A Comparative Analysis of Scalar and Vector Control of Induction Motor Drive

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Abstract: Induction motor drives significantly contribute to the world energy consumption and several methods are available to control speed and torque of the motor. In this paper scalar and vector control techniques of induction motor are discussed and two of them are simulated using Matlab/Simulink.

Scalar control method relies on keeping V/f ratio constant so as to maintain air gap flux at constant value. The vector control analysis of an IM allows decoupled analysis where the flux and torque component can be independently controlled, just like in dc motor. The performance of two control methods is compared via simulation results.

***Keywords**:* FOC, scalar control, simulation, vector control, V/f ratio etc

1. INTRODUCTION

Induction motors (IMs) are widely used in many industrial applications due to their self starting capability, simple structure, mechanical robustness and low cost. Most of drives for industrial process and domestic appliances have been designed to operate at constant speed. But, it is well known that in mechanical system a variable speed drive provides improved performance and energy efficiency. So, more and more emphasis is given to find out means of precise speed and torque control of induction motors.

Various speed control techniques applied by modern-age VFD are mainly classified in the two categories scalar control and vector control, shown in figure 1.

Scalar control involves controlling the magnitude of voltage or frequency of supply fed to the machine. The V/f control method is a control method based on principle of keeping air gap flux constant by controlling stator voltage and frequency, so that the V/f ratio is kept constant. When V/f is constant, air-gap flux remains constant. This will prevent saturation of air gap due to increase in flux [1]. Along with V/f, another well known technique was slip frequency control. This method was adopted in all high performance IM drives until FOC (vector control) became standard for AC drives.

The vector control of AC drives has been widely used in high performance control system. K. Hasse and F. Blashke [2] pioneered the vector control technique starting in 1968 and in the early 1970s. Further, Leonhard and Bose have improved the technique. The FOC was one of the most important innovations in AC motor drives which motivated the researchers for enhancing the control performance. In FOC control, as per principle field flux vector is oriented along with one of the components of the stator current so this method is also called "Field Oriented Control".

In order to obtain high performance of torque and speed of IM drive the rotor flux and torque generating current component of stator current must be decoupled respective to stator flux or rotor flux. When this is available, then controls of AC drives is very similar to separately excited DC machines.

FOC is based on the idea of decoupling torque and flux via non-linear coordinate transformation and controlling these variables by acting on the direct and quadrature current vector components by means of unit vector (sin□$_e$ and cos□$_e$). So, vector control has made AC drives equivalent to DC drives in the independent control of torque and flux and superior to them in dynamic performance [1].

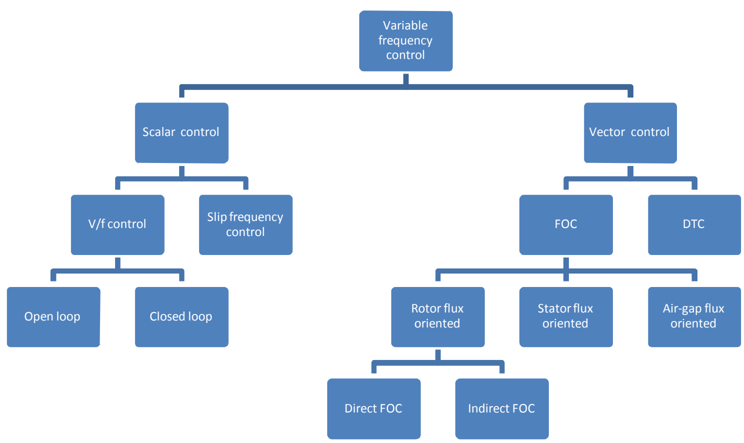

Fig. 1. Classification of variable frequency control of induction motor drive

2. SCALAR CONTROL

With the recent advancements in power electronics and miniaturization of control electronics and microprocessor variable frequency and variable voltage (VVVF) ac motor derives are being increasingly used in various industrial applications. Speed control is achieved by inverter-driven induction motor by using variable frequency. Along with frequency, the applied voltage needs to be varied to keep the air gap flux constant and to avoid saturation of machine. Operating at constant voltage reduced torque capability.

The ratio of applied voltage to applied frequency (V/f) is generally maintained at a constant value between minimum and maximum operating frequencies.

