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A DIGITAL VOLTAGE CONTROLLER FOR REDUCING INDUCTION MOTOR PHASE UNBALANCE

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ABSTRACT

Unbalanced operation of three phase induction machines has long been known as a major source of failure. Numerous papers have been written concerning how to quantify the effects of an unbalance. However, relatively little attention has been paid to methods for correcting the unbalance at the terminals of the machine. This paper describes the use of a thyristor voltage controller (also known as a static starter), to remedy the consequences of phase unbalance. In particular, this paper deals with the design of a new digital controller using a low cost single board computer (INTEL 8088) in conjunction with a thyristor voltage controller for correcting unbalanced supply conditions. The static starter consists of three pairs of back-to-back thyristors connected in series with the stator winding of the induction machine. The digital controller is programmed to control the firing angle of each thyristor independently. Particular attention has been paid to the design of the controller for a general case of unbalance. Confirmation of the theory is demonstrated by experimental results.

INTRODUCTION

The case of unbalanced voltage supply is often a perplexing and difficult application problem. Causes for such an unbalance are numerous. For example, unsymmetrical transformer windings or transmission line impedance, unbalanced three phases loads, and large single phase loads often cause an unbalanced voltage at the point of utilization. Regardless of the cause, large negative sequence currents can occur, even if the phase unbalanced voltage is small, due to the relatively low negative sequence impedance. Induction motors are particularly sensitive to unbalanced operation since localized heating can occur on the stator of the machine and the life of a machine can be seriously affected with only a few percent of voltage unbalance. As a result, utilities typically restrict the limit of the voltage unbalance to a few percent of the normal voltage or, alternatively, specify the limit of the negative sequence voltage at the distribution substation. While the voltage at the substation is within a desirable tolerance, further unbalances can frequently occur at localized portions of an industrial plant resulting in frequent failures of particular machines. A particularly difficult operating condition is often found in industrial plants with large single phase loads or unbalanced three phase loads such as arc furnaces, for example.

Conventional remedies for phase unbalance often involves costly modification of both the incoming substation equipment, redesign of the feeder line layout to the various loads, or perhaps, retrofit with oversize machines. As an alternative, a low cost solution with a voltage controller utilizing back-to-back thyristors in series with the motor lines is an attractive possibility[1]. In this case, a conventional static starter, perhaps already installed for starting and power factor improvement purposes, could be modified so as to control the firing angle of the three thyristor pairs independently. The series connected thyristors then serve the function of unsymmetrical and variable supply impedances which can be used to balance the voltage drop across the motor phases. The important benefits of unsymmetrical voltage control has been set forth in a previous paper[1]. However, the problems associated with the control algorithm required to obtain these benefits was not addressed. The development of a suitable algorithm to optimize the voltage balance across the stator windings of an induction machine in the presence of an arbitrary source impedance is the subject of this paper.

STRATEGY FOR PHASE BALANCING

A simplified circuit diagram of a commercial static starter is given in Fig. 1. The system consists of three pairs of identical thyristors, connected back-to-back in series with the stator phases of the induction machine with feedback of the three motor currents for calculating the firing angle α_0 which is nominally equal for each thyristor. When an unbalance of a few per cent in voltage occurs, maintanence of the same firing angle for the three phases continues to result in strongly unsymmetrical currents in spite of the presence of the voltage controller.

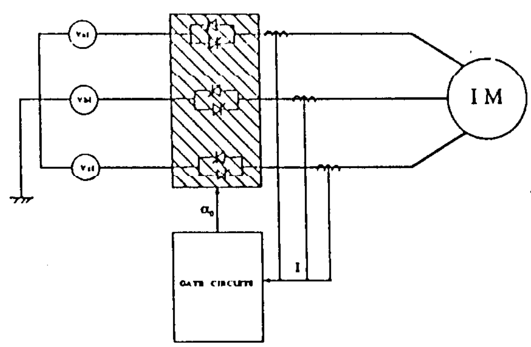

Fig. 1: Commercial thyristor voltage controller.

In general, the stator voltage control is accomplished by adjusting the phase angle α_i by which all thyristors are fired. With unsymmetrical firing, different values of α may occur in each phase. Figure 2 shows a pictorial representation of the control strategy for unsymmetrical control. In this figure the firing angle for each phase is shown as the summation of two components: the angle α_0, equal for the three phases and the angle $\Delta\alpha_i$, calculated separately for the three phases a, b, c.

