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Inter-Phase Magnetic Coupling Effects on Sensorless SR Motor Control

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***Abstract*—**Control of commutation of switched reluctance (SR) motor has been an area of interest for researchers for sometime now with mixed successes in addressing the inherent challenges. New technologies, processing schemes and methods have been adopted to make sensorless SR drive a reality. There are a number of conceptual, offline, analytical and online solutions in literature that have varying complexities and achieved equally varying degree of robustness and accuracies depending on the method used to address the challenges and the SR drive application. Magnetic coupling is one such challenge when using active probing techniques to determine rotor position of a SR motor from stator winding. This paper studies the effect of back-of-core saturation on the detected rotor position and presents results on measurement made on a 4-phase SR motor. The results shows that even for a four phase motor which is excited one phase at a time and using the electrically opposite phase for active position probing, the back-of-core saturation effects should not be ignored.

***Keywords*—**Sensorless, SR motor, saturation effects, detection.

I. INTRODUCTION

THE need for sensorless control of commutation of variable reluctance (VR) drives has been emphasized by many researchers in their effort to minimize inertia and optimize the inherent robustness of the variable reluctance motors [1,2]. The emphasis has been in achieving robustness, accuracy and high performance while optimizing cost [3] of a VR drive. The design of many sensorless commutation control systems for VR motors using active probing techniques like that developed by the author [3] whose principle is shown in Fig. 1 assumes that magnetic coupling between the phases has negligible influence on rotor position detection when the OFF phases are used for detection. In some of the single-stack VR motors, such as the 4-phase SR motor used in this work, the assumption is only correct when the motor is running under light loading conditions. Even then, at the low current levels typical for a motor running light, there can be sufficient inter-phase coupling to cause detection errors [4]. Acarnely etal [5] showed that using active phases to detect VR motors' commutation position is only reliable around the misaligned position as shown in Fig. 2. It is for this reason that there are so many schemes that have been developed that use either passive or active probing techniques. Sensorless rotor position detection has wider application beyond control of motors, e.g. in generators for maximum wind power capture [6] where passive probing is used.

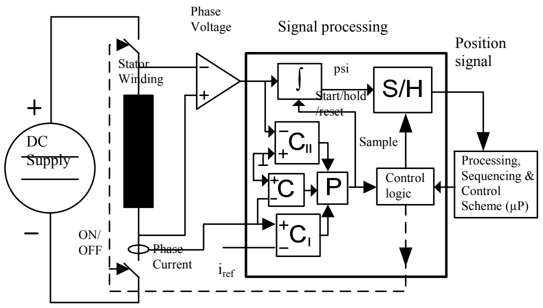

Fig. 1 Position signal generation

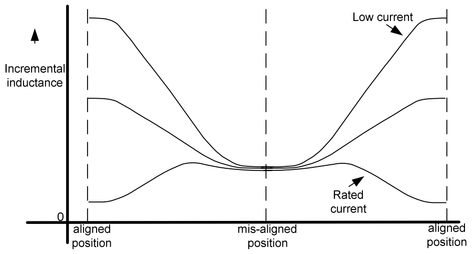

Fig. 2 Incremental inductance variation with position and excitation current magnitude [5]

This paper presents investigation on the contribution of rotor position, principal excitation current level, and connection configuration of different poles to inter-phase coupling effects on rotor position detection signal using active probing techniques. Compensation of these effects is not covered in this paper. It is significant to note that even with single-phase excitation mode when operating at high speeds, flux-linkage can exist simultaneously in up to 3 phases of a 4-phase switched reluctance (SR) motor.

There are two categories of inter-phase magnetic coupling; back-of-core saturation caused by saturation of the common magnetic path for the different phases and mutual coupling between the phases. Back-of-core saturation is perceived as magnetic coupling since the different phases share magnetic path that has finite reluctance that varies with flux level in the core.

An analytical approach is not used to determine inter-phases magnetic coupling effects since the magnetisation characteristics of the SR motor are not readily representable in analytical form [7] for accurate and complete modeling of the motor magnetic behavior under dynamic conditions for online

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control for low cost systems. Such analysis would require handling considering wide range of flux levels from diagnostic to saturation, mutual coupling, eddy currents in core laminations, switching circuits, measurement errors, etc. It is not a trivial problem and is outside the scope of this paper. Therefore, a qualitative treatment and experimental data are used.

The term 'flux' will be used to mean 'flux-linkage' and the 'opposite phase' (electrically) is the phase which will be at the aligned position when the other is at the mis-aligned position.