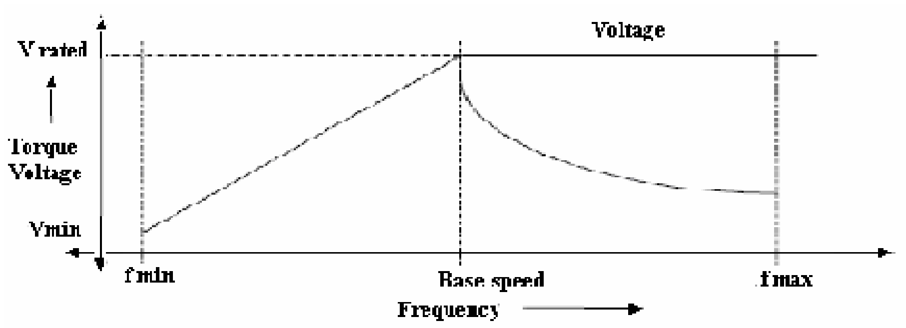

Fig. 2: V/f curve

Above base speed, the constant V/f ratio cannot be satisfied because the stator voltages would be limited at rated value in order to avoid insulation breakdown at stator windings. This region is usually called "Field Weakening Region". Weather the applied voltage is regulated directly or indirectly, the V/f curve tends to follow the general pattern described in Fig 2. Variable voltage variable frequency needed to maintain constant air gap flux is synthesized by using a VSI.

Open loop constant V/f control

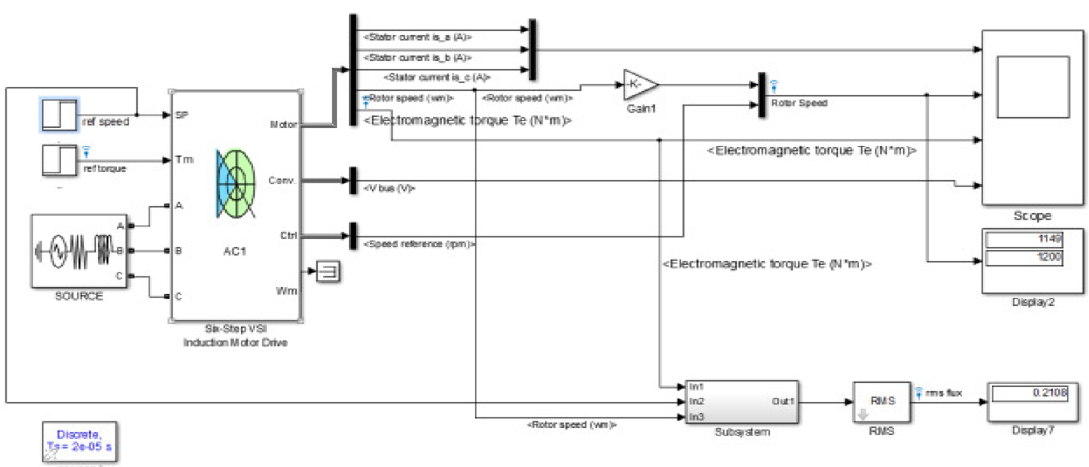

Fig. 3: Simulink Model of Open Loop constant V/f Control of Three-Phase Induction Motor

A simulation model has been developed in Matlab/Simulink. In AC1 block a 3 HP induction motor is fed by VSI. The dc bus voltage is regulated using PI controller in order to maintain constant volts per hertz ratio. Observations made of change in actual speed and speed difference at different load torques is given in Table below.

Table 1: Rotor speed at different loads with V/f=5

Load Torque (Nm)	Rotor Speed (rpm)	Speed Difference (rpm)
0	996	4
5	968	32
10	938	62
12	924	76

From above observations we conclude that as load torque on motor increased, speed difference also get increased, which indicated poor speed regulation.

i) Choice of V/f ratio

In open loop V/f method, speed regulation is poor. But by increasing V/f ratio, flux increases and the difference in the desired speed and actual speed reduces. So, by changing V/f ratio speed regulation can be improved [4].

ii) Determination of saturation limit of flux

If V/f ratio is increased flux also increase, but there is a limit of flux beyond which machine get saturated. This point of saturation decides maximum value of V/f ratio up to which we may increase it. Following tables are observations made for 1000 rpm, 1200 rpm and 1750 rpm.

Table 2: Flux at different torque on speed=1000 rpm

T_L= 5 Nm			T_L= 10 Nm			T_L= 12 Nm		
V/f	Sp-eed	Flux	V/f	Spe-ed	Flux	V/f	Spe-ed	Flux
4	949	0.21	4	897	0.20	4	874	0.20
5	968	0.26	5	938	0.26	5	924	0.26
6	978	0.32	6	958	0.32	6	949	0.32
7	983	0.38	7	969	0.37	7	963	0.37
8	987	0.47	8	976	0.42	8	972	0.42
8.2	988	0.49	8.2	977	0.44	8.2	973	0.44
8.4	988	0.51	8.4	978	0.45	8.4	974	0.45
8.6	988	0.51	8.6	978	0.45	8.6	974	0.45
8.8	988	0.51	8.8	978	0.45	8.8	974	0.45

