REVIEW OF ENERGY SAVING TECHNIQUES FOR THREE PHASE SQUIRREL CAGE INDUCTION MOTOR DRIVE

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Abstract: *Energy conservation is an important factor for the today's industries. In industries induction motor drives are the major power consuming devices and it mostly preferred for industrial applications due to low price, less maintenance, robustness and reliability. So, energy conservation in this squirrel cage induction motor drive leads to reduction in electricity cost of the industry and also considerable reduction in power demand of the country. This paper describes the various energy saving techniques for industrial squirrel cage induction motor drive. This paper provides clear understanding of energy conservation techniques and it is helpful for the researchers of energy conservation field. Here simulation verifications are done in Matlab Simulink for the various energy conservation techniques discussed. Necessary practical verifications are also done for some energy conservation techniques.*

Key words: *Energy Conservation, Three phase induction motor drive, PWM technique, Power electronic switches, Flux optimization.*

1. Introduction

Many energy saving techniques are available for induction motor drives. They are classified into online and offline [1], [2]. Figure 1 shows the various types of energy conservation Methods. In offline, the energy conservation is achieved by selecting suitable rating of motor corresponding to load, by selecting suitable fixed capacitor for reactive power compensation, by selecting good quality coils and by selecting good quality cores. In online, the energy conservation is achieved by running the motor under balanced supply voltage, by flux optimization technique, by reducing losses at power electronic switches, by automatic power factor correction and by proper cooling. This paper clearly explains the above mentioned energy conservation techniques with simulation in Matlab Simulink. In the off line losses can be reduced but it cannot be adjusted, it is fixed. In on line, losses can be reduced and adjusted and it is varied throughout the operation [1]. In the online loss minimization techniques, rotor and stator parameters are calculated on line. Then iron loss and copper losses are calculated. Next both losses are made equal at all the load conditions by varying the voltage and frequency to maximize the efficiency [2]. Design of induction motor with the proper selection of materials results in energy saving with increased investment cost. But using of this motor will repay the investment cost in short period of time [3]. Instead of balancing copper loss and iron loss Adaptive search controller technique is used to control the motor for on line loss minimization (Flux optimization). This technique searches the minimum loss point by reducing of input power up to no change in output power. This technique has advantage of fast response because it eliminates the copper loss and iron loss calculation [4].

The different constant speed varying load torque applications in industries are spinning drive in textile industry, mine hoist load, drill presses and wood saw [5], [6]. Here load is varying from no load to full load at constant speed. Flux optimization is useful for these applications to conserve energy. The difference between ordinary induction motor and energy efficient induction motor is the loss, the iron loss in the energy efficient motor is reduced to low values by selecting good quality core, compared to ordinary motors [5]. In energy efficient induction motor the balance between copper loss and iron loss is achieved at light loads due to reduction in iron loss. So, maximum efficiency achieved at light load conditions. To improve the controller performance intelligent controller is used to optimize the flux for different load conditions in three phase induction motors [7], [8]. Like that various energy saving methods are explained below.

2. Suitable Hp Rating Selection

In induction motor drive, motor power rating is very important. Depending on Hp rating, motor coils and cores are selected during the manufacturing. So, the iron loss is increases as the

Hp rating increases in induction motor [13]. To verify that Matlab simulation is performed, from that, 20 Hp, 400V, 50Hz and 4Pole squirrel cage induction motor consumes 317 Watts of input power at no load and 5.4 Hp, 400V, 50Hz and 4Pole squirrel cage induction motor consumes 145 Watts of input power at no load. As the no load power in induction motor is equal to iron loss. The iron loss in 20 Hp motor is higher that 5.4Hp motor. For example, if 20Hp motor drive is used to drive the variable torque load between 0 Nm to 25 Nm means, the motor can be replaced to 5 Hp. Because 5 Hp motor is enough to drive the maximum torque of 25 Nm.

