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Real And Reactive Power Saving In Three Phase Induction Machine Using Star-Delta Switching Schemes

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ABSTRACT: Induction machines are the most commonly used industrial drives for variety of applications. It has been estimated that induction motors consumes approximately 50 % of all the electric energy generated. Further, in the area of renewable energy sources, such as wind or bio-mass energy, induction machines have been found suitable for functioning as generators. In this context, it may be mentioned that a star-delta switching is common for the starting of three-phase induction motor. Now, it is proposed to use this star-delta switching for energy conservation of induction machines, i.e., at times of reduced loads, the machine switched back to star connection. Using a three-phase, 400 V, 50 Hz, 4-pole induction machine, 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. The predetermined values along with the experimental results have also been presented in this report. A simulation program has been developed for the predetermination of performance of the three-phase induction machine using exact equivalent circuit. 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.

Index Terms: Real and Reactive power saving, light loading, case study of induction machine, phase controlled anti parallel thyristor bank, star-delta switching, harmonics, predetermined values

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1 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, 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. It is also known that the simple star-delta switch commonly used for starting delta connected induction motors can also be employed for running the motor in star connection during the periods of reduced loads. The maximum load for star connection can be about 40 % of the rated load, the applied voltage being reduced by 1/√3 times of normal value. In this paper it is proposed that this star-delta configuration can be more profitably used for improving the power factor and efficiency of operation of the motor/ generator at reduced load conditions.

EXACT EQUIVALENT CIRCUIT OF THREE-PHASE INDUCTION MACHINE

Exact equivalent circuit shown in fig.1 determines the total performance of induction machine and the expression for the various performance quantities are calculated as per the following equations [5]:

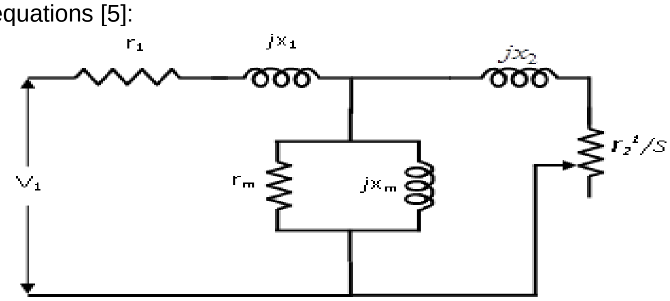

Fig. 1 *Equivalent circuit of induction machine*

Stator impedance $Z_1=r_1+jx_1$

$E1=V1*Z^1_{2S}/(Z_1+C_1*Z^1_{2S})$

Where $C_1=1+Z_1Y_m$

$I_2^1=E_1/Z^1_{2S}$, $Z^1_{2S}=(r_2^1/s)+jx_2^1$

Rotor input$=I_2^1 r_2^1/s$

Rotor losses $= I_2^1 r_2$

Rotor output $Pm= I_2^1 r_2^1/s$ -losses

Torque$= V_1^2 * r21/s /[(r_1+ r_2^1/s)^2+(x+C_1x_2^1)^2]$

$I_1=I_2^1(1+Y_mZ_{2S}^1)$

Stator input $P1 = V_1 I_1 \cos \square_1$ (2.9)

Efficiency $(\eta) = P_m/P_1*100$ (2.10)

STAR- DELTA SWITCHING

Applications requiring varying loads, a two-stage star-delta operation would result in improved overall efficiency and power factor compared to a fixed stator connection. For this two-stage operation, it requires six terminals to be taken out to the machine terminal box. Based on the load variation on the machine, the stator winding has to be switched from one setting to the other. Such a controller can be built as a solid state configuration, using 5 pairs of anti-parallel thyristor units as shown in Fig. 2, suitable for the proposed two-stage switching. Appropriate thyristor units should be given gate pulse and switched-on to obtain the required stator connections. The thyristor units to be switched-on and the corresponding stator connections are given in Table 1. Starting with the delta-connected stator at full load, star-connection will be used during suitable reduced loads. Thus, with the same sinusoidal applied line voltage (V_L) to the motor terminals, the voltage per section for each of the settings are as follows:

	Stator connection	Voltage per section
(i)	Delta (Δ)	V_L
(ii)	Star (Y)	$V_L/\sqrt{3}$

Table 1

Thus, 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.

