MWh AND MVARh SAVING IN THREE PHASE INDUCTION MACHINE USING STAR-DELTA SWITCHING SCHEMES WITH SPWM

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***ABSTRACT*: Induction machines are the most commonly used industrial drives for variety of applications. In this paper, it has been demonstrated that the star-delta switching of stator winding of three-phase induction machine (motor / generator operations) reconnected in star at suitable reduced loads with a switching arrangement, can result in improved efficiency and power factor, as compared to a fixed delta or star connection. In such star-delta stator switching scheme, only two voltage settings are possible for the operation of the three-phase induction machine i.e. line voltage for normal operation (delta-connection) and (line voltage / √3) for reduced load conditions (star-connection). Hence, a Sinusoidal Pulse-Width-Modulated (SPWM) inverter is proposed to employ for feeding a variable voltage applied to the three-phase induction machine. In this context, a method has been evolved to find the optimum voltage fed to the induction machine for the improved performance. A case study on a 250 kW, 400 V, 4-pole, three-phase induction machine, operated with different load cycles, reveals the significant real and reactive power savings that could be obtained in the present proposal. In addition, for feeding the variable voltage to the induction machine, power and control circuit have been designed and fabricated in the laboratory. Experiments have been conducted and the results are presented. A MATLAB program has been developed for the predetermination of performance of the three-phase induction machine using exact equivalent circuit.**

***IndexTerms*: Real and Reactive power saving, case study of induction machine, phase controlled anti parallel thyristor bank, star-delta stator winding, SPWM, harmonics, predetermined values**

Introduction

In recent years, there is an increased emphasis on the energy saving in electrical apparatus and systems. Since Induction motors form major portion of electrical load in industries, two important factors – one concerning the design of the motors and the other relating to their operation need careful consideration. Reactive power/energy saving in induction machines can be principally achieved by minimising iron loss in the motors at a light load by means of decreasing the voltage impressed to the stator terminals [1-3]. A phase control circuit using anti-parallel thyristor units can be designed as a closed loop scheme for automatically adjusting the stator terminal voltage of induction motor depending on the load conditions. Computational procedure has been developed for predetermining the performance of the motor in terms of the firing angle and current hold off angle for the different mode of operation of the motor [3-4]. However, this method introduces harmonics in the motor and supply currents.

Depending upon the load, the applied voltage has to be varied to a large range and this is can be achieved by using power electronic controllers generally called as PWM-based controllers. These controllers are developed with power electronic devices like MOSFET, SCR, IGBT etc., and are highly used in application to control the voltage that applied to electrical apparatus and systems.

The controllers are generally operated at high frequency so that the voltage can be highly controlled as per requirement and higher order harmonic can eliminate easily using small rating filters. Generally the voltage of ac machines can control by inverter, the output voltage from an inverter can be adjusted in a large range and controlled by adjusting a control pulses within the inverter itself. The most efficient method of doing this is by controlling the pulse-width modulation control used in the inverter. In this method, a fixed dc input voltage is given to the inverter and a controlled ac output voltage is obtained by adjusting the on and off periods of the inverter components [3]. This is the most popular method of controlling the output voltage and this method is termed as Pulse-Width Modulation (PWM) Control. PWM inverters are quite popular in industrial applications. PWM techniques are characterized by constant amplitude pulses. The width of these pulses is however modulated to obtain inverter output voltage control and to reduce its harmonic content. The different PWM techniques are as under:

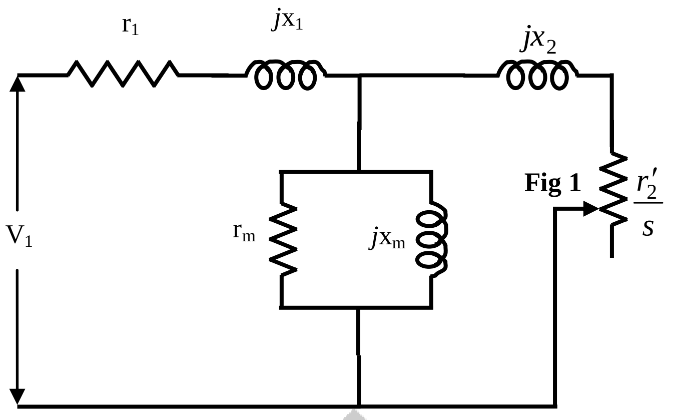
(a) Single-pulse modulation
(b) Multiple-pulse modulation
(c) Sinusoidal pulse-width modulation (Carrier based Pulse-Width Modulation Technique)

