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Encoder Less Hex- Phase Motor Drive Operated Under Fault Using Kalman Filter

Elhussien Abbas Mahmoud[1,*], Hussein Farid Soliman[2]

1 Ain Shams University

2 Electrical Power and Machine Department, Faculty Of Engineering, Ain Shams University

[*] Corresponding author: elhussien.abbas@gmail.com

Abstract

High phase machines (HPM) is the race horse of the near future decades. It offers the distribution of large power over more phases. The capability of the HPM drives to survive even if it is subjected to gate drive circuit fault is of great interest. Such a merit improves the system reliability and dependability. The HPM at post fault condition is able to deliver considerable percentage of its rated torque. The amount of derating depends on the number of the entire HPM phases and the number phases lost. As the number of HPM phases increases, the derating due to a single phase loss decreases. Several researchers exert large efforts solving HPM fault overcome issues. The latest fault overcome technique is the HDPOT. Some other efforts are exerted to get rid of the annoying mechanically weak encoders. Encoder-less operation is an additional factor that enhances the overall system reliability. Attention is paid as well to operation without encoder of the HPM subject to fault. Kalman filter is one of the observer based encoder-less methods. Kalman filter is a well-established encoder-less method that has been applied to three phase machines and HPM as well. Still the HDPOT method is not investigated together with an encoder- less method. This paper hopes to close this gap with proved simulation work. This paper will investigate the encoder-less operation of an asymmetrical six phase machine subjected to single gate drive fault using kalman filter and HDPOT method.

Keywords: *Encoder- less, High phase machine, Kalman filter, Fault overcome.*

1- Eye on History

In history, scientists knew the high phase machines (HPM), famous also as multi- phase machines, couple of centuries back but yet not fully utilized. Spotting on HPM increases after the revolution in the art of power electronics. Cheaper and more efficient power switches open the door widely to build power inverter of sufficient ratings. Operation of alternating current motors covering large speed range regardless of the fixed supply frequency is the traditional goal of power inverter. A front edge rectifier is functionally mandatory for the operation of the conventional two level voltage source inverter. Meaning to say, the characteristics of the supply voltage in terms of frequency and number of phases have nothing to do with the inverter output. End of the day, the supply appears to the inverter as single DC source stabilized by large capacitor. If this is the case, re-inventing the voltage back to the three phase form, as usual, is not a law. Inverter output may be configured for any number of phases. The building stone of an inverter is a power switch inversely paralleled to a power diode. Two pieces of such building stone connected in series across the DC link form what is called inverter leg. Each inverter leg is associated to one phase. The potential difference of the inverter leg centre point relative to the DC link midpoint is the phase voltage of the associated output phase. Three phase inverter consists of three legs. Increasing the number of legs increases the number of phases in the output voltage. Consequently, an endless range of the number of phase is available.

2- High Phase Machines

The availability of a multi- phase inverter gives the life breath to the HPM. HPM is defined as an electrical machine which has a count of phases higher than three. A huge variety of HPM exists. Prime number is a well- known set of configurations includes the five, seven or eleven phase configuration. Another famous set of configurations is three phase multipliers set which includes the six, nine or 15 phases. . Etc. In the HPM the interphases electrical angle equal three hundred sixty divided by the number of phases provided that the configuration is symmetrical. The inter phase angle is half of this value in the asymmetrical configuration. Three phase machines have an asymmetrical configuration as well where the angle between each two successive phases equal sixty electrical degrees instead of one hundred twenty in the symmetrical configuration [1, 2].

