SENSORLESS CONTROL OF SWITCHED RELUCTANCE MOTOR DRIVE WITH SELF-MEASURED FLUX-LINKAGE CHARACTERISTICS

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Abstract - In this paper, a novel discrete position estimation scheme for sensorless operation of Switched Reluctance (SR) Motor drive is proposed. The classical flux-current approach is adopted for estimating the position. In the proposed method, the required flux-linkage characteristics measurement is automated and integrated as a part of the sensorless controller. The algorithm is tested on a real motor and the relevant test results are presented. The method is suitable for low-cost mass-produced applications.

Keyword - SR motor, Sensorless, Discrete position estimation, Self-measurement, Flux-current method.

I. INTRODUCTION

The SR motor is a promising candidate for various adjustable speed drives in industrial and consumer product applications. However, the rotor position sensing requirement is a disadvantage for this motor. These position sensors reduce the reilability of the drive. They also occupy extra space and add to the total cost of the drive. The efforts are on for replacing such sensors by suitable estimation technique. All the indirect rotor position sensing methods are based on measurements of the periodically varying phase inductance or phase flux. The flux-linkage characteristics of SR motor (see Fig. 1) being a function of position and current has been used in several sensorless schemes for position estimation with different degrees of success. Such position estimations are possible on a continuous basis (at every operating points) or discretely, once in every phase cycle. The former needs to store the complete flux-linkage characteristics of the motor which requires more memory space as well as more time for computation. Such expensive methods may be justified for high performance drive such as servo applications. On the other hand, for low-cost mass produced applications, discrete position estimator is preferred. In dicrete estimation, reference position is determined generally by finding the instant when the flux or inductance passes through a particular threshold value. In our case, the flux-current approach is considered for such estimation. Among the family of flux-linkage characteristics shown in Fig. 1, it may be seen that the characteristics in the middle region close to 15° is best suited for the purpose of discrete position estimation since the sensitivity of rotor position to flux around this position is less. In conventional approach, the flux-current characteristics for the reference position is measured off-line and stored in a look up table.

The motivation of the present work is to automate the $\Psi - i$ characteristics measurement at 15° position and integrate the same as a part of the sensorless drive of SR motor. After giving a short review of the existing sensorless schemes, the basic idea of the proposed method, its realisation and advantages are explained in the following sections. The proposed method is tested on an 8/6, 4-kW SR motor and the relevant test results of sensorless operation during starting and running are presented.

II. REVIEW OF THE EXISTING SENSORLESS METHODS

In literature, many position estimators are suggested [1-8]. They are broadly divided into two two groups -

1. Intrusive methods
2. Nonintrusive methods

A. Intrusive methods

In this group, test signals of different kinds are introduced during the time when a phase is normally unenergised. An idle or unexcited phase is injected with high frequency diagnostic signals to obtain the phase

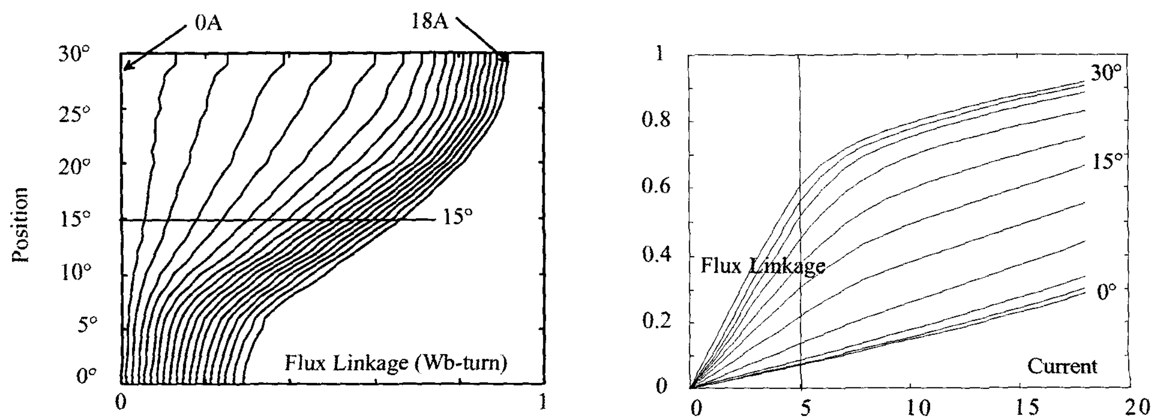

Fig. 1 Flux-Linkage Characteristics

inductance variation information. The phase inductance varies significantly between aligned and unaligned rotor and stator poles; therefore position information can be easily obtained from phase inductance information. For motoring operation, this is done normally during the falling inductance or at low speeds around the minimum inductance periods. Methods based on waveform detection [2], diagnostic pulses [3], and modulation techniques [4],are belong to this family.