$$Ns = (120 \times f) \div P \quad (1)$$

$$Out\ put\ Power = (2 \times \pi \times N \times T) \div 60 \quad (2)$$

$$1\ Hp = 746\ Watts \quad (3)$$

From equation (2) it is clear that for 20Hp motor, 25 Nm is the 25% of full load and for 5 Hp motor, 25 Nm is the 106% of full load. The power rating tolerance is ± 10%. Then, it is not necessary to go for higher rating motors, when the maximum load is below the 110% of full load. So, it is clear that proper selection of motor rating leads to energy and cost conservation. Table I shows the comparison of input power taken by the different Hp motor to drive the load at same torque and speed.

Table I. Comparison of input power for the same load torques in different Hp motors

Load Torque (Nm)	5.4 HP Motor		20 HP Motor	
	Input power (W)	Speed (Rpm)	Input power (W)	Speed (Rpm)
0	145	1499	317	1499
2.5	539	1492	710	1492
5	936	1486	1104	1486
7.5	1337	1482	1497	1482
10	1740	1476	1892	1476

3. Suitable Capacitance Rating selection

Induction motor is called as lagging power factor load. In induction motors reactive power flow causes additional losses at conductors ($I^2 \times R$ Loss). To compensate this reactive power capacitors are connected parallel to the load [13]. The capacitor is connected at the terminals of the motor and it is made to compensate nearly 80% of the reactive power of the motor. For capacitance value calculation, motor is made to run at no load to full load and VAR for each loading condition is noted down, from that least value of VAR is chosen and for that VAR suitable capacitance is calculated.

$$C(in\ F) = (KVAR \times 1000)/((2\pi \times f) \times (KV)2) \quad (4)$$

The capacitor rating is calculated by equation (4). For verification 5.4 Hp motor is made to run at various load conditions and the graph between load and VAR is taken, from that least value 2680VAR is taken for that capacitance value is found out. It is verified that 5.4 Hp motor takes 3.8 A at no load without compensation, after capacitor placement the motor takes only 0.9A. If the conductor resistance is taken as 0.1 ohm (assumption for understanding) then loss is 1.444 Watts for uncompensated scheme and the loss is 0.08 Watts for compensated scheme. So, suitable capacitor placement leads to energy conservation in induction motor.

4. Selecting Good Quality Coils

Generally in induction motors, coils are copper. In copper depending on temperature, resistance value changes. So, conductor loss increases due to poor quality coils [5], [13]. For example, if the coil resistance is 3 Ohms in a induction motor then copper loss is equal to 12 watts for 2A current. If this ordinary coil is replaced by the coils having good quality then coil resistance gets reduced, for example if it is taken as 2 ohm, then the copper loss for 2 A current is reduced to 8 watts. So, selecting good quality coils leads to energy conservation.

5. Selecting Good Quality Core

In induction motor core loss is called iron loss which is the combination of hysteresis loss and eddy current loss. For reducing the eddy current loss the core is made into thin stampings to increase the resistance of the core. To reduce the hysteresis loss, the material for making the core is selected such that the B-H cure area of the material is small. In recent days silicon is mixed with the steel to reduce the iron loss and it is named as silicon steel stampings. The presence of new materials or alloys in core makes the iron loss very low. So, the balance in copper loss and iron loss is achieved at light load conditions [5], [13]. The motors in which balancing of copper and iron loss occur at light load condition is called energy efficient motor. From figure 3 it is clear that for 5.4Hp motor in Matlab simulink, the maximum efficiency is achieved at 44% of load itself. In older machines the balance is achieved near the full load.

6. Voltage Balance

Balanced voltage is necessary for the induction motor. Unbalanced voltage in induction motor causes additional losses [13]. For example in 5.4 Hp motor in Matlab simulink, at balanced voltage the motor takes 145 Watts of input power and for unbalanced voltage the motor takes 180 Watts of input power (voltage reduction in phase A). Then, loss at unbalanced condition is higher than the balanced condition. So, balancing of voltage can be achieved by using stabilizer or auto transformer at the time of unbalanced conditions. Thus balanced voltage leads to energy conservation in induction motor.

