Diesel Engine Driven Stand-Alone Variable Speed Constant Frequency Slip Ring Induction Generator - Theory and Experimental Results

Amit Kumar Jain and **V. T. Ranganathan**
Department of Electrical Engineering
Indian Institute of Science, Bengaluru
amitjain@ee.iisc.ernet.in, vtran@ee.iisc.ernet.in

K. Vijay Kumar and **G. Guruswamy**
IE Power Technologies Pvt Ltd
Peenya Industrial Area, Bengaluru
acdrive.iec@gmail.com, guruswamyg@hotmail.com

***Abstract*—The operation of a stand-alone, as opposed to grid connected generation system, using a slip-ring induction machine as the electrical generator, is considered. In contrast to an alternator, a slip-ring induction machine can run at variable speed and still deliver constant frequency power to loads. This feature enables optimization of the system when the prime mover is inherently variable speed in nature eg. wind turbines, as well as diesel driven systems, where there is scope for economizing on fuel consumption. Experimental results from a system driven by a 44 bhp diesel engine are presented. Operation at sub-synchronous as well as super-synchronous speeds is examined. The measurement facilitates the understanding of the system as well as its design.**

***Index Terms*—Diesel engine, Stand-alone, Slip ring induction generator, Power flow, fuel saving.**

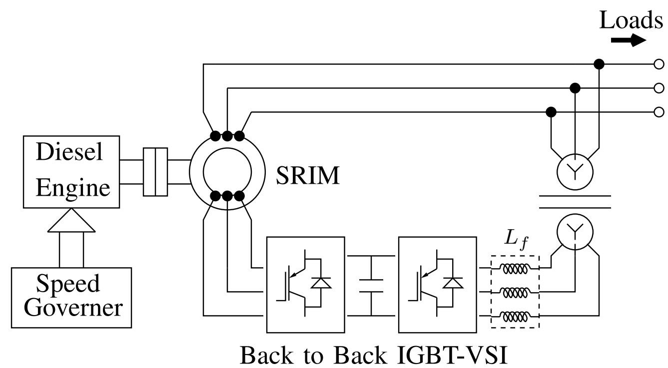


Fig. 1. Stand-Alone slip-ring induction generator driven by a variable speed diesel engine.

I. INTRODUCTION

STAND-ALONE generation is of importance in locations such as islands, ships and areas remote from the power grid. It is usual to cater to the requirements of the local loads by using a mix of systems such as diesel engine driven alternators, solar panels with inverter and wind turbines coupled to a suitable power conversion system. Diesel driven alternators are also commonly used to feed critical industrial processes which cannot tolerate disruptions that can occur in the grid supply.

In diesel driven alternators, the engine is always required to run at a fixed speed, irrespective of the load. In such systems, the diesel engine has high fuel consumption when operating at light load and constant speeds. Moreover, during such a run, not all the fuel is burned by the engine and wet-stacking is produced. This increases the maintenance cost besides decreasing the life of the engine.

A slip ring induction machine (SRIM), with control on rotor side, provide an excellent solution for variable speed constant frequency system [1] - [7]. It is widely used for wind turbine based power generation. In such power circuit configuration, the converter rating is equal to the slip power and is less than the rating required in configurations where the generator output is rectified and inverted back to get constant frequency output.

In the similar context, the variable speed diesel engine based power generation with the slip-ring induction machine can provide an interesting alternative to the conventional alternator. By using a slip-ring induction machine instead of the alternator, the engine can be allowed to vary its speed depending on the load demand. This will increase the efficiency of the system due to the scope for reduction in fuel consumption especially during light load conditions. It reduces the emissions from the engine due to preventation of wet-stacking and also increases the engine life.

In such variable speed constant frequency generation systems, the slip ring induction machine can be operated at sub-synchronous as well as super-synchronous speeds. The synchronous or center speed and the range of speed variation in the sub-synchronous and super-synchronous modes are basic parameters which have to be decided while designing such a system. This requires an understanding of the operation of the machine in the two modes. In particular, the power flows to be handled by the stator and rotor windings and the likely losses have to be understood.

