PRACTICAL ASPECTS IN SENSING VRM MAGNETISATION CHARACTERISTICS FOR ROTOR POSITION DETECTION

by

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ABSTRACT

The detection of rotor position (stator/rotor poles overlap) in a variable reluctance motor using the dependence of permeance on rotor position is the core of the effort to eliminate the need of a physical position sensor in the rotor shaft in the positional feedback operation of the motor. The reliability of the whole process of eliminating the need of a physical sensor rests squarely on the ability to measure the instantaneous permeance of a phase when the motor is in operation and at stand still. This paper presents an experimental investigation on the intriguing problems of obtaining repeatable and reliable instantaneous permeance of a phase from the measurements of phase voltage and current at the control board and hence a measure of position. The results of this work are fundamental in the development of a sensorless position detector.

INTRODUCTION

The variable reluctance motor (VRM) can generally be characterised using three variables; flux linkage , rotor position, and the stator current i normally expressed as a table of $\psi(i, \theta)$[1]. Figure 1 is derived from such a table. There have been attempts to represent the non-linear magnetisation data with an analytical expression but the exercise is tedious, and is of limited accuracy (i.e. assumptions always used for simplicity thus a partial model)[2]. The usefulness of the resulting expression is in using the developed analytical methods to predict the motor 's

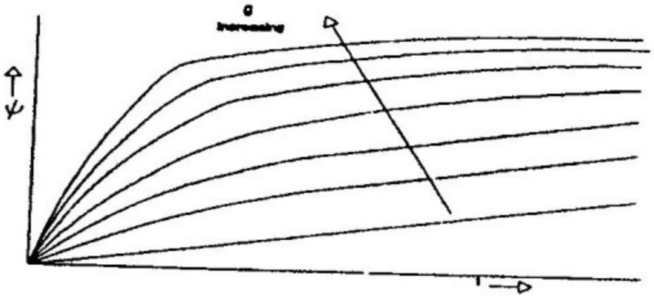


Figure 1: Switched reluctance motor $\psi/i/\theta$ curves.

operational characteristics. However, the doubly salient VRM presents a different degree of complexity[3] compared to other types of motors and thus needs a new approach. Since the transfer of $\psi(i,\theta)$ table to an analytical function introduces errors, a system which utilises directly the $\psi(i,\theta)$ table can be more accurate. Hence, the $\psi(i,\theta)$ table is to be used for position detection purposes. The $\psi(i,\theta)$ table is particular to a motor (motor model). Equation 1 (which can be deduced from figure 1) relates i and ψ in a phase to the reciprocal of inductance, $H(i, \theta)$, which can be regarded as a position and current dependant scaling variable.

$$i(\theta,\psi) = H(i,\theta)\,\psi(i,\theta) \tag{1}$$

Hence, to determine the rotor position from the motor model in a tabular form, the flux-linkage and the phase current must be known[4]. In many operations of a VRM current is usually measured for other control purposes, however, flux linkage cannot be measured directly without having to instal a sensor into the motor. The aim of this work had been to determine rotor/stator poles overlap (rotor position) just by monitoring any information that is available at the phase windings, an area which has attracted a lot of attention[5-18]. Therefore, installing in a motor a flux-linkage sensor is not an option. Flux-linkage is simulated from the measured quantities.

Whenever a phase of a VRM is excited, the equation governing the current i, in a phase is shown by equation 2 where u_{ph} is the voltage across the phase

$$\frac{d\Psi(i,\theta)}{dt} = u_{ph} - iR \tag{2}$$

winding and R the phase resistance. Hence, by measuring u_{ph} directly across the phase winding and with the knowledge of the phase resistance R, the flux linkage can be simulated by integrating equation 2. Therefore, using the simulated flux linkage and measured current together with the motor model ψ (i, θ) table, the corresponding rotor position can be deduced[4]. The problem is to obtain the two variables and the techniques of deducing the third.

The magnetisation status (i, θ, ψ) of a VRM can be monitored from an ON-phase (i.e. phase excited for torque production) or an OFF-phase (phase not excited for torque production), since each phase enters both status during a normal operation[5]. To monitor rotor position using an ON-phase one has to monitor the magnetisation status at its operating point as dictated by the load and by the control laws. This leads to a lot of complications[4] hence the use of OFF-phase is regarded as being more appropriate[5].

