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Effect of the Parameters Variation and Rotor Stator Resistances Error for Induction Motor on its Performance Characteristics with Field Oriented Control Compared to Scalar Control

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Abstract*— Field oriented control is from the best control methods in AC drives but it is very sensitive to vary of parameters specially the rotor parameters so these parameters must be known and matched with control parameters to get high dynamic performance. For this reason, this paper discussed the effect of the parameters variations on the performance characteristics of induction motor with field oriented control compared to scalar control. Also the effect of the matching and mismatching in the rotor and stator resistances inside the machine and inside the field oriented control is discussed. This occurs to show the effect of mismatching in the rotor and stators resistances on the performance characteristics of induction motor with field oriented control compared to matching rotor and stator resistances with the same control and with scalar control. MATLAB program is used to verify this.

***Index Terms*—Field oriented and scalar controls, Induction motor, MATLAB program, Parameters variations and error.**

I. INTRODUCTION

With inventing the converters and inverter the induction motor used in wide spread range this because the frequency of inverter can change from small fraction value to higher value this means that the induction motor can be operated at any speed. This can be done by scalar control (SC) or by field oriented control (FOC). In spite of induction motor has some advantages as low cost and low maintenance, high efficiency, rugged structure and long operating life at higher and medium loads but at light loads, the induction motor has some disadvantages as low power factor, low efficiency and low dynamic performance [1]- [4]. These problems come from the interaction between rotor and stator i.e. the stator multivariable control structure are more effecting on the rotor motor. This problem is existed when the motor is controlled by SC so the SC is preferable when the load doesn't require fast dynamic response as fan load and pump load. In this control, the voltage and frequency are in portion as the magnitude in constant flux region i.e. v/f is constant but in the field weakening control, the voltage applied on the motor didn't vary and frequency increased [5]- [8]. To get rid from these problems (slow dynamic performance) the rotor and stator fluxes must be perpendicular. To achieve this, the FOC must be applied. With this control, the stator current is decoupled into two components one from them represented the flux component and the other component represent the torque component. The major disadvantages of this control scheme is that it is machine parameters dependant. The machine parameters are effected by temperature and saturation. Any mismatched between machine parameters and the same parameters in the control leads to deteriorate in the performance of the drive system over all so many researchers make many models to adjust the machine parameters to get high dynamic performance at any load and any speed [9]- [10]. So this paper is discussed the effect of parameters variation and the effect of rotor and stator resistances error on the performance characteristics of induction motor with FOC. To show this effect, the performance characteristics of induction motor with matching and with mismatching are compared at constant load. Also the correct SC is comparing to FOC at mismatching and matching rotor parameters to show that, in spite of the FOC with good orientation is very good control if it is compared to SC but at mismatching in the rotor and stator resistances, the correct SC becomes better. This paper concluded that, I introduction, II scalar control, III field oriented control, IV simulation results and V conclusion.

II. SCALAR CONTROL

Scalar control is a popular control due to simplicity and low cost. It is used in open loop and closed loop controls. To control in the motor speed, the frequency of the input voltage of the motor must be change. To keep the motor torque constant, the air-gap flux must be constant at rated frequency i.e. $\frac{v}{\omega_e}$ is kept constant. This ratio gives good control at nearer base frequency because the voltage drop in the stator resistance can be neglected this is because this drop on the voltage doesn't exceed 5% of the input voltage but at low frequency this ratio cannot be neglected and the level of the flux is decay. The largest decrease in the flux makes the motor is saturated, cannot get demand torque and the motor becomes over heated to avoid this, a boosting voltage is applied to compensate the drop in the stator resistance as shown in Fig. 1. i.e. to drive the induction motor through open loop SC, the reference speed is used to generating voltage and frequency that are suitable to drive the induction motor nearer to synchronous speed through the inverter and at low frequency, the boosting voltage is added to compensate the lack of the voltage due to effect of stator resistance. This method of control is very good when high dynamic performance isn't required. but when the dynamic performance is required the closed loop speed control can be applied as shown in Fig. 2. In

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this method of control, the motor speed is measured and compared to the reference speed. The error between the measured speed and reference speed is introduced to PI speed controller to deduce the slip frequency. The slip frequency is added to measure motor speed to get electrical frequency which is used to generate the reference voltage. With aid of reference voltages and electrical frequency, the three phase reference wave generate. These waveforms are compared to actual three phase measured as shown in Fig.2 and the output of these comparators are compared to the carrier wave to get the switching frequency of inverter.

