A Back EMF-based Rotor Position Prediction in Permanent Magnet Machines for Survivable Wind Generator Systems

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***Abstract*-In wind power generators, position information is often required for tracking maximum power point as well as implementing control strategies for the Permanent Magnet (PM) generator. For such a system, failure of position sensor could potentially lead to major fault or require the system to be shut down. This could cause significant economic losses and also require unscheduled maintenance. This paper proposes a new sensorless position estimation approach to track position of the PM machine using the back EMF if the position sensor fails. This technique can also be used to provide initial rotor position for the proper implementation of a fall-back strategy. This technique can also be extended to detect position information at low speeds. Simulation and experimental results have been presented showing the effectiveness the proposed scheme and validate the claims presented.**

Keywords: PM Machines, Position Estimation, Survivable Drives, Wind Generation

I. Introduction

Permanent Magnet (PM) machines have been frequently used in wind power generation due to their compactness, reliability, high torque density, high efficiency and structural simplicity [1], [3], [4]. They can operate at a fixed speed to obtain synchronous power [2]. These systems typically require information regarding shaft position and speed in order to control it properly and employing Maximum Power Point Tracking (MPPT) schemes. Researchers have typically used two methods to detect the rotor position. One method is to install position sensors to PM machines such as optical encoders or hall sensors. The advantage of these position sensors is that they are usually very accurate. For such systems, in the event of a failure of the position sensor, the system usually has to be turned off. Another method to get the position information is sensorless prediction. Sensorless prediction can be cost-effective compared to the use of position sensors if the algorithm uses information already available from feedback sensors. Therefore, several sensorless techniques have been developed over the last two decades for motoring and generating applications [5].

This paper presents a new approach for the detection of rotor positions in PM machines in the event of failure of the position sensor in generators for wind power systems. The technique can be broadly described using three operating periods. During "Normal Operation Period", position sensor is used to detect the shaft position for controlling the generator. In case the position sensor fails, power is removed immediately by turning off all the six switches of the inverter. During this period, the PM machine continues to spin down due to inertia and the operation of the PM machine enters a "Transition Period". During this period, the proposed back EMF based sensorless prediction is employed to keep tracking the position of the rotor shaft. Using this information, the machine can be turned on again at certain desired commutation point and the operation of the PM machine reaches to the "Revival Period". During this period, the PM machine could be controlled by a relatively simple control strategy, such as digital control [6] to meet the minimum requirement of the wind power generation based on the second sensorless technique proposed in this paper. Two sensorless techniques have been proposed and implemented during the "Transition Period" and "Revival Period". Simulation and experimental results are included to prove the practicality of the proposed approach.

II. Review of Rotor Position Prediction Techniques for PM Machines Using Back EMF

Sensorless rotor position prediction for PM machines has received increasing attention over the last decade. Many methods have been proposed by researchers. These methods could be divided into three different categories: Motional-EMF based prediction [7], Inductance variation based prediction [8] and Flux-Linkage variation based prediction [5]. Back-EMF based sensorless control techniques are very popular due to the direct relation between the back EMF waveforms and the rotor position. Some Back EMF based techniques are briefly discussed in this section.

A. *Terminal voltage sensing*

This method estimates commutation points by looking at the BLDC back EMF and phase current signals [7]. For ideal operation of the BLDC machine, the phase current and back EMF should be aligned in phase to generate a constant torque. Therefore, the current commutation point can be estimated by the zero crossing point of the back EMFs and a proper degree phase shift. A disadvantage of this method is that only commutation points could be measured and the position information is not continuous.

B. Back EMF integration

This technique uses the integration of the back EMF of the silent phase to determine the commutation points [9]. The integrated area of the back EMF is approximately the same for different speed values. Therefore the commutation point will be at the same value. When the integrated area reaches this value the current is then commutated. This method is also focused on the commutation points instead of continuous position information.

C. Third harmonic of the back EMF

Using third harmonic signals of the back EMF is another possible way to determine the current commutation instants [10]. As the third harmonic has three times greater frequency, it makes this method less sensitive to time delay of a low power filter. External hardware is necessary to measure the third harmonics. Mathematically, it has been demonstrated that the zero crossings of the integrated third harmonic flux linkage are commutation points. This method has wider speed range than the previous two methods. But the position information is also not continuous.