One of the most widely used PWM schemes for three-phase voltage source inverters are carrier-based sinusoidal PWM. The advantages possessed by these SPWM techniques are as under:

(i) The output voltage control with this method can be obtained without any additional components.

(ii) Lower order harmonics can be eliminated or minimized along with its output voltage control. As higher order harmonics can be filtered easily, the filtering requirements are minimized.

Equivalent Circuit of Three-Phase Induction Motor



A MATLAB program has been developed for the predetermination of performance of three-phase induction machine. The procedure to obtain the optimum voltage for different load conditions is presented. The predetermined results obtained on a 3-phase 400 V, 4-pole, 50 Hz, 3.75 kW, star/delta connected induction machine have also been presented. To improve the power factor and efficiency of the three-phase induction machine at light loads, it is recommended to lower its terminal voltage

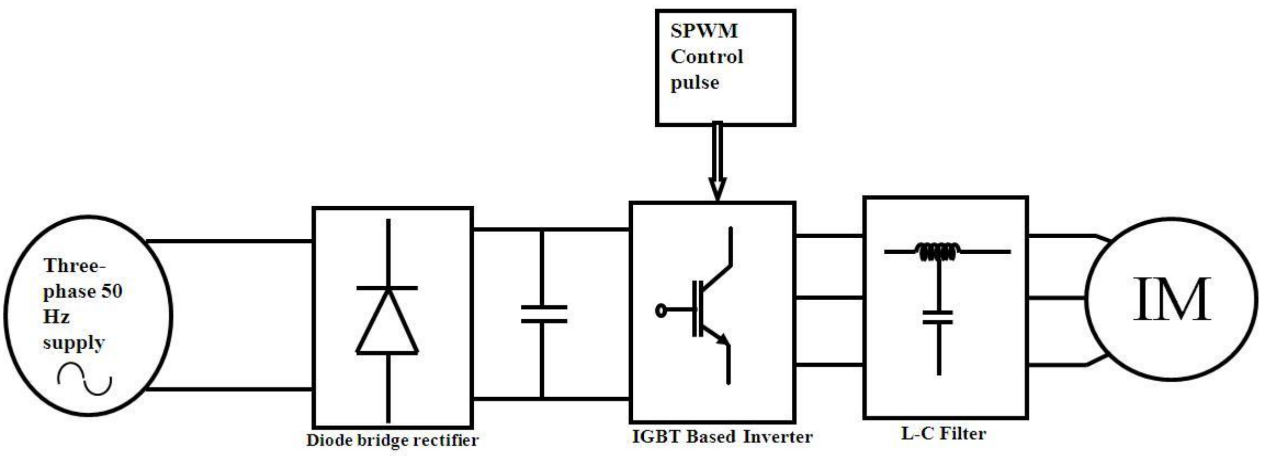
Need for voltage control in induction machines:

Normally, induction motors are designed with high power factor and efficiency at full load conditions. For example (refer the manufacturer data given in Appendix 1), a 415 V, 50 Hz, 110 kW, 750 rpm, three-phase squirrel-cage induction motor may have an efficiency of 93% and a power factor of 0.78 at full load condition. However, there are many applications wherein, over a major duration of the daily duty cycle, the motor works at much less than full load rating. At these reduced loads, both efficiency and power factor of operation become lower. To improve these performance values at reduced load conditions, the motor could be operated at a suitable lower voltage, thereby decreasing the core loss and magnetizing current and hence increasing the efficiency and power factor.