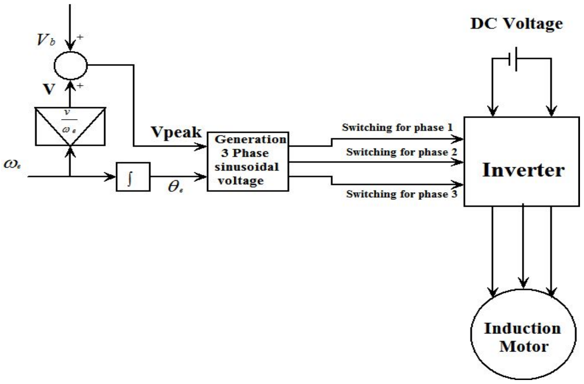

Fig. 1 Open loop scalar control.

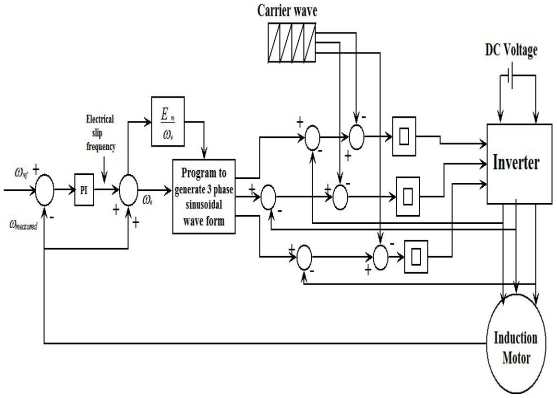

Fig. 2 Closed loop scalar control.

III. FIELD ORIENTED CONTROL

The field oriented control makes the induction motor emulates the separately excited DC motor. To understand this let's start with the principle torque equation

$$T_e \alpha \psi_s \psi_r \sin\varepsilon \cos\Gamma \qquad (1)$$

Where ψ_s and ψ_r are stator and rotor flux linkages, ε and Γ are the space and time angles between stator and rotor flux linkages.

If it is applied on DC machine it is found that,

The space angle is equal to 90 and time angle is 0 because the field comes from DC field hence the torque equation becomes as the follows

$$T_e \alpha \psi_s \psi_r \qquad (2)$$

So the torque becomes maximum value. By applying this equation on induction motor, it found that, the space angle is smaller than 90 . Hence, to verify the same torque taken from DC, the rotor or stator flux must be increased, by such an increase in the stator current and hence it found that, the torque per ampere of DC is higher than the torque per ampere of induction motor. By applying the FOC it is found that, the torque problem is solved this is because the space angle between rotor flux and stator flux becomes 90 . Despite of FOC of induction motors has achieved a quick torque response, and has been applied in various industrial applications instead of DC motors. The FOC is very sensitive to flux estimation (magnitude and orientation) which is mainly effected by parameters variation. These parameters are affecting saturation, temperature, and skin effect. The consequence of any mismatch between the parameter values used in the controller and those in the motor makes the actual rotor flux position does not coincide with the position assumed by the controller. Any parameter mismatched in flux estimation will be detrimentally affect the torque response and then on the FOC dynamic performance. For these reasons, many researches study have been done on automated tuning of induction motor parameters. So this paper shows the effect of parameters variation and mismatching in rotor resistance and stator resistance between the estimated parameters (in mathematical model) and the actual parameters (inside the machine itself) on the performance characteristics of induction motor through applying the FOC, comparing to match parameters on the performance characteristics of induction motor with applying the field orientation. The rotor resistance is chosen due to have more effect on the orientation and it is changed by the skin effect and temperature rising also due to temperature rising the stator resistance is also effect by variation in the temperature and this is more practically case spread. The instantaneous slip speed is employed to obtain correct subdividing of magnetizing current into torque and flux current components, I_{qs}^* & I_{ds}^*. If rotor open circuit time constant is not correct known or it is change due to motor heating or other variation, this subdividing doesn't become correct, its result will be detuned of controller and of loss proper field orientation. This makes calculation of rotor field angle is incorrect hence, rotor and stator fluxes do not become perpendicular so the following occur:

1. The flux level is not properly maintained.
2. The resulting steady state torque is not the command value.
3. The torque response is not instantaneous.

These variations are explored in the following sections when the load torque and rotor speed are at the rated values.

IV. SIMULATION RESULTS

The effect of the parameters variation on the performance characteristics of induction motor at rated conditions with FOC compared to SC are simulated here. Also the effect of mismatched in the rotor resistance and stator resistance on the performance characteristics of induction motor with FOC are compared to match parameters (stator and rotor resistances) with FOC and with SC. These cases are simulated to study the effect of this mismatching compared to matching with FOC through the MATLAB program.