D. Freewheeling diode conduction

This technique is based on letting current flow through a freewheeling diode in silent phase [11]. Every time back EMF crosses zero, a small current flows through the freewheeling diode during the period when the active phase switches are turned off under a switching control. The main drawback of this method is the need of using six isolated power sources for the comparator circuit in order to detect each of the freewheeling currents.

III. Proposed Sensorless Rotor Position Estimation

A. Back EMF based sensorless technique during transition period

During "Transition Period", as mentioned in the introduction, no power is extracted from or supplied to the PM machine. As a result, there is no armature reaction during this period. Under this condition, three back EMF signals can be easily obtained by measuring the stator voltage of the PM machine. In addition, while the rotor speed begins to decrease, it still spins at a relative high speed due to inertia. Therefore, Back EMF based sensorless position estimation can be accurate during this period before the shaft speed goes to very low velocity.

Back EMF waveforms of a PM machine are directly related to the rotor position. Therefore, an algorithm can be created to deduce the rotor position from reading back EMF signals in every instant. In Fig. 1, the measured voltages are first to divided the electrical cycle (360 degrees) into six equivalent areas or zones corresponding to 60 degrees each. Every area is delimited by comparing the voltage values of the three back EMF signals. In other words, every point in which the voltage value of one back EMF signal becomes identical to the other one, a new area begins. Therefore, there are six points in all, delimiting six different areas. These points correspond with 0, 60, 120, 180, 240 or 300 electrical degrees respectively. Representation of the six different areas (from 0 to 360) for sinusoidal back EMF signals is shown in Fig. 1. The rotor position is then estimated by using interpolation of the known position of the two points that delimit the area.

For a complete electrical cycle there are six different combinations to order the back EMF signals from highest to lowest. For our case it can be seen that each of the bounded areas is defined by one of the six possible combinations described in Table I.

From Fig. 1 we observe that the intermediate back EMF signal, which has the highest absolute slope, is characterized by an approximately constant slope from the beginning to the end of the area. That means this signal can be interpreted as a straight line for this interval. The algorithm uses the instantaneous value of this signal to calculate the position using interpolation with the limits of the corresponded area.

This algorithm can be explained using flow charts shown in Fig. 2 and Fig. 3. The first part of the algorithm is shown in Fig.2. It captures input voltages Va, Vb & Vc and identifies the phase with the intermediate value. This value is assigned to V_{ch}, which is used to calculate the position and also for the next iteration. Additionally the variable 'abc' is equated to either 1,2, or 3 depending on the voltage assigned in the previous state, Va, Vb or Vc, respectively.

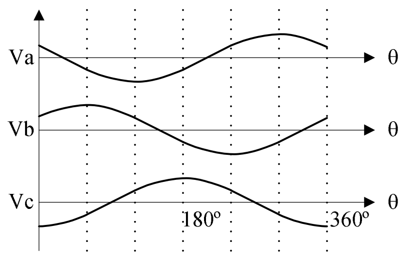


Fig. 1. Sinusoidal back EMF signals separated in six equivalent areas

TABLE I

COMBINATIONS OF VOLTAGES FOR EACH AREA

Zone	Combination	Highest	Lowest	Middle (Vch)
1 (0-60)	Vb>Va>Vc	Vb	Vc	Va
2 (60-120)	Vb>Vc>Va	Vb	Va	Vc
3 (120-180)	Vc>Vb>Va	Vc	Va	Vb
4 (180-240)	Vc>Va>Vb	Vc	Vb	Va
5 (240-300)	Va>Vc>Vb	Va	Vb	Vc
6 (300-360)	Va>Vb>Vc	Va	Vc	Vb