Figure 3 represents a simplified schematic of the overall phase balancing controller [2]. The complete controller consists of five loops: the 'current limiter loop' which operates during the starting of the machine or when during the presence of abnormal conditions. As such, this loop performs the function of a protection loop. The 'voltage loop' is the normal loop controller which controls the average voltage by means of rectification of the three phase voltages and calculates the angle α_0. These two loops operate during different time intervals and the controller switches from one loop to the other one automatically Finally three 'balancing loops' are provided, one for each phase, to compute the angles $\Delta\alpha_a$, $\Delta\alpha_b$, $\Delta\alpha_c$ and compensate the difference of the currents in the three phases due to the unbalance supply voltage. The reference for each 'balancing loop' is the average squared rms current of the three phases that is related to the heating inside the machine. Each loop has a controller of the PID type and the phase angle for each phase is computed as follows:

$$\alpha_i = \alpha_0 + \Delta\alpha_i$$

where i = a, b, c. A detailed schematic of the three 'balancing control loops' is shown in Fig.4.

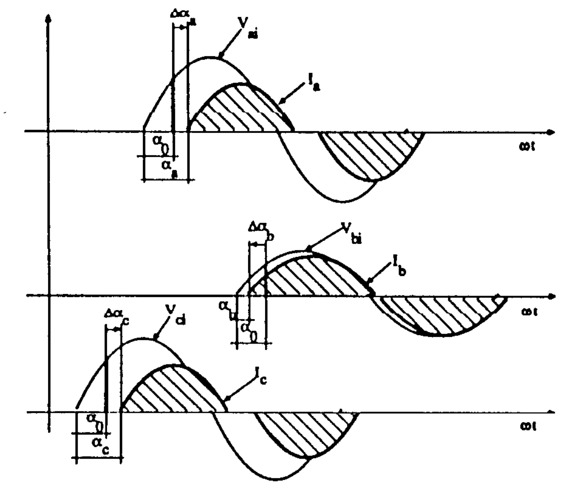

Fig. 2: Current balancing control strategy.

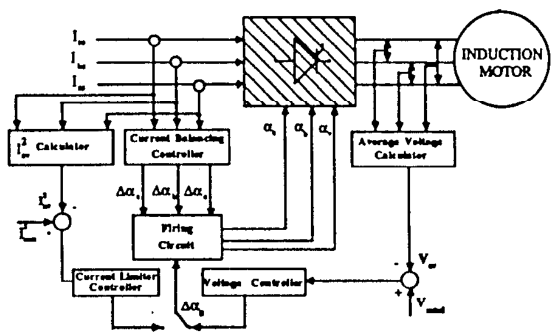

Fig. 3: Overall phase balancing control scheme.

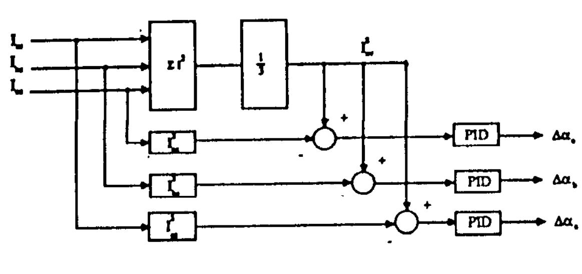

Fig. 4: Details of the current balancing control loops.

IMPLEMENTED SOLUTION

On the basis of the considerations above, a drive system utilizing these control principles has been implemented in our laboratory. A 3 HP, 4 pole, 230 V, three phase squirrel cage induction motor has been utilized, supplied by a static starter which employs six thyristors as its power switching devices. The controller has been implemented in a completely digital manner by using a single board microcomputer with an INTEL 8088 cpu. The one board computer has 8 kB of ROM in which the communication program together with the development system and some subroutines of general utility have been stored. The board also has 8 kB of RAM in which the software for the digital controller has been placed. In addition, a serial port is employed on the single board computer for communication with the development system during the software set up stage and with the terminal and the keyboard for setting the control parameters and checking internal variables, such as currents, voltage or phase angles during normal operation. Also present on the single board computer is an interrupt controller, a parallel I/O controller and a counter.

The interface between the high power and the single board computer has been realized by two additional boards: the first board has a PLL (Phase Locked Loop) for detecting the system frequency and a D/A converter for monitoring voltage and currents. The second board has four A/D converters (three for the current and one for the voltage) and a gate pulse generator. The outputs of the controller are the six firing signals for the SCRs. The software has been designed with a main loop for analyzing the keyboard commands and for setting the control parameters and five levels of interrupts for the main calculations.

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. Two different causes of unbalance have been selected and simulated. In the first simulation voltages of three different amplitudes were obtained using a three phase autotransformer and a single phase transformer as shown in Fig. 5. The second connects three inductances of different values for the three phases in series with the drive. The results reported in this paper are related to the first solution of unbalance.