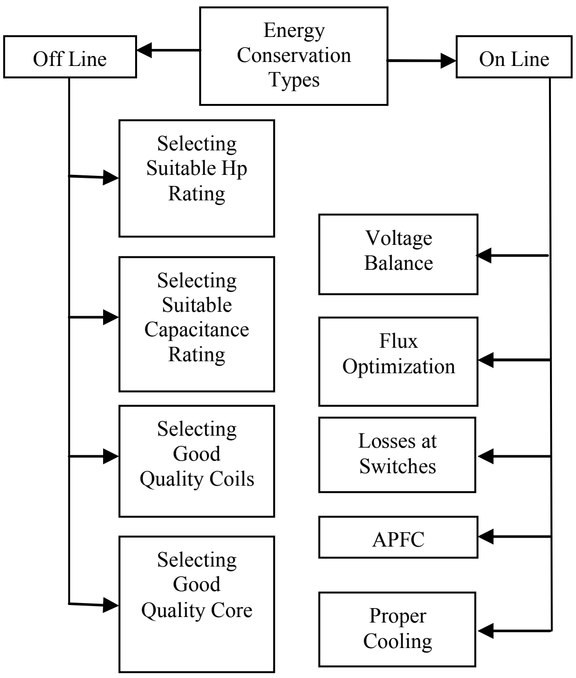

Figure 1.Types of Energy Conservation Methods.

7. Proper Cooling

Cooling is also important for induction motor, for small Hp motors internal fan is provided to cool the coils. In high Hp motors external cooling is provided in induction motors [5]. The electrical resistance of a conductor such as a copper wire is dependent upon collision processes within the wire, the resistance is increases with temperature when collision is more. So, a fractional change in resistance is proportional to the temperature changes. Thus cooling is an important factor for reducing the loss. In industries for many applications, induction motor is made to run continuously throughout the day without stall. In such cases, motor winding gets heated up and due to this coil resistance changes. This results in increased conductor loss. Normally air cooling is used for induction motor, in that hydrogen cooling is used for high Hp motors. Hydrogen cooling dissipates the heat quickly than ordinary air cooling. So, proper cooling is also leads to conservation in energy.

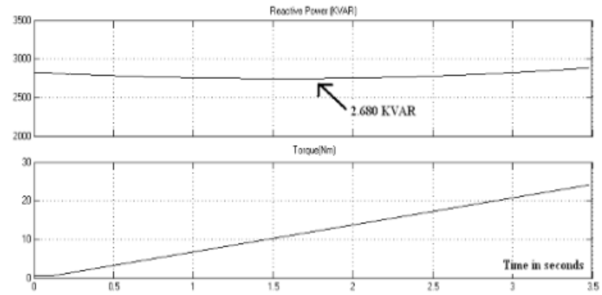

Figure 2.Reactive power and load torque curve for 5.4Hp motor.

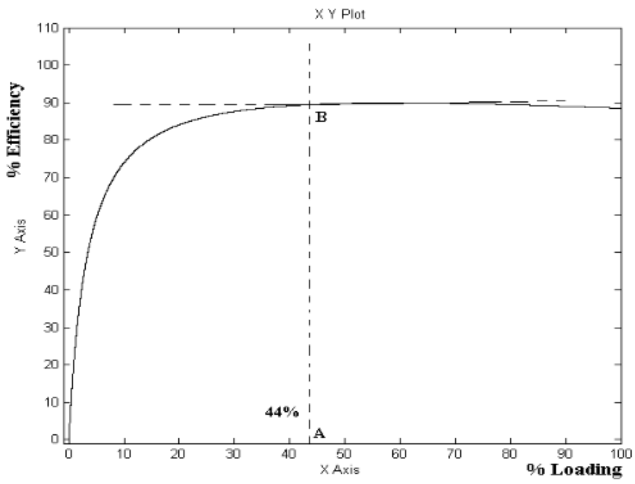

Figure 3. Efficiency Vs % Load curve obtained for 5.4Hp motor in Matlab Simulink.

