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Sinusoidal PWM to Drive the Induction Motor with Reducing the Torque Ripple and THD

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Abstract—Three phase voltage source inverter are widely used to drive the AC motors as the induction motor. There are many techniques to make the inverter reliable to treatment the AC motor. From among these techniques, the sinusoidal pulse width modulation. The paper used this technique due to have some advantages as, reduce the total harmonic distortion and torque ripples. Also in this Paper the open and closed loop scalar controls with the sinusoidal pulse width modulation are compared to show the advantages of the closed loop control. The torque ripples and total harmonic distortions is calculated through many modulation index. The PI current controlled is added to the closed loop drive system to minimize the torque ripple and total harmonic distortion this is to show the effect of adding these PIs on the performance overall.

Index Terms—Induction motor, PI controller, Scalar control and SPWM.

I. INTRODUCTION

Induction motors are the most common used motors in the drive applications this is because they have some advantages as; simple construction, low maintenance, low cost, can be operated in hazard environmental, robust and self-starting. The performance of these motors in drive systems depend up on the motor control and the method of control in power converter. From the most important methods to control the power converter are current and voltage controls. The current control is preferable. This is because it is simple. The quality control of this method depends upon the quality of the waveform is generated by current controlled of converter [1-3]. To get good power waveform this depends upon the following factors: -

1. Switching frequency of the PWM which has low harmonics if it is high but it has drawback such as: high losses.
2. Modulation method which control the magnitude of the output waveform but it has drawback such as: high order of voltage harmonics and ripple current.

3. Types of current waveform. This is because each motor required own current waveform such as: induction motor and PMSM required sine wave but brushless DC motor required quasi square wave form.

Variable voltage variable frequency control as the magnitude is the most common used control this is because it is simple and low cost. It is used in open loop control and closed loop control. This control is called scalar control. From the best methods to get suitable the output voltage to drive the induction motor is a PWM. The PWM is used to reduce the ripples and total harmonic distortions [4-5]. There are many possible PWM techniques like sinusoidal PWM, selected harmonic elimination PWM, space vector PWM etc used for speed control of induction motor [6-7]. In sine PWM Inverter, the width of the pole voltage pulses over the output cycle, vary in a sinusoidal manner. The scheme, in its simplified form, involves comparison of a high frequency triangular carrier voltage with a sinusoidal modulating signal that represents the desired fundamental component of the pole voltage waveform. The peak magnitude of the modulating signal should remain limited to the peak magnitude of the carrier signal. The comparator output is then used to control the high side and low side switches of the particular pole [8-10]. This paper is used to comparing between the operation of induction motor in case of closed loop control and in case of open loop control to show the effective of closed loop scalar control comparing to the open loop scalar control with using sinusoidal PWM (SPWM). This occurs through study three models. These models are classical open loop scalar control with SPWM inverter at different modulation index, closed loop scalar control with SPWM inverter at different modulation index and modified closed loop scalar control with SPWM inverter at different modulation index. In the modified model, the PI current controllers are used to improve the torque ripples, total harmonic distortion (THD) in current and THD in voltage. This paper is organized as; I. Introduction, II. Scalar control, III. Simulation results. IV. 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.

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Fig. 1. i.e. to drive the induction motor through open loop scalar control, 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 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. To more improvement in the motor torque ripples and THD in currents and voltages, three PIs are used one by one for each phase and the input of these PIs are the error comes from comparing the reference sinusoidal waveform and the measured waveform as shown in Fig.3.

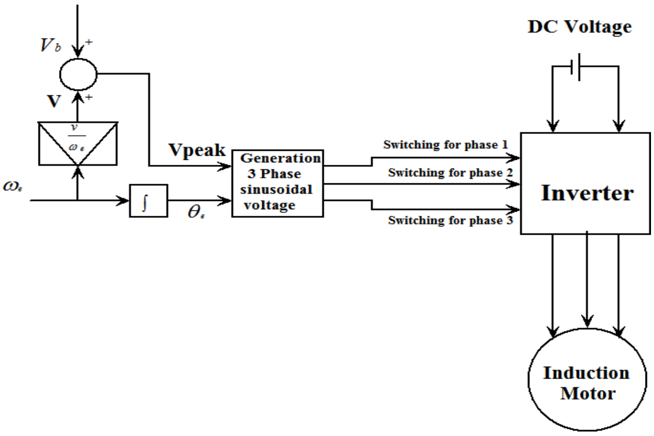

Fig. 1 Open loop scalar control.

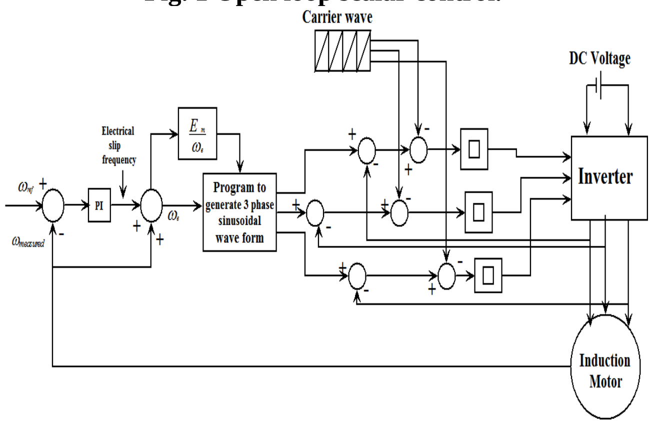

Fig. 2 Closed loop scalar control.