The test signals in these methods need to be low

i. to minimise negative torque production
ii. to reduce back-emf effects
iii. to avoid saturation effects
iv. to minimise the size and cost of additional pulse injection circuitry

The disadvantages of these methods are:

i. The low amplitude test signals are susceptible to mutual interference from the excitation currents in other phases.
ii. At high speeds, the excitation waveform occupies a major part of the phase period. With this condition the duration available for test signal injection is restricted and hence these methods are more suitable for lower speed operation.
iii. Extra hardware circuitry is needed for most estimation methods
iv. Intrusive methods may produce negative torque.

B. Non-intrusive methods

The non-intrusive methods do not need any extra hardware for sensing. They use the existing hardware of the converter and they do not need any probing pulses. Different machine characteristics are used for estimating the rotor positions. The model-based estimator technique [5], the flux/current method [6], the mutual voltage method [7] and the back-emf method [8] fall under this category. The terminal measurements of phase voltage or mutual voltage and current are used as inputs for an estimator to obtain the rotor position estimate.

Earlier it is mentioned that position may be estimated discrete or continuous basis. For low-cost mass produced application, discrete estimators are attractive. Recently Miller suggested a method for discrete position estimation based on the measurement of current gradient [8]. As the back-emf changes its polarity at the middle of the unaligned inductance region, the gradient of the current waveform changes. In their method, voltage PWM is used for controlling the motor and the current waveform takes up a typical single pulse shape with high frequency chopping superimposed on it. By observing the change of current gradient properly the minimum inductance position can be detected. The advantage of this method is that it does not require any prior knowledge of the motor parameters. The disadvantage of this method as illustrated by Miller are:

i. It is not suitable for starting as well as for very low speed operation.
ii. It needs the excitation to take place in the negative inductance region, which reduces the flexibility of the controller.

C. Summary and Remarks on different existing position estimation methods

The above discussion can be summarised in the following way. The Intrusive methods employing low amplitude test signals are susceptible to interference from the excitation currents in other phases. Besides, they are not suitable at high speed. Majority of the intrusive methods require extra hardware.

Among the non-intrusive methods, the most sophisticated one is the observer based method, but it is computationally complex and needs an exact model of the motor and the load. The mutual inductance method and the flux/current method are computationally simpler than observer based method and they do not require any model of the load. In order to obtain precise position estimation, both these methods need accurate measurement of the respective motor parameters. Mutual flux between the phases is one or two orders less than the self-flux. Thus, the mutually induced voltages are weak signals and are prone to measurement errors and susceptible for corruption due to environmental noise. Hence a better alternative is to find out the position from the flux-linkage characteristics of the active phase.

III. Flux/Current method

The main excitation current and its flux-linkage may be used for the purpose of rotor position sensing. If at a given instant, the flux-linkage (Ψ) and the current (i) of a particular phase are known, then from the stored flux-linkage characteristics of the motor, the rotor position θ will be known provided it is also known whether the inductance is rising or falling. The latter is quite obvious from the positioning of the excitation which will be predominantly in the rising inductance region for motoring operation. The position can be looked-up in stored tables of θ against ψ and i. This method can be used in connection with both discrete and continuous estimator [6]. The focus of this paper is on discrete estimation.

A. Discrete Position Estimation method

In discrete estimation, generally, only one rotor position information per phase cycle is obtained by finding when the flux passes through a particular threshold value [1, 2]. The threshold represents a particular rotor position (15° in our case). Intermediate positions in such estimations are obtained from a PLL (phase-locked-loop) [2]. Schematic of such discrete estimator based on flux-current method is illustarted in Fig. 2.

