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A REVIEW ON ENERGY ENHANCEMENT IN GRID CONNECTED SQUIRREL CAGE INDUCTION GENERATOR

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Abstract-- **This paper presents a scheme for improving the power output of Grid Connected Induction Generator (GCIG) commonly used in Wind Energy Conversion Systems (WECS). In general, induction generators are connected in star with line voltage equal to √3 times of the rated winding voltage to yield a lower line current and smaller diameter conductor. In the proposed scheme√3 times of the rated winding voltage for higher wind speed and rated winding voltage for low wind speed is applied to the star connected stator. It has been experimentally demonstrated that with a suitable microcontroller based switching arrangement the proposed scheme results in increased output power. Moreover the switching transient is also significantly decreased during switching between low and high wind speeds. The result of the proposed scheme is also compared with the star delta switching scheme to validate the performance of the proposed scheme. A case study on a 3Φ 50kW, SCIG has been presented to emphasize the performance improvement with the proposed scheme.**

Index Terms-- **Delta-star switching, SCIG, WECS**

I. Nomenclature

v	Instantaneous voltage (V)
i	Instantaneous current (A)
V	Per-phase steady-state voltage (V, rms)
I	Per-phase steady-state current (A, rms)
R	Resistance (Ω)
X	Reactance (Ω)
Z	Impedance (Ω)
L	Inductance (H)
P	Real power (W)
Q	Reactive power (VAR)
s	Slip
ω_{ms}	Angular frequency of stator flux rad/s (electrical)
ω_e	Angular speed of rotor rad/s (electrical)
η	Efficiency
First subscripts	
r	Rotor
s	Stator
m	Mutual
M	Mechanical
i	Iron loss
loss	Total loss
Second subscripts	
cu	Copper loss
d	Direct axis
q	Quadrature axis

II. Introduction

THE global electrical energy utilization is increasing and there is a steady increase in the demand for power generation. The available conventional energy sources are fast depleting and hence alternative energy source investment is becoming more important these days [1]-[2].The Squirrel Cage Induction Generator (SCIG) is quite popular in wind turbine systems due to its simpler, rugged construction, reduced maintenance and low cost [3]. In recent years, variable speed Doubly Fed Induction Generators (DFIG) are also being deployed to improve the voltage regulation, power output and to reduce the size of converter in the WECS [5]. DFIG supports wide speed range typically ±30% of synchronous speed and the rotor energy can be fed back to the grid using power converters. The power converter controls the rotor frequency and thus the rotor speed. However, lot of research is going on to improve the performance of SCIG. The existing SCIG can be utilized effectively by adding suitable controllers to improve the performance of the system [6]-[7]. The induction generators are operated in grid connected [8] or stand-alone modes [9]. The induction generators always need reactive power to generate real power. In self excited induction generator (stand-alone), the excitation current is supplied by the capacitors connected at the stator terminals. In Grid Connected Induction Generator (GCIG), the reactive power required by the machine is provided by the grid [10]-[12].

It is known that due to seasonal variations the wind velocity is not constant. Most wind power sites experience high wind speeds only for a few hours per day [13]. Depending upon the wind speed, the generated power also varies. Therefore the efficiency and power factor of these generators are low at low wind speeds. In such cases, the generator efficiency can be marginally improved by pole changing method [14]-[15]. In this method, two schemes of windings are provided for the stator so as to change the synchronous speed of the machine according to the number of poles in the winding scheme. The additional winding placed at the bottom of the slots increases the weight and the slot leakage reactance of the machine.

To improve the performance of the induction generator or

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motor in terms of efficiency and power factor, De Almeida et al [16] proposed a change of the stator winding connection based on the load of the machine. The stator winding is connected in delta at heavy loads and in star at low loads. These changes in stator winding improve the efficiency of the machine. Likewise Hughes [17] developed a star-delta parallel combination of three phase winding to reduce the space harmonics as compared to that with the conventional star or delta connection. The conventional three phase 60° spread winding is divided into a delta component and star component winding. The two components are connected in parallel across the same supply with a time displacement of 30°.This method of connection for the three phase winding give high spread factor and reduced the harmonic content.

Kumaresan et al [18]-[21] proposed a delta-star configuration for wind generator in which the stator winding is connected in series star for low wind speeds, series delta for medium and delta-star for high wind speeds and changing the stator winding connection from star to delta and vice versa creates heavy transients in line current [22]-[23]. Further, 12 terminals are taken out from the stator winding for external connection to the grid and the presence of 3rd harmonics in delta connected stator winding increases the power losses. In 2001 M. A. Abdel-Halim [24] developed a solid state control circuit for a grid connected induction generator connected using a transistorized AC voltage controller. In 2004 Almarshoud A. F. et.al [25] presented an analysis of a grid connected induction generator using anti parallel thyristor. In 2012, P raja et al [6] has modified the star delta switching scheme by including a permanent capacitor across each phase winding of the stator of the generator. This addition of capacitor reduces the reactive power taken by the generator from the grid. Christo Ananth et al.[4] presented a brief outline on Electronic Devices and Circuits which forms the basis of the Clampers and Diodes.The circulating 3rd harmonics current and the switching transients are not considered in the above analysis which increases the current rating of equipments which are connected to the stator terminal [6], [18]-[21].

This paper proposes a scheme for improving the performance of IG by connecting the machine stator winding permanently in star while the winding voltage levels are switched based on the wind speed. Rated voltage of the winding is applied during low wind speeds and a higher than the winding voltage is applied during high wind speeds. Connecting the stator winding permanently in star has the benefits of eliminating the circulating current which exists in a delta connected stator winding [26]. Moreover, the switching transient is also significantly decreased when switching between low and high wind speeds. Detailed studies are carried out using the laboratory setup consisting of a 3-Φ, 220 / 380 V (Δ / Y), 50 Hz, 1-HP grid connected SCIG. A dc motor is used as the prime mover to emulate the wind turbine. A microcontroller-based thyristor switching unit has been developed, for implementing the delta-star switching and also the proposed dual voltage switching.