To monitor the magnetisation characteristics of a VRM using OFF-phases it is necessary to introduce diagnostic excitation pulses (i.e. short excitation pulses in the OFF-phase(s) for the purpose of position detection only). There are two possible options to limit the $\psi(i,\theta)$ data to two dimensions when using the OFF-phases for monitoring the magnetisation characteristics of a VRM for position detection purposes;

(a) maintaining the current in a phase constant and hence equation 1 reduces to 3 which can be re-arranged to give 4.

$$i = H(\theta,i_c)\,\psi(i_c,\theta) = H(\theta)\,\psi(\theta)|_{i=i_c} \tag{3}$$

$$\psi(\theta) = i_c(\theta)|_{i=i_c} \tag{4}$$

(b) maintaining the flux-linkage constant, then equation 1 degenerates to equation 5

$$i(\theta) = \psi_c H(\theta)|_{\psi=\psi_c} \tag{5}$$

Equations 4 and 5 gives two possible magnetisation characteristics which can be used as position indicators in a VRM.

This paper looks at the techniques to measure (obtain) magnetisation characteristics of VRM using the OFF-phases by implementing equations 4 and 5. Practical difficulties, limitations and possible solutions to achieve a reliable, repeatable and accurate magnetisation characteristics for the purpose of rotor position detection are presented and discussed.

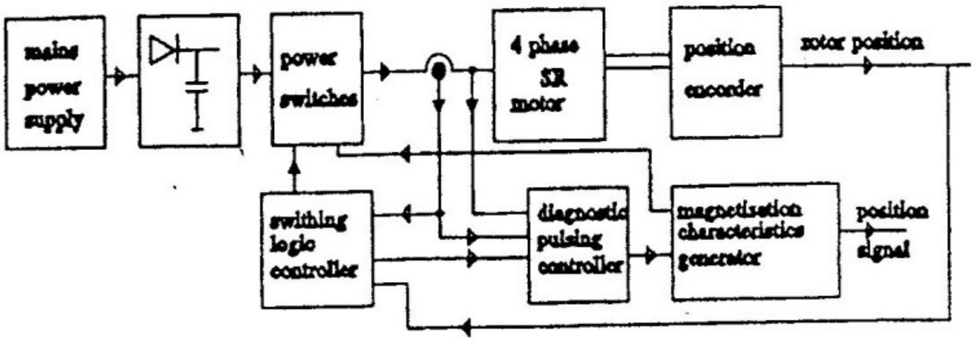


Figure 2: Block diagram of experimental set up.

EQUIPMENT USED

Figure 2 is a schematic block diagram of the experimental set-up. The VRM used to test the generation process of the magnetisation characteristics to represent rotor position (rotor position transfer characteristics (RPTC)) is a 1kW, 4-phase SR motor with eight stator poles and six rotor poles. This was the motor available in the laboratory and was bi-filar wound. The motor was particularly useful in that the influence of the commonly encountered power switching circuits (a) a single switch per phase with passive snubber and bi-filar windings[1] (b) two switches per phase with passive snubbers and (c) two snubberless power MOSFETS[4] could be investigated.

CONSTRAINTS

Flux linkage in a phase is zero when the current in the phase is zero if mutual coupling between phases is negligible. Therefore, at each starting of the flux-linkage simulation cycle the current in a phase must be zero (and detected to be so) for the initial value of the simulator to be correct.

Snubber circuits are normally connected across semiconductor power switching devices to protect the devices from destruction by either transient over-voltage due to switching, or switching losses. The snubber circuits have a secondary effect of introducing under-damped current and voltage oscillations in the phase windings and the snubber components when the protection diodes turn off after a phase is switched off. The frequency and characteristics of the oscillations depends on the permeance of the phase (which is position dependent), the value of the snubber circuit components and/or the stray capacitance. Figure 3 shows the observed voltage and current waveforms when a short voltage pulse is impressed on to the phase winding using two switches per phase and passive snubber switching circuit.