A. Effect of Parameters Variation on Performance of Induction Motor with FOC Compared to Scalar Control

This section shows the effect of parameters variation at full load, on the torque, input power, power loss, output power, efficiency and on the stator current with FOC and with SC. In this section, the parameters vary from 50% to 150%; from its value at full load where it is found that,

Figs. 3 shows the effect of parameters variation on the motor torque with FOC compared to SC where can be concluded that:

1. Higher variation in oriented torque is caused by variation in rotor resistance. The oriented torque is inversely proportional to rotor resistance; any increase in rotor resistance leads to a decrease in the torque current component which is directly proportional to torque. In SC the torque is inversely proportional to rotor resistance.
2. The oriented torque is inversely proportional to rotor reactance due to the effect of slip relation. In SC method, any increase in rotor reactance leads to a decrease in the torque due to a decrease in rotor current i.e. the torque in SC is inversely proportional to rotor reactance.
3. The torque is inversely proportional to stator resistance and stator reactance in both of SC and FOC due to decrease in the stator current. This means that, in SC reducing rotor current has much effect on the torque. In FOC, the decreasing in rotor flux leads to a decrease in orientation torque.
4. The torque is directly proportional to magnetizing reactance in both of SC and FOC at constant frequency. This means that in FOC, the torque increases due to an increase in flux, while in the SC, increasing in magnetizing reactance means that there is an increase in rotor current.
5. The oriented torque is directly proportional to core loss resistance in both of FOC and SC. This is because an increase in rotor current.

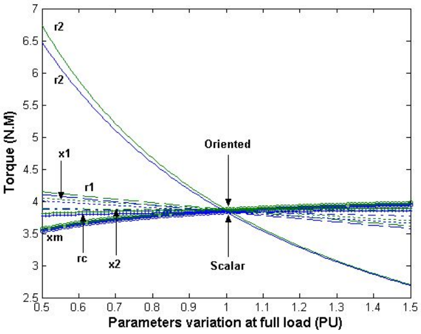

Fig.3 Variation of torque with parameters at 50 HZ

6. The oriented torque is bigger than the scalar torque this is because the rotor and stator fluxes are perpendicular in one so the torque is directly proportional to them. In SC the torque is directly proportional to rotor flux and stator flux and the sine angle between them, this angle is less than 90 so the production torque becomes less than the oriented torque by the sine angle value.

Fig. 4 shows the effect of parameters variation on the stator current with FOC comparing to SC from it can be concluded:

1.The higher variation in the stator current comes from variation in magnetizing reactance with FOC but higher variation in the stator current with SC comes from variation in rotor resistance.

2. When the FOC is applied, the stator current is directly proportional to rotor reactance due to an increase in torque current component also; in SC the same effect is occurred.

3. effect of core loss resistance on the stator current with oriented and SC can be neglected.

4. Scalar stator current is inversely proportional to stator resistance and stator reactance. The effect of stator reactance variation is small on the oriented stator current if it's compared to the same effect of that parameter variation on the scalar stator current.

6. When the stator current of the FOC is compared with SC, the stator current of the FOC is less than stator current of the SC because stator and rotor fluxes are perpendicular. But the same angle of the SC is less than 90 so the torque per ampere of the FOC is higher than the torque per ampere in the SC case.

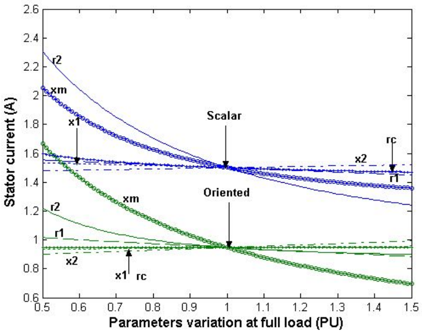

Fig.4 Variation of stator current with parameters at 50 HZ

From Fig. 5 it is found that,

1. In both of oriented and scalar controls, the input power is inversely proportional to stator reactance due to the decrease in power factor.

2. In both of oriented and scalar controls, the higher variation in input power comes from variation in rotor resistance, it is inversely proportional to rotor resistance.

3. In both of oriented and scalar controls, the input power is inversely proportional to stator resistance, due to the decrease in stator current.

4. In both of oriented and scalar controls, the variation of the input power due to vary of core loss resistance can be neglected.

5. Input power with FOC is less than it if comparing with SC method. This is due to the decrease in the oriented stator current when compared with the scalar stator current.