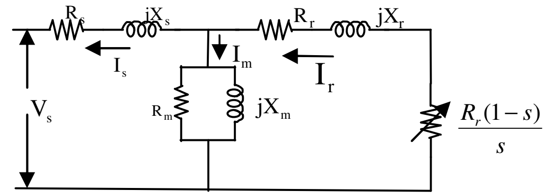

Fig. 1. Equivalent circuit of an Induction Generator

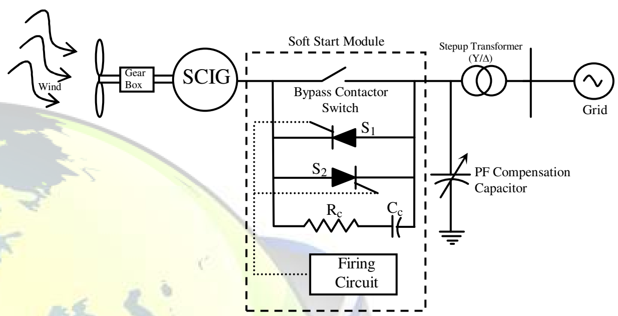

Fig. 2. Schematic of a Wind Energy Conversion System

III. Analysis of System Performance

In this section, the theoretical basis for predicting the steady-state and the dynamic performance of the wind power generating system are explained .

A. *Steady State Operation*

Fig. 1 shows the per phase equivalent circuit of a grid connected induction generator.

The mechanical power delivered is determined by

$$P_M = \frac{I_r^2 R_r (1-s)}{s} \tag{1}$$

The efficiency of the machine is calculated by segregation of losses, which are divided into fixed and variable losses. Fixed losses are magnetic core loss and friction and windage loss. Variable losses include stator and rotor copper loss. The total losses in the generator are calculated by using the equivalent circuit parameters.

$$P_{loss} = P_i + P_{scu} + P_{rcu} \tag{2}$$

The total magnetization loss of the induction machine is calculated from the parallel resistance and reactance.

$$P_i = \frac{\left(V_s + I_s(R_s + jX_s)\right)^2}{R_m} \tag{3}$$

The copper loss in the stator of the induction generator is

$$P_{scu} = I_s{}^2 R_s \tag{4}$$

energy. This can be expressed by the following equation

$$\eta = \frac{P_M - P_l}{P_M} \tag{5}$$

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The above equation are used to determine the steady state performance of the induction generator for a given slip

B. Dynamic Modeling

The d-q axes model of the induction machine is considered for the dynamic analysis where d-axis is aligned with stator flux and q-axis is aligned with stator voltage. The dynamic equations governing the stator and the rotor currents in the stator flux coordinates is written as

$$L_s \frac{d}{dt}(i_{sq}) = v_{sq} - R_s i_{sq} - (\omega_{ms})(L_s i_{sd} + L_o i_{rd}) - L_o \frac{d}{dt}(i_{rq}) \quad (6)$$

$$L_s \frac{d}{dt}(i_{sd}) = v_{sd} - R_s i_{sd} - (\omega_{ms})(L_s i_{sq} + L_o i_{rq}) - L_o \frac{d}{dt}(i_{rd}) \quad (7)$$

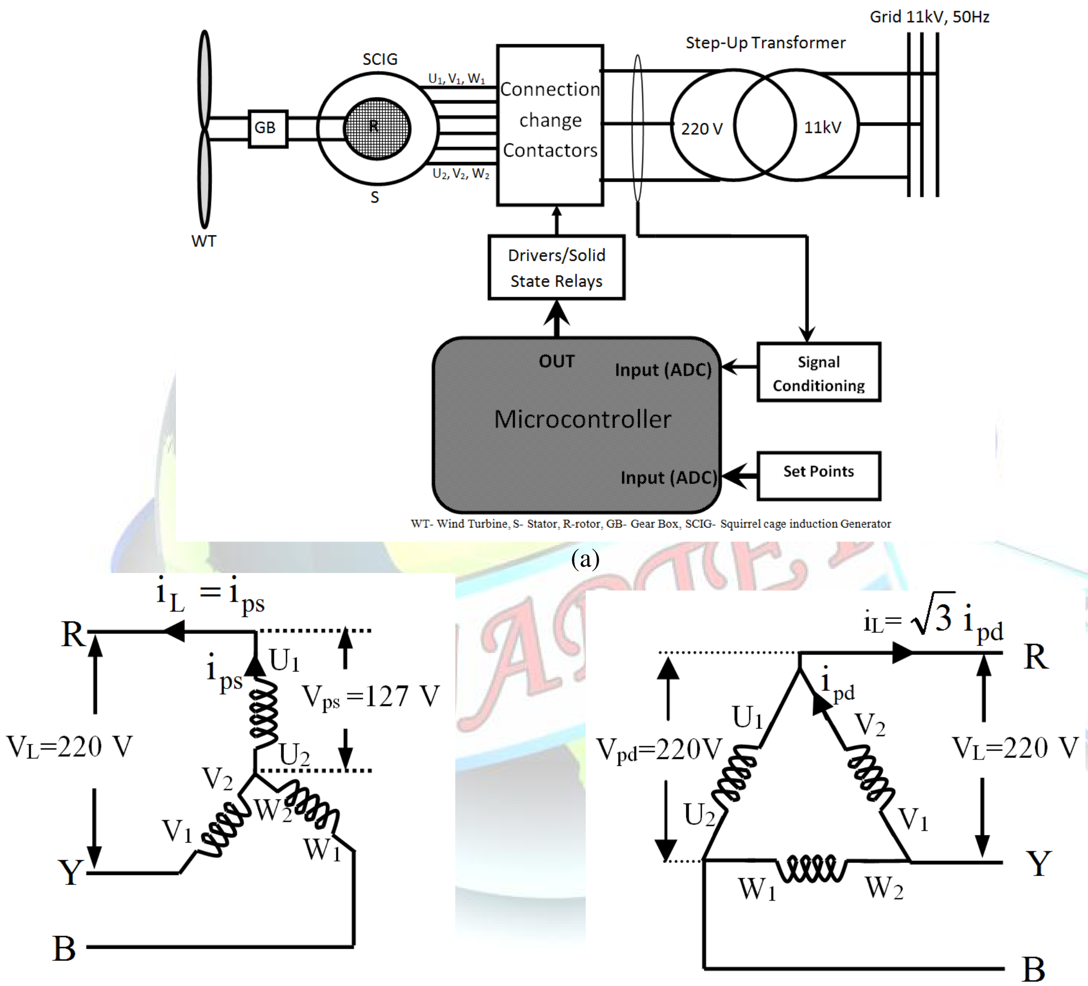


Fig. 3. Delta-star switching scheme, (a) Hardware details of delta-star switching scheme and its control,(b)Star connected stator winding for low wind speed, (c) Delta connected stator winding for high wind speed.