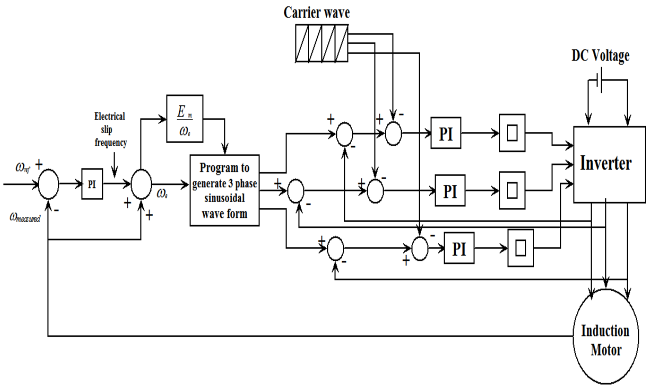

Fig. 3 Closed loop scalar control with modified method.

III. SIMULATION RESULTS

The MATLAB program is used to simulate the results for open loop scalar control, closed loop scalar control and modified closed loop scalar control for induction motor which has the parameters in appendix I. Where it is found that;

A. *Simulation Results for Open Loop Scalar Control*

Here two cases are studied, the first case studies the operation of the induction motor with full load at rated speed and the second case studies the effect of sudden applied and removal the load on induction motor under open loop control.

1. ***Simulation results for fist case:***

In this case, the motor is starting with full load. The stator voltage is applied gradually as shown in Fig.4 and increasing to reach the rated value at 1 sec. also from table 1, the total harmonics distortion in phase voltage and line voltage can be seen.

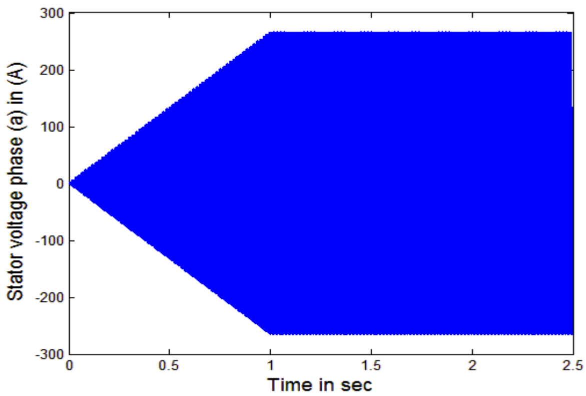

Fig.4 output voltage of inverter with open loop scalar control

Due to the inverter voltage is increasing gradually so the motor torque starting from zero torque, increasing gradually and reaches the peak value of the torque at 1.35 sec after that, the motor torque decrease rapidly and settled at load torque at 1.5 sec. in this type of control it is found that, the motor torque has high distortion and ripples and this can be seen in Fig.5. and in table 1. Due to applies voltage starting from zero and increasing gradually it found that, the motor speed starting in the negative direction after that speed is increasing in the positive direction and reaches to the rated value at 1.5 sec as shown in Fig. 6.

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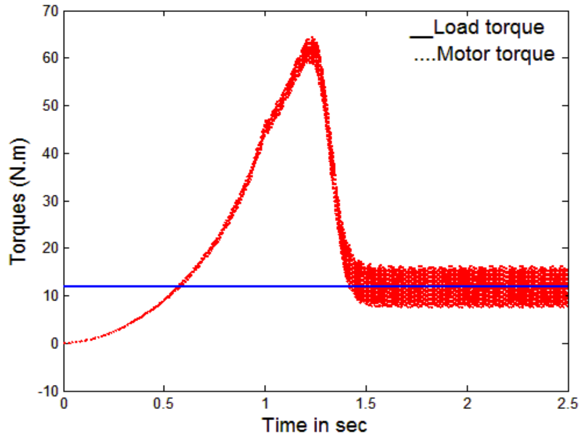

Fig.5 motor torque with using open loop scalar control

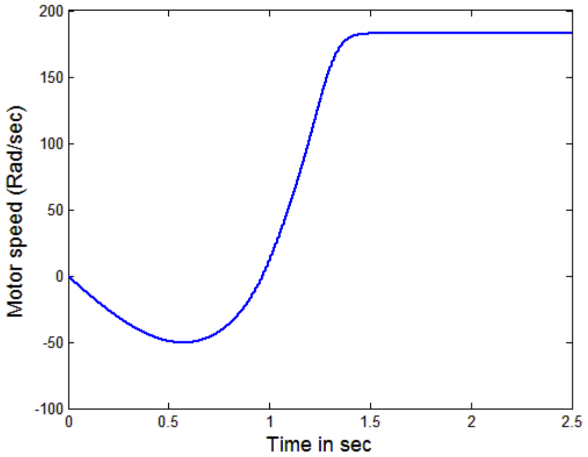

Fig.6 motor speed with using open loop scalar control

The motor current is shown in Fig. 7 where increasing gradually and reach to the rated value when the motor torque and motor speed reach the motor load torque and motor speed.