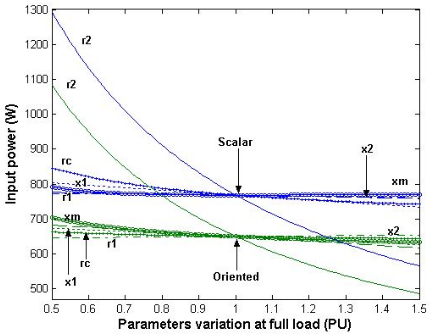

Fig.5 Variation of input power with parameters at 50 HZ

Fig. 6 represents the effect of parameters variation on the output power at FOC comparing to SC, from which, it is found that the variation of motor parameters on the output power are identical to the variation of motor parameters with the motor torque due to direct relation between the motor torque and output power.

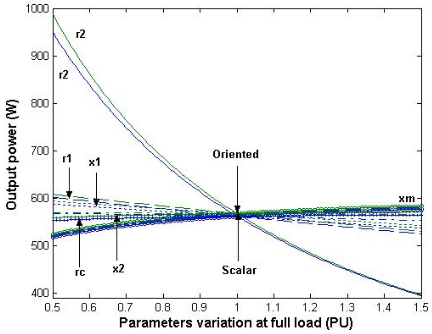

Fig.6 Variation of output power with parameters at 50 HZ

Figs. 7 show the effect of the parameters variation on the power loss with FOC comparing to SC. From these curves it can be concluded:

1. Higher variation in scalar power loss is obtained from variation in rotor resistance while higher variation in oriented power loss is by variation in magnetizing reactance. Scalar power loss is inversely proportional to rotor resistance and oriented power loss is inversely proportional to magnetizing reactance. These are occurred due to decrease in stator current.
2. Scalar power loss is inversely proportional to stator reactance. The effect of stator reactance variation is very small on the oriented power loss if it's compared with the same effect of that parameter variation on the scalar power loss. The decrease in scalar power loss comes from decreasing in stator current which leads to a decreasing in stator and rotor copper.
3. With the two methods of control, (oriented and scalar) power losses are inversely proportional to magnetizing reactance.
4. In the two control methods under discussion, power loss is directly proportional to rotor reactance.
5. In the two control methods under study, power loss is inversely proportional to core loss resistance, because the decrease in stator current leads to a decrease in the copper loss.
6. Power losses (oriented and scalar) are directly proportional to stator resistance.
7. Power loss of the motor with FOC is less if it is comparing to SC method. This is due to the decrease in the oriented stator current when compared to the scalar stator current.

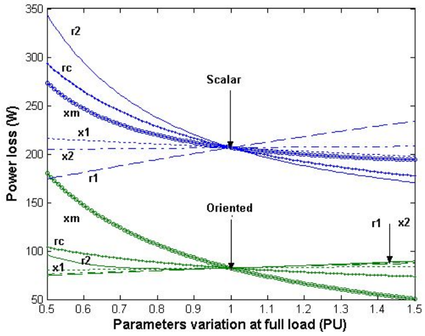

Fig.7 Variation of power loss with parameters at 50 HZ

Fig. 8 represents the effect of parameters variation on the efficiency with FOC, compared to SC. From this Fig. the following can be concluded:

1. The efficiency with FOC is higher than that with the SC.
2. Higher variation in efficiency arises from variation in core loss resistance in both of field oriented and SC where efficiency is directly proportional to magnetizing reactance.
3. The efficiency of both FOC and SC is inversely proportional to rotor reactance, stator and rotor resistances. The effect of stator reactance on the efficiency can be neglected.

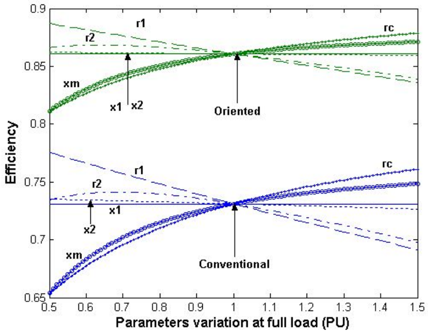

Fig. 8 Variation of efficiency with parameters at 50 HZ

B. Effect of Mismatching in Rotor and Stator Resistances on Performance of Induction Motor with FOC

Due to the instantaneous slip speed depends upon rotor resistance which is changed by varying operating temperature and accurate torque control depending upon the rotor resistance so the rotor resistance must be identified. The effect of the variation in stator resistance is less if it is compared to the variation of rotor resistance. So any detuning in the value of any one or them causes an error in rotor flux estimation which leads to deteriorate in torque dynamic. So for an accurate torque control, the rotor and stator resistances identifier is required even for $I_{qs} = 0$,

The rotor resistance identifier required to perform the following,

1. Identify rotor resistance before motor start up.
2. Identify rotor resistance under any load condition and

at any speed condition.