$$L_r \frac{d}{dt}(i_{rq}) = v_{rq} - R_r i_{rq} + (\omega_{ms} - \omega_e)(L_r i_{rd} + L_o i_{sd}) - L_o \frac{d}{dt}(i_{sq}) \quad (8)$$

$$L_r \frac{d}{dt}(i_{rd}) = v_{rd} - R_r i_{rd} + (\omega_{ms} - \omega_e)(L_r i_{rq} + L_o i_{sq}) - L_o \frac{d}{dt}(i_{sd}) \quad (9)$$

The developed electromagnetic torque T_e in d-q variables is given as,

$$T_e = \frac{3}{2}\left(\frac{p}{2}\right) L_o \left(i_{sq} i_{rd} - i_{sd} i_{rq}\right) \quad (10)$$

Equation (6)-(10) are used to develop the generator model for analyzing the dynamic response of the machine

IV. SYSTEM DESCRIPTION

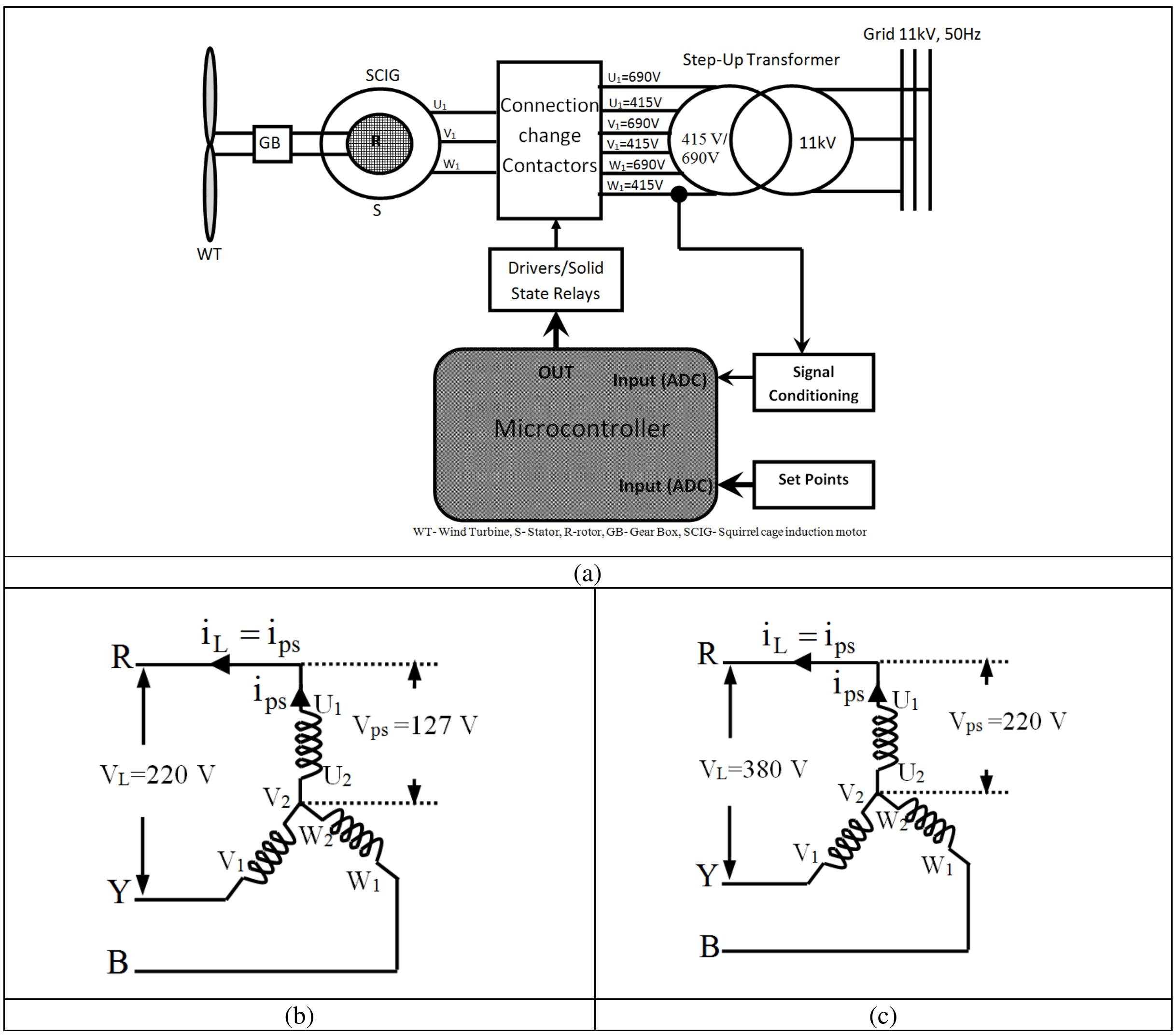
The main components of a wind turbine system are the turbine rotor, a gear box, a generator, a power electronic system and a transformer for grid connection. Fig. 2 shows the schematic of a wind energy conversion system in which the wind energy is converted into electrical energy using wind generator [27]. The electrical power from the generator is fed into a grid through a soft start module and a transformer with circuit breakers and electricity meters [28]-[29].