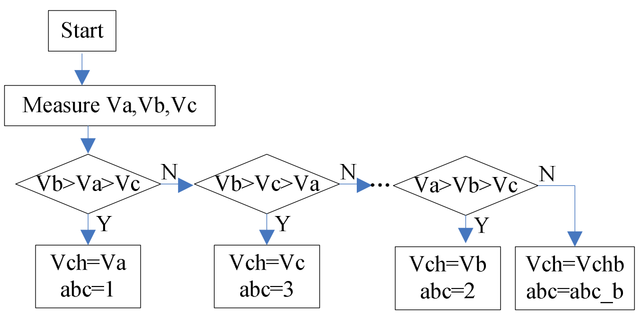


Fig. 2. First part of the algorithm which captures the intermediate voltage

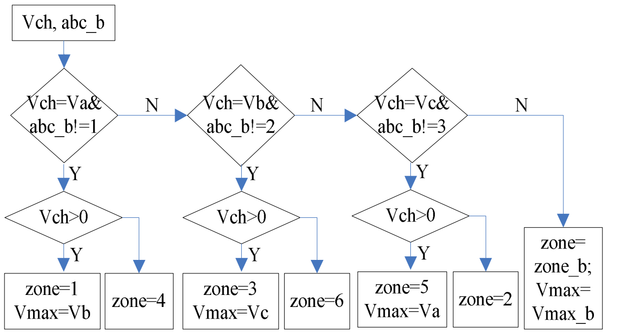


Fig. 3. Second part of the algorithm calculates the zone number and Vmax

The second part of the algorithm is shown in Fig.3. Here the variable 'abc' is used for the next iteration as 'abc_b' to predict if the area has changed with the new value. In other words, if 'abc' is not the same as 'abc_b', it implies that the zone has changed and this point is a maximum or minimum voltage value for V_{ch}. If we are at the maximum value (V_{ch} positive), the value is saved in another variable called V_{max}, which is used to store the maximum value of V_{ch} to later interpolate the measured voltage and obtain the rotor position. V_{max} is also delayed and fed back to the algorithm so if we are not at the maximum point the value stay constant. This method of calculating the maximum point is useful for cases we change the rotor speed thus the frequency and hence the maximum value of the back EMF also changes.

The rotor position is calculated finally based on the zone and voltage magnitude which is known. Using equation (1), the electrical rotor angle position θ can be obtained. It must be noted that θ is always a value between 0 and 360 degrees as it can be seen from the equation used.

$$\theta = 30 + 30*(Z-1) - 30*\frac{Vch}{V\max}*(2*rem(Z,2)-1) \qquad (1)$$

Where θ is the estimated electrical rotor position in degrees, Z is the zone number, V_{ch} is the instantaneous voltage value of the intermediate back EMF signals, V_{max} is the maximum voltage value at the boundary of each zone.

B. Back EMF based sensorless technique during survival period

During "Survival Period", the PM machine needs to turn ON again at a desired commutation point. If we need to control the PM machine and let it operate at fix speed, a "six-step" method is assumed to be used. The initial operation of these six switches of the inverter at this commutation point is given by the previous sensorless technique.

After the machine is powered on, three Back EMF signals can not be obtained easily at the same time due to armature reaction. Therefore, the previous sensorless method can not be used in this period. In order to continue tracking the position information during this period, another Back EMF based sensorless technique is designed and implemented. This algorithm is very similar to the previous one. First, the electrical cycle (360 degrees) is also divided into six equivalent areas, as shown in Fig.1. But in this case, every area is delimited by status of the six switches of the inverter in Fig.4. Every time, when the status of the six switches changes, a new area begins. Therefore, by checking the switch status at each instant, we can identify the area that the rotor enters and a corresponding "idle" phase. Subsequently the back EMF of this "idle" phase can be used to predict the rotor position in this area. Based on the estimated rotor position, the moment at which the rotor position reaches the boundary of the current area can be detected and then the switch status can be changed accordingly.

For a complete electrical cycle there are six different combinations of switch status and back EMF. These combinations could be listed in Table II. Similar to the previous algorithm, the back EMF signal of the unexcited phase can be mathematically expressed by a straight line in each region. At the same time, the voltage values of the extreme points of every area need to be recorded for the interpolation calculation. This value is measured when switch status changes. After that, this algorithm uses the instantaneous value of this signal and the recorded boundary values to calculate the position. This algorithm is explained in detail in the flow charts in Fig.5 and Fig.6.