Even though induction machines are largely used for motoring operation, in recent times, with increased emphasis on renewable energy sources, induction generators are being increasingly used in wind farms in Wind Energy Electric Conversion Systems, for delivering power to the grid. Due to seasonal variation in wind speed, these generators deliver less than 25 % of the rated power, for more than 70 % of time in a year. So, for these generators also, reducing the stator applied voltage with decreasing wind speeds, would result in increased energy supplied to the grid and reduced reactive power drawn from the grid [6-8].

To obtain such suitable reduced voltages for application to induction motors or generators, use of three-phase phase control circuits employing anti-parallel thyristor units has been suggested [1-4, 9-10]. But with these circuits, a non-sinusoidal voltage is applied to the stator of the induction machine and these results in a non-sinusoidal current, leading to undesirable current harmonics in the supply lines. So, a method of reducing the applied phase voltage to the motor, without affecting its sinusoidal waveform would be very much desirable.

Three Phase Control Circuits



In applications requiring varying loads, a SPWM inverter fed induction motor operation would result in improved overall efficiency and power factor compared to a fixed stator connection and a two-stage star-delta operation.

From the Fig.2, the supply voltage can be varied efficiently and the controlling of inverter voltage can obtained by using SPWM controlled pulses, so that the lower order harmonics reduced and eliminated the higher order harmonic with small requirement of filter.

Comparison of Performance of Star and Delta Connected Induction Machine

When the motor is connected in delta connection the all predetermination which obtained from developed MATLAB program and experimental characteristics of induction motor is shown in Fig 3, Fig 4 and Fig 5.

Using the exact equivalent circuit of the motor, the following performance quantities of the motor / generator were calculated for various loads starting from the full load:

(i) Torque vs slip

(ii) Torque vs output power

(iii) input current vs output power

(iv) input power factor (PF) vs output power

(v) efficiency (η) vs output power

These results are given in Figs 3, Fig 4 and 5 at same stator line voltage are same for all the connections.

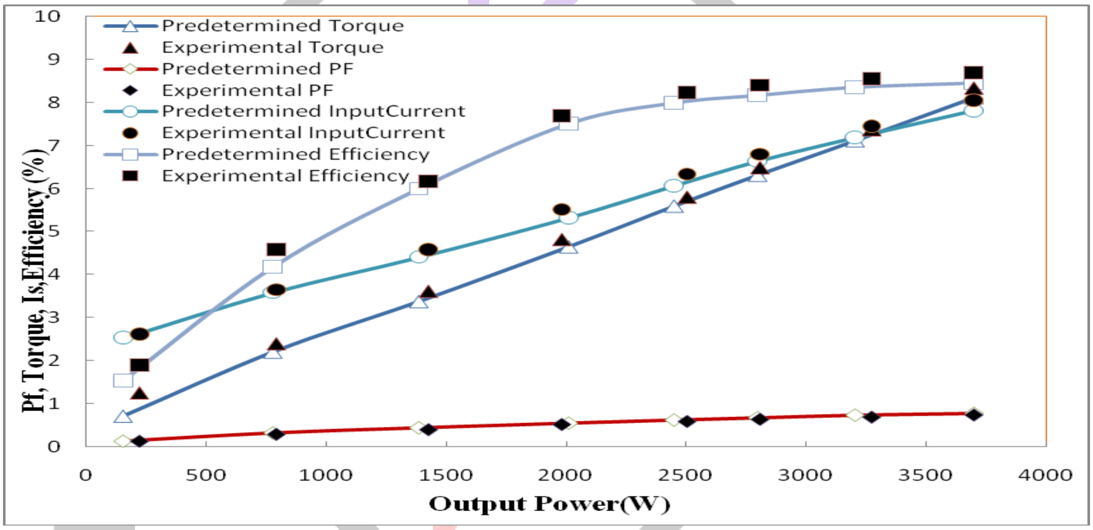


Fig 3 All Performance characteristics of three-phase 3.7 kW delta connected induction motor