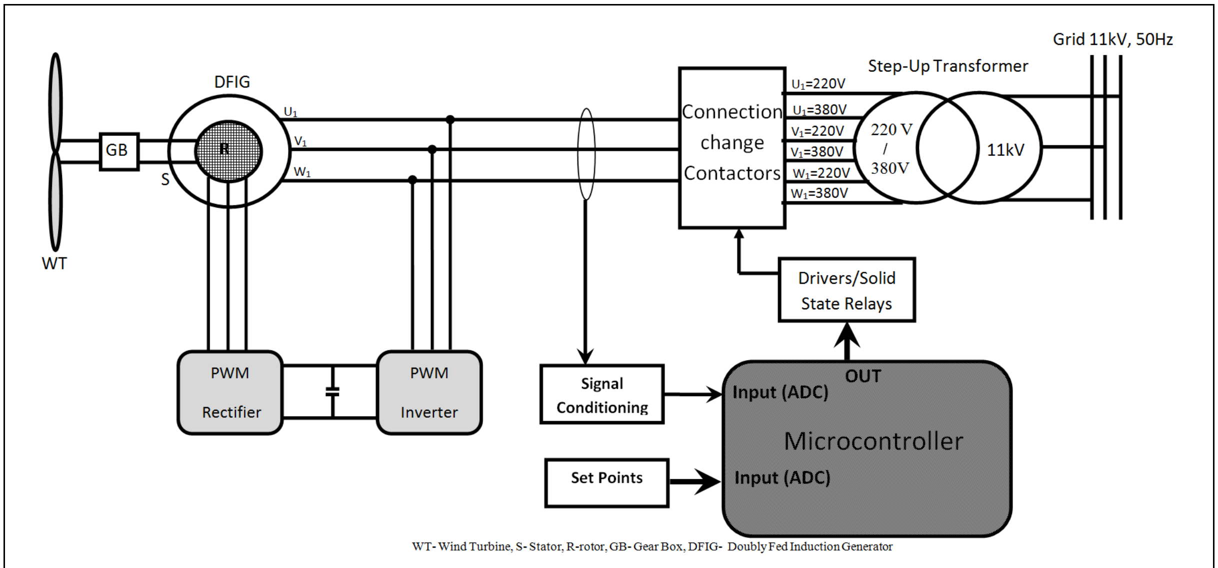
A. Delta-star Switching Scheme

Fig. 3a shows the hardware details of star and delta connected stator winding of a grid connected SCIG. Depending upon the level of wind speed, the stator winding is switched to star or delta connection to improve the efficiency of the SCIG. In delta-star switching scheme the line voltage is maintained at rated winding voltage of the SCIG. Fig. 3b shows the star connected stator winding for low wind speed, in which the stator winding current and the line current are equal, and Fig. 3c shows the delta connected stator winding in which the line current is √3 times higher than the winding current yields big diameter conductor. Moreover, six winding terminals (U_1, U_2, V_1, V_2, W_1, and W2) are required to be taken out to change the winding connection from star to delta.

B. Proposed Switching Scheme

In the proposed switching scheme, the stator winding is permanently connected in star as shown in Fig. 4 and the stator applied line voltage is selected based on the wind speed. The applied line voltage is equal to the winding voltage at low wind speeds and a line voltage equal to √3 times of rated winding voltage is applied at high wind speeds. At low wind speeds the SCR pair T_{L1} in R phase, T_{L2} in Y phase and T_{L3} in B phase are switched on and the rated winding voltage is applied to the stator terminals of the SCIG to inject the power to grid. This is similar to star connection in delta star switching scheme. During high wind speed the switching pair T_{U1} in R phase, T_{U2} in Y phase and T_{U3} in B phase are switched on and √3 times of the rated voltage is applied to the stator terminals





(d)

Fig. 4. Proposed dual voltage switching scheme,(a)Hardware details of solid-state switch and its control,(b)Star connected stator winding for low wind speed,(c) Star connected stator winding for high wind speed. (d) proposed scheme with DFIG

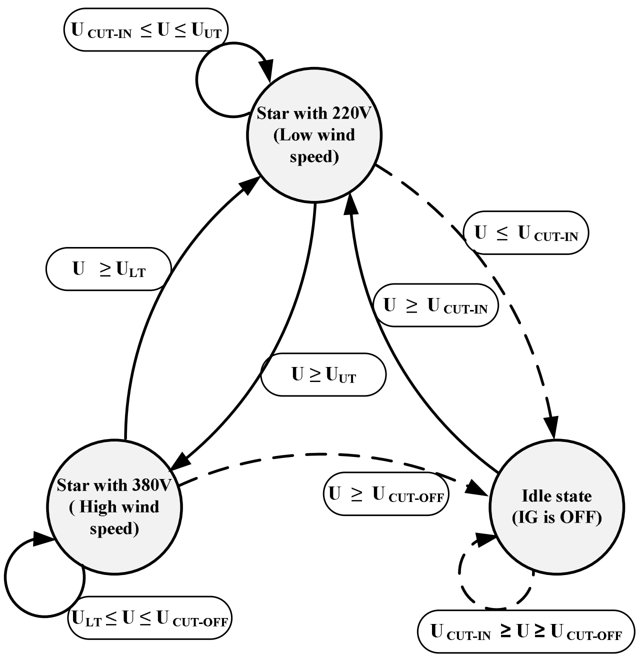


Fig. 5. Control strategy for switching

TABLE I
Control strategy for switching

Wind velocity	Mode	Applied voltage
$U \leq U_{CUT\text{-}IN}$	IDLE	VL= 0V
$U \geq U_{CUT\text{-}IN}$	Low wind	V_L= Vw = Rated winding voltage
$U_{CUT\text{-}IN} \leq U \leq U_{UT}$	Low wind	V_L= Vw
$U \geq U_{UT}$	High wind	V_L= √3 Vw
$U_{LT} \leq U \leq U_{CUT\text{-}OFF}$	High wind	V_L= √3 Vw
$U \geq U_{CUT\text{-}OFF}$	IDLE	V_L= 0V
$U_{CUT\text{-}IN} \geq U \geq U_{CUT\text{-}OFF}$	IDLE	V_L= 0V

to inject the power to the grid. As seen from the schematic of proposed scheme shown in Fig. 4a, it is clear that only three terminals (U_2, V_2, and W_2) are needed from the machine as against the six terminals in the delta-star scheme [18]. The increase line voltage yield to a lower line current and smaller diameter conductor.