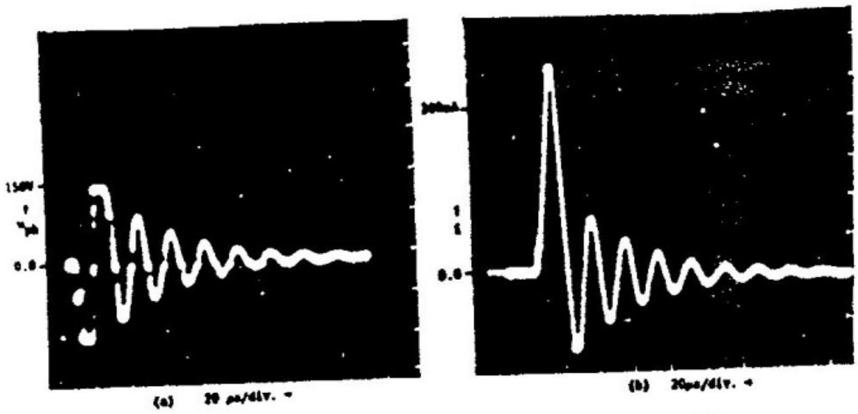


Figure 3: Diagnostic current and voltage oscillogram

The oscillation have no influence on the protection function of the snubber circuitry and in torque production because of the low energy content but are a nuisance in rotor position detection since their current magnitudes are significant compared to the level used for position detection as can be observed in figure 4. Therefore, the frequency and decay time of the oscillation can determine when a diagnostic pulse can be re-applied after its removal to ensure correct initial condition of the flux-linkage simulator. The effect is to reduce the feasible maximum diagnostic rates by 4-7 times below those for rise and fall of current in a phase without oscillations.

Ideally, one needs to maintain flux-linkage or phase current at a given value and the corresponding phase current or flux-linkage signal respectively will give a continuous position representing signal. However, this is generally not possible because of switching devices frequency limitations, tolerable snubber circuit losses and drifts of integrator, limiting the feasibility of accurate continuous flux-linkage simulations particularly at low-speeds.

VOLTAGE MEASUREMENTS

The potential difference across the phase winding and its polarity whenever current is switched in a winding is a function of switching circuit configuration, the status of the switches, and duration since the last change in status of the switches and the supply voltage. The supply voltage which is dc can be high and possibly variable and floating relative to that of the signal processing and control circuit. Hence, isolated dc voltage-measuring devices should be used to monitor phase voltage. However, available isolated dc voltage measurement devices with sufficient bandwidth are too expensive. An economical solution was found to be a single-ended-output differential amplifier with sufficiently high input impedance based on conventional operational amplifiers. A bandwidth of 5MHz was considered sufficient for the purpose of position detection [4]. A symmetrical high impedance resistance network whose centre point is directly or indirectly grounded is connected across a phase to scale down the voltage.

CURRENT MEASUREMENTS

A 1% accurate position detector will require a resolution of 0.01 of the peak position detection current values. If the transducer also measures the rated current and assuming the diagnostic current to be 1% of the rated value, then the current transducer needs to achieve a resolution of 0.01% of the rated. The resolution requirements of the current sensor decreases when separate transducers are used for diagnostic and motor operation current. However, one needs to be aware that compensation for inter-winding magnetic coupling may require measurements of rated current[6].

Two methods of sensing current were considered; using a non-reactive resistor in series with the phase winding or using dc current transducer working on flux-nulling principle. The resistor option may appear economically sound, but for the high common-mode voltage rejection requirement (the supply voltage magnitude being much higher than the voltage drop across the sensing resistor) particularly for the two power switches configuration since none of the ends of the current sensing resistor can be tied to any fixed potential. Furthermore, the fast switching speed of devices like power MOSFET transistors needs wide bandwidth differential amplifier to faithfully provide the current signal from the sensing resistor. In addition, the output current signal is not isolated from the power circuit. The flux-nulling dc current measurement transducer was found to be more appropriate because of the isolation feature, flexibility in setting the measuring range (by altering the turns ratio) and thus resolution, high output signal and high overload capability (800%).

PRINCIPLE OF THE ROTOR POSITION TRANSFER CHARACTERISTICS (RPTC) GENERATOR

The RPTC generator uses the current and voltage signals to give a voltage signal which is a function of angular position. The principle of the generator is shown in a block diagram in figure 4. The functions of the generator can be observed in the block diagram.

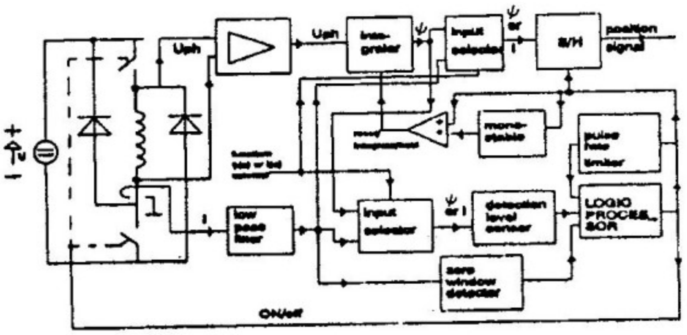


Figure 4: Block diagram of a rotor position transfer characteristic generator

The generator must be able to cope with transient noise either pick-up or otherwise inherent in the current signal.