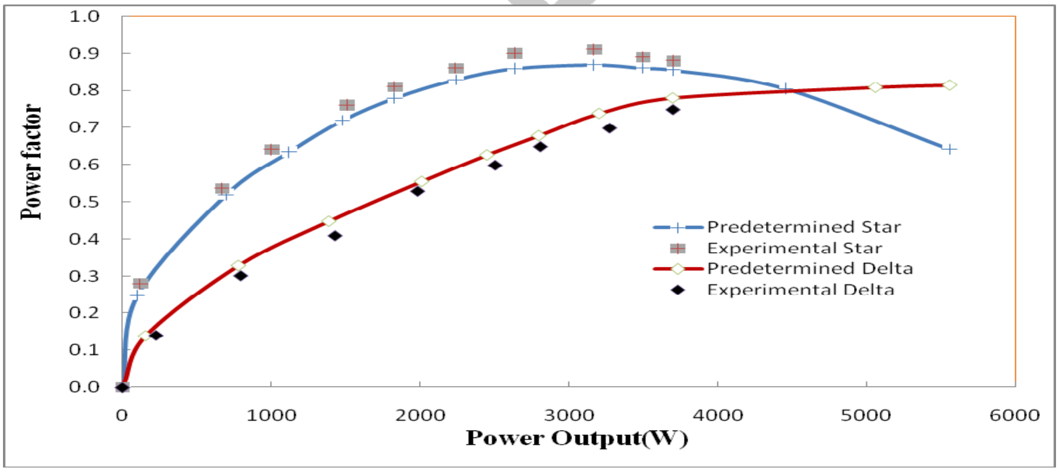


Fig 4 Comparison of power factor of three-phase 3.7 kW star-delta connected induction motor

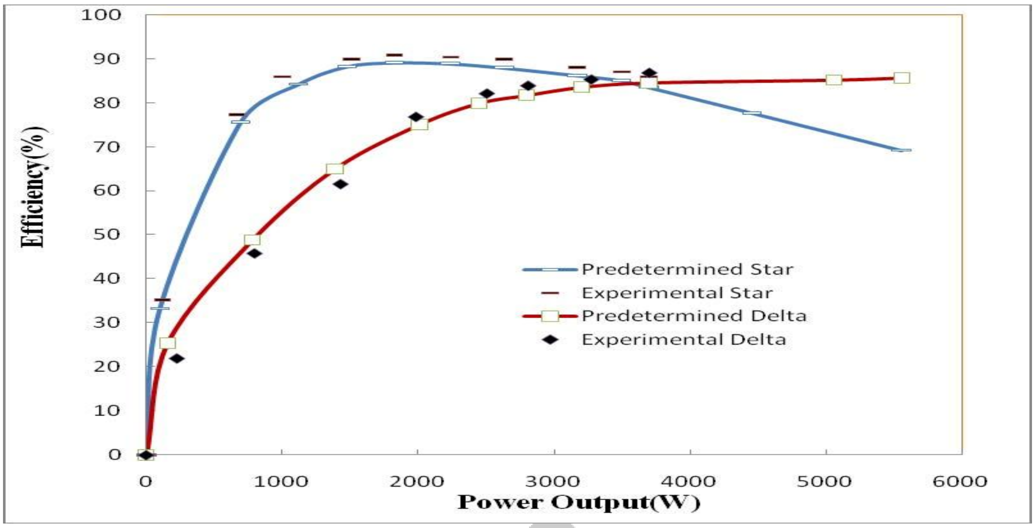


Fig 5Comparison of efficiency of three phase 3.7 kW star-delta connected induction motor

From Figs 3, Fig 4 and Fig 5, it is demonstrated that decreased power drawn from the grid in motor operation and increased PF are achievable, by incorporating a facility to operate the delta / star stator settings of the stator winding at appropriate power levels.