8. APFC

APFC can be implemented for individual drives or group of drives, depending on requirement. The different methods of power factor correction in industries are distributed power factor correction, group power factor correction, centralized power factor correction, combined power factor correction and automatic power factor correction (APFC).

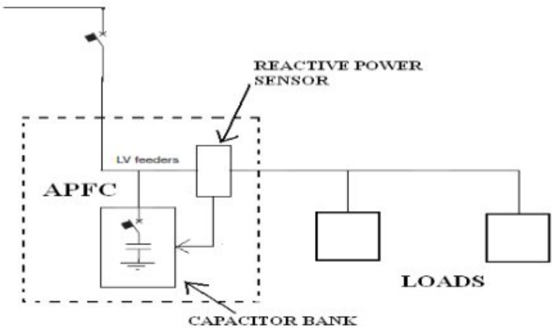

Figure 4.Block diagram of Automatic Power Factor Correction

Distributed power factor correction is the old method. This method has disadvantage like possibility for leading power factor. In this method, motor VAR compensation is done for full load by fixed capacitor. If the motor operates at light loads or no load, the current becomes leading and the system starts to consume more power [13]. In industries they are using a thumb rule which is 2KVAR capacitor for 5 Hp three phase motor. If the reactive power compensation is done like that then 100% compensation (i.e. to achieve unity power factor at all conditions) cannot be achieved because for the same Hp motor, VAR rating differs slightly due to materials and construction and also due to variation in the loading of the motors. In group power factor correction, group of motor loads are compensated with fixed capacitor banks at their supply terminals due to the same reasons mentioned previously.

Here also we cannot achieve 100% compensation. In centralized power factor correction, all the loads are compensated by switching the capacitors corresponding to the load. The capacitor bank is connected at the feeder terminal. Here also we cannot achieve unity power factor because compensation is done by switching the fixed capacitor corresponding to the load. Combined power factor correction is the combination of distributed power factor correction and centralized power factor correction. Here large continuously operated loads are compensated with distributed power factor correction and remaining loads are compensated with centralized power factor correction at the feeder input terminal. Here also we cannot achieve unity power factor. In the above mentioned methods, unity power factor cannot be achieved because the compensation is done with respect to Hp (same problem as the previous methods). In APFC shown in figure 4, compensation is done with respect to VAR and the capacitors are switched with the help of semiconductor switches according to VAR consumed by the load. So, it is possible to achieve unity power factor in APFC. Here sensors are used to measure VAR consumed by the load. Semiconductor switches are used to switch the capacitors for fine variations in their values, for accurate VAR compensation.

This APFC unit is connected at the input terminal line of the industry. APFC contains sensor and capacitor bank with semiconductor switches. APFC is the latest system used by companies. So, it is possible to achieve 100% compensation in APFC and this result in energy conservation due to reduction in conductor loss by 100% reactive current reduction. Matlab simulation is done for 5.4 Hp motor with conductor resistance of 1 Ohm (For understanding). From table II it is clear that input power required for without APFC scheme (Without reactive power compensation) is higher than input power required for APFC scheme. So, implementation of APFC leads to energy conservation.

Table II. Comparison of input power to drive the load with APFC and without APFC

%Load	Input power (W) 5.4Hp Without Reactive Power compensation	Input power (W) 5.4Hp With APFC
0	196	145
25	1234	1186
50	2312	2250
75	3430	3357
100	4593	4495

9. Losses at Switches

The power electronic switch which is used in the inverter has on state resistance. The power loss in that resistance is called switch conduction loss [11], [12], [13]. The most common power electronic switches used in inverter are SCR, MOSFET and IGBT. Due to commutation problem SCR is not preferred today. MOSFET or IGBT is used in the inverter in today’s industries. MOSFET has advantages of, suitable for high frequency operation due to low switching loss and disadvantage of, not suitable for high power operation due to high conduction loss (on state resistance high). Cost of the MOSFET is very low compared to IGBT. IGBT has the advantage of, suitable for high power application due to low conduction loss (on state resistance low). Cost of the MOSFET is only 10% compared to the cost of IGBT.