A stand-alone slip ring induction machine based generation system driven by a variable speed diesel engine as prime mover is considered (Fig. 1). The control scheme to obtain constant output voltage and frequency is explained in brief with relevant dynamic equations in section II. Section III presents the analysis of system to understand the power flow in stator and rotor circuit with and without losses. Measurements from an experimental setup driven by a 44 bhp diesel engine are presented in section IV. Discussion and conclusion for the paper is given in section V. Lastly appendix A gives the details

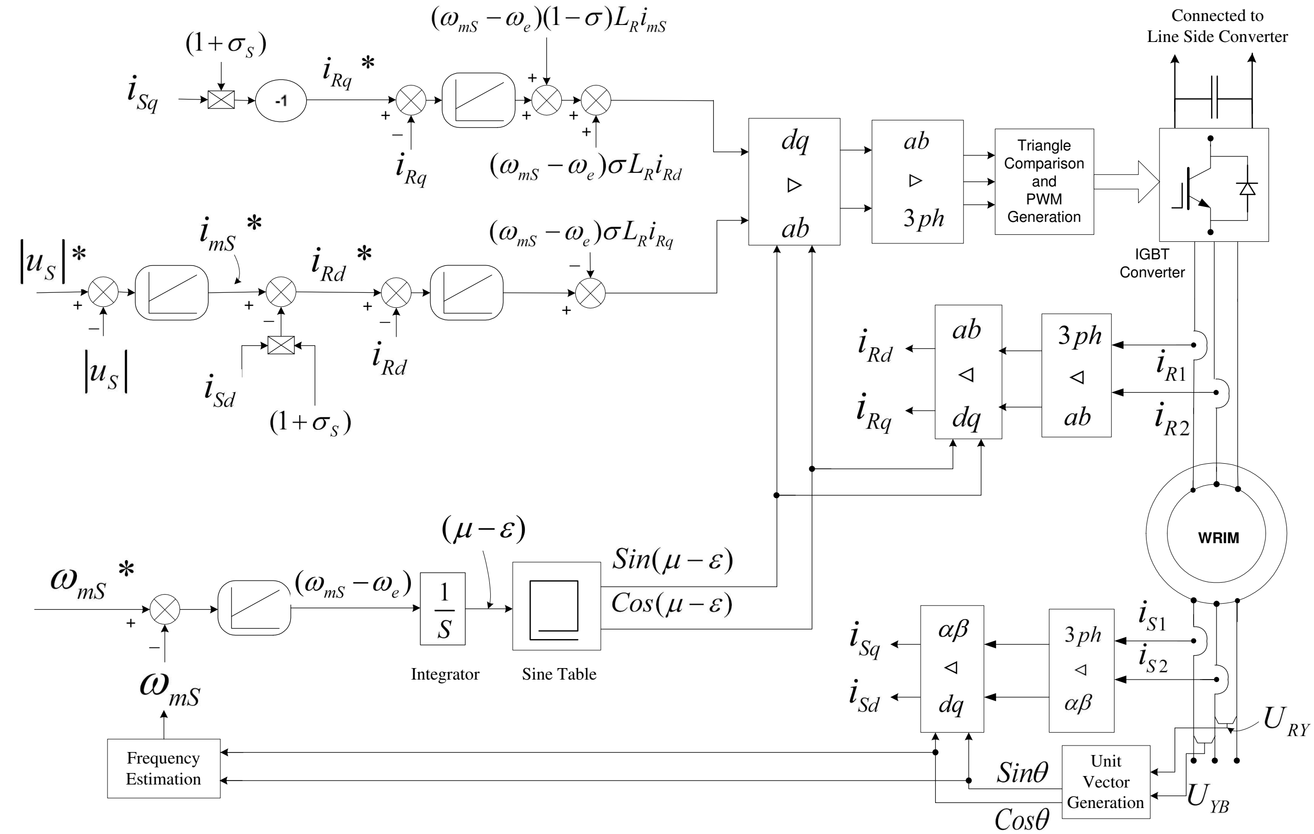


Fig. 2. Control block diagram of rotor side converter.

of the hardware setup.

II. Control of the slip-ring induction machine

The slip-ring induction machine is controlled on the rotor side through two three phase voltage source inverters (VSIs) connected back to back (Fig. 1). The rotor side inverter is controlled to inject currents of appropriate phase, frequency and magnitude into the rotor winding. The line side inverter acts as a front end converter. It regulates the dc bus voltage allowing bidirectional flow of active power. It is connected to the terminals of the generator through a transformer which is required for matching rotor side and stator side voltages. The front end converter can also be used to control the power factor seen by the stator. For example, it can compensate the reactive power consumed by the load and ensure that the stator always sees a unity power factor load.

The usual method to control such a machine is to control the components of the rotor current vector in a rotating coordinate system aligned to the stator flux linkage vector ([1]-[6]).