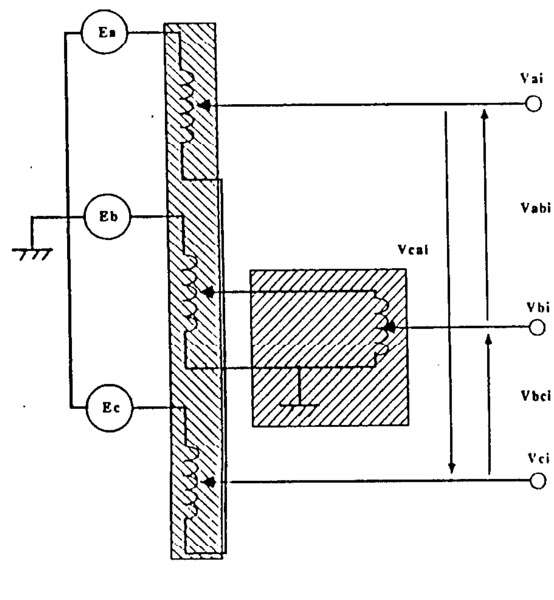

Fig. 5: System for realizing the unbalanced power supply.

The percentage of unbalance voltage can be defined by the following expression:

$$V_{unb} = \frac{V_{abi} - V_{cai}}{V_{cai}} * 100$$

Three different experiments have been set in our laboratory. In the first experiment the motor is fed directly with an unbalanced sinusoidal supply (EXPER. 1). In the second experiment the unbalanced voltage test is repeated but in addition a commercial static starter is interposed between the motor and the unbalanced source. The static starter uses conventional control principles without a "balancing loop' (EXPER. 2). Finally the test is repeated employing a static starter prototype with the complete control loop (EXPER. 3).

In Fig. 6 is shown the current in phases a and b when the machine is supplied by a sinusoidal waveform with V_{unb} = +7.5% and when the machine is in the no load condition. It is interesting to note that the currents become nonsinusoidal even for the case of sinusoidal supply due to high flux level in the machine. Figure 7 shows the results for the second stage of the experiment in which the same condition of unbalance is impressed but with a conventional static starter. Finally Fig. 8 shows the two phase currents I_a and I_b for the case of a static starter supply with the new controller. The advantages of operation of the voltage controller with substantially differcnt α's is clearly shown.

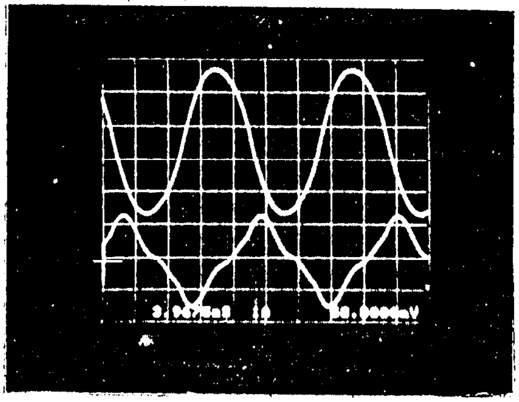

Fig. 6:Motor supplied by sinusoidal supply (EXPER. 1).
Top: Current phase A (4.028 A rms)
Bottom: Current phase B (1.993 A rms)
Time scale: 3.9675 ms / div.

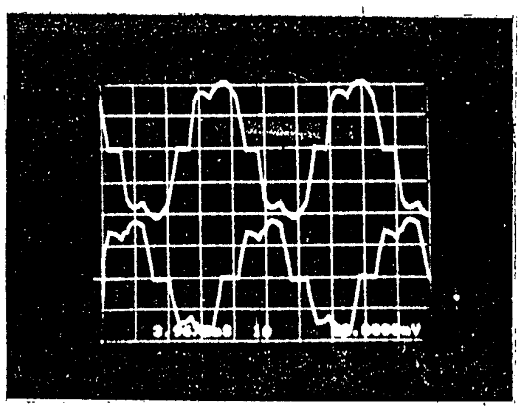

Fig. 7: Motor supplied by commercial static starter (EXPER.
Top: Current phase A (3.778 A rms)
Bottom: Current phase B (2.928 A rms)
Time scale: 3.9675 ms / div.

For each experiment the machine was tested with different degrees of unbalanced voltage supply. In Fig. 9 is shown the currents in the three phases expressed as the percentage of the average current with different degrees of unbalance voltage from -10% to +7.5%. For the traces shown, the machine is simply supplied by a sinusoidal (unbalanced) supply. Figure 10 shows the results of a similar experiment when the machine is supplied by the commercial static starter.