The benefits gained from the HPM are enormous. Regardless the great progression in the field of industrial electronics, the ceiling of its capability to withstand large currents or high voltage still limited. The maximum power rating of the electronics is also limited in consequence. Distributing the required power over larger number of devices offers an acceptable solution. This is what actually the HPM does. Each individual phase share a smaller amount of power. The associated devices ratings are then lowered. Several applications are sensitive to power density. Air crafts are an example where everything is required to be smaller and lighter. HPM leads in this regard with the largest power density. Machine designers prefer to distribute the coils forming each phase over the largest possible number of slots, called phase belt, to reduce the space harmonics. Sinusoidal flux pattern is needed for smooth operation. Time harmonics other than the fundamental in the supplied voltage are avoided as they result in power loss. This distribution of windings is also valid for the HPM. Concentrating the phase winding in a single coil per pole per phase is known to be the worst design, But not with the HPM. A concentric winded HPM gains advantage of certain unwanted time harmonics and utilizes them to produce useful torque. This art is known as field enhancement of the HPM. The audible noise and torque ripples are less in the HPM. The novel part of the HPM characteristics is its ability to withstand at least one open circuit within the machine or the associated inverter [3]. The subject is named fault tolerance of the HPM.

3- Fault Overcome

Single phasing is a sever fault condition in the three phase machine. Motor protection normally opens the motor contactor. On the other hand, similar malfunction in the HPM system does not result in service interruption. Changing the current manipulation technique can maintain the service. Circular flux is a must for smooth operation. The harm caused by the fault is basically distorting the flux distribution. Obtaining a circular flux while the system is in well condition is possible through a unique solution. Such solution is to apply balanced set of voltage having the same count of phases as the motor does. The situation is different when the system is suffering from a down phase. A variety of solutions are able to maintain the flux pattern. The fact that several techniques may achieve the aimed mission rises the need for election criterion. Machine theory often substitute the three phase machine with an equivalent twin phase machine to avoid mathematical complicity. In addition, machine theories analysis the twin phase machine in a different frame axis rather than the natural frame to get rid of machine non linearity and state coupling. One of the decoupled current component is aligned in the heading of the flux (If) and its amplitude is regulated for keeping rated flux value. The second current vector is orthogonal to the flux heading (IT) and is responsible for providing the mechanical torque. After returning the twin current back to the normal axes, it may be named as (IɅ) and (IɃ).

The same is valid for the HPM. If the zero sequences are excluded, HPM has more than two current motif. The number of current motifs depends on the count of machine phases. For five and six phase machines, four current motifs are there. Seven phase machine has six motifs. Current motifs are generally disciplined in independent pairs called plans. The first pair is the fundamental one which is analogous to the three phase case. For the machine in focus, the six phase machine, one more pair exists and is referred as (Iu) and (Iv). In case of losing the flux form circularity due to unavailability of one of the machine phases, proper choice of the instantaneous value of the redundant current pair is good enough to reform the flux again in the circular shape. Beating the fault consequences using the extra current pairs is the greatest outcome of the HPM. Equations (1 and 2) govern the election of the instantaneous value of current pairs.

$$I_u = Z_{u\Lambda} I_{\Lambda} + Z_{u\text{Ƀ}} I_{\text{Ƀ}} \tag{1}$$

$$I_v = Z_{v\Lambda} I_{\Lambda} + Z_{v\text{Ƀ}} I_{\text{Ƀ}} \tag{2}$$

Where: Z_x is an election constant. x ∈ $\{u\Lambda, u\text{Ƀ}, v\Lambda, v\text{Ƀ}\}$
The choice of the election constant allows a variety of optimization criteria. The famous criterion concentrate on maximizing the efficiency while the other focus on the produced torque. For better efficiency equation (3 to 6) are applied.

$$Z_{u\Lambda} = 0 \tag{3}$$
$$Z_{u\text{Ƀ}} = 0 \tag{4}$$
$$Z_{v\Lambda} = 0 \tag{5}$$
$$Z_{v\text{Ƀ}} = -1 \tag{6}$$

Unavailability of a complete phase is not always the case. A single corrupted switch within the drive owning higher probability. Reference [4] introduced a technique to interact with such a case called HDPOT method. Successive switching over between the normal and corrupted case was the key of this method.