The dynamic equations describing the behavior of the magnitude and angular velocity of the stator flux magnetizing current (i_{mS}) are as follows ([1]-[6])

$$T_S \frac{di_{mS}}{dt} + i_{mS} = (1+\sigma_S)\frac{u_{Sd}}{R_S} + i_{Rd} \tag{1}$$

$$\frac{d\mu}{dt} = \omega_{mS} = \frac{1}{T_S i_{mS}}[(1+\sigma_S)\frac{u_{Sq}}{R_S} + i_{Rq}] \tag{2}$$

$$i_{mS} = (1+\sigma_S) i_{Sd} + i_{Rd} \tag{3}$$

The machine torque is given by

$$m_d = -\frac{2}{3}\frac{P}{2}\frac{L_O}{(1+\sigma_S)} i_{Rq} i_{mS} \tag{4}$$

The rotor current components i_{Rd} and i_{Rq} are controlled in order to control the flux and the torque. This is done by current control loops around the rotor side converter. The dynamic voltage equations of the system are

$$\sigma T_R \frac{di_{Rd}}{dt} + i_{Rd} - \frac{u_{Rd}}{R_R} = (\omega_{mS}-\omega_e)\sigma T_R i_{Rq} - (1-\sigma) T_R \frac{di_{mS}}{dt} \tag{5}$$

$$\sigma T_R \frac{di_{Rq}}{dt} + i_{Rq} - \frac{u_{Rq}}{R_R} = -(\omega_{mS}-\omega_e)\sigma T_R i_{Rd} - (\omega_{mS}-\omega_e)(1-\sigma) T_R i_{mS} \tag{6}$$

Fig. 3 shows the relative locations and angular velocities of the various vectors. The control block diagram is shown in Fig. 2. The magnitude of the output voltage $\underline{U}_S$ is controlled by varying the magnetizing current i_{mS}. The output frequency is kept constant at the desired value using a sensor-less scheme [2]-[3]. The difference between the set frequency and the actual frequency is acted upon by a PI controller which produces the required slip frequency. The slip frequency is then integrated to generate the slip angle ($\mu - \epsilon$). The control scheme for rotor side converter and front end converter are given in detail in [2]-[3].

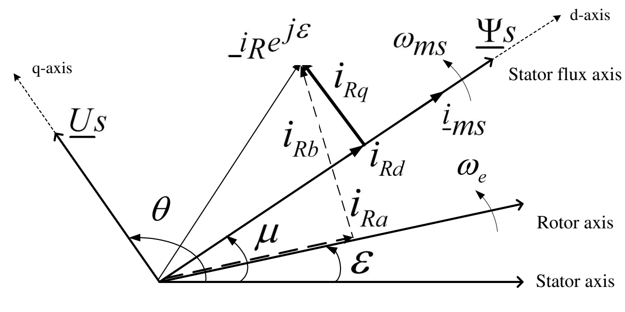


Fig. 3. Vector diagram of the field oriented control.

III. Analysis of the System

In a stand-alone generation system, the direction of power flow is from the machine shaft (connected to the prime move) to the generated grid. However, in the stator circuit the direction of power flow is always from the machine terminals to the grid, while the direction of flow in rotor circuit is dependent on the slip of the machine. Therefore, the stator circuit has to carry more load power in sub-synchronous mode (slip = '+'ve) compared to super-synchronous mode (slip = '-'ve) for the same load power.

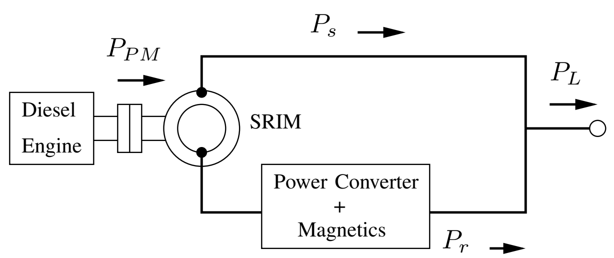


Fig. 4. Notation adopted for analysis of power flow in slip ring induction generator.

While designing such a system, the following constraints should be taken into account

- The dependence of the load sharing between the stator and rotor circuits on operating speed (slip) of the machine.
- The maximum allowable power flow in the stator and the rotor circuit should be limited to the rating of the machine.

Considering the above points, the magnitude of the maximum power that can be generated by slip ring induction generator at different prime mover speeds and the respective load sharing between the stator and the rotor circuits can be evaluated as follows.

Let P_{rated} be the rating of the machine and P_L be the load power demand. P_s and P_r are respective stator and rotor power. The convention of power flow is as given in Fig. 4.