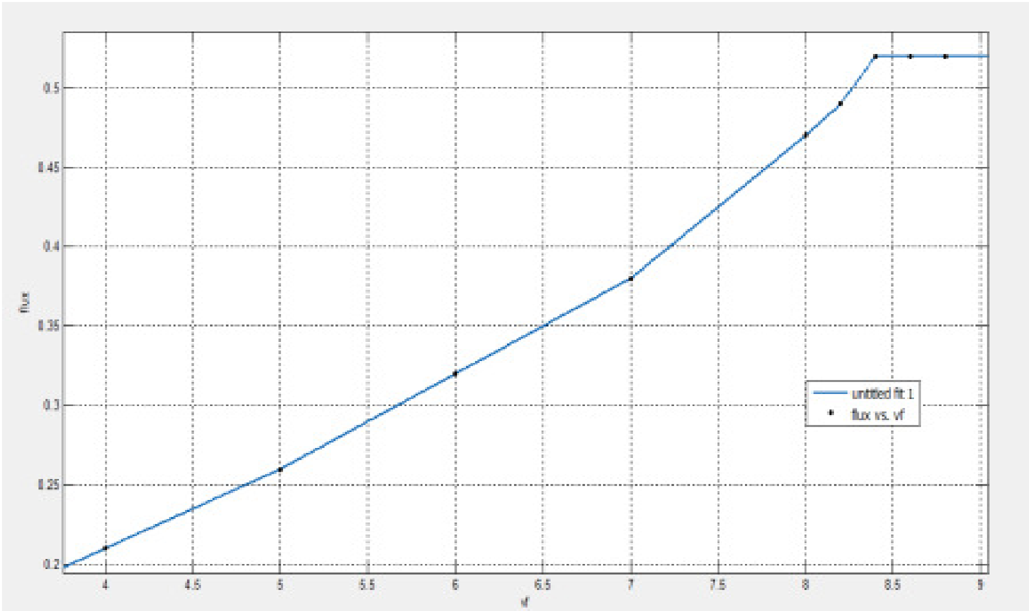

Fig. 4: Flux vs. V/f ratio curve for T_L=5Nm, Speed=1000 rpm

Above Table & graph shows that above V/f=8.2, flux became constant. So, at 1000rpm last value of V/f for improved speed regulation is 8.2.

Table 3: Flux at different torque on speed=1200 rpm

T_L= 5 Nm			T_L=10 Nm			T_L= 12 Nm		
V/f	**Spe-ed**	**Flux**	**V/f**	**Spe-d**	**Flux**	**V/f**	**Spe-d**	**Flux**
4	1149	0.21	4	1098	0.21	4	1077	0.20
5	1168	0.27	5	1138	0.26	5	1125	0.26
6	1177	0.32	6	1157	0.32	6	1149	0.32
6.2	1179	0.33	6.2	1160	0.33	6.2	1152	0.33
6.4	1180	0.34	6.4	1162	0.34	6.4	1155	0.34
6.6	1181	0.35	6.6	1165	0.35	6.6	1158	0.35
6.8	1182	0.37	6.8	1167	0.36	6.8	1161	0.36
7	1183	0.38	7	1169	0.37	7	1163	0.37
7.2	1183	0.38	7.2	1169	0.37	7.2	1163	0.37
7.4	1183	0.38	7.4	1169	0.37	7.4	1163	0.37