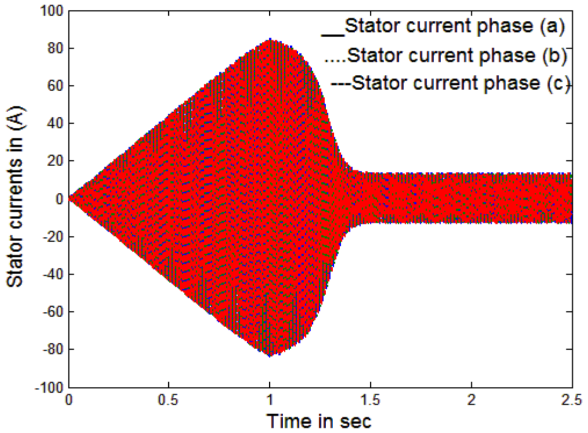

Fig.7 motor current using open loop scalar control

2. *Simulation result for second case:*

In this case, the motor is starting without load, at 1.5 sec the full load is suddenly applied, at 3 sec the load is suddenly removed. Fig. 8 shows the performance of the motor torque due to sudden applied and removal the load where it is found that, the motor torque increases gradually and decreases gradually when reaches to the peak value and settled to zero torque at 1.15 sec. when sudden load is applied the motor torque increases to rated load, when the load is removed the motor torque decreases to zero.

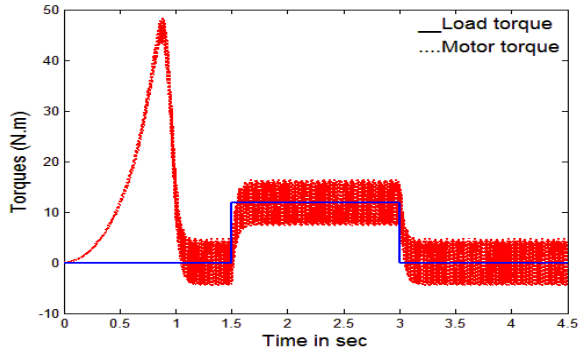

Fig.8 motor torque with using open loop scalar control

Fig. 9 shows the motor speed where at 1 sec. the motor reaches rated speed, when the load is suddenly applied the motor speed decreases and continues with this speed, when the load is removed, the motor speed is increased again and is reached original speed which was before appling the load from these it is found that, the motor speed doesn't return the original speed when the load is applied due to the motor working under open loop speed control.

From studding the motor current in Fig. 10 at sudden applied and removal the load it is found that, the no-load current is nearest from the full load current, when the load is applied the motor current increase and return to no-load current value when the load is removed.

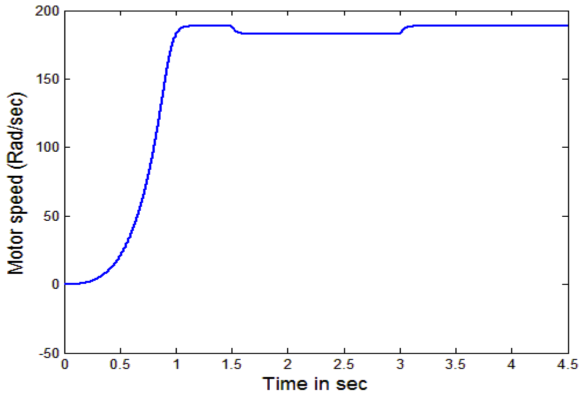

Fig.9 motor speed with using open loop scalar control

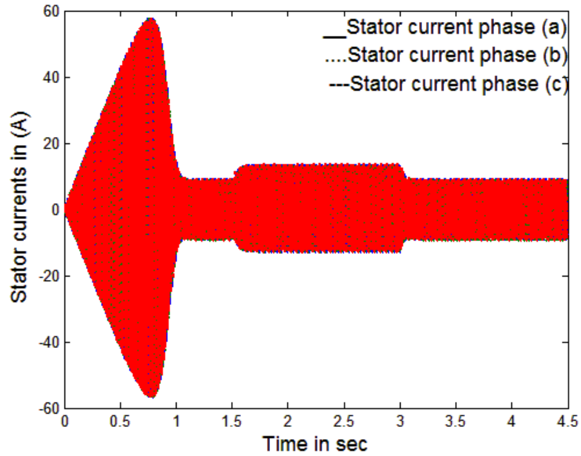

Fig.10 motor current using open loop scalar control

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B. Simulation Results for Closed Loop Scalar Control

The simulation results when the induction motor is running from closed loop scalar control can be seen here where in this simulation three cases are studied these cases are

1. The motor starting with full load at rated speed.
2. Sudden applied and removal the load.
3. Reversing speed.

1. *Simulation result for fist case:*

In this case, the motor is starting with full load. The stator voltage is applied gradually as shown in Fig.11 and increasing to reach the rated value at 1 sec. also from table 1, the total harmonics distortion in phase voltage and line voltage are decrease if it is compared to the same case with open loop scalar control.