Such method needs the knowledge of flux-current characteristics at the reference position. In conventional approach, these characteristics are obtained through off-line measurement. In order to measure the flux-linkage characteristics, the rotor is held standstill at the required position and a pulsed voltage is applied across the phase. The voltage across and current through the excited phase are measured and flux-linkage is computed from Eq. (1).

$$\psi = \int (v - iR)dt \qquad (1)$$

In such measurements [9], mechanical blocking arrangements and a position marking disk with a pointed

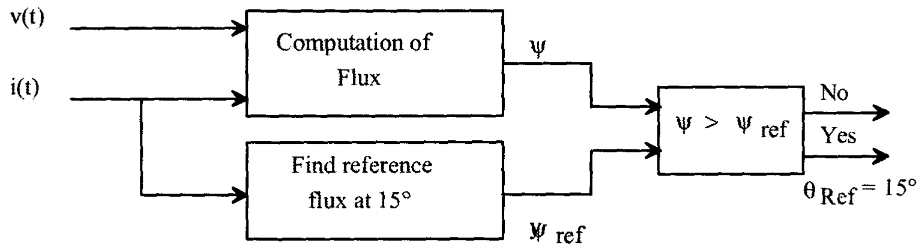

Fig. 2 Schematic of discrete position estimation using flux-current method with reference position as 15°

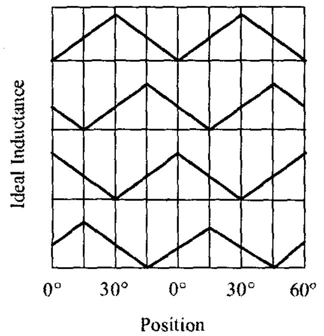

Fig. 3a Idealised Inductance profile and reative displacement of all the phases.

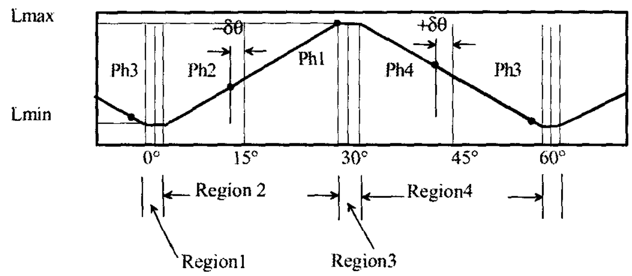

Fig. 3b The relative position of all the phases when Ph1 is in the aligned position

indicator are used. These methods are tedious and expensive. In this proposed method, by exploiting the motor geometry and adopting suitable control algorithm, the required flux-linkage characteristics are measured without any mechanical arrangement. Finally sensorless operation of the motor is realised with the obtained data. The measurement of flux-current characteristics is made a part of the controller.

IV. Proposed Self-measurement Method

A. Flux-linkage measurements through blocked-rotor test without mechanical arrangement

From the motor geometry, it can be found that for an 8/6 motor, the relative displacement between two consecutive phases is 15°. In order to explain the relative phase displacement, the inductance profile of each of the phase is shown in Fig. 3a. When Ph1 is at 30° (aligned position), the two neighbouring phases- Ph2 and Ph4 are at 15° and 45° respectively. Since, the flux-linkage characteristics of an 8/6 pole SR motor is symmetric with respect to 30°, the flux-linkages and torque produced at both 15° and 45° will be the same. Thus, if Ph1 is made aligned to 30° by some means and in that condition if excitation is given to Ph2 and Ph4 simultaneously, then the rotor should not experience any torque, since the torque produced by these phases at this position will cancel each other. Thus the motor can be locked at this position even under excitation in these phases. Similarly, keeping any other phase in the aligned position, and exciting its neighbouring phases together, the rotor can be kept in locked condition. At this position, the flux-linkage characteristics of any of these two neighbouring phases represents the characteristics of 15° and these characteristics may be computed from (1).

B. Choice of the phase to be aligned

In the above method of flux measurement, it is to be ensured that one of the phases is aligned at 30°. The actual unsaturated inductance profile (c.f. Fig. 3b) of an SR motor shows that there are zones where the phase inductance remains constant. Such zones are referred as no-torque zone (dead zone) in SR motor. If a particular phase is in the dead zone at near 0° (region 1), then even under excitation the rotor will not move. Thus by merely exciting a particular phase, the rotor may not get aligned along its axis. Therefore, the phase which is in region 2 or region 4 should be chosen for alignment depending on the desired direction of rotation. For forward direction of rotation, the phase in region 2 should be chosen. In practice, more than one phase can be in region 2 or region 4. In that case, the phase closer to the aligned position is preferred. This is advantageous in two respects- 1) it needs minimum energy and time to bring the rotor in aligned position and 2) It incurs minimum movement of the rotor before actual starting of the motor.