In Fig.5, we find that this algorithm first captures the back EMF signal of the unexcited phase and zone number by examine the switch status. The voltage value of the back EMF is assigned to V_{ch}, which is used to calculate the position. Fig.6 shows the algorithm for capturing the boundary voltage value at the moment when current switch status is different from previous switch status. In other words, if V_{ch}=Va, current switch status should be T3=T6=1 or T4=T5=1. If the previous switch status is T1_b=T6_b=1. It reflects a zone change and this point is a maximum or minimum voltage value for V_{ch} value. This value is saved in V_{max} and will be used to interpolate the measured voltage and obtain the rotor position. The rotor position is finally calculated using equation (1) as described in the previous section.

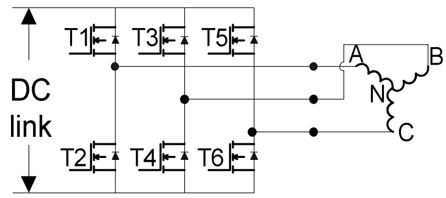


Fig. 4. Back EMF based Simulink Rotor Position Estimation Model

TABLE II
COMBINATIONS OF SWITCH STATUS AND BACK EMF OF UNEXCITED PHASE

Zone	Switch Status (ON)	Unexcited (Vch)
1 (0-60)	T3 T6	Va
2 (60-120)	T2 T3	Vc
3 (120-180)	T2 T5	Vb
4 (180-240)	T4 T5	Va
5 (240-300)	T1 T4	Vc
6 (300-360)	T1 T6	Vb

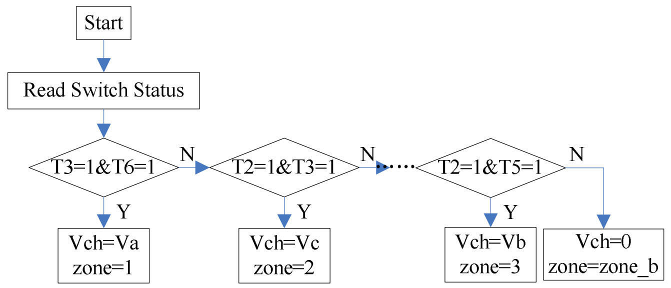


Fig. 5. First part of the algorithm which capture the back EMF of the unexcited phase and calculate the zone number based on switch status.

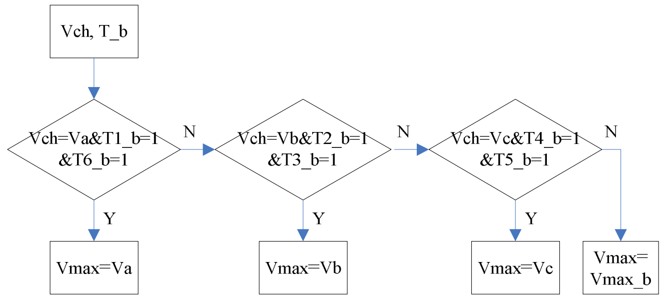


Fig. 6. Second part of the algorithm which captures the boundary voltage value at the moment when the current switch status and previous switch status are different

IV. SIMULATION AND EXPERIMENTAL RESULTS

A. Sensorless technique during "Transition Period"

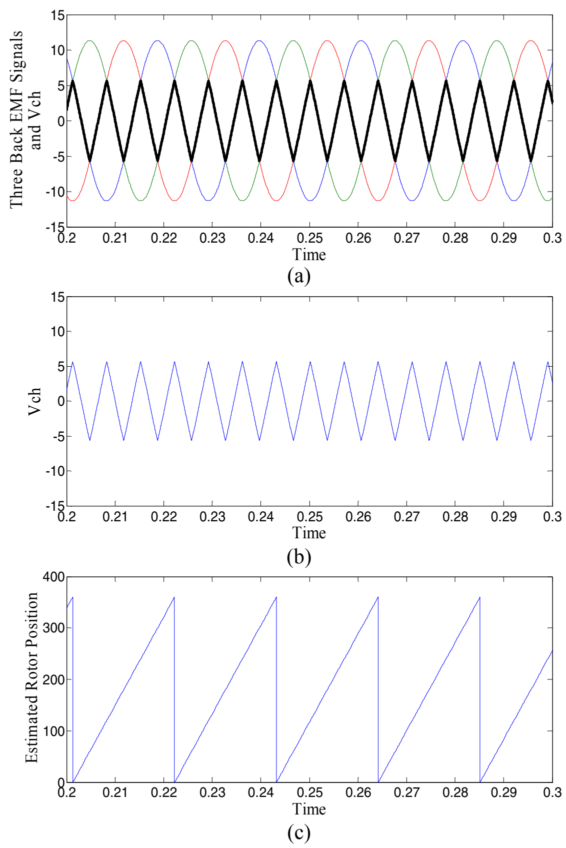


Fig. 7. (a)Sinusoidal back EMFs and reference voltage.(b) Reference waveform Vch. (c) Rotor position estimated in degrees from 0 to 360