C. *Control Strategy for Switching*

The switching control strategy is illustrated using Table I and Fig. 5. The control strategy for switching the stator voltage

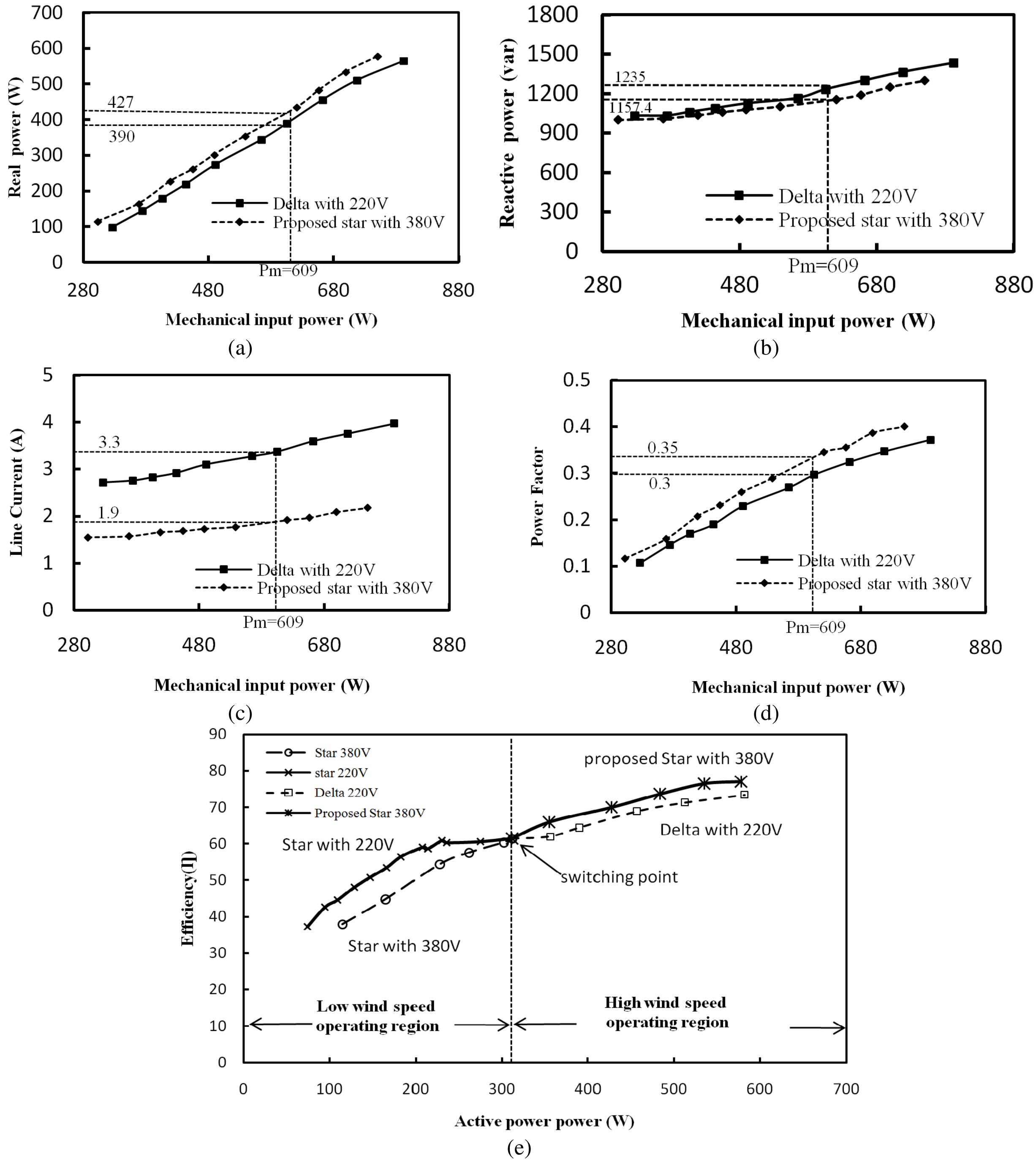


Fig. 6. Steady state performance of delta star and proposed switching, (a) Active power (b)Reactive power (c) Line current (d) power factor (e) Efficiency

Table II

Comparison of steady state performance of delta star and proposed scheme

Mechanical input power (Pm)	Line Current (IL)		Power factor(PF)		Real Power (Pe)		Reactive power(Q)		Efficiency (η)	
	Star with 380V	Delta with 220V	Star with 380V	Delta with 220V	Star with 380V	Delta with 220V	Star with 380V	Delta with 220V	Star with 380V	Delta with 220V
538.4	1.77	3.27	0.29	0.27	355.00	334.70	1102.9	1168.1	65.94	59.25
609.0	1.92	3.3	0.35	0.30	427.10	390.10	1157.4	1235	70.1	64.45
656.2	1.97	3.59	0.36	0.32	483.30	456.70	1191	1323.4	73.65	68.95
699.2	2.09	3.76	0.39	0.35	534.90	512.10	1250.7	1367.4	76.50	71.34
749.8	2.18	3.97	0.40	0.37	577.80	565.80	1299.3	1436.4	77.07	71.45

is determined from the wind velocity (U). To avoid the oscillation between the low and high wind operation two inner threshold limits and two outer limits are determined. The operating mode and idle mode of the induction generator is determined by two outer limits, i.e., the outer upper limits ($U_{CUT\text{-}OFF}$=18m/s) and the outer lower limits ($U_{CUT\text{-}IN}$=3.5m/s) and the switching between low and high wind speed is determined by inner threshold limits i.e., the inner upper limits (U_{UT}=13m/s) and the inner lower limits (U_{LT}=10m/s). The main feature of the control strategy is that, it does not oscillate between the high and low wind speed. Initially the induction machine is in idle mode, when the wind velocity is higher than the cut-in wind velocity ($UCUT_{\text{-}IN}$), then the induction machine enters into the generator mode and operates in low wind speed region. During low wind speed operation, the rated voltage of the induction machine is applied across the stator terminal to extract more power. Due to increase in wind velocity, the input mechanical power also varies and when the wind velocity exceeds the U_{UT}, the generator switched to high wind speed and the stator winding voltage is increase to √3 times of the rated winding voltage to extract more power from the wind. If the wind velocity decreases below the U_{LT} the generator again enter to the low wind speed region. If the wind velocity is greater than cut-off region ($U_{CUT\text{-}OFF}$), the generator will goes to off state to avoid the mechanical damage. Similarly in low wind speed, if the wind velocity is less than $U_{CUT\text{-}IN}$ the generator will goes to idle state to avoid the motor operation.