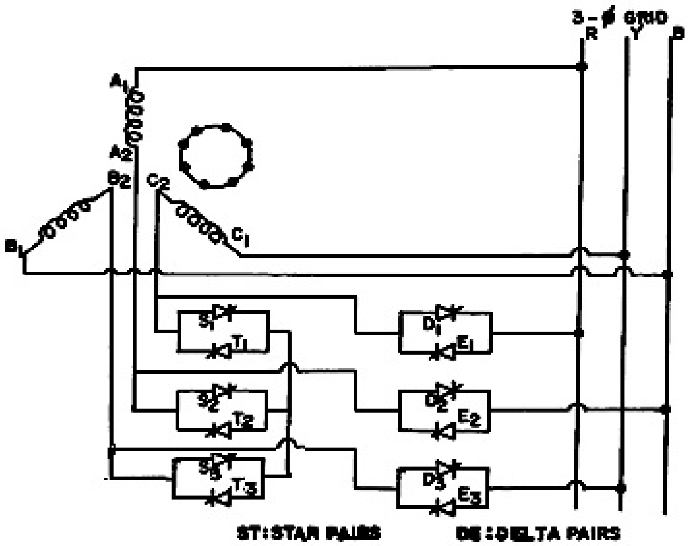

Fig. 2 *Star-delta switching circuit (two-stage operation)*

The delta / star settings of stator winding connections and the corresponding thyristor units to be switched-on

Stator winding connection	Thyristor units to be given gate pulse
Delta	D1, D2, D3, E1, E2 & E3
Star	S1, S2, S3, T1, T2 & T2

Table 1

CALCULATIONS OF 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 R_1 = 0.033 Ω, R_2 = 0.025 Ω, X_1 = 0.150 Ω, X_2 = 0.150 Ω, R_m = 40.0 Ω and X_m = 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. 2 are considered.

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

Table. 2 *Loading patterns considered for the motor over a day*

To prove the benefit of using the two-stage switching, with each of the loading pattern given in Table 2, the kWh and kVARh taken by the motor in a day are calculated for the following cases:

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

For any given load on the motor, the real power (kW) and reactive power (kVAR) input to the motor can be calculated. Then, kWh and kVARh can be calculated taking into account, the time duration at each load setting. As an example, such calculations made with loading pattern 1, are given in Table. 3. Table. 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	P_{out} kW	Connection	Time Hours	P_{in} kW	Q_{in} kVAR	kWh	kVARh
Full load	250	Delta	3	270.73	132.52	812.19	397.56
(3/4) Full load	187	Delta	3	204.20	112.36	612.60	337.08
(1/2) Full load	125	Star	3	136.20	65.77	408.60	197.31
(1/3) Full load	83	Star	3	90.24	44.17	270.72	132.51
(1/4) Full load	63	Star	3	68.07	37.45	204.21	112.35
(1/5) Full load	50	Star	3	54.97	34.49	164.91	103.47
(1/10) Full load	25	Star	3	29.21	30.72	87.63	92.16
No load	0	Star	3	6.46	29.6	19.38	88.8
Total for a day						**2580.24**	**1461.24**

Table 3

Let the motor be operated with a fixed stator connection from full load to no-load namely, delta connection itself. The kWh and kVARh calculations made with loading pattern 1 are given in Table. 4. Table. 4 Daily kWh and kVARh taken by the 250 kW case study motor for loading pattern 1 with fixed delta stator winding connection

Loading	P_{out} kW	Connection	Time hours	P_{in} kW	Q_{in} kVAR	kWh	kVARh
Full load	250	Delta	3	270.73	132.5	812.19	397.56
(3/4) Full	187	Delta	3	204.20	112.3	612.60	337.08
(1/2) Full	125	Delta	3	138.97	98.78	416.91	296.34
(1/3) Full	83	Delta	3	96.13	93.02	288.39	279.06
(1/4) Full	62	Delta	3	74.90	91.08	224.70	273.24
(1/5) Full	50	Delta	3	62.20	90.20	186.60	270.60
(1/10) Full	25	Delta	3	36.96	89.08	110.88	267.24
No load	0	Delta	3	14.39	88.78	43.17	226.34
Total for a day						2695.4	2387.46

Table. 4

For each of the above two cases, similar calculations were made for the other loading pattern listed earlier in Table. 2. The summary of kWh and kVARh values is given in Table. 5 . Taking the single setting as the reference, the percentage saving in kWh and kVARh in the two-stage switching is also shown in the Table 5. It can be concluded that, compared to the fixed stator connection, the two-stage operation 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 two-stage and single setting stator connections for the different loading patterns for the 250 kW case study motor

Loading pattern	Single Setting (delta)		Two Settings (delta and star)			
	kWh	kVARh	kWh	kVARh	% saving kWh	% saving kVARh
1	2695	2387	2580	1461	**4.27**	**38.79**
2	2098	2300	1957	1202	**6.72**	**47.74**

Table. 5

Note: Percentage saving is with respect to single setting.