During the "Transition Period", power supplied to the machine is removed and the machine spins due to its inertia. Therefore, three back EMF signals can be utilized to predict the rotor position. In this simulation, we made an assumption that the spinning speed of the machine is constant.

This simulation deals with the performance of the first algorithm when three sinusoidal back EMFs generated in Simulink are applied as system input. These waveforms are shown in Fig. 7(a). As mentioned in section III, the first step of the algorithm is to identify the signal which serves as the phase voltage for the rotor position estimation. This signal is formed by the intermediate voltage values of the three back EMF signals. In order to see the behavior of the algorithm in this stage this reference voltage is plotted over the other three voltage signals in Fig. 7(a).

The reference signal V_{ch} is extracted and used for the rotor position estimation. Fig. 7(b) shows the extracted V_{ch}. The next step involves comparison of the reference voltage value with every phase voltage to identify the range (zone) for the rotor position. Once the zone is established, the rotor position is estimated using the equation for the back EMF for the idle phase. Fig. 7(c) represents the rotor position (theta) estimated for every point from 0.2 to 0.3 seconds.

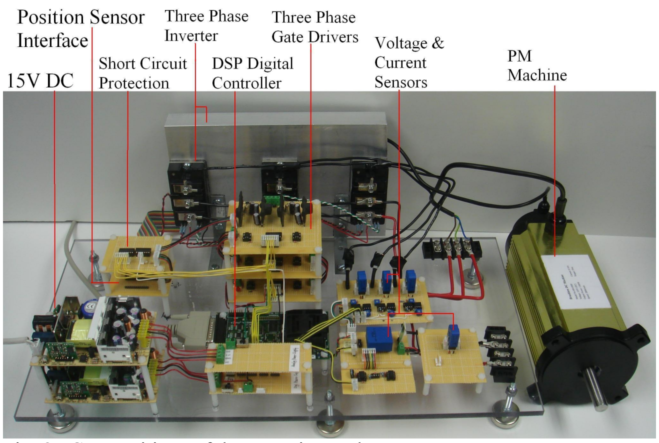
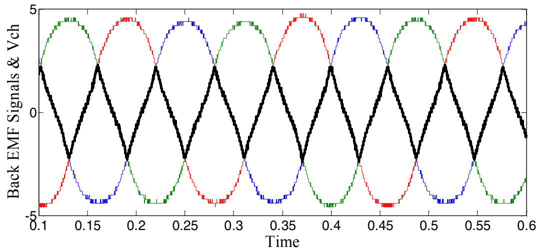


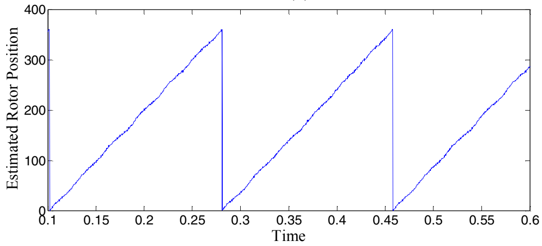
Fig. 8. Compositions of the Experimental setup

Three back EMF signals were sampled from the PM machine which was driven by a prime mover at a constant speed. Reference voltage was captured using the algorithm and plotted over these back EMF signals, as shown in Fig. 9(a). The input signals in this case are not perfectly sinusoidal and change slightly their magnitudes along time. The extracted reference voltage is then used to estimate position of the rotor. The results are shown in Fig.9 (b), which shows a very good estimation of the rotor position at each instant.