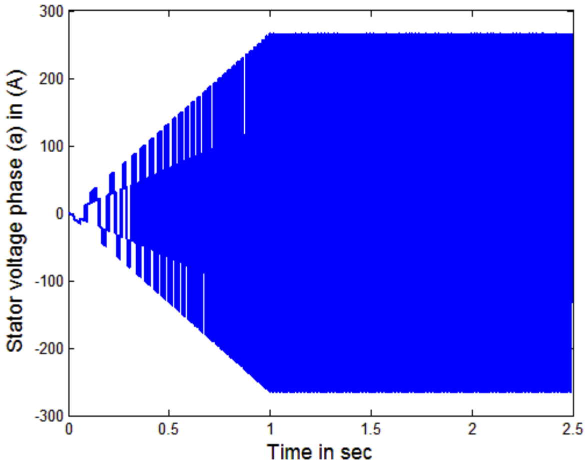

Fig.11 inverter output voltage with closed loop scalar control

Due to the inverter voltage is increasing gradually so the motor torque starting from zero torque, increasing gradually and reaches the peak value of the torque at 0.35 sec after that, the motor torque decrease rapidly and settled at load torque at 1.3 sec. in this type of control it is found that, the motor torque has low distortion and ripples if it is compared to the same motor for open loop scalar control (Fig.5) and this can be seen in Fig.12. and in table 1. Also the peak motor torque with this method is decreased if it is compared to the same case for open loop scalar control.

Fig. 13 shows the motor speed versus the reference speed. When comparing between motor speed in this case with the same case of motor speed in the open loop scalar control it is found that; the negative speed at starting is very low if it is compared to Fig.6 in case of open loop scalar control also the motor speed reaches the rated load faster than that the open loop scalar control.

Fig. 14 shows the motor current when the motor starting with load. The THD in the current is less if it is compared to the open loop scalar control also it has low starting current.

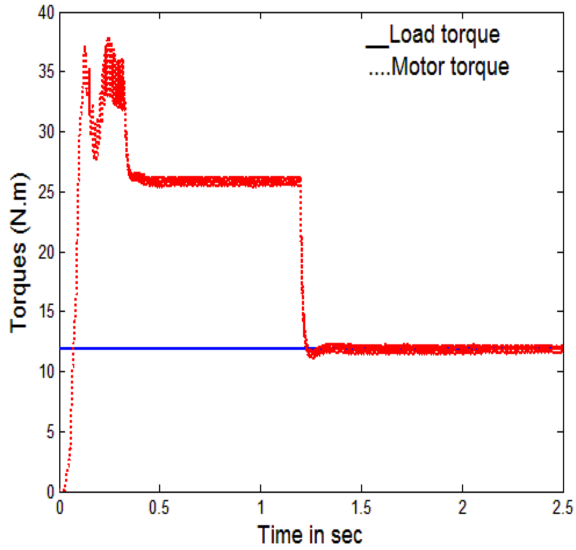

Fig.12 motor torque with using open loop scalar control

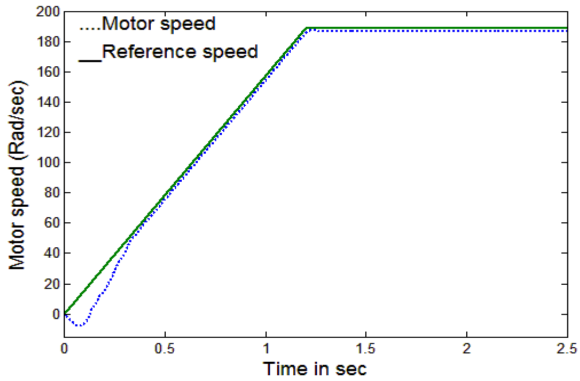

Fig.13 motor speed with using closed loop scalar control

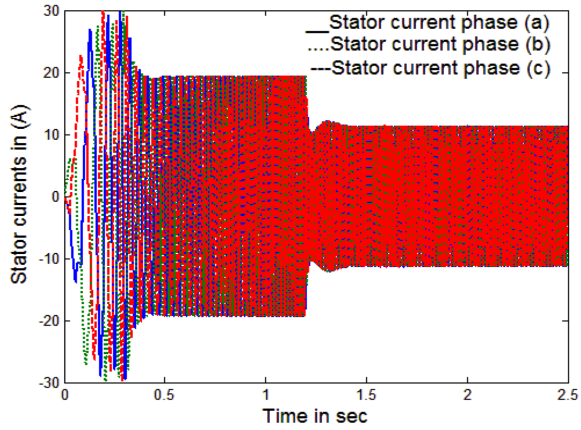

Fig.14 motor current using closed loop scalar control

2. *Simulation results for second case:*

In this case, the motor is starting without load, at 2 sec the full load is suddenly applied, at 3.5 sec the load is suddenly removed. Fig. 15 shows the performance of the motor torque due to sudden applied and removal the load where it is found that, the motor torque increases gradually and decreases gradually when reaches to the peak value and settled to zero torque at 1.35 sec. when sudden load is applied the motor torque increases to rated load when the load is removed the motor torque decreases to zero.