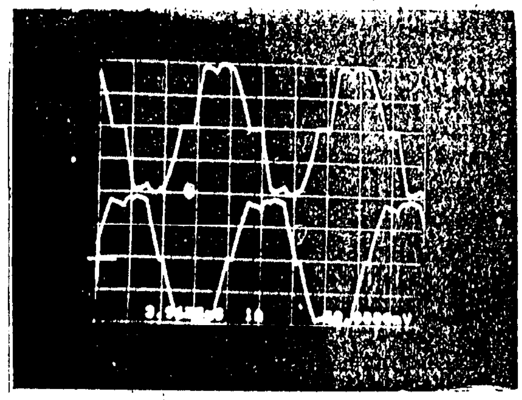

Fig. 8: Motor supplied by static starter with new controller (EXPER. 3).
Top: Current phase A (3.495 A rms)
Bottom: Current phase B (3.482 A rms)
Time scale: 3.9675 ms / div.

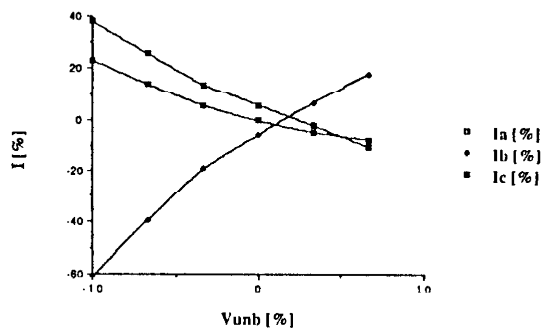

Fig.9: Currents in each phase versus the unbalanced voltage (EXPER. 1)

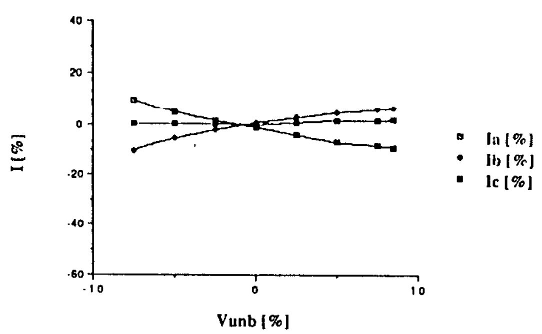

Fig.10: Currents in each phase versus the unbalanced voltage (EXPER. 2)

In Fig. 11 is reported the results related to the machine supplied by the static starter with the new controller. The enormous improvements in correcting current unbalance with the new controller are clearly evident.

Finally in the table of Fig.12 is summarized the most significant results of the previous experiments (no load condition and in the range of unbalance voltage of +/- 7.5%), reporting the maximum positive and negative unbalance of current for the three experimental set ups. The results shown indicate the excellent capability of the new controller for balancing motor currents when subjected to an unbalanced supply.

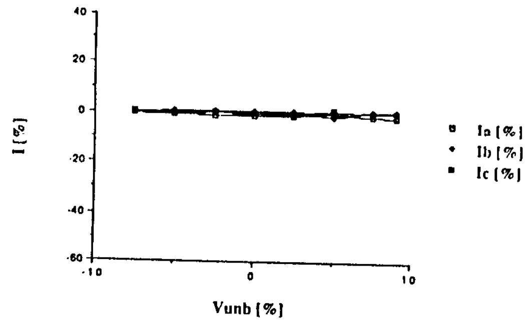

Fig. 11: Currents in each phase versus the unbalanced voltage (EXPER. 3)

	EXPER. 1	EXPER. 2	EXPER. 3
Maximum positive unbalance of current	+30 %	+10.0 %	+1.1 %
Maximum negative unbalance of current	-45 %	-10.3 %	-1.3 %

Fig. 12: Table with the maximum positive and negative unbalanced current for the three experiments selected.

Clearly, the remaining current unbalance is negligible. On the other hand, the results of the EXPER. 1 confirm that only a few percent of unbalance voltage can cause very large unsymmetrical currents inside the motor, due to the relatively low negative sequence of the motor impedance.

CONCLUSIONS

A new control scheme for phase balancing an induction motor supplied by an unbalanced set of voltages has been presented. The major feature of the approach that has been implemented results from the relatively inexpensive and straightforward use of power electronic components. The controller is robust and can be shown to converge on the best available balance condition even if perfect phase balancing cannot be achieved. In cases where the voltage controller is needed for starting purposes, the phase balance feature should be able to be incorporated for only a few hundred dollars. The approach should prove to be most useful in difficult industrial applications where rapidly changing unbalance conditions preclude the use of fixed capacitor banks or other conventional compensation schemes. Additional tests will be done for verify the system performance from the harmonic content and the efficiency point of view.

ACKNOWLEDGMENTS

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