The next test was conducted to test the algorithm during the transition period, when the machine spins down due to inertia. This measurement is shown in Fig. 10(a). During this period, the magnitude of back EMF signals keeps decreasing, as expected. The reference voltage was captured using the algorithm and plotted over these three back EMF signals, as shown by the bold lines in Fig. 10(a). The result of the rotor position estimation in this case is shown in Fig. 10(b). These experimental results verify the accuracy of the proposed sensorless estimation method during transition period.

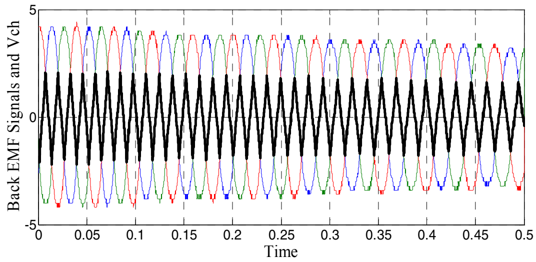


(a)

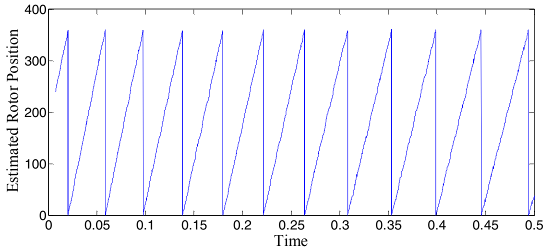


(b)

Fig.9. (a) Experimental back EMF signals and Vch. (b) Estimated rotor position in degrees for constant speed



(a)



(b)

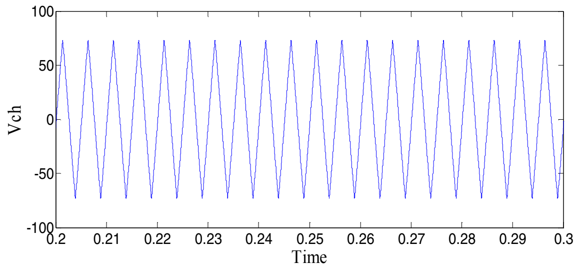
Fig.10. (a) Vch Extracted from back EMF signals (b) Estimated rotor position in degrees during spin down in the event of sensor failure

B. Sensorless technique during "Survival Period"

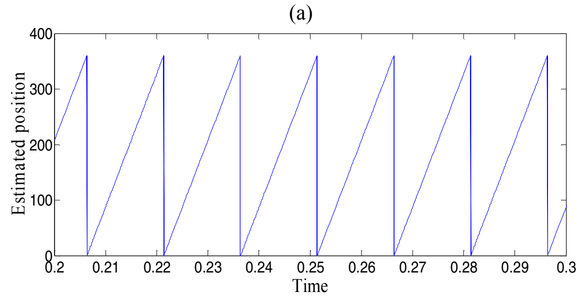
During this period, the PM machine is turned on again. Therefore, the previous sensorless technique can not be used because these three back EMF signals can not be obtained easily due to armature reaction. This method is based on the back EMF of the unexcited phase of the machine every time by examine the switch status of the inverter. Fig. 11(a) shows the back EMF signals of the unexcited phases. Similar to the previous method, the rotor position can be calculated using equation (1) and its simulation result is shown in Fig. 11(b).

Experimental results are shown in Fig. 12. The PM machine is operated at a constant speed of 500rpm with its current rms value equals to 0.5A. Three phase voltages could be easily obtained by measuring the terminal-to-neutral voltages. As shown in Fig. 12(a) the reference voltage V_{ch} is captured according to the switch status in Fig. 12(b) (Table II) and plotted over these phase voltages. The reference voltage V_{ch} represents the unexcited phase of the PM machine in operation. Based on reference voltage, the rotor potion can be estimated and its result is shown in Fig. 12(c). Fig. 12(d) shows the error of position estimation compared to the actual position from a position sensor. The maximum position error is 10 electrical degrees which is an acceptable value for the operation of the PM generator.

It must be noted that this sensorless technique has some limitations. Line-to-neutral (phase) voltages are not easy to sense due to the unavailability of the neutral point. Phase voltages will be greatly distorted and phase-shifted in high current application due to the strong effect of armature reaction. Therefore, this sensorless technique has been found to be most suitable for low current and low speed application. However, this method meets the operation requirement of the PM generator in wind power applications under position sensor failure.