Paralleling of MOSFET leads to reduction in conduction loss and brings the inverter to opt for high frequency applications also. For MOSFET - IRF840 on state resistance R_d on = 0.85 ohm, V_{max} = 500 Volts and I_{max} = 8 Amps. In Matlab simulink 5.4 Hp motor is used to drive the load with inverter having the MOSFET (switch resistance = 0.85ohm).

Figure 5 shows the Matlab Simulink diagram of Inverter without paralleling of MOSFET and figure 6 shows the Matlab Simulink diagram of Inverter with paralleling of MOSFET. At load current of 4A the conduction loss at each switch for without paralleling case is 13.6 Watts and for with paralleling case is 3.4 Watts. The conduction loss at each set of switch is 6.8Watts. Thus the conduction loss at each switching place is reduced to 6.8 Watts from 13.6 Watts. So, reducing the conduction loss of the switch leads to energy conservation in induction motor drives [18], [21], [22]. As previously explained switching loss was very low in MOSFET compared to IGBT. The switching losses are reduced by Soft switching techniques [12], [17] such as Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS). Due to the harmonics the Rms value of current increases and makes the conductor loss to increase.

To reduce the harmonics PWM techniques are used [9]. The main techniques which are used by the industry are Space Vector Modulation technique and Sinusoidal Pulse Width Modulation technique. This technique reduces the harmonics and keeps the THD below 5%. The loss due to switching and harmonics are low compared to conduction loss.

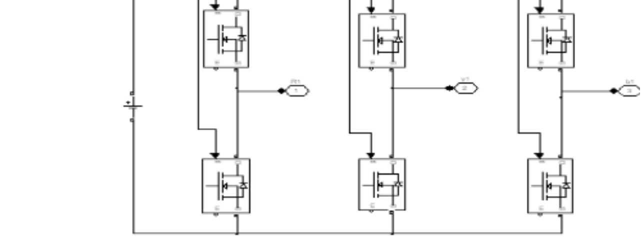

Figure 5.Matlab Simulink diagram of Inverter without paralleling of MOSFET

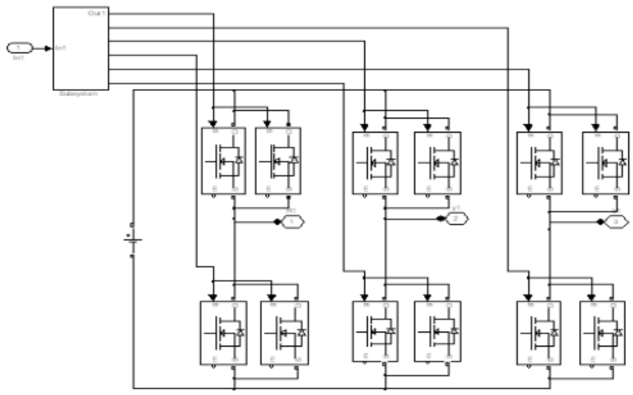

Figure 6.Matlab Simulink diagram of Inverter with paralleling of MOSFET

10. Flux Optimization

Flux optimization is the major energy conservation technique [13], [14] which leads to better conservation in energy. In industries induction motor drives are used for the constant speed varying load torque applications such as drill presses, wood saw etc. For these applications the load is varied from no load to full load at constant speed. Generally in induction motor the flux requirement varies from no load to full load [42], [43], [1].