In order to decide on the phase closest to the aligned position, a simple method is proposed here. The idea is to excite all the phases simultaneously and monitor the current of each phase. When current of any of these phases exceed certain value (around 1/3rd of the rated current, 5A for the test motor), see which phase is carrying the minimum current. Obviously, the phase carrying minimum current will be closest to the aligned position. Once that phase is detected, rest of the phases are switched off and excitation is continued in that phase for sufficient time so that the particular phase gets aligned. Once this phase is aligned, excitation is given to the phases left and right to it simultaneously and continue with the proposed self-measurement scheme. In this method, before the actual test, the motion of the rotor is restricted to only ±7.5°. If the backward direction of rotation is not desired, then the phase next to the minimum current phase in the sequence should be chosen for aligning. In the later case, the rotor movement will be confined to the desired direction but the maximum rotor movement will be 22.5°.

C. Averaging of the two neighbouring phase fluxes

Apart from the minimum inductance zone, each phase is having another no-torque zone near the aligned position. In Fig. 3b, region 3 is such no-torque zone. Therefore, if the position of a particular phase is originally in this position, then even under excitation in this phase the rotor will not move. Hence, the phases may not get exactly aligned at 30°, it may remain anywhere within the dead zone around 30°. In this condition, none of the two neighbouring phases truly represents 15° position. Depending on the position of the aligned-phase (suppose, it is $\delta\theta$ away from the aligned position, c.f. Fig. 3b), the neighbouring phases may deviate from the 15° position by $\delta\theta$ degree in either way. If the flux-linkage characteristic is measured at this condition by choosing any one of these two phases, the measured characteristics will not exactly represent the 15° position. Since the relative displacement between these two phases is fixed (30°), if one phase is displaced by $+\delta\theta$, then the other phase must be displaced by $-\delta\theta$ from the desired positions (c.f. Fig. 3b). Thus the errors in flux-linkage in these phases will be in opposite directions. The averaging of these two phase fluxes will certainly reduce the net error and the obtained average flux may be considered as more reliable flux-linkage characteristics at 15°.

V. Practical Implementation and Critical aspects

The complete control algorithm including self measurement process, position estimation and control of the motor is implemented using a TI DSP (TMS320c50). The whole algorithm is divided in three subsection

1 Initialisation of the processor
2 Self-measurement process
3 Starting and running of the motor

A. Initialisation

Fist all the internal registers and flag of the DSP is properly set or reset. Then the required parameters and variables for the estimator and controller are initialised.

B. Self-measurement process

As soon as initialisation is completed the processor starts executing the self-measurement algorithm. The required flux-linkage characteristics for 15° position is measured using the proposed scheme. The measurement results are stored as a look-up table on DSP. The complete self-measurement process is outlined in a flow-chart given in Fig. 4.

Sampling Frequency and excitation voltage limitation

During standstill, the voltage eqn acoss a phase may be expressed by the following expressions.

$$v = iR + \frac{d\Psi}{di}\frac{di}{dt} \quad (2a)$$

$$= iR + l\frac{di}{di} \quad (2b)$$

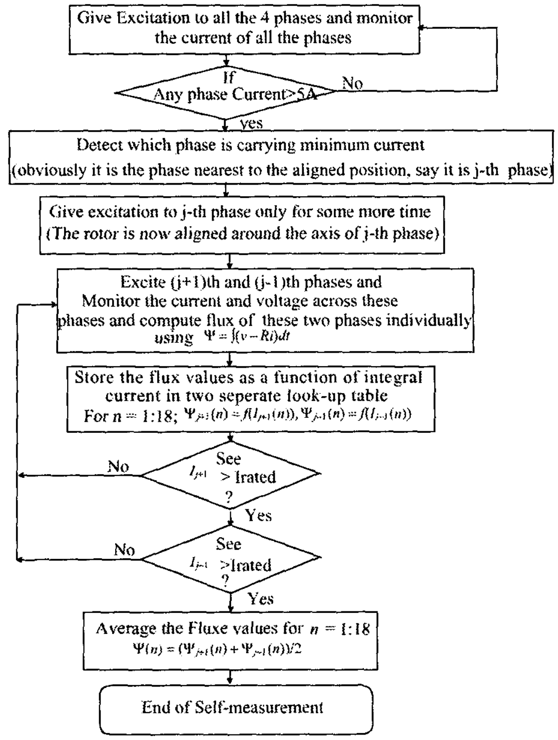

Fig. 4 Flow-chart of the self-commissioning scheme for measuring the flux at 15° position.