At load junction, $P_L = P_s + P_r$

Also $P_r = -sP_s$

Therefore, $P_L = P_s(1 - s)$

The constraint of maximum power flow $(P_s, P_r) \leq P_{rated}$ is to be followed. Considering the maximum power loading of stator and rotor circuits to $P_s = P_{rated}$ and $P_r = -s(P_{rated})$, the load power in terms of machine rated power and slip can be evaluated as

$$P_L = P_{rated}(1 - s) \tag{7}$$

The above can be used to plot and understand the maximum load power that can be delivered from a slip ring induction machine of a particular rating at various prime mover speeds. It is shown in Fig. 5. It can be noted here that the power generated from a SRIM can be twice the rating of the machine provided prime mover speed is twice the synchronous speed of the machine.

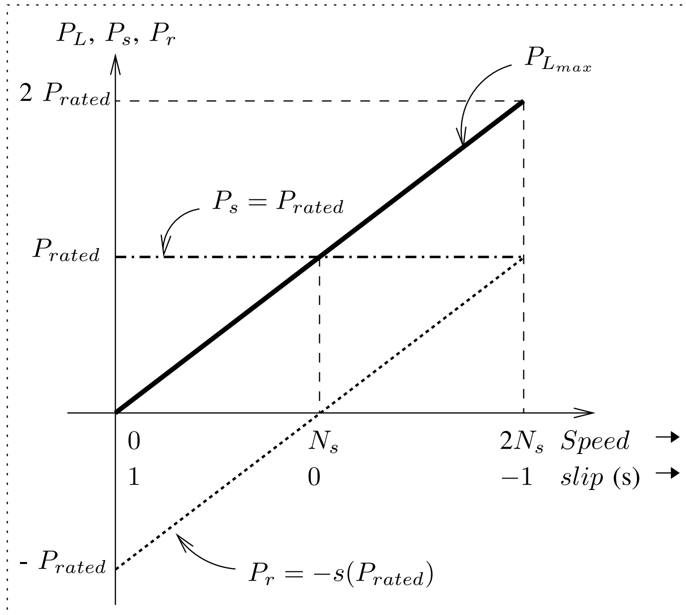


Fig. 5. Maximum possible load power generation ($P_{L_{max}}$) at different prime mover speed with a SRIM of rating equal to P_{rated}.

The system operation with variable load power at different prime mover speeds will give a more clear understanding of the variation of power flow in stator and rotor circuits. To investigate the same, the general expressions of stator and rotor power with respect to a constant load power (ignoring losses) can be used. They are

$$P_s = \frac{P_L}{(1-s)}, \qquad P_r = -s\frac{P_L}{(1-s)}$$

Two cases are considered are for the above investigation i.e. for $(P_L < P_{rated})$ and $(P_L > P_{rated})$.

(a) $(P_L < P_{rated})$

This case is analyzed with a constant load power of $P_L = 0.5 * P_{rated}$ and the expressions of stator power and rotor power are plotted as a function of slip in Fig. 6. As expected and can be extrapolated from Fig. 4, the available range of

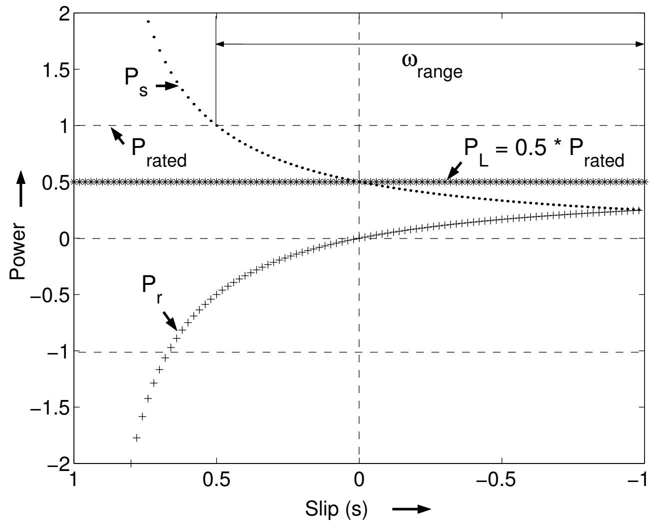


Fig. 6. Variation in P_s and P_r for ($P_L = 0.5 * P_{rated}$) for full slip range.

prime mover speed variation is from 0.5 N$_s$ to 2 N$_s$.