By comparing these star and delta connection the optimum voltage that could be applied to the induction motor can be determined and corresponding load at which it gives high power factor and efficiency. The voltages per section for each of the settings are as follows:

Stator connection	Voltage per section
(i) Delta (Δ)	VL
(ii) Star (Y)	VL/√**3**

If the motor connected with star settings the magnetizing current and iron loss reduce, thereby improving the power factor and efficiency leading to decreased kWh and kVARh drawn from the supply. That means up to certain load the motor has to be run in star connecting and after switch over to delta connection because of at reduced load the voltage should be low and further increased with increasing in load.

With an experimental machine, it has been demonstrated that, by switching the stator winding from delta and then to star settings at respective suitable reduced load conditions, high efficiency and power factor could be obtained as compared with fixed delta-connected stator winding.

In such star-delta stator switching scheme, only two voltage settings are possible for the operation of the three-phase induction machine i.e. line voltage for normal operation (delta-connection) and line voltage / √3 for reduced load condition (star-connection). But, in case of the proposed scheme of SPWM based inverter fed induction motor control of applying optimum voltage to the stator winding with different load conditions, results in a improved efficiency compared to the other methods.

Calculations of energy Savings for Motoring Operation

A three-phase, 4-pole, 400 V, 250 kW induction motor with a delta / star stator winding is considered. Typical resistance and reactance parameters (all in terms of stator) for this machine are R1 = 0.033 Ω, R2 = 0.025 Ω, X1 = 0.150 Ω, X2 = 0.150 Ω, Rm = 40.0 Ω and Xm = 5.250 Ω.

For the calculation of kWh and kVARh taken by the motor, the loading pattern of the motor over the day is to be known and it depends on the application of the motor. For the present study, two loading patterns given in Table 1 are considered.

Table 1 Loading patterns considered for the motor over a day

Loading	Numbers of hours in a day at each loading
	Pattern 1
Full load	3
(3/4) Full load	3
(1/2) Full load	3
(1/3) Full load	3
(1/4) Full load	3
(1/5) Full load	3
(1/10) Full load	3
No load	3

Table 2 to Table prove the benefit of using the optimum voltage control, with each of the loading pattern given in Table 1, the kWh and kVARh taken by the motor in a day, are calculated for the following cases:

(i) No switching (i.e., motor operated only in delta connection at all loads)

(ii) motor operated with the two-stage star-delta switching
(i.e. with delta connection in the range of 250 kW to 140 kW and in the star connection in the range of 140 kW to no-load)

(iii) motor operated with delta and the optimized voltage supplied from the SPWM inverter

Table 2 Daily kWh and kVARh taken by the 250 kW case study motor for loading pattern 1 with fixed delta stator winding connection

Loading	Pout kW	Connection	Time hours	Pin kW	Qin kVAR	kWh	kVARh
Full load	250.00	Delta	3	270.73	132.52	812.19	397.56
(3/4) Full load	187.50	Delta	3	204.20	112.36	612.60	337.08
(1/2) Full load	125.00	Delta	3	138.97	98.78	416.91	296.34
(1/3) Full load	83.33	Delta	3	96.13	93.02	288.39	279.06
(1/4) Full load	62.50	Delta	3	74.90	91.08	224.70	273.24
(1/5) Full load	50.00	Delta	3	62.20	90.20	186.60	270.60
(1/10) Full load	25.00	Delta	3	36.96	89.08	110.88	267.24
No load	0.00	Delta	3	14.39	88.78	43.17	226.34
					Total for a day	**2695.44**	**2387.46**

Table 3 Daily kWh and kVARh taken by the 250 kW case study motor for loading pattern 1 for two-stage stator switching (stator winding connection for each load is also indicated)