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Also from this Fig. it is found that the starting torque is low if it is compared to the starting torque in case of open loop scalar control with the same case.

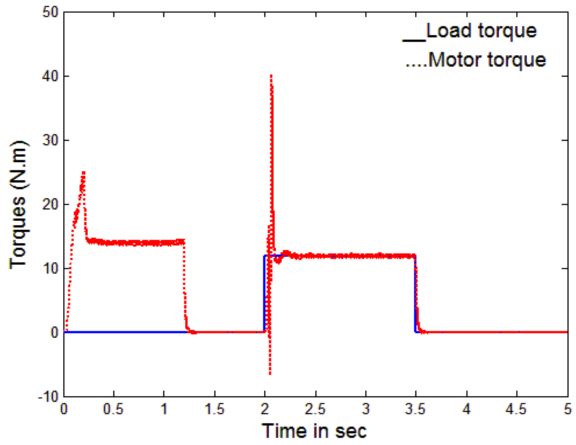

Fig.15 motor torque with using closed loop scalar control

Fig. 16 shows the motor speed where at 1.05 sec. the motor reaches rated speed when the load is suddenly applied the Motor speed approximately doesn't affect also at removed the load the motor speed doesn't affect. This is because the motor works at closed loop scalar control. If comparing this case with the same case in case of open loop scalar control it found that the problem of sudden applied or removal the load is solved with the closed loop scalar control.

From studding the motor current in Fig. 17 at sudden applied and removal the load it is found that, the no-load is decreased if it is compared to the same case with in open loop scalar control and THD is decreased.

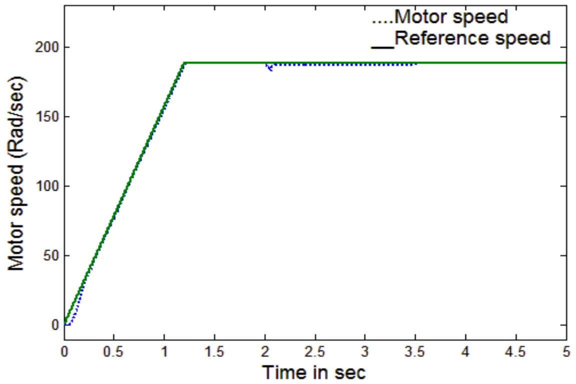

Fig.16 motor speed with using closed loop scalar control

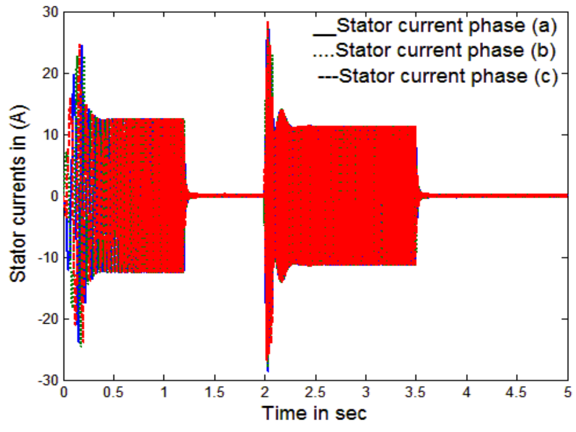

Fig.17 motor current using closed loop scalar control

3. *Simulation results for third case:*

In this case, the motor is starting with load; at 2.5 sec the motor speed is reversed and the performance of the motor can be seen here. Fig. 18 shows the performance of the motor torque due to reverse speed. Where it is found that; the motor torque is reversing due to reverse speed and return to the load torque because it operates at closed loop scalar control.

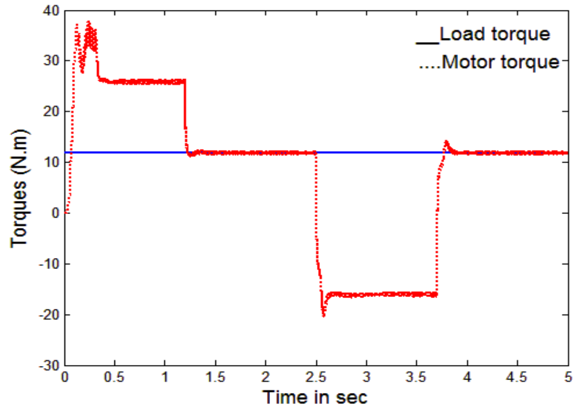

Fig.18 motor torque with using closed loop scalar control

Fig. 19 shows the motor speed where at 2. 5 sec. the motor speed is reversed due to the reference speed is reversing. From studding the motor current in Fig. 20 it is found that, the motor current is reversed when the motor speed is reversed.