For example, if an induction motor running under varying load condition, with constant rated voltage and frequency means, the flux is maintained constant at full load flux level for all the load condition, from no load to full load. So, flux optimization techniques are used for these kinds of applications to give the optimum flux corresponding to the load. This is called flux optimization technique. For easy understanding in this paper 'VSI set' is consider as VSI with IGBT switches employs SPWM technique. In induction motor drive for constant speed operation V/F control is preferred. Figure 7 shows the block diagram flux optimization control for the constant speed operation of induction motor drive.

The table III shows the simulation and practical readings of VSI set fed V/F controlled 5.4 Hp and 1Hp induction motor drive for the set speed of 1173 rpm and 1400Rpm. The table IV shows the simulation and practical readings of VSI set fed flux optimization controlled 5.4 Hp and 1Hp induction motor drive for the set speed of 1173 rpm and 1400Rpm. Figure 3 shows the efficiency Vs %load curve obtained for 5.4 Hp induction motor in Matlab Simulink by conducting load test. From this curve it is clear that maximum efficiency occurs for this motor at 44% of load. In this curve, point B is called as maximum efficiency point and point A is called as maximum efficiency load point.

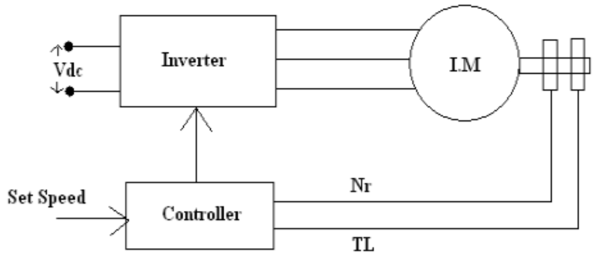

Figure 7.Block diagram for flux optimization control.

TABLE III. V/F Control

Simulation Results for 5.4Hp Motor				Practical Results for 1Hp Motor			
%Load	Input power (W)	Output Power (W)	%Efficiency	%Load	Input power (W)	Output Power (W)	%Efficiency
00.00	74	-	-	0	48	-	-
03.70	204	123	60.29	10	118	78	66.10
07.40	336	246	73.21	20	239	194	81.17
11.10	469	368	78.46	40	364	304	83.51
14.80	601	491	81.69	60	511	451	88.25
18.50	734	614	83.65	80	668	586	87.72
22.20	864	737	85.30	100	829	724	87.33
29.60	1123	983	87.53	-	-	-	-
33.30	1254	1105	88.11	-	-	-	-
42.55	1576	1412	89.59	-	-	-	-
50.00	1867	1658	88.80	-	-	-	-
100.0	3745	3316	88.54	-	-	-	-

In the flux optimization technique for every load condition from no load to maximum efficiency load point, the flux levels are decreased up to no change in their output power [4] , [28], [29], [37], [39]. Here maximum efficiency load point means, the %load at which maximum efficiency occurs. From the table III and IV it is clear that the output power are same for all the load condition and the input power was maximum in V/F control compared to flux optimization control up to maximum efficiency load point. In flux optimization control the flux levels are varied up to no change in their output so, the input power for the flux optimization control is reduced compared to V/F control. Thus efficiency of the motor drive is increased from no load to maximum efficiency load point compared to V/F control. The output power is calculated from equation (2).

TABLE IV. Flux Optimization Control

Simulation Results for 5.4Hp Motor				Practical Results for 1Hp Motor			
%Load	Input power (W)	Output power (W)	%Efficiency	%Load	Input power (W)	Output power (W)	%Efficiency
00.00	116	-	-	0	74	-	-
03.70	240	123	51.25	10	125	78	62.40
07.40	365	246	67.39	20	246	194	78.86
11.10	489	368	75.25	40	368	304	82.60
14.80	616	491	79.70	60	511	451	88.25
18.50	745	614	82.41	80	668	586	87.72
22.20	875	737	84.22	100	829	724	87.33
29.60	1133	983	86.76	-	-	-	-
33.30	1266	1105	87.28	-	-	-	-
42.55	1576	1412	89.59	-	-	-	-
50.00	1867	1658	88.80	-	-	-	-
100.0	3745	3316	88.54	-	-	-	-