4- Encoder-Less Drives

The field side of any industrial drive is the point of weakness. The sensors installed on site are subjected to a lot of harmful factors including and not limited to sun, rains, wind, sand and other weather related agents. Accidental damage for mechanically weak components by unintentionally actions is the frequent reason of service interruption. Encoders, resolvers and tacho-generators are examples of the essential sensors subjected to mechanical damage. Damage for such kind of sensors is fatal for vector controlled drives. Measured signals are subjected to electromagnetic interference while transported from the field side to the drive panel [5, 6]. Nowadays, the trend is to dispose the speed transducer. Drive system will be simpler, more reliable, stronger and even smaller if the weak transducers are eliminated. In reality, the motor current and voltages inherently have sufficient notions about the shaft speed and/ or position. Straight ahead integration of the back electromotive force is the traditional way of obtaining the shaft position. The integration outcome is the flux as given by equation (7 to 9).

$$\phi_{\Lambda} = \int [U_{\Lambda} - R * I_{\Lambda}]\, d\text{ʈ} \tag{7}$$

$$\phi_{\text{Ƀ}} = \int [U_{\text{Ƀ}} - R * I_{\text{Ƀ}}]\, d\text{ʈ} \tag{8}$$

$$\ominus = \tan^{-1}\left(\frac{\phi_{\text{Ƀ}}}{\phi_{\Lambda}}\right) \tag{9}$$

Where :
ϕ_{Λ} and $\phi_{\text{Ƀ}}$ are the flux projection on the stationery axes
U_{Λ} and $U_{\text{Ƀ}}$ are the voltage projection on the stationery axes
$\ominus$ is the flux orientation
ʈ is the time

Actually, the flux orientation is the value directly needed by the vector controller. In the encoder based operation, the shaft speed is added to the slip value to obtain the synchronous speed. The latter is integrated to achieve the flux orientation. In the straight forward integration the flux orientation is got directly. This method is highly sensitive to the measurement accuracy. The difference between the current and voltage sensors outputs and the correct value due to low devices accuracy or interference is the annoying factor. The disturbance is integrated as well and consequently the estimated flux orientation deviates from the correct value. The deviation accumulates and goes larger and larger due to the integration. Results may not converge. Low quality estimation might take place as a result of voltage switching. The effect of the high frequency ripples in the machine current is additional source of error which became more effective near the zero crossing. The current reverses its direction several times around the zero point. More over its value is so much smaller than the ripple contamination. Fig.1 illustrate the zero crossing problem.

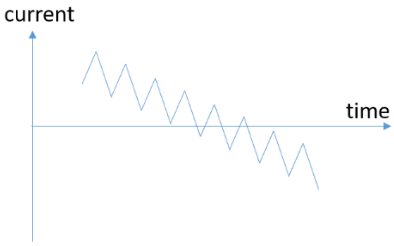

Fig.1: Zero crossing problem

Solution is proposed by including feedback link to the integrator. The integration process will be upgraded to the first order equation given by equation (10)

$$T_0 \frac{d\hat{\Phi}}{dt} + \hat{\Phi} = T_0[U - R * I] \tag{10}$$

Where:
The hat sign indicates estimated value.
T_0 is the system time constant.

Equation (10) represents a low pass filter as shown in fig. 2.

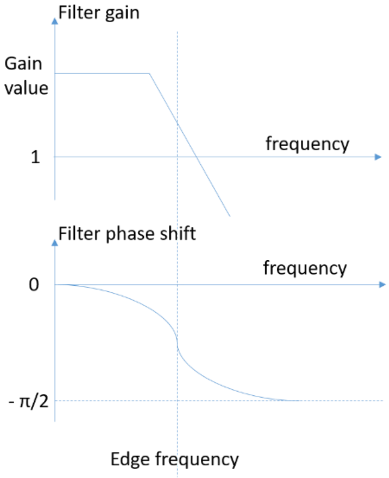

Fig.2 : Low pass filter characteristic.

Low pass filters even if removes the high order ripples, it change the signal amplitude and phase when the fundamental frequency is near the filter edge frequency.

