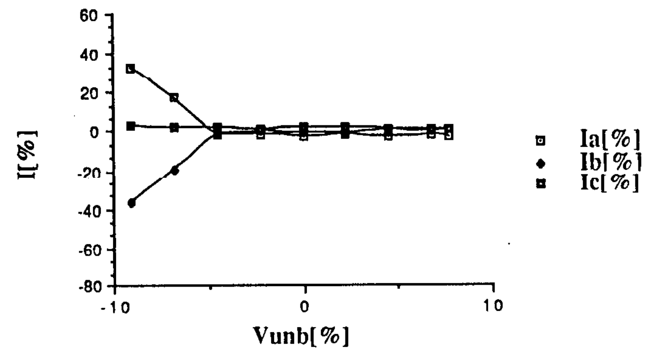

Fig. 15: Currents in each phase versus the percentage of unbalanced voltage (EXPER.2) (no load condition).

In Figs. 16 and 17 the results related to EXPER.1 and EXPER.2 during full load are shown. It can be noted in Fig. 17 that the controller again loses control capability around -5% of unbalanced voltage, but the three currents remain more balanced than for the no load case.

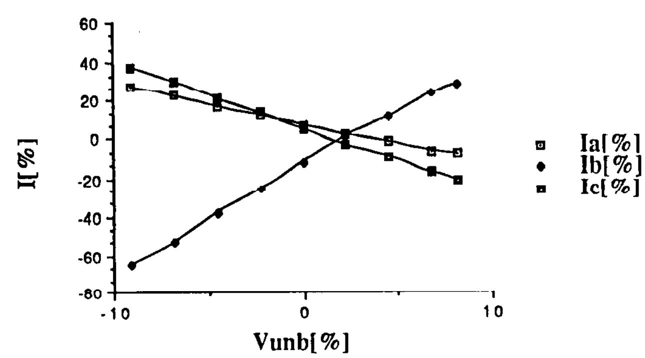

Fig. 16: Currents in each phase versus the percentage of unbalanced voltage (EXPER.1) (full load condition).

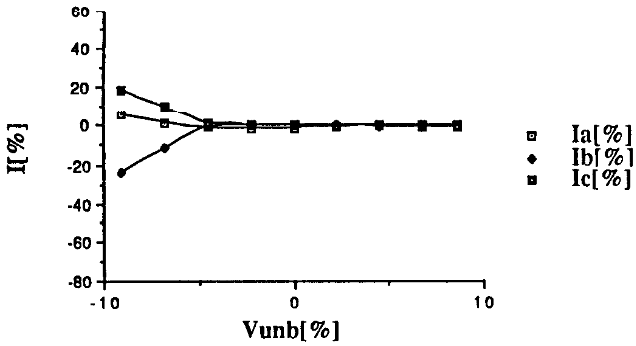

Fig. 17: Currents in each phase versus the percentage of unbalanced voltage (EXPER.2) (full load condition).

In Table 1 are summarized the results of the previous tests together with some additional data. Of particular interest are the figures reported in lines (3) and (4). In the case of EXPER.1 with just a few percent of negative sequence voltage, the related ratio between the negative and the positive sequence current is 70%. In the case of EXPER.2 the ratio between the negative and positive sequence of current is only 4%.

	EXPER.1	EXPER.2
Maximum positive unbalance of current	+40.0 %	+2.0 %
Maximum negative unbalance of current	-60.0 %	-2.5 %
Max. ratio negative over positive sequence of volt.	6.0 %	3.0 %
Max. ratio negative over positive sequence of curr.	70.0 %	4.0 %
Min. ratio negative over positive sequence of imp.	8.0 %	7.0 %

Table 1: Summary of the maximum positive and negative unbalance of current, maximum ratio negative over positive sequence of voltage, current and impedance.

In Fig. 18 the efficiency versus the percentage of unbalanced voltage for EXPER.1 is shown. The result is clearly encouraging. The efficiency is almost constant over the entire range of control. Out of the control range, the efficiency decreases in significantly.

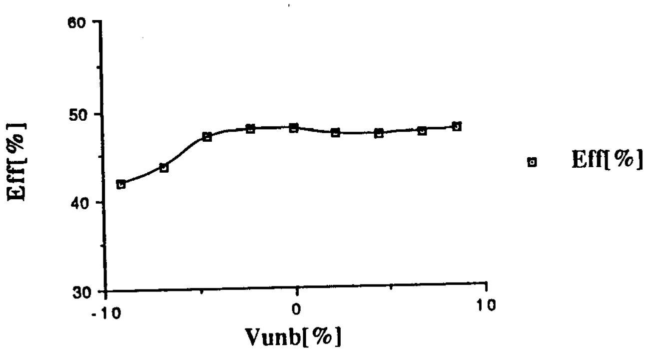

Fig. 18: Efficiency versus the percentage of unbalanced voltage (EXPER.2).

Finally, Table 2 shows the "distortion factors" for the motor current over the range of unbalanced voltage -5% to +10% for the EXPER.1 and EXPER.2 for the no load and full load conditions are reported. The voltage factor for the case of unbalanced is defined here as:

$$DF = \frac{1}{3} \sum_{k=a,b,c} I_k \qquad (9)$$

where

$$I_k = \frac{\sqrt{\sum_{n=2}^{\infty} I_{kn}^2}}{I_{k1}} \qquad (10)$$

	95% Vrated	100% Vrated	108% Vrated
	D.F. %	D.F. %	D.F. %
EXPER.1 no-load	11.0	2.4	15.1
EXPER.1 full-load	10.5	1.5	13.0
EXPER.2 no-load	21.3	19.8	23.9
EXPER.2 full-load	20.9	18.9	23.1

Table 2: Summary of the harmonics contents in no load and full load condition versus the percentage of unbalanced voltages.

As expected, in the balanced condition the distortion factors in the case of a back-to-back thyristor supply is poor. On the other hand, with an unbalanced condition the distortion factors for the sinusoidal supply and the back-to-back thyristor supply are much closer. Moreover, the "distortion factor" is quite consistent over the entire control range in the case of converter supply, whereas for the case of sinusoidal supply the harmonic content is remarkably variable.

CONCLUSION

A powerful digital controller for correcting phase unbalance in an induction motor supply has been presented by utilizing unsymmetrical control of a static starter. The major advantage of the approach that has been implemented results from the relatively inexpensive and straightforward use of power electronic components. In cases where the static starter is needed for starting purposes, the phase balance feature can be incorporated for only a few hundred dollars. If the static starter is not installed the approach could still prove desirable in chronic situations due to the rapid response and extreme flexibility of the approach. In such situations the added benefits of soft starting and efficiency improvement under light load could be attractive. The approach should prove to be particularly useful in difficult industrial applications where rapidly changing unbalance conditions preclude the use of fixed capacitor banks or other conventional compensation schemes.

ACKNOWLEDGMENTS

The work reported in this paper was made possible by support from the industrial sponsors of the Wisconsin Electric Machines and Power Electronics Consortium (WEMPEC) to whom the authors are greatly indebted.

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