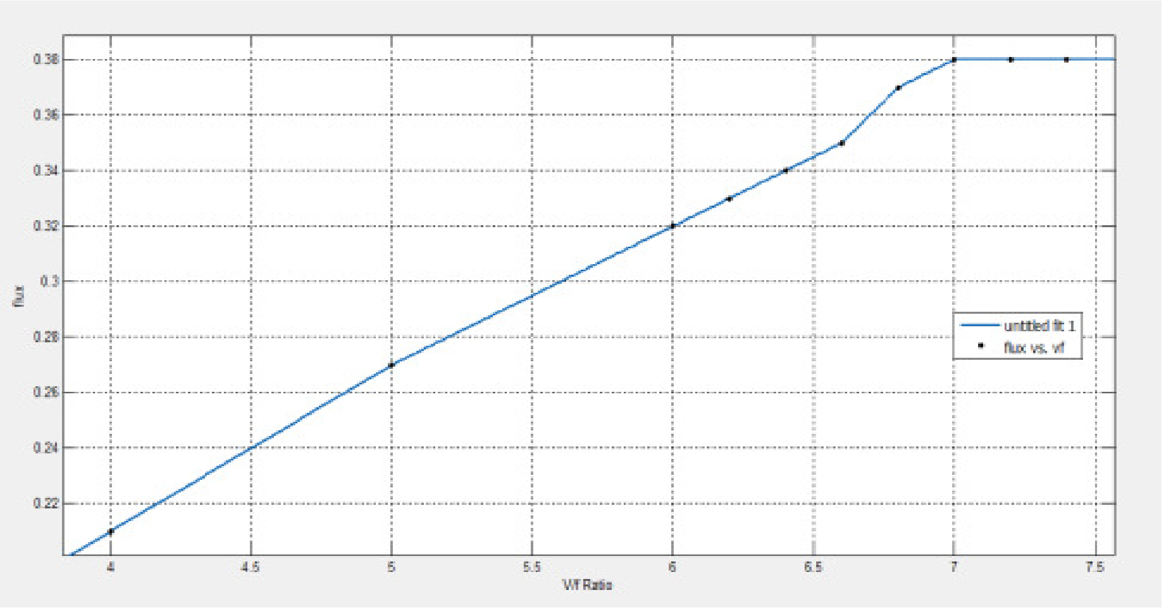

Fig. 5: Flux vs. V/f ratio curve for T_L=5Nm, Speed=1200 rpm

From above Table and graph for 1200rpm last value of V/f =6.8.

Table 4: Flux at different torque on speed=1750rpm

T_L= 5 Nm			T_L= 10 Nm			T_L= 12 Nm		
V/f	Speed	Flux	V/f	Speed	Flux	V/f	Speed	Flux
4	1695	0.21	4	1648	0.21	4	1628	0.21
4.2	1700	0.22	4.2	1658	0.22	4.2	1640	0.22
4.4	1705	0.23	4.4	1667	0.23	4.4	1651	0.23
4.6	1708	0.24	4.6	1674	0.24	4.6	1660	0.24
4.8	1711	0.25	4.8	1680	0.25	4.8	1667	0.25
5	1711	0.25	5	1680	0.25	5	1667	0.25
5.2	1711	0.25	5.2	1680	0.25	5.2	1667	0.25
5.4	1711	0.25	5.4	1680	0.25	5.4	1667	0.25

From above Table and graph at 1750 rpm last value of V/f =4.6.