An alternative method known as the MRAS method utilizes an adaptation controller. MRAS compares between the outputs of two different machine model. A datum model and a tuning model. An error generator base is needed as an input to the method controller. More clearly, an electrical quantity is selected and is calculated twice. One time the chosen electrical quantity is evaluated using the datum model and in the second time the same quantity is evaluated based on the tuning model. The MRAS takes the name of the selected quantity and is named as X based MRAS. Where X could be the reactive power, magnetizing current, back electromotive force, rotor flux, ..etc. the datum model is constructed using the stator quantities where its output is independent of the shaft speed. Alternatively, the tuning model utilizes the rotor quantities and knowing the shaft speed is a must to calculate its output. Rough estimation of the shaft speed or its previous value is used by the tuning model. The difference between the outputs of the two models is handled to a proportional integral controller. The controller gives the updated value of the shaft speed or its increment. Upgraded versions of the MRAS theory results from using higher order controller or replacing the tuning model by a virtual artificial intelligent model. The quality of the velocity estimation degrades severely as the speed reduces. The measured signals become unreadable small as compared to the noise. Near the zero speed there will be no signals to be measured.

Many researchers prefer to use the artificial intelligent tools (AI) as a stand-alone method. The AI offers robustness against parameters variation. AI does not require any machine model and allow the integration of people experience with the system. Excessive math is the main drawback and explanation of the outcomes not always available.

Observers are alternative trend aimed to find the shaft speed value. The machine equations are rewritten in the form of equation (11 and 12). The variables under investigation Ƶ is called the system states. In general, the flux components are among the selected states.

$$\dot{\text{Ƶ}} = A\text{Ƶ} + \mathcal{B}\upsilon \tag{11}$$

$$\mathit{\Upsilon} = C\text{Ƶ} \tag{12}$$

Where :
A , $\mathcal{B}$ and C are matrices depends on the machine parameters.
υ is the system inputs.
$\mathit{\Upsilon}$ is the measurable variables

The starting point is the election of a gain matrix to link the system inputs to the states, equation (13).

$$\upsilon = -\text{KƵ} \tag{13}$$

Then to rewrite equation (11 and 12) in discrete form after substitution from equation (13) and including error correction term. As shown by equation (14 and 15).

$$\hat{\text{Ƶ}}(\text{ʈ} + 1) = (A - \mathcal{B}\text{K})\hat{\text{Ƶ}}(\text{ʈ}) + \text{£}(\mathit{\Upsilon}(\text{ʈ}) - \hat{\mathit{\Upsilon}}(\text{ʈ})) \tag{14}$$

Where: £ is the error correction matrix.

$$\hat{\mathit{\Upsilon}} = C\hat{\text{Ƶ}} \tag{15}$$

Equations (14 and 15) form a simple observer. The observer performs two steps and repeats them over and over. Equation (15) gives the estimated system outputs using the estimated states. Then equation (14) provide new states estimation utilizing the previous estimated states together with the error in the estimated outputs. Proper choice of the error correction and gain matrices pushes the system to converge.

Observers reject the majority of noise but yet face difficulties at low velocities.

The arena contains three more competitors. Three families of harmonic dependent methods are able to pick the shaft speed value.

Injecting additional current component superimposed on the flux producing one at low frequency causes the shaft to oscillate. The shaft oscillation in turn creates harmonics in the back EMF of the machine. The back EMF response to the superimposed current component when filtered is sufficient to detect the shaft speed. This method can succeed at low speed because it does not use the normal machine current which decay with the speed reduction. The shaft oscillation is the barrier between the low frequency injection method and the practical implementation.

Higher frequency injection is the second family of competitors. The method depends on the machine saliency. Saliency may be clearly obvious like the salient poles of an alternator. Or saturation dependent as in the case of induction machine. A sinusoidal flux pattern raises the flux density at several points, at least two, coincident with its peaks. The positions of the highest flux density forms the machine non-salient poles. The injection is applied as an extra voltage component through the inverter. The machine saliency divides the response to extra voltage component into forward and backward current sequences. The forward part is non-informative. The information contained in the backward sequence, if filtered separately, is good enough to achieve the estimator goal.

Recent techniques uses the normal inverter switching instead of the high frequency injected voltage. The normal frequency range of the inverter switching is from 10 to 100 MHz.

The last family of estimators is the Fourier transform based method. The slots of the rotating core contaminates the flux pattern with special frequencies correlated to the shaft speed. Analysing such frequencies using Fourier theory leads to knowledge of the shaft speed.