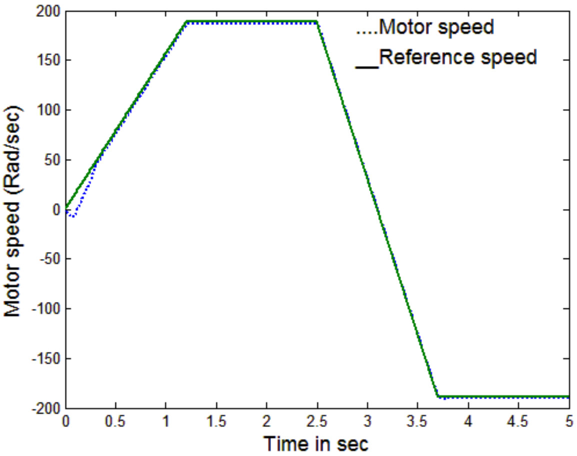

Fig.19 motor speed with using closed loop scalar control

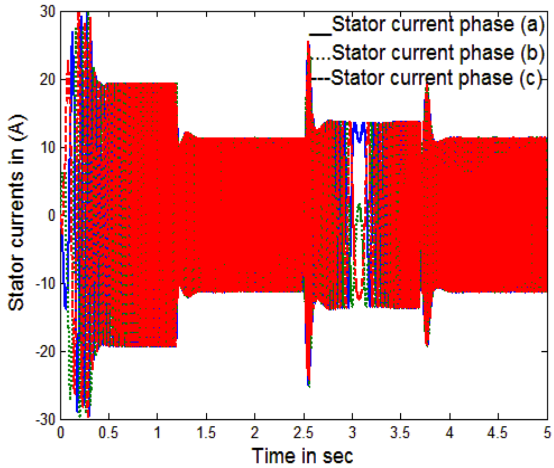

Fig.20 motor current using closed loop scalar control

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C. Simulation Results for Closed Loop Scalar Control Modified Method.

The simulation results when the induction motor is running from modified closed loop scalar control can be seen here where in this simulation three cases are studied these cases are

1. The motor starting with full load at rated speed.
2. Sudden applied and removal the load.
3. Reversing speed.

1. *Simulation results for fist case:*

In this case, the motor is starting with full load. The stator voltage is applied gradually as shown in Fig.21 and increasing to reach the rated value at 1 sec. also from table 1, it is found that; the total harmonics distortion in phase voltage and line voltage are decrease if it is compared to the previous cases. Due to the inverter voltage is increasing gradually so the motor torque starting from zero torque, increasing gradually and reaches the peak value of the torque at 0.25 sec after that, the motor torque decreases rapidly and settled at load torque at 1.3 sec. in this type of control it is found that, the motor torque has low distortion and ripples if it is compared to the previous cases and this can be seen in Fig.22. and also can be seen this in table 1.

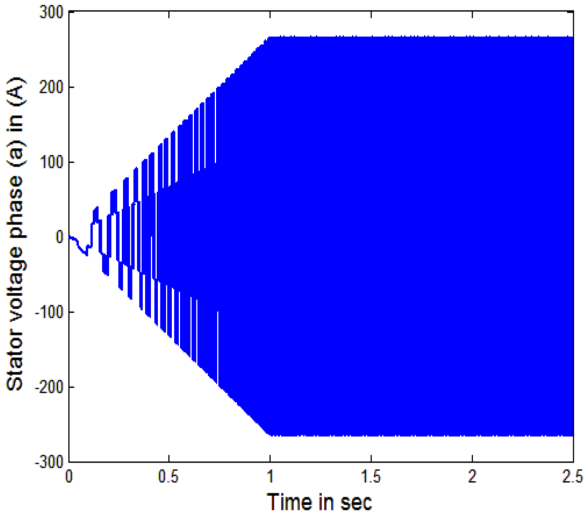

Fig.21 inverter output voltage with closed loop scalar control

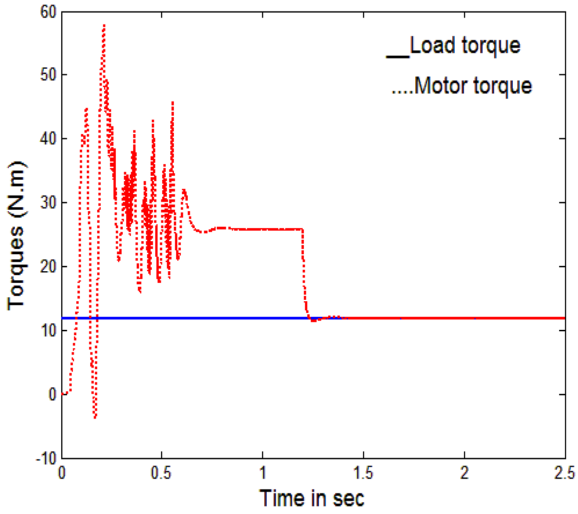

Fig.22 motor torque with using open loop scalar control

Fig. 23 shows the motor speed versus the reference speed. This case is similar to the last case.

Fig. 24 shows the motor current when the motor starting with full load. The THD in the current is less in this case if it is compared to the previous cases.