This occurs due to the slip frequency simulator includes estimated value of rotor resistance which varies with temperature. The occurring error between estimated and actual rotor value of resistance, causes undesirable transient pulsations in torque and it can introduce an error in the estimation of rotor flux position hence occurs misalignment between estimated and actual rotor flux position, Fig. 9

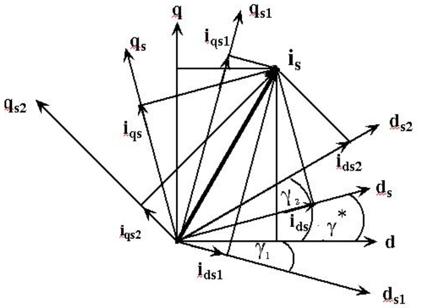

Fig.9 Misalignment of rotor flux oriented control

Assuming that, the estimated rotor flux angle is γ* and the angle of actual rotor flux position is γ. The difference between estimated and actual rotor flux position is ϕ where

$$\phi = \gamma^* - \gamma$$

The error in rotor resistance leads to the following:

1. When actual rotor resistance is higher than the estimated rotor resistance; the actual flux (d_{s2}-q_{s2}) leads the estimated rotor flux (d_s-q_s). In this case there will be more in flux and less torque current components, compared with the matched parameters.
2. When actual rotor resistance is smaller than the estimated rotor resistance hence the actual flux (d_{s1}-q_{s1}) lags the estimated rotor flux (d_s-q_s). In this case there will be less in flux and more torque current components compared with the matched parameters.

When there is a misalignment between actual rotor flux and estimated one, this causes coupling between torque and flux current components which degrades the performance of induction motor as follow,

Figs. 10 and 11 represent the effect of the error in rotor and stator resistances on the orientation angle, comparing with SC case and matching parameters case. Fig. 10 shows the effect of the error, when the rotor and stator resistances actual values are higher than their estimated values in the model. Whereas Fig. 11 shows the effect of the error, when the rotor and stator resistances actual values are less than their estimated values in the model. From which it may be concluded that:

1. With applying SC, the angle between rotor and stator fluxes is less than 90 .
2. With applying FOC of matching parameters, the oriented angle is kept constant at the best value which is 90 .
3. With applying the FOC of mismatching rotor resistance, there is an occurring error in orientation angle, this error makes the orientation angle be less than 90 . This occurs due to inconvenience in the rotor resistance which depends upon the value of error between estimated and actual value of rotor resistance, i.e. the error in orientation angle is directly proportional to the error between actual and estimated rotor resistance, this degrades the performance of induction motor.

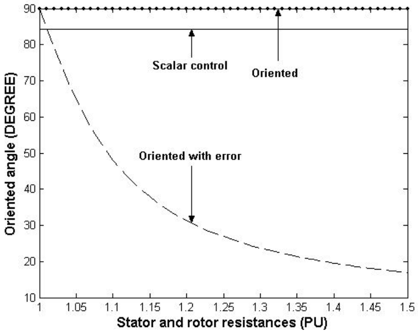

Fig.10 Variation of oriented angle with stator and rotor resistances

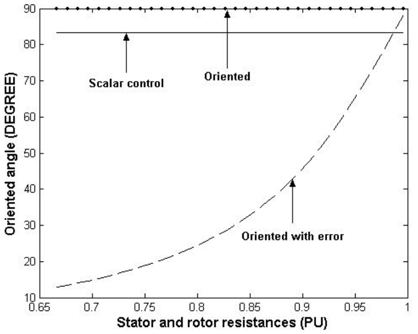

Fig.11 Variation of oriented angle with stator and rotor resistances

Figs. 12 and 13 show the misalignment effect on the stator current. This misalignment comes from the mismatching between stator and rotor resistances occurring in both actual machine and its simulated model. Fig. 12 shows the effect of the error, when the rotor and stator resistances actual values are higher than their estimated values in the model. Whereas Fig. 13 shows the effect of the error, when the rotor and stator resistances actual values are less than their estimated values in the model. It is clearly seen that, the FOC won't work correctly, if compared with matched parameter and SC. It can be concluded that:

1. In SC case, the stator current is at its rated value thus load torque is at its rated value.
2. At field orientation with matched parameters, the stator current becomes the smallest, if compared with SC and the misalignment case. This is because matching parameters means no misalignment in oriented rotor flux, hence the torque and flux current components are perpendicular.

3. With mismatching in the value of stator and rotor resistances between the modelling and actual values, some errors occur when applying the FOC. The estimating value may be either less or more than the actual values inside the machine. The wrong FOC application causes the stator current is degrading as follow,

The stator current increases gradually; depending upon the error in mismatched parameters, i.e. an increase in the stator current is directly proportional to the errors between the estimating and actual values of both the stator and rotor resistances.