(b) ($P_L > P_{rated}$)

This case is analyzed with a constant load power of $P_L = 1.5 * P_{rated}$ and the expressions of stator power and rotor power are plotted as a function of slip in Fig. 7.

As expected and can be extrapolated from Fig. 4, the available range of prime mover speed variation can be only from 1.5 N$_s$ to 2 N$_s$.

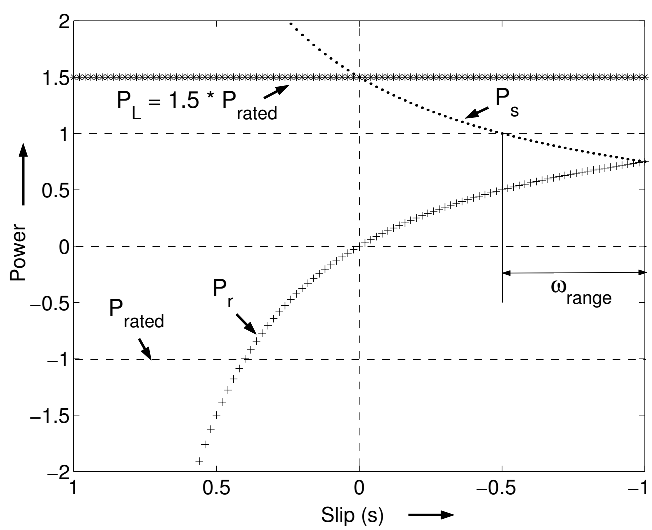


Fig. 7. Variation in P_s and P_s for ($P_L = 1.5 * P_{rated}$) for full slip range.

The prime mover has to supply the losses of the system along with the load power demand. The loss of the stator circuit is mainly stator copper loss. The loss in the rotor is more significant as it includes converter losses and rotor iron loss in addition to the rotor copper loss. The iron loss is present in the rotor circuit as the full magnetizing flux is supplied by rotor side converter.

The expression of the rotor power including losses will be

$$P_r = -s\frac{(P_L + \sum(Losses))}{(1-s)} \quad (8)$$

The sub-synchronous mode of operation requires circulation of power. The stator circuit supplies the load power in addition to the rotor power including losses. In a variable speed and variable load operation (i.e. where the speed of the prime mover is decreased with decrease in load power demand), the stator power will increase to a slight extent, rather than remaining constant (Fig. 5), due to increase in rotor losses with rise in rotor power and drop in prime mover speed. For a constant load and variable speed operation, the situation is worse. The rate of rise of rotor power and stator power is very high as slip approaches to the value of 1 from 0 (Fig. 6).

On the other hand, in super-synchronous operation the situation is better as the rotor power now aids the stator power to supply the load demand and there is no circulation of power as well as the losses.

The analysis of Fig. 6 and Fig. 7 shows the range of speed available for delivering a particular load and the variation of stator and rotor power. It is evident that the total losses of the generator will decrease as the prime mover speed is raised due to the decrease in the power carried by the stator and rotor circuits. However, the general characteristics of the diesel engine projects that its efficiency will improve if the speed is decreased for a lower load demand. Therefore while designing such a generator system, the optimum prime mover operating speed should be judiciously decided based on the total losses of diesel engine and slip ring machine to achieve the higher overall efficiency for the total system.

IV. Measurements and Experimental Results

To assess and understand the performance of a variable speed diesel engine driven slip ring induction generator (SRIG), the complete hardware set is designed and commissioned. The setup consists of a variable speed diesel engine with speed control through a speed governor, 4-pole and 6-pole SRIMs, and the associated power converters and magnetic components. The detailed specifications of each is given in Appendix.A. The control of the entire system is implemented on a Digital Signal Processor (DSP - TI320LF2407A of Texas Instruments).

The specifications of diesel engine indicate the possible speed variation from 700 rpm to 2000 rpm with a base speed of 1500 rpm and power rating of 44 bhp. To analyze the generator system with the given diesel engine, two sets of SRIM were designed; one is a 4-pole 30 kW machine with a synchronous speed of 1500 rpm and another is a 6-pole 20 kW machine with synchronous speed of 1000 rpm. Note that both the above machines are capable of delivering 40 kW when operated in the super-synchronous mode at 2000 rpm. The SRIG system using these machines and driven by the available diesel engine were commissioned.

The performance of these SRIG systems is compared against the performance of a standard constant speed diesel engine driven alternator where the speed of the system is always 1500 rpm irrespective of the magnitude of the load power demand.