Loading	Pout kW	Connection	Time Hours	Pin kW	Qin kVAR	kWh	kVARh
Full load	250.00	Delta	3	270.73	132.52	812.19	397.56
(3/4) Full load	187.50	Delta	3	204.20	112.36	612.60	337.08
(1/2) Full load	125.00	Star	3	136.20	65.77	408.60	197.31
(1/3) Full load	83.33	Star	3	90.24	44.17	270.72	132.51
(1/4) Full load	62.50	Star	3	68.07	37.45	204.21	112.35
(1/5) Full load	50.00	Star	3	54.97	34.49	164.91	103.47
(1/10) Full load	25.00	Star	3	29.21	30.72	87.63	92.16
No load	0.00	Star	3	6.46	29.6	19.38	88.8
					Total for a day	**2580.24**	**1461.24**

Table 4 Daily kWh and kVARh taken by the 250 kW case study motor for loading pattern 1 with fixed delta stator winding connection supplied by optimum voltage

Loading	Pout kW	Connection	V_{opt}	Time hours	Pin kW	Qin kVAR	kWh	kVARh
Full load	220.31	Delta	**400**	3	282.11	102.39	846.34	307.18
(3/4) Full load	180.06	Delta	**400**	3	193.37	82.21	580.10	246.62
(1/2) Full load	128.04	Delta	**400**	3	132.00	71.25	396.00	213.74
(1/3) Full load	64.85	Delta	**300**	3	64.69	37.65	194.06	112.95
(1/4) Full load	39.58	Delta	**240**	3	38.81	23.57	116.43	70.70
(1/5) Full load	23.40	Delta	**180**	3	23.24	13.79	69.72	41.37
(1/10) Full load	5.85	Delta	**90**	3	5.81	3.45	17.43	10.34
No load	0	Delta	**50**	3	2.39	1.78	7.17	5.34
					Total for a day		**2221.25**	**1008.24**

Let the motor be operated with a fixed stator connection from full load to no- load namely, delta connection itself.

Taking the single setting as the reference, the percentage saving in kWh and kVARh in the two-stage switching and optimum supply voltage is also shown in the Table 3.5. It can be concluded that, compared to the fixed stator connection and the two-stage operation, the SPWM fed inverter supplying optimum voltage gives an increased saving in

kWh and kVARh. Consequently, in industries employing a number of medium or large size three-phase induction motors, there will be a reduction in the Energy bill and overall kVA demand and hence in the kVA tariff. This increase in saving becomes more and more in the case of motors working at light loads for greater time duration in a day.
Table 5 Comparison of kWh and kVARh for optimum supply voltage, two-stage and single setting stator connections for loading patterns for the 250 kW case study motor

Loading pattern	Single Setting (delta)		Two Settings (delta and star)				SPWM based inverter supplying optimum voltage			
	kWh	kVARh	kWh	kVARh	% saving in kWh	% saving in kVARh	kWh	kVARh	% saving in kWh	% saving in kVARh
1	**2695**	**2387**	**2580**	**1461**	**4.27**	**38.79**	**2221**	**1008**	**17.58**	**57.76**

Conclusion

It has been estimated that induction motors consumes approximately 50 % of all the electric energy generated. Further, it may be mentioned that a star-delta switching is common for starting the three-phase induction motor. This star-delta switching scheme may be employed for energy conservation of induction machines i.e., at times of reduced loads, the machine switched back to star connection. The detailed analysis and performance of the induction machine with such star-delta switching scheme have been attempted in phase-I of the project and shown that the performance of the induction motor results in improved efficiency and power factor, as compared to a fixed delta or star connection. The efficiency of a lightly loaded induction motor can substantially be improved by controlling the voltage applied to it. In addition, controlling the voltage also improves the power factor of the induction motor at light load conditions. So, in this proposal, an attempt has been made to employ a SPWM inverter for feeding a variable voltage applied to the three-phase induction machine. Procedure has been devised to obtain the optimum voltage fed to the induction motor for the improved performance and the details are presented in this report.

Since the proposal is economical for medium and large size motors, an example of a250 kW induction motor with typical parameter values has been considered for a case study. The usefulness of the SPWM inverter fed induction machine is illustrated with certain assumed load cycles on the motor. It is shown that a significant savings can be obtained due to the reduced energy (kWh) and kVARh drawn from the grid, if the motor fed with optimum voltage at times of reduced loads.

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