With this error the stator current may increase to be more than rated value i.e. the machine becomes over-loaded. In general, with mismatching in the parameters value, the machine is converted from decoupled control into coupled control with degraded in performance.

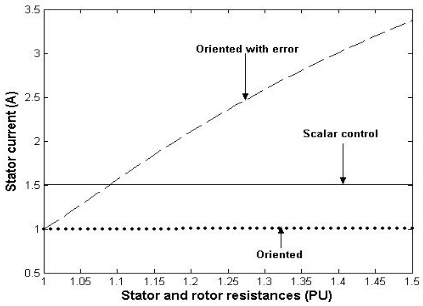

Fig.12 Variation of stator current with stator and rotor resistances

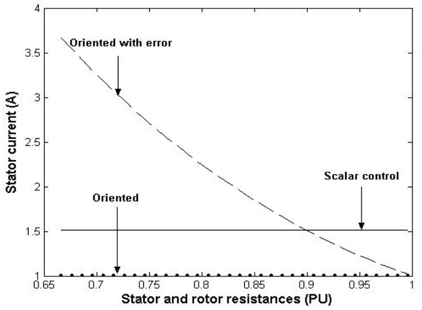

Fig.13 Variation of stator current with stator and rotor resistances

Here the effect of mismatching in stator and rotor resistances with field orientation on the input power is studied. Fig. 14 shows the effect of the error, when the rotor and stator resistances actual values are higher than the estimated values in the model. Whereas Fig. 15 shows the effect of the error, when the rotor and stator resistances actual values are less than their estimated values in the model. When the mismatching effect is compared with both matching parameters and SC, the following can be concluded:

1. The input power of SC is directly proportional to stator and rotor resistances.

2. The input power of field orientation with matched parameters is directly proportional to rotor resistance and stator resistance. That input power is less than input power in SC case, this occurs due to decrease in the stator current with FOC whereas in SC case the stator current is higher. At field orientation with mismatched in stator and rotor resistances there are some errors. These errors convert the induction motor with decoupled control into coupled control. This means that, there are an increase in stator current and an error in orientation angle which make the input power increase gradually. The increase in input power is directly proportional to the values of error between estimated and actual values of stator and rotor resistances.

The effect of mismatching in stator and rotor resistances with field orientation on the output power is studied. This effect is compared with both matched parameters and SC as shown in Figs. (16 – 21) consequently, it has been concluded that:

1. In SC case the output power is directly proportional to speed at constant load torque.

2. In field orientation with matched parameters and without matched parameters the output power is constant due to FOC make at constant load torque and constant speed i.e. closed loop speed control.