V. RESULTS AND DISCUSSION

To evaluate the performance of the proposed switching scheme, various simulations and experiments are carried out on a prototype unit built in the laboratory. For the purpose of comparison with the proposed switching technique, a delta-star switching scheme and conventional scheme are implemented experimentally. The details of the experimental machine set up are shown in Appendix I. The three phase switch shown in Fig. 3a and 4a is built using SCR 50RIA120 while the SCIG is connected to the grid through a 400: 380/220 V line frequency transformer. The switching algorithm is implemented using PIC 16F876A microcontroller. The performance of the proposed switching technique for steady state and transient conditions is analyzed and is compared with that of delta-star switching technique. The power output of the delta star and proposed switching schemes in matlab simulations are identical. This is due to fact that, the simulation has been carried out using per phase equivalent circuit which does not reveal the difference in winding specific performance.

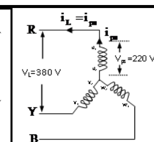
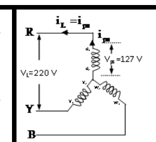
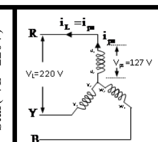
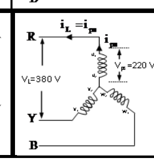
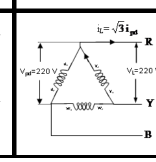
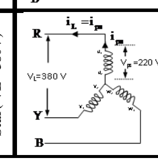
A. Steady State Response

The steady state performance of a grid connected induction generator with various winding configuration are investigated and the experimental results are obtained by varying the mechanical input power of the generator and the test results are presented in Fig. 6-7 and Table II. The Table III shows the stator winding configuration of conventional, delta star and proposed schemes.

During the low wind speed, the conventional stator winding is connected in star and a line voltage equal to √3 times of the rated winding voltage is applied across the stator terminals. In delta star and proposed scheme, the stators winding are connected in star and rated winding voltage is applied to the stator terminals. It should be noted that from Fig 6e, in low wind speed the efficiency of the conventional scheme is less when compared to the delta star and proposed scheme. The performance of delta star and proposed schemes are identical during low wind speed. This paper discussed about the effectiveness of proposed scheme in high wind speed region.

During high wind speed, the conventional scheme line voltage and stator winding connection configuration are maintained as same as low wind speed. In delta star scheme, the star connected stator winding is switched to delta connection and maintains the line voltage equal to rated winding voltage. In delta connected stator winding, the phase current is distorted due to the presence of the triplen harmonics current in the delta loop and it is shown in Fig. 7a. In the laboratory test, it is observed that, when the mechanical input is 609W, the rms value of delta connected stator line current is 3.306A, and the phase current measured from the stator winding is 2.025A. A 6.5% increase in phase current against (3.306/√3) is due to the presence of 10.1% THD in the

TABLE III
Stator winding configuration

Input Mechanical Power Pm	Conventional Scheme		Delta star Switching Scheme		Proposed Switching Scheme	
Pm≤ 0.51p.u.	Star(VL= 380V)		Star(VL= 220V)		Star(VL= 220V)	
Pm ≥ 0.51 p.u	Star(VL= 380V)		Delta(VL= 220V)		Star(VL= 380V)	

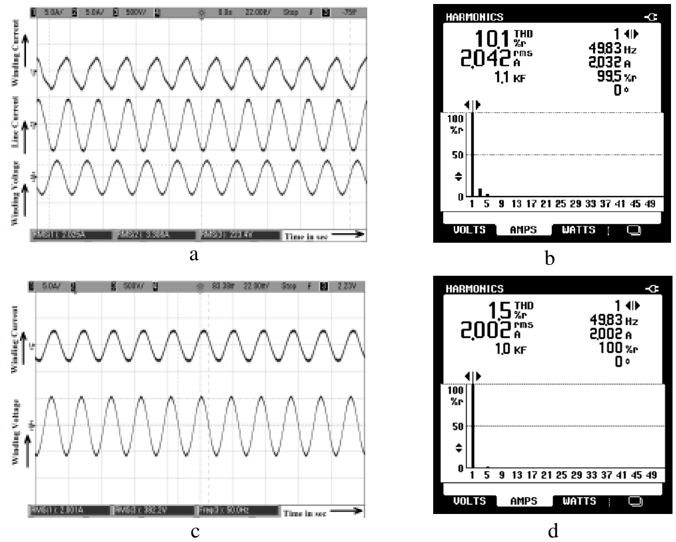


Fig. 7.Comparison of harmonics in conventional and proposed switching (a) current and voltage in delta connection,(b) current and voltage of star connection,(c) winding current harmonics in Delta connected stator (conventional),(d) winding current harmonics in star connected stator (proposed)