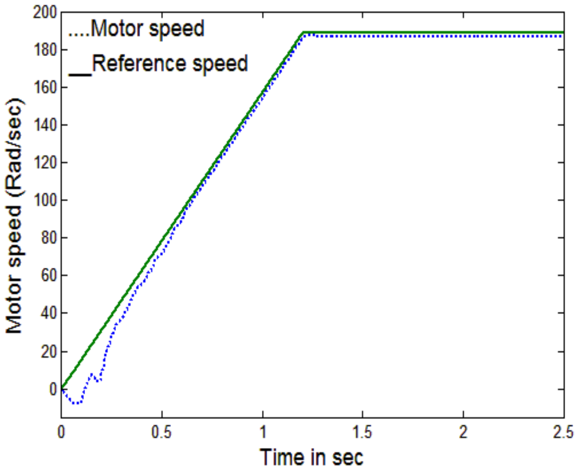

Fig.23 motor speed with using closed loop scalar control

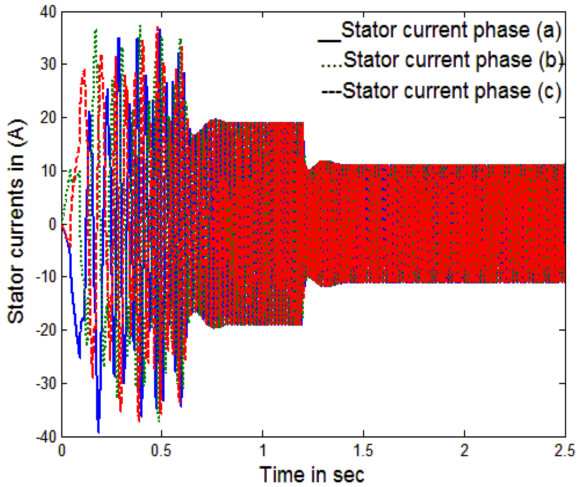

Fig.24 motor current using closed loop scalar control

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2. ***Simulation results for second case:***

In this case, the motor is starting without load, at 2 sec the full load is suddenly applied at 3.5 sec the load is suddenly removed. Fig. 25 shows the performance of the motor torque due to sudden applied and removal the load where it is found that, the motor torque increases gradually and decreases gradually when reaches to the peak value and settled to zero torque at 1.3 sec. when sudden load is applied the motor torque increases to rated load when the load is removed the motor torque decreases to zero. Also from this Fig. it is found that the starting is low if it is compared to the starting torque in case of open loop scalar control.

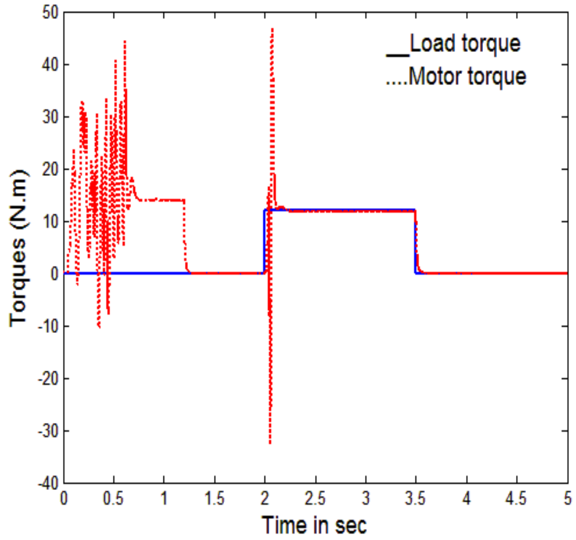

Fig.25 motor torque with using closed loop scalar control

Fig. 26 shows the motor speed where at 1.05 sec. the motor reaches rated speed. when the load is suddenly applied the motor speed approximately doesn't affect also at removed the load the motor speed doesn't affect. This is because the motor works at closed loop scalar control. If comparing this case with the same case in case of open loop scalar control it found that the problem for the sudden applied or removal the load is solved with the closed loop scalar control.

From studding the motor current in Fig. 27 at sudden applied and removal the load it is found that, the no-load is decreased if it is compared to the same case in the previous method of control and THD is decreased.

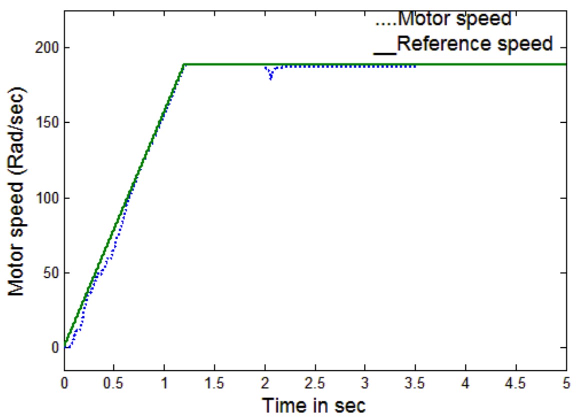

Fig.26 motor speed with using closed loop scalar control

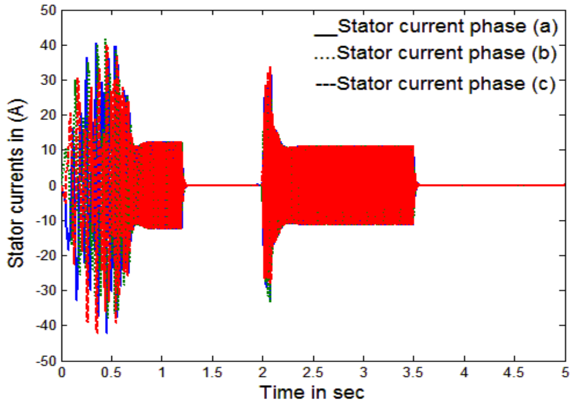

Fig.27 motor current using closed loop scalar control

3. ***Simulation results for third case:***

In this case, the motor is starting with load; at 2.5 sec the motor speed is reversed and the performance of the motor can be seen here. Fig. 28 shows the performance of the motor torque due to reverse speed. Where it is found that; the motor torque is reversing due reversing speed and return to the load torque due to closed loop scalar control is used.