5- Proposed Estimator

Kalman filter is one of the recursive observers. It trace the observed variable with the aid of several previous values without storing them due to its recursive nature. Kalman filter is inherently noise rejecter. Kalman filter is superior to the simple observer by taking the error covariance in consideration. The filter starts with a rough intermediate states estimation, denoted by (–) sign, followed by roughly calculated error covariance (Ᵽ). The kalman gain (Ҡ) is then evaluated. The intermediate states values are corrected with the aid of the plant feedback and the observer gain. Finally, the error covariance matrix is updated.

Equations (16 to 20) summarizes the previously mention five steps.

$$Ƶ^{-}(ʈ) = AƵ(ʈ - 1) + \mathcal{B}U(ʈ - 1) \tag{16}$$

$$Ᵽ^{-}(ʈ) = AᵱP(ʈ - 1)A^{T} + Ϙ \tag{17}$$

$$Ҡ(ʈ) = Ᵽ^{-}(ʈ)AҤ^{T}(ҤᵱP^{-}(ʈ)Ҥ^{T} + я)^{-1} \tag{18}$$

$$Ƶ(ʈ) = Ƶ^{-}(ʈ) + Ҡ(ʈ)\big(ϒ(ʈ) - ҤƵ^{-}(ʈ)\big) \tag{19}$$

$$\text{Ᵽ}(\text{ʈ}) = (II - \text{Ҡ}(\text{ʈ})\text{Ҥ})\text{Ᵽ}^{-}(\text{ʈ}) \tag{20}$$

Where:

Ϙ and я are noise covariance.

II is the identity matrix

The equations forming the well-known induction motor model can be manipulating to reach the form given in equation (21).

$$\begin{pmatrix} \frac{d\Phi_{\text{Ʌ}r}}{d\text{ʈ}} \\ \frac{d\Phi_{\text{Ƀ}r}}{d\text{ʈ}} \end{pmatrix} = \begin{pmatrix} -I_{\text{Ʌ}r} & -\Phi_{\text{Ƀ}r} \\ -I_{\text{Ƀ}r} & \Phi_{\text{Ʌ}r} \end{pmatrix} \begin{pmatrix} R_r \\ \mathit{\Omega} \end{pmatrix} \tag{21}$$

Where:

The subscript (r) means that the variable belongs to the rotor circuit of the induction motor.

$\mathit{\Omega}$ is the shaft speed.

Observers are model based. Kalman filter as any observer need the plant model. In other words, the equation represents the dynamic behaviour of the plant under investigation should be reformed and put in the form of equations (11 and 12) [7]. As these two equations are the model needed by the observer.

For the case in hand, equation (21) is in the form of equation (12). The other equation is chosen empirically as depicted by equation (22).

$$\begin{pmatrix} R_r(\text{ʈ}) \\ \mathit{\Omega}(\text{ʈ}) \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ 0 & \varepsilon \end{pmatrix} \begin{pmatrix} R_r(\text{ʈ} - 1) \\ \mathit{\Omega}(\text{ʈ} - 1) \end{pmatrix} + \begin{pmatrix} 1 \\ 0 \end{pmatrix} R_{ro} \tag{22}$$

Where:

The subscript (o) refer to the cold value of the rotor resistance.

ε is a tuning parameter.

6- Results

The authors of this work aim to proof that Kalman filter is a suitable software substitution of the physical encoder for an asymmetrical 6 phases squirrel cage motor (A6ph-M) subjected to one IGBT loss and controlled with HDPOT. A system composed of A6ph-M, mechanical load, IGBT based inverter with passive front edge and several control techniques is simulated. The first controller is a simple proportional/integral type and its function is to regulate the speed and decide the amount of torque required. The second controller is utilized to determine the value of each independent current component to achieve the needed torque based on the flux vector control technique. The last controller is of hysteresis type and its function is to realize the previously mentioned current values. The mechanical load is assumed to have a parabolic speed torque characteristic. An example of the parabolic loads is the centrifugal pumps. Step reference velocity of rated value is requested from the drive. After 2 second a scenario of losing one gate drive circuit is pretended. The assumed lost gate drive circuit is selected to be belonging to the top switch in the third phase of group number 2. Three successive reduction in the requested velocity is commanded. One reduction takes place each two seconds. Fig. 3 provides the entire speed curves (command, actual and estimated). Fig. 4 shows the associated output torque. Fig. 5 zooms the speed curve around the fault instant.