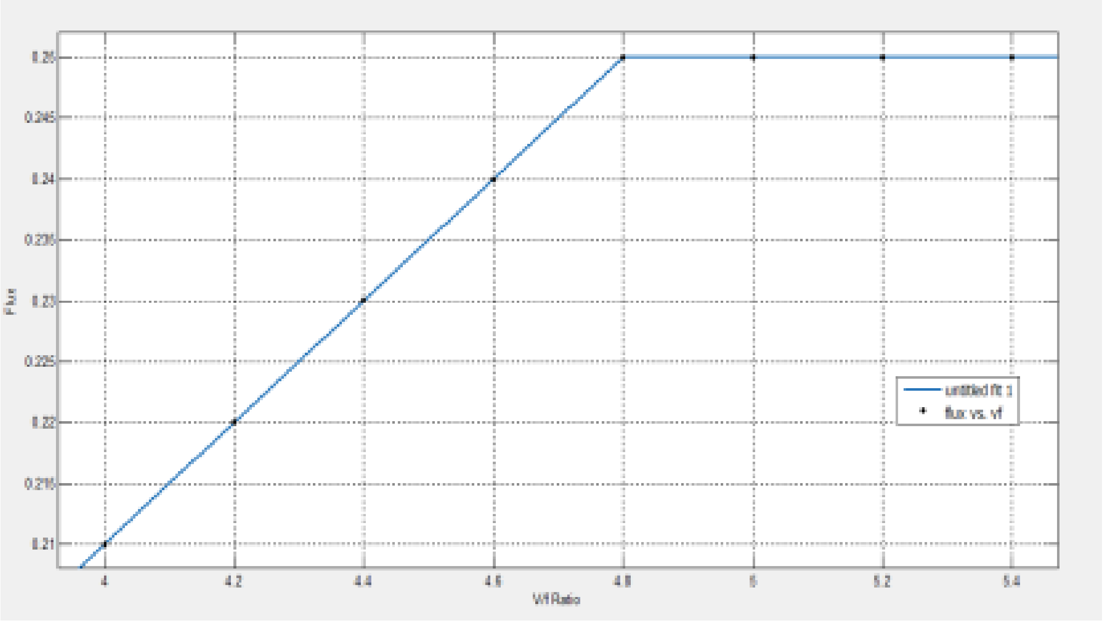

Fig. 6: Flux vs. V/f ratio curve for T_L=5Nm, Speed=1750 rpm

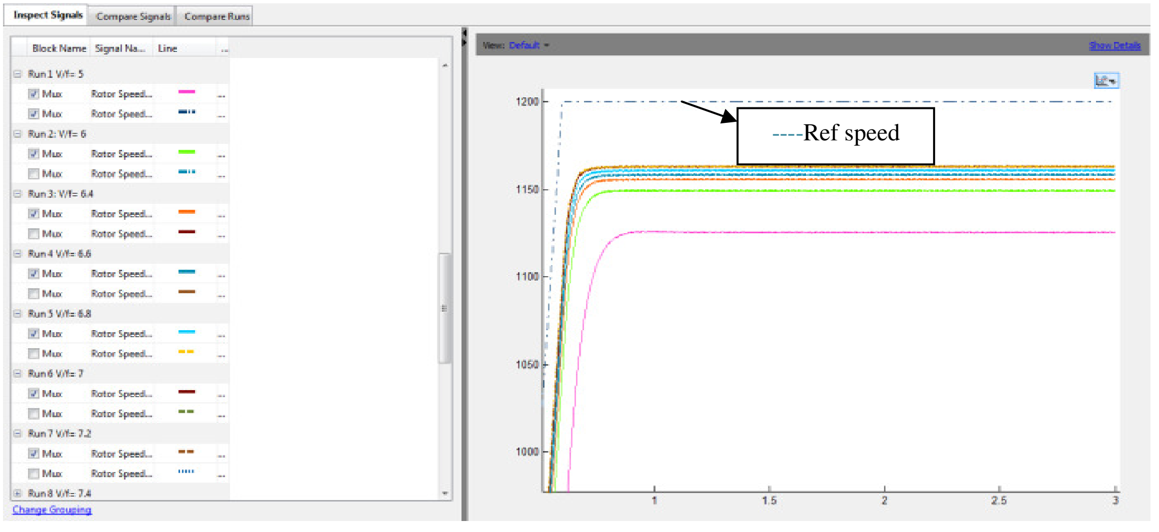

Fig. 7: Simulation result for different V/f ratios (5, 6, 6.4, 6.6, 6.8, 7, 7.2 & 7.4) for Reference speed = 1200 rpm, Load Torque= 12 Nm

Figure 7 showing increase in speed with increase in V/f ratio while keeping other parameters constant.

3. COMPARISON OF SIMULATION RESULT OF OPEN LOOP V/F SPEED CONTROL FOR V/F=5 & 6

Table: 5 Variation in actual speed in case for 1200 rpm

Load torque (T_L), N-m	Rotor speed (N), rpm for V/f=5	Rotor speed (N), rpm for V/f=6	Speed improvement, rpm
5	1168	1177	9
10	1138	1157	19
12	1125	1149	24

From above table it is observed that when V/f is set V/f =6, at 5, 10, 12 N-m load torque, the rotor speed increased towards reference speed as compared to when V/f =5. With decrease in difference between ref speed and actual speed, speed regulation of the drive gets improved.

Open loop constant V/f control method is used in low performance applications where precise speed control is not necessary. Some problems are encountered in operation of this open loop drive. The speed of motor cannot be controlled precisely. The rotor speed is not measured in this derive scheme, so the slip speed cannot be maintained. This can lead to operation in the unstable region of the torque-speed characteristics.

2.2 Closed loop constant V/f control

The closed-loop method offers a more precise solution to controlling the speed than the open-loop method. Further, the closed-loop technique controls the torque too, which is not done in open-loop control method. The closed-loop method contains a slip control loop, because the slip is proportional to the torque.

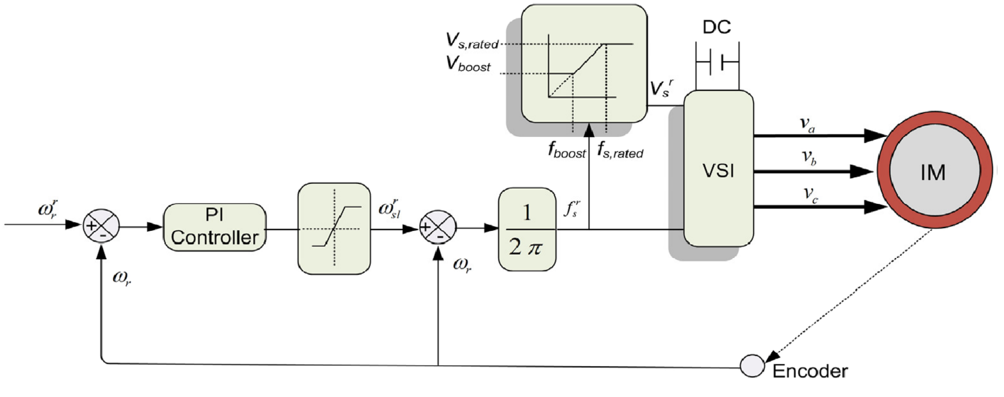

Fig. 8: Closed Loop V/F Control of Three-Phase Induction Motor [6]

The actual rotor speed is compared with desired speed value and is processed through PI controller and a limiter to obtain desired speed. In closed loop induction motor drive, the limits on slip speed, offset voltage and reference speed are externally adjustable variables. The external adjustment allows the tuning and matching of the induction motor to converter and inverter and the adjustment of its characteristics to match the load requirements. A disadvantage of the method is uncontrolled magnetic flux.