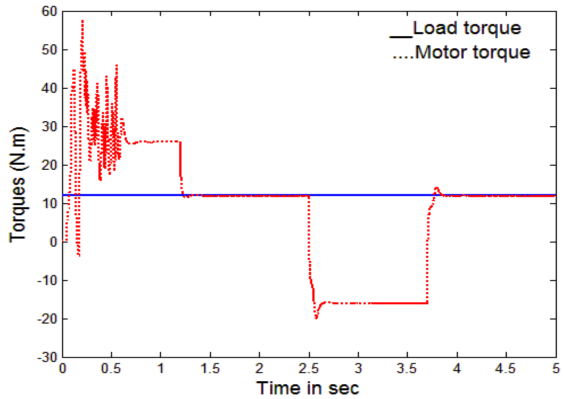

Fig.28 motor torque with using closed loop scalar control

Fig. 29 shows the motor speed where at 2. 5 sec. the motor speed is reversed due to the reference speed is reversing. From studying the motor current in Fig. 30 it is found that, the motor current is reversed when the motor speed is reversed. And the THD is the least.

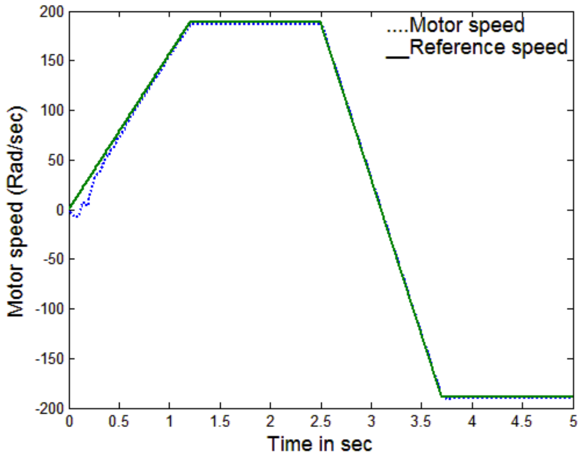

Fig.29 motor speed with using closed loop scalar control

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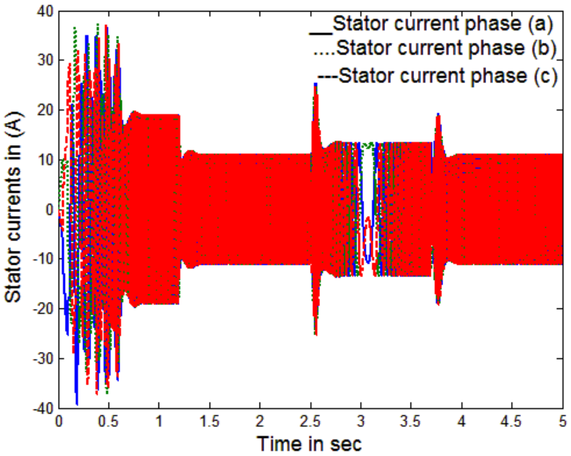

Fig.30 motor current using closed loop scalar control

IV. CONCLUSION

The open loop scalar control, closed loop scalar control and modified closed loop scalar control are simulated. The results for these models show that; the closed loop scalar controls are solved the problems of the open loop scalar control such as effect of sudden applied and removal the load. Also the closed loop scalar controls improve the torque ripples and THD in the current and in the voltage. The starting torque and current are decreased if it is compared to open loop scalar control. In case of adding PI current controllers in each phase of the motor control, this is more improvement in the THD overall.

"Table 1"

Method of control at modulation index 1	THD in %			Motor torque Ripples in %
	Phase voltage	Line voltage	Motor current	
Open loop scalar control	60.84	61.7	15.1	16.02
Closed loop scalar control	59.45	58.2	3.18	2.45
Modified closed loop scalar control	51.02	52.08	2.2	0.25

"Table 2"

Method of control at modulation index 0.8	THD in %			Motor torque Ripples in %
	Phase voltage	Line voltage	Motor current	
Open loop scalar control	83.64	84.1	22.67	24.45
Closed loop scalar control	67.1	66.27	5.35	3.75
Modified closed loop scalar control	58.23	57.14	3.25	0.85

APPENDIX (I)

MOTOR DATA for INDUCTION MOTOR

Line to line voltages	220V
Inertia	0.0289Kg.m^2
Pole pairs	2
Rated power	3 HP
Rated speed	11725 R.P.M
Stator resistance	0.435 ohm
Rotor resistance	0.816 ohm
Stator leakage inductance	4mH
Rotor leakage inductance	2mH
Magnetizing inductance	69.3mH

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