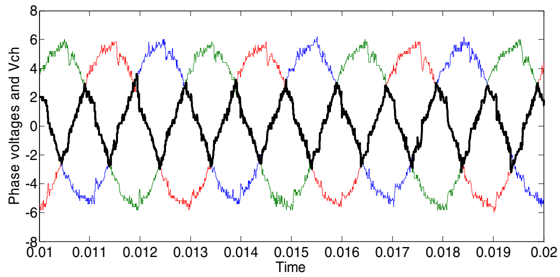


(a)



(b)

Fig.11. (a) Back EMF signal from the unexcited phase. (b) Estimated rotor position in degrees



(a)

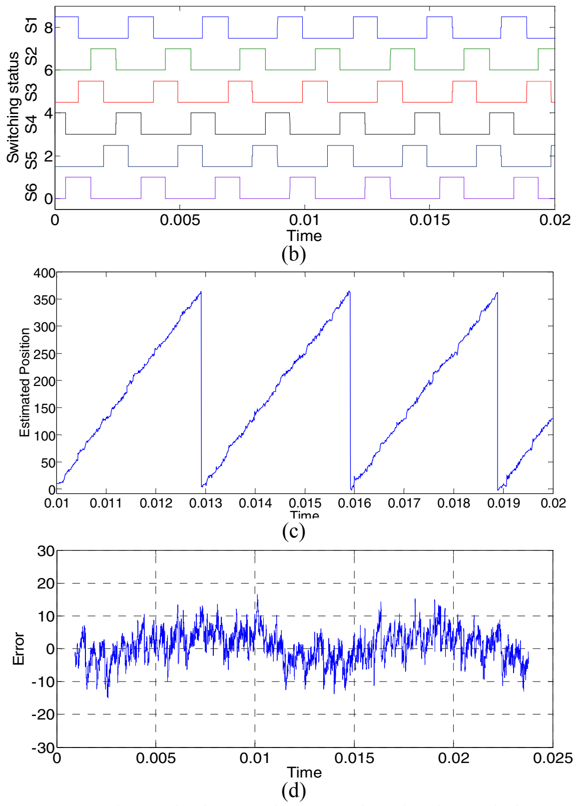


Fig.12 (a) Experimental phase voltages and Vch. (b) Switch status. (c) Estimated rotor position in degrees. (d) Position error in degrees.

C. *Sensitivity of the proposed techniques to sampling frequency*

The two proposed sensorless techniques are based on the measured back EMF signals and phase voltages. Therefore, voltage sampling frequency is an important factor which determines the accuracy of position prediction. Fig. 13 shows the relationship between sampling frequency and rotor position estimation error. In order to get the best performance of the proposed sensorless estimation methods, sampling frequency above 50 kHz has been recommended.

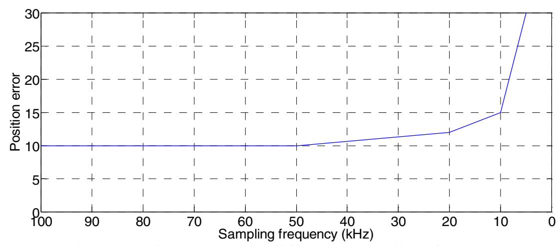


Fig. 13. Position error in degrees at different sampling frequency

V. CONCLUSION

In this paper, a new approach has been presented for the detection of the PM machines' rotor position under fault conditions in wind power generation. Two sensorless position estimation methods are used to predict the rotor position in two different periods after faults occur. One sensorless position estimated method is design based on the three back EMF signals during transition period when PM machine is powered off. This method can track the rotor position in every instant and could provide the initial position information to the second sensorless method. The second sensorless method is similar, but is based on the back EMF signals of the unexcited phase when machine is powered on again using "six-step" methods. The extraction of the back EMF of the unexcited phase is based on the switch status. Simulation and experiment results have been presented in this paper to validate the effectiveness of these two sensorless position estimation methods, which make the operation of PM machine during fault condition possible.

ACKNOWLEDGEMENT

Authors would like to thank the U.S. Department of Energy grant number # DE-EE 0002979: "A World-Class University-Industry Consortium for Wind Energy Research, Education, and Workforce Development" for funding this project.

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