The RPTC generation process can be classified on the basis of the mechanism used to initiate successive diagnostic excitation pulses. There are two distinct methods; one based on timing, the other on current. The third is a combination of both. These are:

(a) using timing, the diagnostic pulses are applied at a pre determined time interval (constant diagnostic pulsing rate).
(b) using current, the diagnostic pulses are re-applied whenever the phase current becomes zero (variable diagnostic pulse rate).
(c) using both current and timing, re-application of diagnostic pulse at zero current but only after a fixed period after pulse application (controlled variable diagnostic pulse rate)

Whichever method of controlling diagnostic pulses is used, a detection level of current or flux-linkage (equations 4 and 5) must be set.

REFERENCE EXCITATION LEVEL

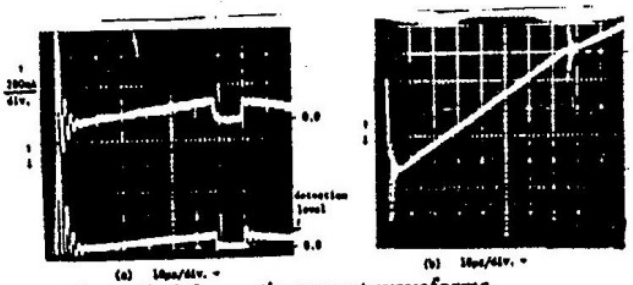
When the OFF-phase is used for rotor position detection, the magnitude (level) of diagnostic current or flux linkage can be selected freely with respect to the load, since it does not provide load torque. However, a number of other factors need be taken into account in selecting the diagnostic current level. The diagnostic current must produce negligible torque and winding resistance voltage drop (iR drop). Thus the maximum excitation level was set at 3% of the rated current so the peak torque produced by diagnostic excitation will be below 0.1% (linear magnetic assumed)[1]. This torque is sufficiently low to be neglected in any dynamic or static analysis of the motor. Also, the iR drop will be low compared to the supply voltage particularly for voltage driven systems.

Moreover, diagnostic excitation has to be maintained low for the rotor to remain stationary under diagnostic excitation when starting from rest at all loading conditions. This is important since correct position detection depends on the fixed relative displacement between phases. Experiments on practical motors have shown that the average torque at the above selected excitation level was not enough to overcame static friction of the bearings of the unloaded motor. However, after starting, higher diagnostic excitation levels may be tolerated. Selecting lower levels will only complicate further the separation of current signal from interference signals without any added advantage.

To accommodate the delay between switch OFF command and the actual switching OFF, the detection level must be below the above excitation level. 1-2% of the rated was found appropriate.

CURRENT SIGNAL CONDITIONING

The measurement environment is electrostatically and electromagnetically noisy due to transients generated when switching takes place in other phases in case of multi-phase excitation. The transients are coupled electromagnetically or electrostatically or via the supply to the current signal. Even under single-phase excitation, the current signal has superimposed transients which occur at every switching ON or OFF of the phase. The transients are generated by the current transducer in the flux-nulling process which takes time to settle following a step change in the rate of change of current. The peak of the transient signal depends on the power switching circuit configuration and the magnitude and polarity of the voltage across the phase winding at the instant of switching.



(a)

(b)

Figure 5: Diagnostic current waveforms for different current sensors and switching circuits

Figure 6: Successive diagnostic current and flux-linkage signals

The frequency of the transients for the snubberless switching circuit is of the order of 100kHz. The transient's highest amplitude may be 10 to 15 times the reference detection current level when snubberless power MOSFET devices are used in the power switching circuit. The amplitude was found to be much lower when bipolar power switching devices with snubber circuits were used, being 8 times lower. Figure 5 is an example of such transients (when the amplitude was minimised by selective switch-on timing) for the two switching circuits.