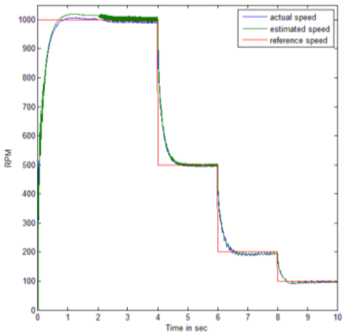

Fig. 3: Shaft speed.

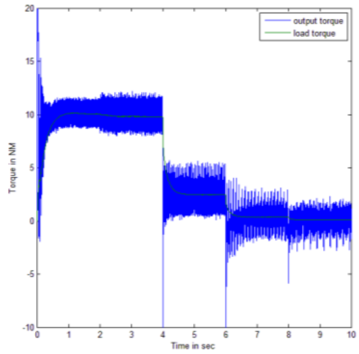

Fig. 4: Output torque.

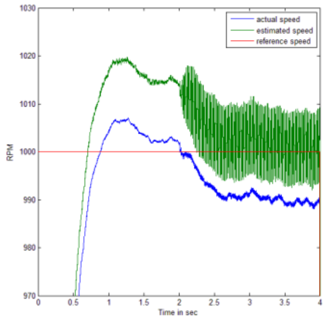

Fig. 5: Speed behaviour around the fault instant.

Finally, fig. (6 and 7) focus on samples of the line currents during each different operating condition.

To create a comprehensive view, two quality factors are monitored. The first factor tells how far the estimation from the real values is. The second quality factor is an indication for how stable is the overall system after adding the kalman filter. The two factors are graphed in fig. (8 and 9) respectively. The purpose of the previously described test is to show the power of the kalman filter as an estimator. The steady state miss- estimation is less than 6 percent in general as proved by fig. 8. Smooth starting of the induction motor can be seen associated with slight under damping as shown in fig. (3 and 5). The fault occurrence results in minor increase in the steady state error as can be noticed from fig.5. The entire system performance is proved satisfactory where the steady state error is always below 3 percent, fig.9.

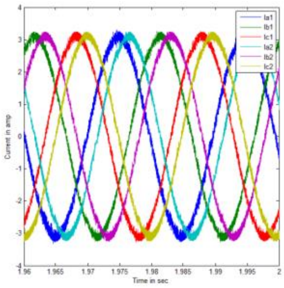

Fig. 6: Normal current profile.

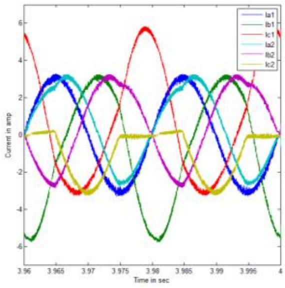

Fig. 7: Current profile during fault management region.

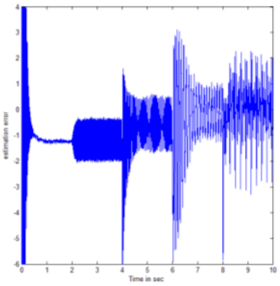

Fig. 8: Estimation quality factor.

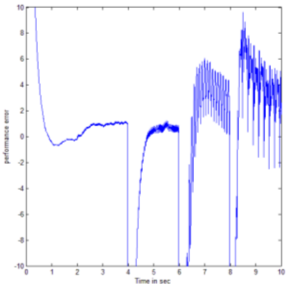

Fig. 9: Performance quality factor.

7- Conclusion

This study tries to prove the robustness of the kalman filter while being used as an estimator for A6ph-M under one drive gate circuit loss managed by HDPOT. Two isolated neutrals connection is chosen for the motor. A simulation study is processed to investigate the effect of substituting the shaft encoder by kalman filter under the said conditions. The paper proposal is proved acceptable by the simulation results.

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