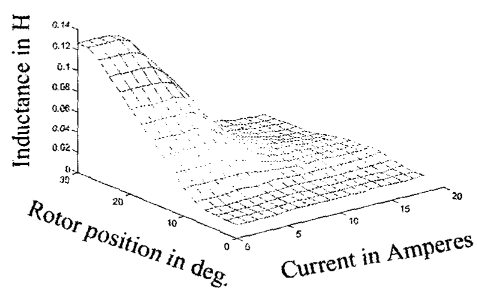

Fig. 5 Surface plot of increamental inductance

Thus, at standstill, the rate of rise of current largely depends on excitation voltage and incremental inductance (l) of the winding. The incremental inductance [10] for our test motor is computed from static flux-linkage characteristics and plotted in Fig. 5 as a function of position and current. It may be seen that the said parameter varies largely with excitation current. For example, at 15°, it varies from 40mH to 15mH as the current increases. If we choose, excitation voltage as 280V (which is the rated voltage of the motor) and sampling interval (T_s) as $200\mu s$, then at 15°, the maximum rate of rise of current per sample time may be found around 4A by Eq. (3)

$$\Delta i = \frac{v}{l} \times T_s = \frac{280}{15 \times 10^{-3}} \times 200 \times 10^{-6}$$

$$\cong 4A \quad (3)$$

In such case, the flux-linkage characteristics may be stored only at the step of 4A and intermediate values of the characteristics may be obtained through linear interpolation. From, Fig. 1, it may be seen that the characteristics at 15° is prone to saturation and no longer, the linear interpolation for such a large step jump of 4A is valid. Obviously, this type of interpolation will result in poor accuracy of position estimation. For better accuracy, faster sampling is desirable. For our test set up, a DSP has been used for controlling the drive. The sampling time achieved through the DSP is 50μs during self-testing as well as in operation. With this sampling time, the resolution of stored data is made at the step of 1A which gives resaonably better accuracy.

C. Starting, Running and Execution of Position Estimation

Once the self-measurement process is completed, the initial position of the rotor is defined (since one phase is stationed at 30°) and the phases which are in the positive inductance slope should be switched on first. Whenever a phase is within 0° to 15°, it is chosen for estimating the position and this phase is called hereafter as the active phase. The flux in the active phase is computed and when it exceeds the reference flux (i.e. the flux at 15°, obtained through the self-commissioning), the phase prior to this active phase is switched off and the next phase in the sequence is switched on. Through this process, the conduction angle during starting is fixed for 0° to 30° for each phase. The sequential switching of the different phases in the above manner will enable reliable starting. Once the motor has gained sufficient speed, the angle control mode can be adopted. The block diagram of the position estimator in running condition is given in Fig. 6.

VI. Discussions on Advantages and Limitations

The following are the advantages and limitations of the above self-measurement scheme:

A. Advantages

1. The flux-linkage characteristics at 15° is obtained without physically locking the motor.
2. The measurement can be taken while the motor is connected to a drive.
3. The accuracy of the characteristics is assured through the process of measurement.
4. The proposed method can be a part of the controller, so that every time while starting it can generate the characteristics of its own.
5. For a given pole numbers, the proposed method is not dependent on other design aspects, like the (rating of the machine,) pole widths, stator and rotor pole arc ratios etc.
6. With the proposed method sensorless starting and running both are possible

B. Limitations

1. This method can not be used for continuous position estimation
2. Though the method is quite simple and needs minimum information of the motor, still it is not fully machine independent, it needs information regarding the pole numbers of the machine.
3. The method needs some rough idea about the flux-linkage characteristics to decide the test pulse current limit (5A for this case) for detecting the phase which is to be aligned during the test.
4. High sampling frequency is needed to minimise the sampling and quantisation error.

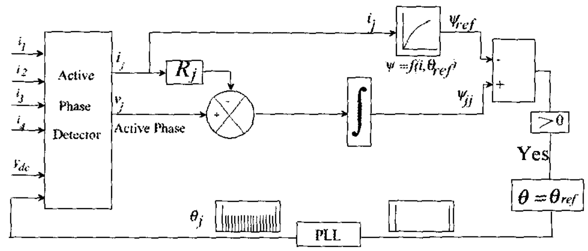

Fig. 6 Block diagram of the discrete position estimator using self-measured flux-linkage characteristics.