The use of filters to remove transients can introduce significant phase errors at frequencies well below those at which magnitude errors become significant. A phase shift leads to time delay, an effect not desirable. The separation between the frequencies of the current signal and that of interference is not large (less than a decade). The highest frequency of the current signal is approximately at 12kHz triangular waveform. Hence, to filter effectively, the above transient noise would require high-order filtering. Such a filter would introduce significant phase error at the higher frequency end of the signal and thus time delay. Since the two signals to be processed, that is, current and flux-linkage, do not have the same frequency component, the phase error problems can not be overcome by passing them through similar (identical) filters without resorting to linear types. A second-order Sallen-Key-equal-component filter was found to be sufficient to remove transients for power switching circuits with snubbers. But blanking of current level detection circuit for a short period of 10-20μs at every switching ON of diagnostic phase together with the filter was the best compromise for the snubberless power switching circuit.

Another problem observed in the current signal, also at switch-on is an observable 'step' in the current signal, (see figure 5). The 'step' was considered to be caused by eddy current in the stator and rotor laminations. The magnitude of the 'step' varies with voltage or current status of the phase winding at the instant of switching and the interval between pulses (example, figure 5). The 'step' could not be subtracted easily because of switching transient problems. Therefore, the influence of the 'step' on position was only minimised through synchronization of particular zero point crossing and diagnostic pulse excitation.

CONSTANT DIAGNOSTIC PULSING RATE METHOD

The constant diagnostic pulsing rate method of obtaining magnetisation characteristics, is based on re-excitation at preset interval. It is assumed that current will have decayed to zero at each re-excitation. Therefore, the pulsing rate must be determined before hand for each switching circuit, supply voltage, snubber circuit components values and/or stray capacitances and phase permeance and diagnostic excitation level. The period can be obtained by observing the current decay period at the aligned position. Example, when a two switches power switching circuit with passive snubber, a supply voltage of 150V used and the reference current set to 1.4% of the rated value, the minimum re-excitation period required was 0.95ms. However, to accommodate possible power supply variation a higher value, e.g. 1.2ms, was necessary. The bifilar winding circuit with passive snubber required the period to be increased to 5.4ms. With constant diagnostic pulsing rate, the ON time is negligible compared to OFF-time in a diagnostic excitation cycle.

The sampling of phase current or the flux-linkage at preset value of flux-linkage or current respectively (figure 4) is done by tracking technique thus eliminating the need of ultra fast, expensive sample and hold (S/H) amplifier. Thus S/H amplifier with acquisition time of 10μs could be used with excellent results since it is the switching from tracking to hold mode which is significant. With this method, the constant current detection method does not need a S/H amplifier as the integrator's hold mode can be utilised for A/D conversion.

VARIABLE DIAGNOSTIC PULSE RATE METHOD

When obtaining magnetisation characteristics at variable diagnostic pulsing rate, re-excitation of the diagnostic pulse is controlled by the occurrence of zero-current either temporarily or continuously. Therefore, diagnostic phase is turned ON whenever the protection diodes stop conducting which corresponds to the first zero-current crossing after switch off. Hence, zero current detection in steady state is only necessary to ensure that the detection circuit is self starting. When snubbeless power MOSFET devices are used as power switching devices, the transient in the current signal at switch-ON and -OFF must be suppressed to ensure proper operation.

Since phase permeance is position dependent and the rate change of current in a phase is directly influence by the phase permeance, the resulting diagnostic rate varies considerably with position. The mis-aligned position pulse rate being as much as six to ten times that at the aligned position. The consequence is that wide variation of the position resolution of successive position samples to be deduced from the magnetisation characteristics results once the motor is in operation.