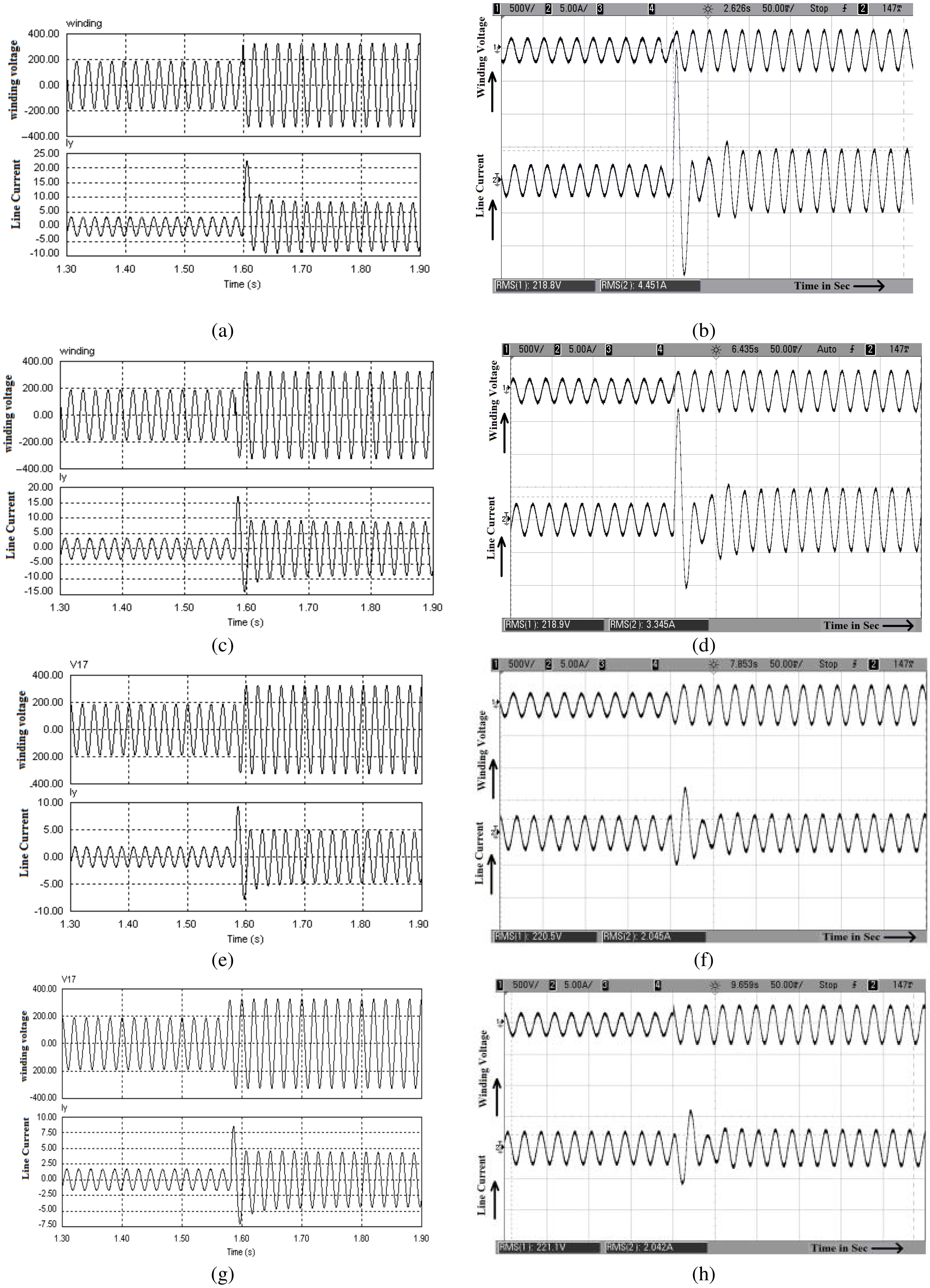


Fig. 8. Transients in line current and winding voltage of grid connected SCIG during switching the stator winding (a) conventional switching at peak voltage (Simulation), (b) Conventional switching at peak Voltage (Experimental), (c)Conventional switching at peak current (Simulation), (d) Conventional switching at peak current (Experimental), (e) Proposed switching at peak voltage (Simulation),(d) Proposed switching at peak voltage (Experimental) (e) Proposed switching at peak current (Simulation),(d) Proposed switching at peak current (Experimental)

winding current. Fig. 6c shows the profile of line current of the generator. Here again it clears that proposed star connected stator have a line current of 1.92A which is 1.73 time lesser than the delta star scheme. The real and reactive power requirement of the generator moderately increases with increase in mechanical input power. It is notable from the Fig. 6a-b that when the mechanical input is 609W, the output real power fed to the grid from the generator with proposed stator configuration scheme (427W) is higher than the delta star scheme (390W). Similarly for a mechanical input of 609W, the VAR consumed by the induction generator in proposed scheme (1157VAR) is lessthan the delta star scheme (1235VAR). Fig. 6d shows that the delta star scheme has less power factor due to the presence of harmonics content. From the Fig. 6e, it is observed that in low wind speed the efficiency of star with 220V stator winding has higher efficiency when compared to the star with 380V stator and during high wind speed the proposed star with 380V has higher efficiency than the delta with 220V line voltage. Thus it is evident that increased power output and efficiency are achieved by incorporating the stator winding in star with rated winding voltage during low wind speed and √3 times of rated winding voltage during high wind speed. The Table IV shows the effectiveness of proposed scheme while comparing with conventional scheme, delta star scheme.

B. Dynamic response

As it is anticipated that the switching currents would depend on the switching instant, two switching instants were taken for study. One switching instant at zero voltage and other instant at peak voltage of the generator. Fig. 8b and Fig 8f shows the switching current at zero voltage and the Fig. 8d and Fig. 8h shows the switching condition at peak voltage. From the waveforms, the Fig. 8a depicts the waveform of winding voltage and line current of GCIG when the winding is switched from star to delta. Initially the winding voltage is 127 V and the line current is 2.56 A and when the connection is changed to delta, the winding voltage is switched to 220V and the current is increased to 4.45 A. During the switching period, stator line current rises nearly to 19.5 A and it takes 5 cycles to settle to the steady state value. This high transient current further increases the current rating of equipments which are connected to the stator terminal, which increases the cost of the equipment. Similarly Fig. 8e and 8f shows the switching characteristics during proposed switching scheme. In the proposed scheme, the stator winding of induction machine is winding. After a period of time, the stator line voltage is switched to 380V. In this case, stator current rises near to 7.2A which is 63% less than the overshoot in the delta star switching scheme and the response settles in 2.5 cycles.