There are some methods which use current control. Current control methods solve the problem of uncontrolled flux beside these methods are more complex. These methods are generally called Vector control methods. Therefore, for applications requiring precise torque control, vector control schemes are normally adopted.

4. FIELD ORIENTED CONTROL

Various control methods used for control of inverter-fed induction motor like scalar control method, have good steady-state but poor dynamic response. The cause of such poor dynamic response was found to be that the air gap flux linkages deviate from their set values [1]. The deviation was not only in magnitude but also in phase. Scalar control methods utilize the stator phase current magnitude and frequency and not their phases. In order to avoid variation in flux linkages, the magnitude and frequency of stator and rotor phase currents and their instantaneous phases have to be controlled.

In contrary to scalar control, the FOC scheme is based on dynamic model of IM. This is done by converting 3-□ quantities into 2-axis system called the d-axis and the q-axis. The d-q axis can be chosen to be rotating or stationary. The rotating frame can either be the rotor oriented or magnetizing flux oriented. Another one is synchronous reference frame in which the d-axis is aligned with the rotor flux. The rotor flux FOC scheme is based on frame transformation of all quantities to a rotating frame fixed to the rotor flux. In this rotating rotor flux frame, all quantities rotating at synchronous speed appear like DC quantities [1]. The d and q components of stator current represent the flux and torque components respectively. It shows that using FOC, IM can be controlled similar to dc motor where the torque and flux components are decoupled. If stator flux is oriented instead of rotor flux, is known as stator flux FOC.

Based on how the rotor flux position is obtained, FOC is classified as:

i) Direct FOC

ii) Indirect FOC

If the field angle is calculated by using terminal voltages and currents or flux sensing windings and rotor speed, then it is known as direct FOC. The field angle can also be obtained by using rotor position measurement and slip position by partial estimation with only machine parameters but not any other variables such as voltages or currents, this class of control scheme is known as indirect FOC. The rotor field angle is obtained by submission of rotor speed and slip frequency.

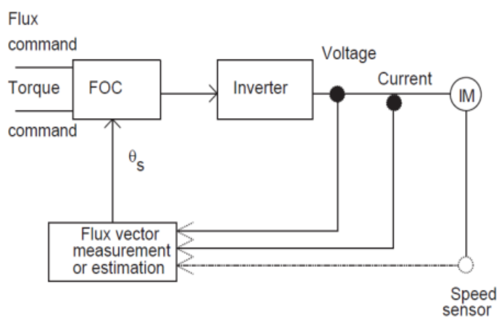

Fig. 9: Direct FOC method

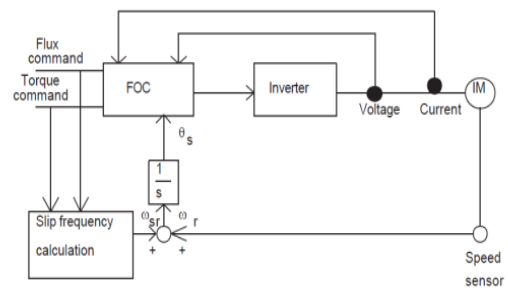

Fig. 10: Indirect FOC method

In FOC, to perform the frame transformation, accurate rotor flux position is needed to be acquired. Because with inaccurate rotor flux position torque and flux components are not be completely decoupled, as a result of which dynamic response become poor [6]. So, knowledge of rotor flux position is the core of the FOC.

The measurement of the rotor flux position is different if we consider synchronous or induction motor. In synchronous machine the rotor speed and rotor flux speed are equal. Then rotor flux position is directly measured by position sensor or by integration of rotor speed. In the induction machine the rotor speed is not equal to the rotor flux speed, then it needs a particular method to calculate field angle.

3.1 Simulation of Indirect FOC of 3-□ IM

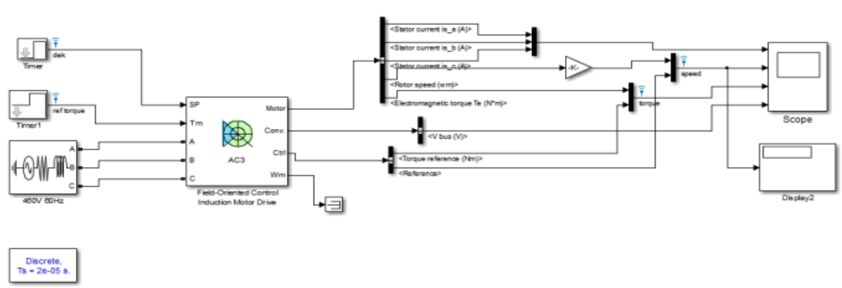

Fig. 11: Simulink model of Indirect FOC

In above simulink model, AC3 block of Simpower Systems library is used. A FOC IM drive with a breaking chopper is modeled for 3 HP ac motor. IM is fed with PWM VSI. In AC3, the speed control loop uses a PI controller to produce torque and flux references for the FOC controller. Corresponding to the torque and flux references, the FOC controller computes three reference motor line currents and then feeds the motor with these currents using a 3-□ current regulator.