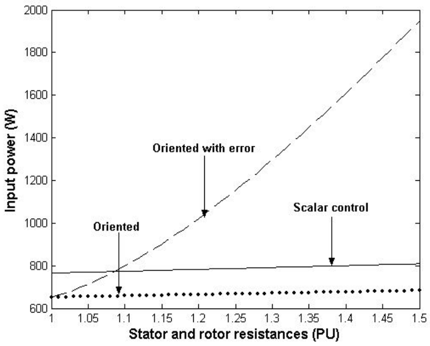

Fig. 14 Variation in input power with stator and rotor resistances

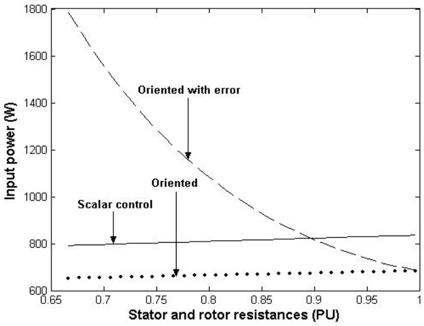

Fig. 15 Variation in input power with stator and rotor resistances

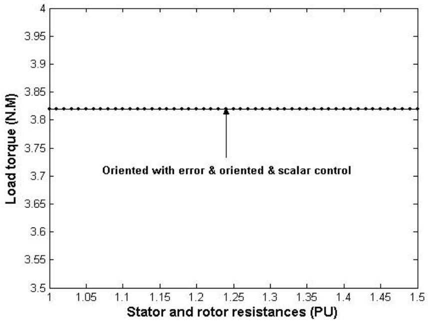

Fig. 16 Variation in load torque with stator and rotor resistances

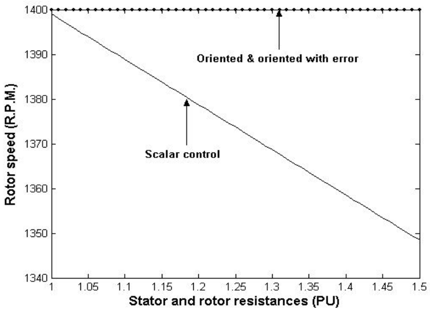

Fig.17 Variation in rotor speed with stator and rotor resistances

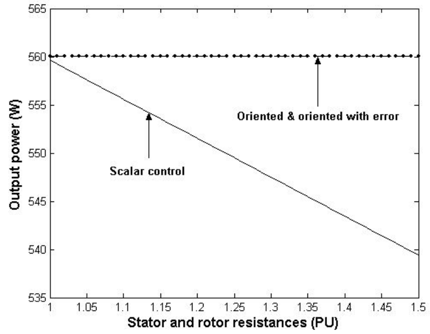

Fig. 18 Variation in output power with stator and rotor resistances

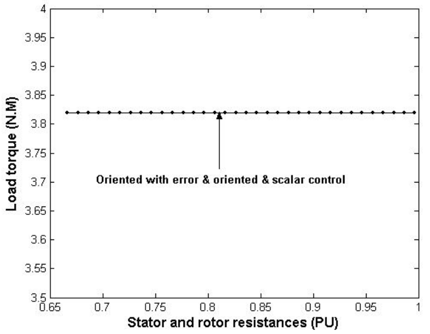

Fig.19 Variation in load torque with stator and rotor resistances

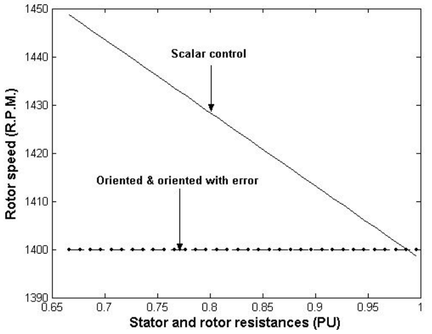

Fig. 20 Variation in rotor speed with stator and rotor resistances

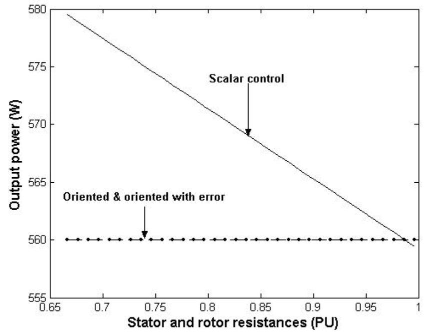

Fig. 21 Variation in output power with stator and rotor resistances

Figs. 22 and 23 indicate the misalignment effect on the power loss resulting from the stator and rotor resistances mismatching between actual machine and its simulated model. Fig. 22 shows the effect of the error, when the rotor and stator resistances actual values are higher than their estimated values in the model. Whereas Fig. 23 shows the effect of the error, when the rotor and stator resistances actual values are less than their estimated values in the model. If mismatching parameters is compared with matched parameters and SC the following can be concluded:

1. In SC case, the power loss is directly proportional to stator and rotor resistances.
2. In the field orientation with matched parameters, the power loss becomes the smallest due to orthogonally between rotor and stator fluxes. Also power loss is directly proportional to the stator and rotor resistances.
3. At field orientation with mismatching in the stator and rotor resistances, there are some errors occurring in the applying of the FOC. These errors convert induction motor with decoupled control into coupled control; this means that, there is an increase in stator current and an error in orientation angle which make the power loss increases gradually. Increasing in the power loss is directly proportional to the error between estimated and actual values of stator and rotor resistances

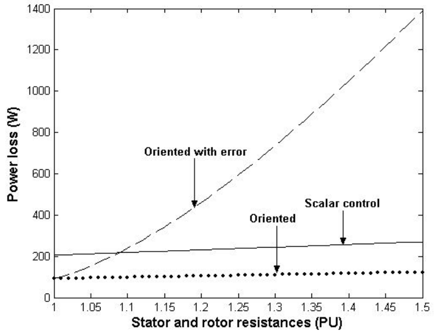

Fig. 22 Variation in power loss with stator and rotor resistances

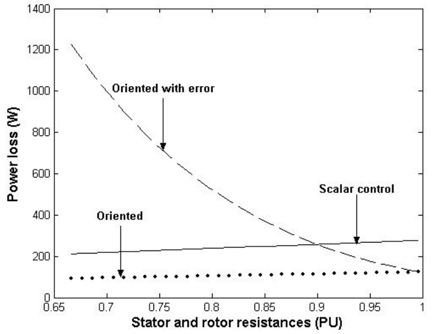

Fig. 23 Variation in power loss with stator and rotor resistances

Figs. 24 and 25 indicate the misalignment effect on the efficiency. This misalignment comes from the mismatching between stator and rotor resistances occurring in both actual machine and its simulated model. Fig. 24 shows the effect of the error, when the rotor and stator resistances, actual values are higher than their estimated values in the model. Whereas Fig. 25 shows the effect of the error, when the rotor and stator resistances, actual values, are less than their estimated values in the model. This effect is compared to both matching parameters, mismatching parameters and SC as shown in Figs. 24 and 25 Consequently, it has been concluded that:

1. In SC case, the efficiency is inversely proportional to stator and rotor resistances.
2. At field orientation with matching parameters, the

efficiency becomes the highest if compared with other cases.

This takes place because the parameters are matched, there is no misalignment in oriented rotor flux, consequently, the torque and flux current components are perpendicular. And Efficiency is inversely proportional to stator and rotor resistances.

3. In the field orientation with mismatching in stator and rotor resistances, the FOC is operated by wrong way. That makes, both input power and power loss increase simultaneously, thus the efficiency decreases. This decreasing in efficiency is directly proportional to the error between the actual values of stator and rotor resistances and estimated values of both.

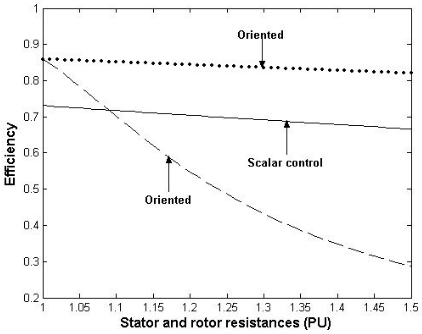

Fig. 24 Variation in efficiency with stator and rotor resistances

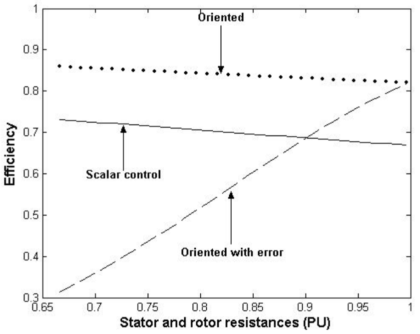

Fig. 25 Variation in efficiency with stator and rotor resistances

V. CONCLUSION

The effect of parameters variation on the performance characteristics of induction motor with FOC at full load comparing to SC is studied where from that it can be concluded;

1. FOC torque is higher if it is compared with the SC torque. Higher variation in oriented torque is caused by variation in rotor resistance. The oriented torque is inversely proportional to rotor resistance. The oriented torque is inversely proportional to rotor reactance, stator resistance and stator reactance. The oriented torque is directly proportional to the magnetizing reactance. The oriented torque is approximately not affected by core loss resistance.
2. FOC power loss is smaller if it is compared with the SC power loss. Higher variation in the oriented power loss comes from variation in magnetizing reactance which is inversely proportional to one where higher variation in the scalar power loss comes from variation in rotor resistance. The power loss is directly proportional to stator resistance. Power loss is directly proportional to stator reactance.
3. Input power with FOC is less comparing to SC method. Higher variation in oriented input power is due to the variation in rotor resistance.
4. FOC efficiency is higher compared to the SC efficiency. Efficiency is inversely proportional to stator resistance. Higher variation in efficiency arises from variation in core loss resistance. The FOC efficiency is inversely proportional to rotor reactance. The efficiency is directly proportional to core loss resistance.

The effect mismatched in the rotor and stator resistances is studied and from that it can be concluded;

With the error in parameters, the oriented angle is less than 90 . This means that the level of the flux is not properly maintained, and the torque response is not as desired. With this error the stator current may be increased above the rated. This increasing depends upon the error in parameters. It leads to that the motor will to be over loaded current. The power loss increases and leads to the decreasing efficiency with FOC. Thus the mismatched in parameters will be degraded the performance of induction motor.

APPENDIX 1

MOTOR DATA

Line to line voltages	380V
Full load current (I_f)	1.47A
Rotor speed (n_r)	1400 R.P.M
Pole pairs	2
Full load torque (T_f)	3.82 N.m
Power factor (pf)	0.8
Stator resistance	13 Ohm
Stator reactance	10.5 Ohm
Magnetizing reactance	231 Ohm
Rotor resistance	2.25S+12.35 Ohm
Rotor reactance	-3.694S+19.2643 Ohm
Output power	0.75 hp
T_s/T_f	2.33
T_{max}/T_f	2.62
I_s/I_f	4.22
Efficiency	0.72

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