II. BACK-OF-CORE SATURATION

A. Effects of Back-of-Core Saturation on Position Detection Signals

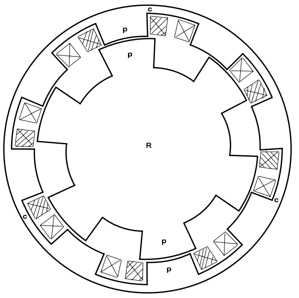

Fig. 3 The 4-phase SR Motor

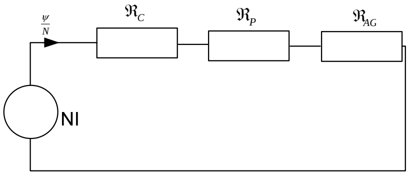

Fig. 4 VR motor phase equivalent magnetic circuit

Active probing rotor position detection techniques assume that the permeability of the magnetic material of the magnetic circuit of the diagnostic phase is determined by the flux due to the diagnostic current only. However, for a single-stack VR motors shown in fig. 3 it is only valid at the poles (labeled P), since different phases share the back-of-core section (labeled C) as a flux return path. Therefore, current in any of the phases shall influence the permeance of the other phases in proportional to level of saturation of the back-of-core caused by such currents. The influence of the back-of-core saturation on position detection when using an OFF phase depends on position, phase current, motor design (e.g. ratio of back-of-core cross-sectional area to that of stator poles) and excitation mode used. The connection configuration (i.e. NNNN-SSSS or NSNS-SNSN) is only significant in multi-phase excitation. Back-of-core saturation effects can be treated as an interference input to the position detection system. The rotor core area labeled R is having sufficient cross-sectional area to remain out of saturation, and hence its permeance is assumed infinity. Fig. 4 gives the simplified lumped parameters magnetic circuit for the VR motor of Fig. 3 where $\Re$ is reluctance. The three components of the phase reluctance of the diagnostic phase $\Re(\theta,\underline{i})$ are $\Re_C(\theta,\underline{i})$, $\Re_P(\theta,\underline{i})$ and $\Re_{AG}(\theta,\underline{i})$ for the back-of-core, poles and air gaps respectively. Equation 1 relates the flux in the magnetic circuit with current for a single phase where $\underline{i}=[i_1,.......,i_m]^T$, m is the number of phases, k denotes the diagnostic phase and N the number of turns in the phase winding.

$$N\,i_k=\left[\Re_c(\underline{i},\theta)+\Re_p(\theta,i_k)+\Re_{AG}(\theta)\right]\frac{\psi_k(\underline{i},\theta)}{N} \qquad (1)$$

For the diagnostic phase k, $i_k = i_c =$ constant (low level current) thus reducing (1) reduced to (2).

$$N\,i_c=\left[\Re_c(\underline{i},\theta)+\Re_p(\theta)+\Re_{AG}(\theta)\right]\frac{\psi_k(\underline{i},\theta)}{N}\Big|_{i_k=i_c} \qquad (2)$$

The reluctance of the back-of-core magnetic material increases with saturation determined by the principal excitation current and position, hence the reluctance of the back-of-core in the presence of the principal current in terms of that at low currents $\Re_C(\theta)$ is given by (3).

$$\Re_c(\underline{i},\theta)=\Re_c(\theta)\left[1+\Delta\Re_C(\underline{i},\theta)\right] \qquad (3)$$

where $\Delta\Re_c(\underline{i},\theta)=\frac{\Re_c(\underline{i},\theta)-\Re_c(\theta)}{\Re_c(\theta)}$. Note that $\Delta\Re_c(\underline{i},\theta)$ is dimension less. Equation 4 is obtained by substituting (3) into (2) with rearrangement.

$$i_c=\left[\Re_c(\theta)+\Re_p(\theta)+\Re_{AG}(\theta)+\Re_c(\theta)\Delta\Re_c(\underline{i},\theta)\right]\frac{\psi_k(\underline{i},\theta)}{N^2}\Big|_{i_k=i_c} \qquad (4)$$

The reluctance of a phase in (4) has two components: that at low current given by (5) and the perturbation component arising from the effects of saturation of the back-of-core.

$$\Re(\theta)=\Re_c(\theta)+\Re_p(\theta)+\Re_{AG}(\theta) \qquad (5)$$

By substitution (5) in (4) and replacing $\Re$ by N^2/L, (6) is obtained.

$$\psi_k(\underline{i},\theta)=i_cL(\theta)\left[\frac{1}{1+\frac{L(\theta)\Delta L_c(\underline{i},\theta)}{L(\theta)}}\right]_{i_k=i_C} \qquad (6)$$