5. SIMULATION RESULTS

a) Effect on speed when load torque changed

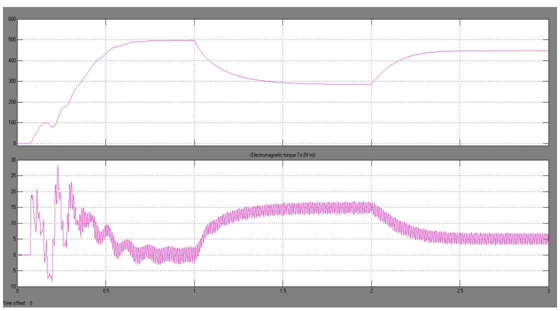

Fig. 14: open loop constant V/f control (Reference speed = 500rpm, Load torque = 0, 15, 5 N-m at 0,1,2 second)

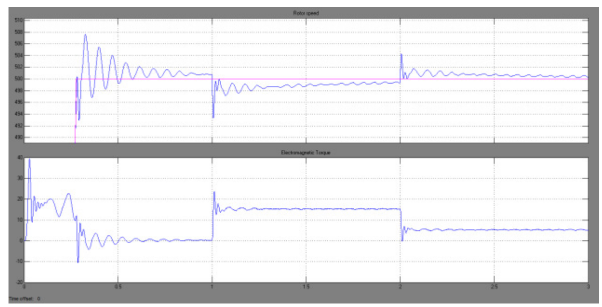

Fig.15. Closed loop constant V/f control (Reference speed= 500rpm, Load torque= 0, 15, 5 N-m at 0,1,2 second)

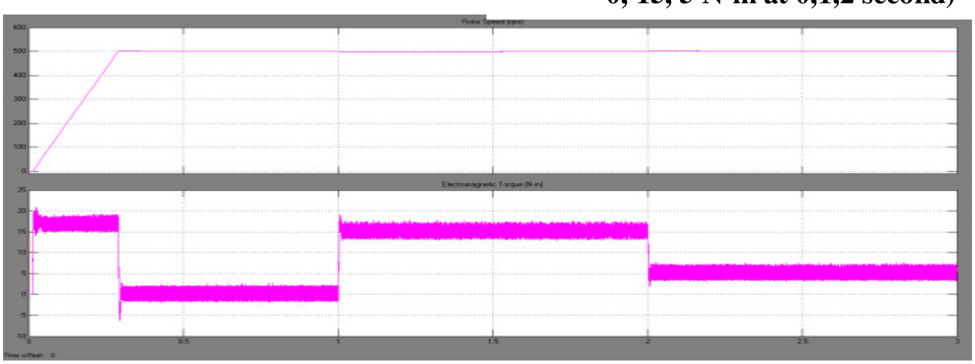

Fig. 16: IFOC (Reference speed =500 rpm, Load torque= 0, 15, 5 N-m at 0, 1, 2 second)

From above graphs, it is clear that in the scalar control technique when load torque is increased, speed decreased and when load torque is decreased, speed increased. Means rotor speed fluctuates with change in load torque. So, it is not possible to meet requirement of constant speed without having any effect of load torque variations. From figure 14 and 15 it is observed that in closed loop control variation in speed with load torque variation is much less than open loop control.

On the other hand, FOC provides a constant torque response. From figure 16 it is observed that speed response is unaffected by variation in load torque. In FOC the requirement of constant speed independent of load torque is possible.

b) Speed regulation

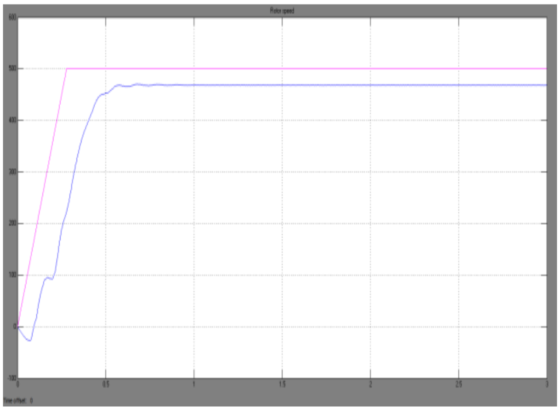

Fig. 17: open loop constant V/f control (reference speed =500 rpm, Load torque = 10 N-m)