VII. Results

In order to validate the scheme, important experimental results are provided. The flux and current plots versus time obtained at 15°, during self-measurement process, are given in Fig. 7. An off-line measured flux-linkage characteristics at 15° is compared with the obtained data through the proposed method in Fig. 8. It may be seen that the results are matching closely. With the obtained data a discrete position estimator is realised and sensorless operation of the drive is achieved. The sensorless operation covers both starting and running operation. The current and speed trajectories during sensorless starting are given in Fig. 9. During steady-state, the phase currents at two operaticing points are shown in Figs. 10 and 11 respectively. These experimental results validate the feasibility of the proposed scheme.

VIII Conclusion

It is shown that the flux-linkage characteristics required for discrete position estimation can be obtained without any mechanical blocking arrangement and the measurement method can be integrated as a part of the controller. Every time the motor starts, the required flux-linkage characteristics are generated automatically by the controller. The flux-current characteristics obtained through this method takes care of the manufacturing nonidealities. Satisfactory sensorless starting and running of the motor with the obtained flux-linkage characteristics through the proposed method is demonstrated. Thus the proposed method is more covenient and in turn cost-effective. This self-measuring scheme is suitable for low-cost mass produced household appliances like washing machine, mixer, grinder etc.

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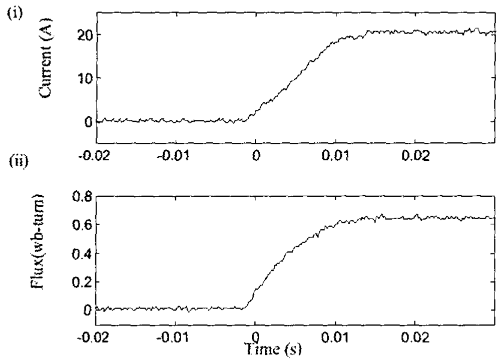

Fig. 7 (i) Current and (ii) Flux trajectories at 15° during self-measuring process.

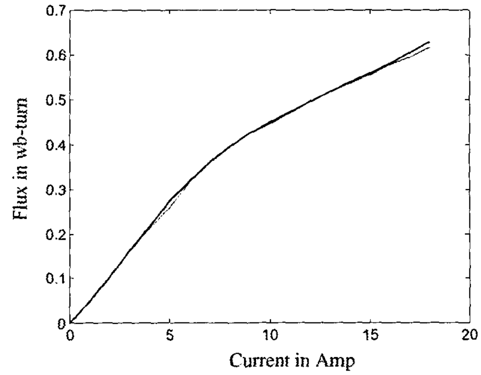

Fig.8 Comparison of flux-linkage characteristics at 15° between off-line measured values (solid) and self-measured values with the proposed scheme (dotted line).

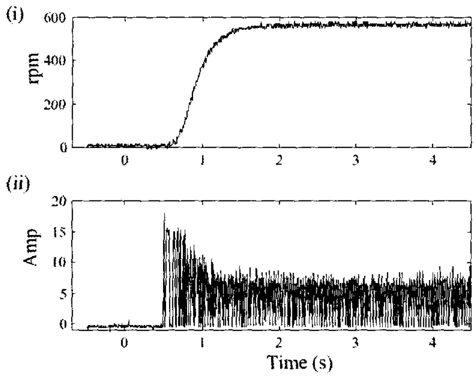

Fig. 9 (i) Speed and (ii) Phase Current waveform during sensorless starting with self-measuring scheme.

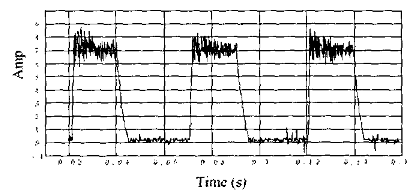

Fig. 10 Exp[erimental results of phase currents during staedy-state : at 200 rpm and 10Nm load,;
[Vph =150V, Load =10Nm, T-on = 0°, T-off = 25°].

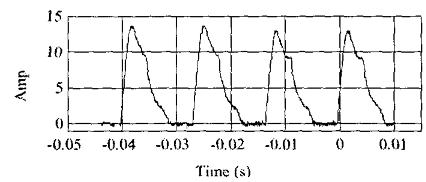

Fig. 11 Exp[erimental results of phase currents during staedy-state : at 750 rpm and 16Nm load;
[Vph =150V, Load =16Nm, T-on = 0°, T-off = 22.5°].

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