Equation (6) makes it possible to compare directly the diagnostic flux-linkage signal with and without saturation, which is given as the diagnostic flux-linkage signal error $\psi_\in(\underline{i},\theta)$ by (7).

$$\psi_\varepsilon(\underline{i},\theta)=i_cL(\theta)\left[\frac{1}{1+\frac{L_c(\underline{i},\theta)}{L(\theta)\Delta L_c(\underline{i},\theta)}}\right]_{i_k=i_C} \qquad (7)$$

Equation (7) expresses the relative diagnostic flux-linkage signal error in terms of permeance of the phase expressed in terms of inductance L. The change in permeance of the back-of-core in (7) can be measured indirectly or may be obtained by calculations. The diagnostic flux-linkage signal error $\psi_\in$ is obtained indirectly as the difference between values measured at low currents and those measured when the magnetic material in the back-of-core is in saturation. By measuring the diagnostic flux-linkage signal error at a given value of current at different positions and repeating it for different values of current, a table of $\psi_{\in}\left(\underline{i},\theta\right)\Big|_{\underline{i}=cons\tan t}$ can be obtained which can be used for compensation for back-of-core saturation effects.

B. Measurement of Influence of Back-of-Core Saturation in Effects on Position Detection Signal

The magnitude of the influence on the diagnostic flux-linkage signal, which is used to deduce position, by the back-of-core saturation was measured using a constant dc bias current in phases other than the diagnostic one. A dc bias current from a dc current source is used to set a steady level of mmf in the magnetic circuit of one of the phases. A diagnostic flux-linkage signal was then recorded from the diagnostic phase at different rotor locked positions for different values of dc current and for different phases relative to a particular diagnostic phase. The measurement results in Fig. 5 shows the diagnostic flux-linkage error magnitude $\psi_{\in}\left(\underline{i},\theta\right)$ for different values of current, position and phases under locked rotor condition. Fig. 6 re-expresses the results in Fig. 5 in relative form as a ratio of the diagnostic flux-linkage signal with and without the influence of currents in other phases in place of the actual magnitude.

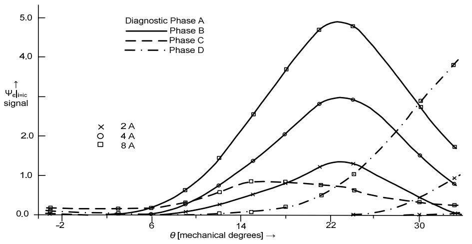

Fig. 5 Diagnostic position signal back-of-core saturation error

The values of flux-linkage errors due to back-of-core saturation in Fig. 6 when translated using a graph of $\psi\left(i,\theta\right)$ measured on the same motor $^{[4]}$ to position magnitude error gives result shown in Fig. 7. The shape of the error curves around 0° is due to the values of the diagnostic flux-linkage signals being lower than the minimum value without errors, hence assigned the mis-aligned position value.

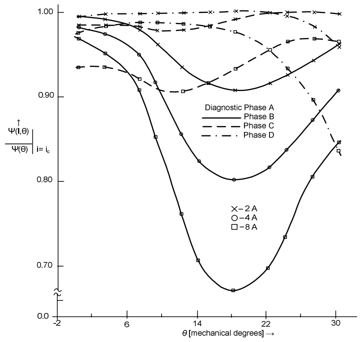

Fig. 6 Normalised diagnostic flux-linkage signal with back-of-core saturation errors

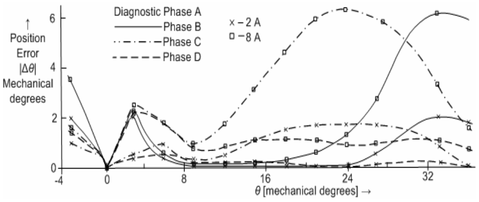

Fig. 7 Back-of Core saturation position errors

Measured results show that the back-of-core saturation errors become particularly large when the principal excitation phase carries current while close to the aligned region (where the air-gap reluctance is minimum) while the diagnostic phase is away from the mis-aligned region. This is due to the high level of saturation in the back-of-core while the influence of the air-gap on the permeance of the diagnostic phase is diminishing.

Furthermore, the results show that when the diagnostic phase is the one that is electrically opposite to the principal phase, the error due to the back-of-core saturation remains below 1° mechanical for most of the commutation cycle, when the single-phase excitation control mode is used (for the prototype motor.) Also, high currents around the mis-aligned region make a small contribution to the back-of-core saturation errors.