CONTROLLED VARIABLE DIAGNOSTIC PULSE RATE METHOD

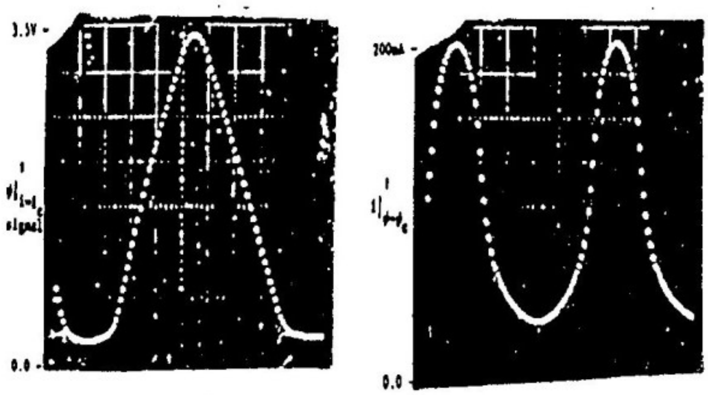
To obtain the magnetisation characteristic at variable but controlled diagnostic pulse rate, the re-excitation of a phase is done at zero-current transition or steady state after a certain minimum time elapse since the switch on of a diagnostic pulse. In this way, the diagnostic pulse rate variation is limited while avoiding the necessary circuity set-up and unnecessarily low sampling rate. It was observed that higher magnitude of transients, superimposed on the current signal at switch ON, occurs when the negative slope zero-current transition (i.e. current crossing zero from positive to negative values) is used to switch on the diagnostic pulse than when a positive slope zero-current transition is used. Since it is of interest to minimise this amplitude, only the positive zero current transition was used. A 'step' in the current signal is not desirable, since it is not reflected in simulated flux-linkage, leading to position detection errors as can be observed in Figure 6.

Therefore, the effect of the 'step' is that a stationary rotor can give an impression of motion because of the difference in the levels of successive position signal. The effect of the 'step' in the current signal on position detection as deduced from the magnetisation characteristics of a VRM can be minimised by using one of the two transitions to enable diagnostic excitation. The positive transition is used since the magnitude of its step is comparatively smaller. By limiting the significance of the 'step', using repeatable conditions, its contribution to rotor position detection is minimised, since conditions existing during calibration will be the same when using the magnetisation characteristics to detect position.

With this method, the diagnostic pulse rate varies with position but the ratio between the lowest and the highest pulse rate can be limited to 1:2 compared to 1:10 if no limitation is imposed. This method is considered the most appropriate for use for position detection purposes in comparison to the other two.

ROTOR POSITION TRANSFER CHARACTERISTICS

When the magnetisation characteristic of the VRM is that at a fixed current, then rotor position is represented by the diagnostic flux-linkage signal sampled at the present current value. The characteristic relates position to an equivalent voltage signal which can be translated into position using a microprocessor. Figure 7(a) and (b) shows the oscillogram of the characteristics observed when the VRM was driven at constant speed using a dc motor, showing the sampling nature of the detection mechanism. This magnetisation characteristics is similar to those obtained using other methods[1]. When the magnetisation characteristics is obtained at constant flux-linkage, then rotor position is represented by a current signal sampled at the preset value of flux-linkage. Figure 7(b) shows such a characteristic as displayed on the oscilloscope.



(a) 50ms/div.

(b) 50ms/div.

Figure 7: Magnetisation characteristics of VRM oscillogram at constant (a) current (b) flux-linkage

POWER SWITCHING CIRCUIT CONFIGURATION AND CONTROL OF DIAGNOSTIC PULSES.

The power switching circuit configuration has direct impact on the all methods of obtaining magnetisation characteristics using diagnostic pulses. Two switches per phase configuration was used in the generation of RPTCs, being the configuration mostly used for medium and high power doubly salient drives. In the controlled-variable diagnostic pulse rate, the configuration influences the condition for re-excitation of the diagnostic phase. The power circuits can be grouped into two categories here: Snubberless and those with snubbers.

In circuits with snubbers, under-damped oscillatory current continues to flow after protection diodes turn off and the magnitude of the first peak (valley) can be as much as 50 to 75% of the reference value, see figure 5. Therefore, zero current must be obtained by direct measurements. The snubberless circuits however do not have a current path other than that presented by stray capacitance when both power switches and protection diodes are off. The peak current magnitude is very low (<0.05% of the reference value) and can be neglected. Therefore, ideally, the diagnostic phase can be re-excited anytime after protection diodes turn off. In practice the magnitude of the transient in the current signal at switch ON, and the current 'step' are dependent on the voltage across the winding at the switching instant. Thus, the phase voltage status is used to determine when to enable the diagnostic phase excitation. The zero-phase-voltage condition was chosen since it is repeatable. Again, continuous or positive slope zero-voltage transition is used for the same reasons that positive slope zero-current transitions were chosen. Using both transitions introduce significant errors as can be observed in figure 8.