Detailed experiment tests were conducted with the above three generator sets i.e. 4-pole SRIG, 6-pole SRIG and standard alternator for different ranges of load power and wide range of speed variation (only for SRIG sets). A sample set of experimental data is reproduced in Table. I. to analyze the relative performance. An important point to be noted in Table. I. is that each row is a separate experiment. The fuel consumption with the alternator is taken to be 100% for the indicated load; the other two SRIG sets indicate the comparative fuel consumption when delivering the same load at a different engine speed.

TABLE I
EXPERIMENTAL DATA SHOWING THE REQUIRED FUEL CONSUMPTION BY THE THREE GENERATOR SETS FOR DIFFERENT LOAD POWER DEMAND

Load Power Demand	Fixed Speed Diesel Engine driven Alternator (1500 rpm)	Variable Speed Diesel Engine driven Slip Ring Induction Generator		
		Engine Speed	4-pole	6-pole
5.8 kW	100 %	740 rpm	73 %	71 %
2.6 kW	100 %	990 rpm	75 %	71 %
5.8 kW	100 %	990 rpm	78.5 %	73 %
25 kW	100 %	1500 rpm	100 %	92 %
30 kW	100 %	1900 rpm	100 %	100 %

The sample experimental data given in Table. I covers the full range of speed variation possible with the available diesel engine. It can be observed that the generator with 4-pole SRIM has better fuel efficiency (lesser fuel consumption) compared to the standard alternator based system for low loads. Again, the generator set with 6-pole SRIM offers better fuel economy compared to the 4-pole counterpart. An important variation can be observed from the results that indicate the fuel consumption of all generator sets tends to converge to the similar values at high speeds.

Based on the performance achieved (Table. I) with the three sets, the 6-pole SRIG is selected as the machine to be used for the stand-alone generator system driven by the given variable speed diesel engine for further analysis.

The 6-pole SRIG system is exhaustively tested experimentally over a wide range of diesel engine speeds while delivering the different load power demands. The fuel consumption of the diesel engine during these tests is measured. Based on the criteria of least fuel consumption or highest overall efficiency of the system, the final optimum speeds were decided against the range of load power demand. The variation of load power demand versus the optimum diesel engine speed is plotted in Fig. 8.

The curve shown in Fig. 8. is stored as a look up table in the DSP digital controller and the signal of optimum speed reference is sent to the diesel engine speed governing system against the instantaneous calculation of load power demand from the measured stator as well as rotor voltages and currents.

The experiment waveforms of voltage (U_{s1}) and current (i_{fec1}) at the input of front end converter are shown in

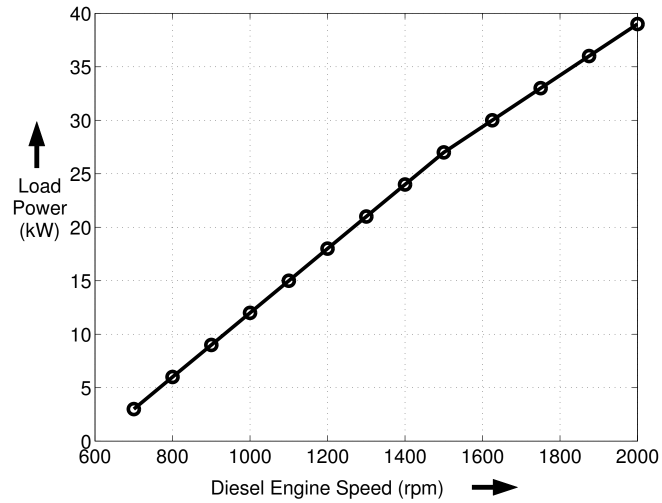


Fig. 8. Plot showing the experimently obtained data of the optimum diesel engine speed versus the load power demand for least fuel consumption requirement.

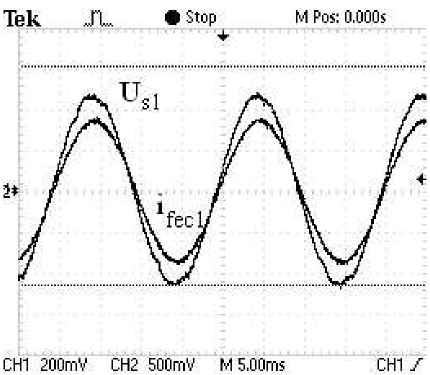
Fig. 9(a)-(c). The voltage and current waveforms are in-phase during sub-synchronous (Fig. 9(a)) and 180^o out of phase in super-synchronous mode of operation (Fig. 9(b)). The reversal of power flow occurs in the front end converter during transition between these two modes. (Fig. 9(c)) shows the transition from super-synchronous to sub-synchronous mode. The photograph of the diesel engine, SRIM, power converter and the monitoring system is shown in Fig. 10.