Figure 8 shows the %efficiency Vs % load curve obtained for V/F and flux optimization scheme for 5.4Hp motor drive in Matlab Simulink. Figure 9 shows the %efficiency Vs % load curve obtained for V/F and flux optimization scheme for 1Hp motor drive in practical implementation. From figure 8 and 9 it is clear that efficiency is increased in flux optimization control compared to V/F control. In the flux optimization scheme energy saving is nearly 25% at light loads and energy saving goes on decreasing while load approaching towards full load. Figure 10 shows the experimental Setup for practical verification. So, flux optimization in induction motor drives leads to major energy conservation.

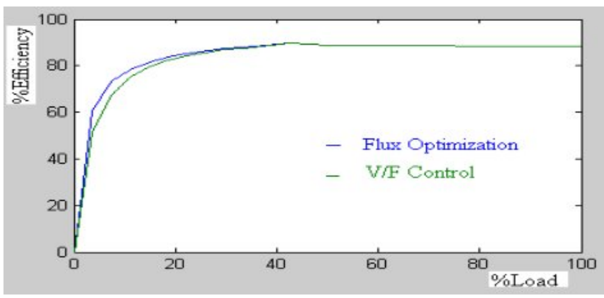

Figure 8. %Efficiency Vs % Load curve obtained for V/F and Flux optimization scheme for 5.4Hp motor drive in Matlab Simulink.

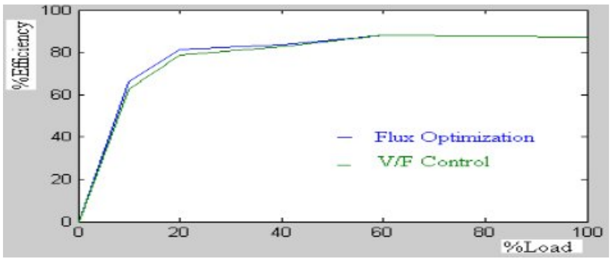

Figure 9. %Efficiency Vs % Load curve obtained for V/F and Flux optimization scheme for 1Hp motor drive in practical implementation.

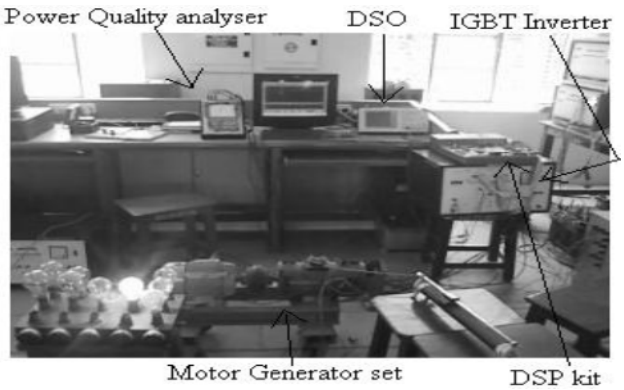

Figure 10.Experimental Setup for practical verification

11. Conclusion

Presented results shows the different ways of energy conservation in induction motor drive. From this review, higher energy conservation is achieved in methods such as selecting good quality cores and coils, flux optimization, automatic power factor correction, selecting suitable fixed capacitor for reactive power compensation, voltage balance and selecting suitable rating of motor corresponding to load. Smaller energy conservation is achieved in methods such as reducing losses at power electronic switches and proper cooling. This paper provides the information for the researchers of electrical energy conservation field.

APPENDIX A

V = Phase Voltage in Volts
VL = Line Voltage in Volts
I = Phase Current in Amps
F, f = Frequency in Hz
Nr = Rotor speed in Rpm
Ns = Synchronous Speed in Rpm
T = Load Torque in Nm
α = Angle between voltage and current
I.M = Induction Motor
Vdc = Constant DC Voltage
Hp = Horse Power
P = Number of Poles
W = Watts

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