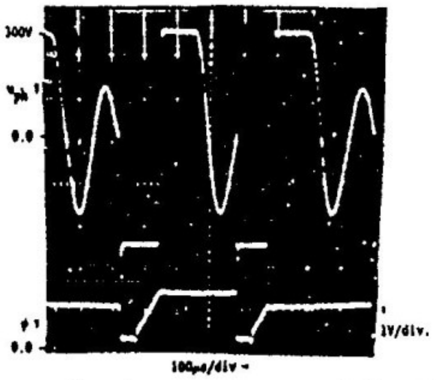


Figure 8: Successive diagnostic phase voltage and flux linkage signals

The usage of a voltage signal to control diagnostic pulses for snubberless circuits is more convenient than current signal since the signal is relative much larger, but the voltage signal contains coupled switching transients which must be taken care of. Moreover, the phase voltage can hardly assume a continuous zero value in mult-phase excitation, particularly in current chopping operation, due to mutual coupling. Therefore, mostly transient zero voltage transition will be encountered.

Another factor which is influenced by the power switching circuit configuration is current measurement. The value of current is not required when the power switches are off in snubberless circuits since the phase voltage controls re-excitation of the diagnostic phase. Therefore, resistors connected in the emitter of the lower transistors (used as power switches) can conveniently be used for diagnostic current measurement.

DISCUSSION

The constant diagnostic pulse rate is simpler to implement (does not need zero-current detection) and requires fewer components, but depends on the clock frequency for its operation. The clock frequency has to be determined for each motor, switching circuit configuration, and voltage level. Thus, if any of them changes then clock frequency has to be checked. Moreover, the diagnostic pulse rate can be very low when a large value of snubber capacitance is used. Such sensitivities are not desired, rendering the method unsatisfactory for general purpose application.

The variable diagnostic pulse rate uses the zero-current condition to safeguard against the shortcomings of the constant diagnostic pulse rate method making it more robust. However, there is a wide variation in pulse rate between the aligned and the mis-aligned VRM rotor position leading to large variation in the resolution of successive position samples for the constant-current detection method. Such a variation is useful when the commutation position is around the region of high pulse rate and the position samples are used directly to control commutation. By limiting the pulse rate, the variation in the resolution of successive position samples during VRM operation is controlled. Therefore, the maximum diagnostic pulse rate can be set without any reference to any particular motor, switching circuit configuration, or supply voltage. Hence, controlled variable diagnostic pulse rate method is the most appropriate for general-purpose applications.

The preset detection level of current or flux-linkage needs be adjusted with motor size to ensure that excitation current remains between 1-2% of the rated. Although inductance of a motor decreases with increase in motor size, the magnitude of detection current increase with motor size. Therefore, the diagnostic excitation time becomes to a large extent independent of motor size. Hence, processing circuits designed for medium size motors should also work on comparative larger motors by simply changing the current sensor and possibly the voltage measurement sensitivity. However, signal processing for motors of small sizes can be less demanding because of the lower magnitudes of switching transients.

The constant-current and the constant-flux-linkage RPTC give functions which are reciprocal of each other. The former can resolve rotor positions with comparable resolution for most of the permeance variation cycle because the RPTC is approximately a linear function except near the aligned and the mis-aligned positions. The constant-flux-linkage characteristics is highly non-linear. However, the characteristics can be used to differentiate any two rotor positions for the whole cycle or when it is of interest to determine positions near or around the misaligned position.

The current transducer working on flux-nulling principle seemed appropriate but was found to introduce a number of problems. It has poor zero point stability particularly when set to give high output signal at low levels of current used for diagnostic purposes. Also, a current surge can move the zero point. Moreover, the transducer does introduce transients in the power circuit observable in the current signal whenever the power is switched on or off because of the finite time required for the flux in the device to stabilise. The transients were taken care of by a combination filtering action and momentary blanking of the level detection circuit at switch-on.

The effect of the 'step' observed in the current signal due to effects of eddy current in the VRM lamination was taken care of through its minimisation and the use of repeatable conditions so that its effects on position detection remain minimal. Conditions during calibration are ensured to be the same during operation.

Oscillations after protection diodes turn off, after switching off the power device in a phase, can not be ignored irrespective of the power switching circuit configuration. For circuits with snubbers it is the current that is important, while for snubberless circuits it is the instantaneous phase voltage that is more significant in controlling position detection errors.

CONCLUSION

The paper describes different methods of generating VRM magnetisation RPTC with emphasis on the practical aspects. A number of problems associated with the process were discussed. Techniques to overcome the problems or to minimise their effect on the detection of rotor position were described and supported by experimental results illustrating that repeatable magnetisation-based RPTCs have been realised.

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