CALCULATIONS OF SAVINGS FOR GENERATOR OPERATION

The usefulness of this two-stage controller is illustrated, with a case study on the same three-phase, 400 V, 50 Hz, 250 kW, 4-pole squirrel-cage induction motor considered in section 4.2, now used for generator operation, when the rotor is driven by a wind turbine above synchronous speed. As explained in earlier section, in the case of induction motor, the mechanical load on the motor varies as the application demands. In the case of induction generator, the mechanical input to the generator from the wind turbine, varies as per the annual seasonal variations in the wind velocity in a given location. Hence the electrical power output of the generator fed to the grid varies with wind speed. The data regarding the wind velocity variation over one year period and the corresponding mechanical input for a 250 kW wind turbine is given in Table. 6 [7]. This table shows Mechanical power input to a wind driven generator versus the time duration over one year period To prove the benefit of using the two-stage switching, the kWh supplied to the grid and kVARh taken by the generator are calculated on an annual basis (since wind speed varies seasonally over a one year period). Such calculations were made for the following cases:

S. No.	Mechanical power input to the generator kW	Time duration, Hours
1.	15.08	1048
2.	30.16	2177
3.	57.30	2419
4.	87.46	1048
5.	111.59	484
6.	147.78	404
7.	183.97	484
Total (24 hours x 12 months x 28 days)		8064

Table. 6

i. generator operated with the two-stage star-delta switching i.e. with delta connection in the 266 kW to 150 kW range and in the star connection in the 150 kW to no-load range
ii. generator operated only in delta connection throughout the power range of operation i.e., at all wind speeds

For any given input to the generator, the real power output (kW) of the generator and reactive power (kVAR) input to the generator can be calculated. Then, kWh and kVARh can be calculated taking into account the time duration for each power output of the generator. So, with two-stage switching, such calculations made are given in Table.7. Let the generator be operated with a fixed stator connection from full load to no-load with delta connection itself. Table. 7 kWh and kVARh obtained with two-stage stator switching for the 250 kW case study generator (stator winding connection for each power output are also indicated)

Table.7 *the kWh and kVARh obtained with two winding star-delta stator winding connection*

P_{in} kW	Connection	Time hours	P_{out} kW	Q_{in} kVAR	kWh	kVARh
15.08	Star	1048	11.03	30.06	11,559	31,503
30.16	Star	2177	25.86	31.30	56,297	68,140
57.30	Star	2419	52.11	35.44	1,26,054	85,729
87.46	Star	1048	80.66	69.81	84,532	41,721
111.59	Star	484	103.00	51.11	49,852	24,737
147.78	Star	404	135.62	67.36	54,790	27,213
183.97	Delta	484	167.88	108.78	81,254	52,650
Annual Total					**4,64,338**	**3,31,693**

Table. 7

Table.8 *kWh and kVARh obtained with fixed delta stator winding connection*

P_{in} kW	Connection	Time hours	P_{out} kW	Q_{in} kVAR	kWh	kVARh
15.08	Delta	1048	3.18	88.99	3,333	93,262
30.16	Delta	2177	18.17	88.99	39,556	1,94,754
57.30	Delta	2419	45.01	90.95	1,08,879	2,20,008
87.46	Delta	1048	74.62	93.58	78,202	98,072
111.59	Delta	484	98.15	96.41	47,505	46,662
147.78	Delta	404	133.17	101.87	53,801	41,155
183.97	Delta	484	167.88	108.78	81,254	52,650
Annual Total					4,12,530	7,46,563

Table. 8

The summary of kWh and kVARh values is given in Table 4.8. Taking the single setting as the reference, the percentage increase in kWh and percentage decrease kVARh in the two-stage switching is also shown in the Table 4.8. It can be concluded that, compared to the fixed stator connection, the two-stage operation gives an increased energy fed to the grid and reduced kVARh drawn from the grid. Table. 9 Comparison of kWh and kVARh for two-stage and single setting stator connections for the different loading patterns for the 250 kW case study Generator

Single Setting (delta)		Two Settings (delta and star)			
kWh	kVARh	kWh	kVARh	% increase in kWh	% saving kVARh
4,12,530	7,46,563	4,64,338	3,31,693	**12.56**	**55.57**

Table. 9

Note: Percentage increase / saving is with respect to single setting.

CONCLUSION

Detailed analysis of performance of the induction machine in the delta and star settings has been presented. It is shown that the machine can be designed for a given voltage and power rating to operate with delta for above 40% rated load and then switched to star at reduced load conditions for improving power factor and efficiency. This has been demonstrated with experimental results on a three-phase, 4-pole, 50 Hz, 400 V, 3.70 kW induction machine. Both predetermined and experimental results obtained on the induction machine are presented. Further, it is of interest to predetermine the quantum of improvement in power factor when the induction machine is switched to star connection from delta

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