III. INFLUENCE OF POLE CONNECTION CONFIGURATION ON BANK-OF-CORE SATURATION ERRORS

There are four possible pole connection configurations for a 4-phase SR motor; NNNN-SSSS, NSNS-SNSN, NNSS-SSNN and NSNS-NSNS. However, only the first two are significant since they do not involve changing the internal connections of the geometrically opposite stator poles of the motor. Moreover, for the other two, the benefits of symmetry when only one phase is excited at a time will be lost since the two geometrically opposite stator poles whose windings are usually connected in series to form a phase, will be of the same polarity.

When two adjacent phases are excited simultaneously, which is common when switching excitation from one phase to another; the distribution of the resultant flux in the back-of-core will be different for the NNNN-SSSS and NSNS-SNSN connection configurations. The former will have summed flux occupying most of the back-of-core for three out of every four steps while the later will have differential flux. However, the actual combination of pole polarities of excited adjacent phases determines the distribution of the resultant flux in different parts in the back-of-core because of the odd adjacent pole pairs. This is illustrated in oscillograms in fig. 8. In three out of every four commutation cycles, the diagnostic phase will be less sensitive to currents in other phases with the NSNS-SNSN connection configuration than with the NNNN-SSSS configuration. The pattern in the distribution of the magnitude of the resultant flux in the back-of-core in relation to the diagnostic phase, is similar irrespective of whether the

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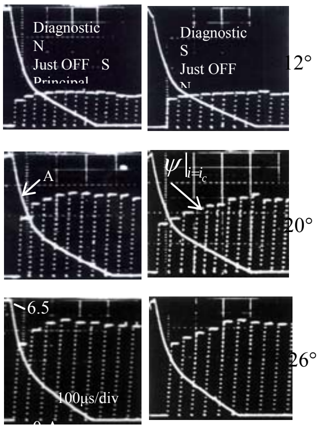

Fig. 8 Oscillograms showing magnetic coupling effects

flux in the just-off-phase or the ON-phase is higher, so long as both exist. When only the diagnostic and the principal excitation phases carry current, the connection configuration will have no bearing on the degree of influence of the back-of-core saturation on the diagnostic phase. Therefore, the connection configuration will not influence the accuracy of detection of the commutation position at low speeds but its influence will increase with speed as current decay time become significant compared to commutation cycle time.

IV. MOTOR DESIGN INFLUENCE

There are a number of motor design factors which influence the back-of-core saturation, but the present discussion will be restricted to motors with an even number of rotor and stator poles, which is typical for many SR motors. The two main factors considered are: design features controlling level of saturation and the number of phases.

The ratio between the cross-sectional area of half of the stator pole and that of the back-of-core determines the design saturation level for the core. The ratio is chosen by the motor designer to achieve a desired operating characteristic. The smaller the ratio the higher the saturation and hence the worse will be the back-of-core saturation effects on position detection.

The significance of the number of phases on the back-of-core saturation is that for the:

- 2-phase motor; one phase is for principal excitation while the other can be used for diagnostic purposes making the degree of saturation to be the same in the entire back-of-core.
- 3-phase motor, there is no odd adjacent pole pair in the NSN-SNS connection configuration, hence differential flux will flow in large part of the back-of-core, giving a symmetrical back-of-core saturation effect for all commutation cycles.
- 4-phase motor, there will always be an odd adjacent pole pair whichever connection configuration is used. When operating in a single-pulse excitation mode, the diagnostic phase can be electrically opposite to the principal phase which makes saturation in the back-of-core at a fixed value of current to be a function of position thus increasing the significance of the air-gap in the reluctance of the diagnostic phase increases. Therefore, the % error in the measured reluctance of the phase decreases, making position detection less sensitive to back-of-core saturation.

V. CONCLUSION

The pattern and magnitude of the errors in the diagnostic flux-linkage signal observed during the operation of the motor due to magnetic coupling between phases, have been illustrated, measured, and their causes explained. It was observed that the accuracy with which the commutation position can be detected when a 4-phase SR motor operates in a single-phase excitation mode at low-speed without compensation, can be maximized when the diagnostic phase is that opposite to the principal excitation phase. The results show that for operation in the medium-speed range or higher speeds compensation for magnetic coupling effects is necessary to improve commutation position detection accuracy. For positions detected close to the mis-aligned position the errors will be small even without compensation because the diagnostic pulse will occur just prior to commutation when the current in the adjacent phase (just-off-phase) is significantly smaller than that at switch off.

Compensation has not been addressed in this paper, but the microprocessor used for detection scheme promises flexibility and adaptability in the implementation of the compensation scheme for magnetic coupling effects. It promises flexibility and adaptability for the compensator, so that the same compensator can be used for different motors by reprogramming the position detection errors. However, a fast processor is necessary than that used in this work. There are other options too.

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