VI. CASE STUDY

To evaluate the performance of the proposed switching scheme, a case study is carried out on a 3 phase 4-pole, 400 V, 50kW induction generator. With respect to the parameters given in Appendix, the performance characteristics of generator are predetermined for both conventional and proposed switching scheme. The full load input power up to which the delta and star settings can operated are determined from the input mechanical power.($P_{mY} \leq$ 30Kw and $P_{m\Delta} \geq$ 30kW). To determine the annual Wh and VARh of this generator, the wind-farm site data regarding the seasonal wind speed variation over one year is required and these were taken from an actual wind-farm location [13]. This average has been calculated considering the variation in wind speed for that one hour duration in all the days in that month. The number of hours the turbine works in each day and every month are obtained and shown in the Table V. Thus it is seen that, in a year 812 hours the turbine is running in low wind speed and 1036 hours the turbine met high wind speed. Assume that the turbine is kept in operation for 28 days in each month in a year and leaving few days for maintenance, grid failure and other unforeseen reasons. The total hours of working is 24(hrs) x 12(months) x 28(days) =8064hours is taken as 1 p.u. time.

Table IV
Comparison between conventional and proposed switching scheme

	Conventional Scheme	(Y/Δ) Scheme	Proposed Scheme
Applied Line Voltage	$\sqrt{3}\ V_p$	V_p	$V_p / \sqrt{3}\ V_p$
Grid connected transformer	33KV/690V	33KV/(400V)	33KV/(690V/400V)
Switching	No	Yes	Yes
Output terminals	3	6	3
Steady state Equipment Rating	I	√3 I	I
Transient in Line current	-	high	low
Presence of 3rd harmonics	nil	Yes(delta mode)	nil
Efficiency	Less in low wind speed	Less in high wind speed	High in all speed

TABLE V
Operating time of 50kW SCIG in a year

Generator input power range in KW	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
less than 30kW	Hours/Day	2	4	6	5	2		3	1	3	2		1	29
	Hours/month	56	112	168	140	56	0	84	28	84	56	0	28	812
more than 30kW	Hours/Day	1	3		4	8	7	7	7	0	0	0	0	37
	Hours/month	28	84	0	112	224	196	196	196	0	0	0	0	1036

TABLE VI
Estimated annual Wh and VARh

Generator input power range in KW	Stator Connection	Time Duration	Generator Average input Power	Generator Average output Power	Total Power Loss	Wh	VAR	VARh
0-30kW	Star	0.100	0.252	0.148	0.104	0.015	0.207	0.021
30-50kW	Delta (conventional)	0.130	0.496	0.354	0.142	0.045	0.903	0.116
30-50kW	Star (Proposed)	0.130	0.496	0.372 (0.354 + 5.1% of 0.354)	0.124	0.048	0.875	0.114
Total Energy supplied to grid (Conventional)						0.0603 (0.015 + 0.045)		0.137
Total Energy supplied to grid (Proposed)						0.0632 (0.015 + 0.048)		0.135

For the given mechanical input power and time, the real power, reactive power ,total energy input to the grid and total reactive volt-ampere-hours drawn from the grid over one year are shown in Table VI. The base Wh and VARh are calculated by the product of base kVA and base time (1 p.u Wh=1 VARh = (Base kVA x Base time) = (58.8 x 8064) = 474.3 x 10^6) =1p.u. From the Table V, it clearly shows that, for 0.496 p.u. average input power, the delta connected stator winding delivers 0.354 p.u. output power. If the generator runs for 0.13 p.u. time, then the energy generated during high wind speed is 0.045p.u. Total energy supplied to the grid over one year is 0.06p.u. From the Table II, the output power of proposed star connected SCIG is observed to be 5.1% higher than that with the conventional delta connected stator winding.

A. Star-Delta Switching Scheme

With conventional star-delta switching scheme, when the generator runs under low wind speed for 0.1 p.u time , then the real power generated is 0.148 p.u. when the generator runs for 0.13 p.u. during high wind speed, it generates 0.354 p.u. of energy.

The total energy supplied during low wind speed
$= 0.148 \times 0.1 = 0.015$ p.u.
The total energy supplied during high wind speed
$= 0.354 \times 0.13 = 0.045$ p.u.
The total energy supplied to the grid over a year in conventional scheme = 0.0603 p.u.

B. Dual Voltage Switching Scheme

For proposed dual voltage switching scheme, when the generator runs under low wind speed for 0.1 p.u time , then the real power generated is 0.148 p.u. when the generator runs for 0.13 p.u. during high wind speed, it generates 0.372 p.u.

The total energy supplied during low wind speed $= 0.148 \times 0.1 = 0.015$ p.u.
The total energy supplied during high wind speed $= 0.372 \times 0.13 = 0.48$ p.u.
The total energy supplied to the grid over a year in proposed scheme = 0.0632 p.u.
Thus typically in the proposed switching scheme, the power output increases to 0.0018 p.u. which is 8537.4 kWh per annually with the given wind profile.

VII. Conclusion

This paper proposes a simple, dual voltage switching for the wind driven induction generation system. In this approach, stator winding of the machine is always connected in star and the stator winding voltage levels are switched based on the wind speed. The steady state and the dynamic response of the system indicates, a reduction of line current and switching transients with improved power output A case study on a 3-Φ, 50kW, 400V SCIG has been studied under different wind speeds to emphasise the performance improvement of proposed scheme and it shows better performance under high wind speed conditions. Typical annual wind turbine data is considered for a comparison of kWh generated and kVARh drawn by the wind turbine in the two schemes (i.e., star-delta switching and dual voltage switching). Computation reveal that the dual voltage switching yields higher kWh and reduced reactive power

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IX. Appendix

A1. Parameters of the induction machine: 3Φ, 0.75 kW ,380 V, 2.2 A 50 Hz, stator resistance (R_s)=9.5Ω/ph, rotor resistance (R_r)=12.08Ω/ph, stator and rotor leakage reactance ($X_{ls\ and}\ X_{lr}$) =12Ω/ph

A2. Case study machine parameters: 50kW,400V/690,50Hz, stator resistance (R_s)=0.02155Ω/ph,rotor resistance (R_r)=0.01231Ω/ph, stator and rotor leakage reactance ($X_{ls\ and}\ X_{lr}$) = 0.000226H Ω/ph