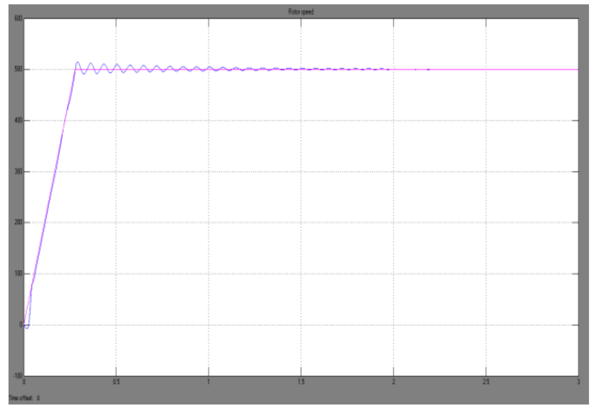

Fig. 18: Closed loop constant V/f control (reference speed

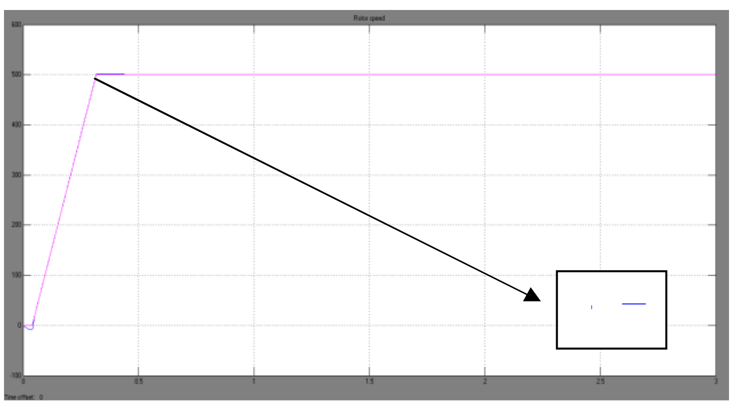

Fig. 19: Indirect FOC (reference speed=500 rpm, Load torque=10 N-m)

From fig 17, 18 & 19, speed regulation of scalar control (open loop and closed loop) and vector control can be directly compared. In open loop V/f control method, even with maximum possible value of V/f for reference speed 500 rpm, speed regulation is poor when compared with that of FOC. However, in closed loop V/f control speed regulation is improved but pulsations are observed in speed response. Also, scalar control is a sluggish method because it is based on controlling voltage amplitude and frequency, instead of current. In FOC, control is very robust and rapid.

6. CONCLUSION

The strategies of induction motor control techniques are discussed and simulated in the paper. In open loop control technique, the results obtained from simulation shows the effect of change in V/f ratio. It is observed that if V/f ratio is increased better speed regulation is obtained.

Scalar control method is easy to implement and a low price technique. But because of many drawbacks like poor transient response, unsatisfactory speed accuracy at low speed regions, sluggish response and inability to control two important variables i.e. torque and magnetic flux, it is not used in high performance applications. So, scalar control is a low performance but stable and simple control technique.

Vector control is a complex and high price control technique. But in spite of that it is a high performance control technique. FOC use space vector representation which is valid in both steady and transient conditions. So, along with satisfactory steady state response FOC have excellent transient response. It operates with fast dynamic response. Its speed regulation is very good.

APPENDIX

Induction Motor Electrical Parameters
3hp, 220 V, 60 Hz, 4 pole

L_s [H]	L_r [H]	L_m [H]	R_s [Ω]	R_r [Ω]
0.002	0.002	69.31×10^{-3}	0.435	0.816

REFERENCES

[1] Krishnan R., “Electric Motor Drives – Modeling, Analysis and Control”, *Pearson Prentice Hall,* 2013

[2] Blaschke F. “The principle of field orientation applied to the new trans-vector closed loop system for rotating field machines” *Siemens-Review 39,* pp. 217-220, 1972

[3] Bocker, J., “State of the Art of Induction Motor Control” *IEEE,* pp. 1459-1463, 2007

[4] Karkar H. M., “Improvement Speed Regulation In Open Loop V/F Control of Three Phase Induction Motor Drive”, *IJDI-ERET,* pp. 52-58, 2013

[5] Kohlrusz G., Fodor D., “Comparison of scalar and vector control strategies of induction motors”, *Hungarian Journal of Industrial Chemistry,* pp. 265-270, 2011

[6] Alsofyani I. M., Idris N. R. N., “A review on sensorless techniques for sustainable reliability and efficient variable frequency drives of induction motors*”, Renewable and Sustainable Energy Review (24),* pp. 111-121, 2013

[7] www.mathworks.com