V. DISCUSSION AND CONCLUSION

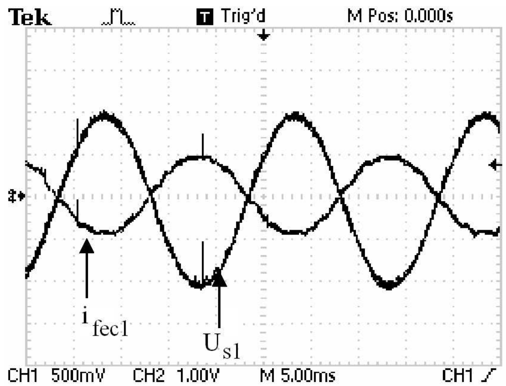
The slip ring induction generator driven by a variable speed diesel engine with a 4-pole and 6-pole machine is experimentally tested and the performance of the system in terms of saving in fuel consumption is verified against the standard constant speed alternator based system. The 6-pole generator demonstrated better fuel economy compared to 4-pole generator. The results are in agreement with the expected performance. The circulation of power in sub-synchronous mode results in increased electrical losses in the machine. Therefore the generator system which operates more in the super-synchronous range is likely to give higher fuel efficiency.

This paper is concluded with the following points

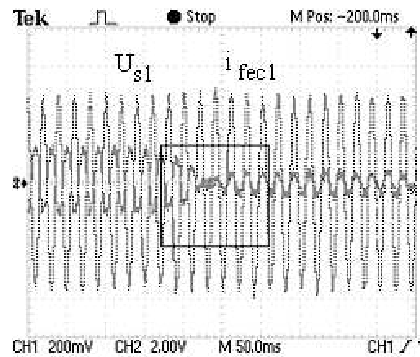
- The variable speed diesel engine based SRIG offers saving in precious fuel consumption. In addition it improves the life of the diesel engine, requires lower engine maintenance and reduces the emissions. These advantages can offset the additional cost due to the converter, magnetics etc. It can be a viable alternative to the standard alternator based system.
- A diesel engine generator system with SRIM can be the backbone of a micro-grid having a mix of sources such as wind, solar, diesel etc. The flexibility of the variable speed operation can be taken advantages of in optimizing the overall performance of the micro-grid



(a) FEC input phase voltage and current during sub-synchronous mode of operation.

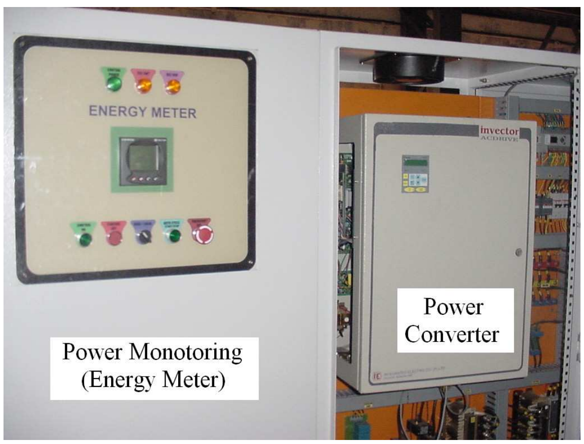


(b) FEC input phase voltage and current during super-synchronous mode of operation.

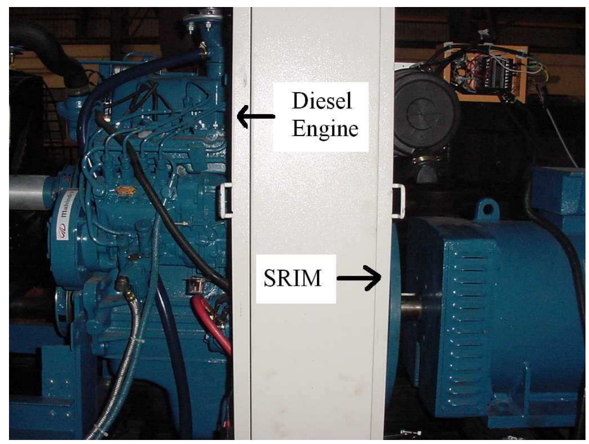


(c) FEC input phase voltage and current during reversal of power flow from super-synchronous to sub-synchronous mode of operation.

Fig. 9. Experimental waveforms showing the front end converter control response during different modes of operation.



(a) IGBT based voltage source converter and the power monitoring system.



(b) Diesel engine coupled to slip ring induction machine.

Fig. 10. Photograph of the experimental hardware setup

Appendix A
Experimental set up

Diesel Engine:- 44 Bhp, 4-cylinder, Mahindra Make. *Base Speed*: 1500 rpm. *Range of Speed Variation*: 700 rpm - 2000rpm. *Speed Control*: Electronic governor.

Slip Ring Induction Machine:- **SRIM-1**: 20 KW, 415 V, 50Hz, 4 Pole, 3-Phase. *Stator*: Y connected, 36 A. *Rotor*: Y connected, 44 A. **SRIM-2**: 30 KW, 415 V, 50Hz, 6 Pole, 3-Phase. *Stator*: Y connected, xx A. *Rotor*: Y connected, xx A.

Power Converter and Magnetics:- *IGBT rating*: 1200 V, 100 Amps IPM, *DC link Capacitor*: 2350 μF, *AC Side Inductor*: 7.5 mH, 32 Amps.

Acknowledgment

The authors would like to thank M/S IE Power Technologies Pvt Ltd and staff of AC drives division and AC machine design division for assistance and test facilities provided for carrying out the experimental tests.

References

[1] Werner Leonhard, " Control of Electrical Drives ", *Springer-Verlag*, Third Edition, 2003.

[2] Amit Kumar Jain, V.T.Ranganathan, " Wound Rotor Induction Generator with Sensorless Control and Integrated Active Filter For Feeding Non-Linear Load in a Stand-Alone Grid", *IEEE Transactions on Industrial Electronics*, Vol.55, No.1, pp 218 - 228, Jan 2008.

[3] Amit Kumar Jain, " Control of Stand-Alone Variable Speed Generation System Using Wound Rotor Induction Machine", *MSc.(Engg).Thesis, Dept. of Electrical Engineering,* Indian Institute of Science, Bangalore, December 2004.

[4] Rajib Datta, V.T.Ranganathan, " A simple position sensorless algorithm for rotor side field oriented control of wound rotor induction machine", *IEEE Transactions on Industrial Electronics*, Vol.48, No.4, pp 786 - 793, Aug 2001.

[5] Pena R, Clare J C, Asher G M, " A doubly fed induction generator using back-to-back PWM converters supplying an isolated load from a variable speed wind turbine", *IEE Proceedings Electrical Power Applications*, Vol.143, No.5, pp 380 - 387, September 1996.

[6] R. Pena, R. Cardenas, J Proboste, J. Clare, G. Asher, " WindDiesel Generation Using Doubly Fed Induction Machines ," *IEEE Transactions on Energy Conversion*, Vol. 23, No. 1, pp 202 - 214 , Mar. 2008.

[7] Iwanski, G.; Koczara, W., " DFIG-Based Power Generation System With UPS Function for Variable-Speed Applications ," *IEEE Transactions on Industrial Electronics*, Vol. 55, No. 8, pp 3047 - 3054 , Aug. 2008.

BIOGRAPHIES

Amit Kumar Jain (S'05) received the B.E degree in Electrical Engineering from Shri Govindram Sakseria Institute of Technology and Science, Indore, India in 1999 and M.Sc(Engg). degree in Electrical Engineering from the Indian Institute of Science (I.I.Sc.), Bengaluru, India in 2004. He is currently working for his Ph.D. degree at the Department of Electrical Engineering, I.I.Sc, Bengaluru, India.

Following the receipt of the B.E. degree, he spent three years, at the Department of Electrical Engineering, I.I.Sc, Bengaluru, India, as a Research Assistant. He was involved with various research industrial consultancy projects in the field of ac drives for defence, automotive, grid as well as stand-alone generation systems and others. His research interests are in the area of ac drives, power quality and converter design.

V. T. Ranganathan (M'86 − SM'95) received the B.E and M.E degrees in electrical engineering from the Indian Institute of Science (I.I.Sc.), Bengaluru, India, in 1977 and 1979, respectively, and the Ph.D degree from Concordia University, Montreal, QC, Canada, in 1984.

He joined the Electrical Engineering Department at I.I.Sc. in 1984 as an Assistant Professor and is currently a Professor. He has made significant research contributions in the areas of vector control of ac drives, pulsewidth-modulation techniques, split-phase induction motor drives, and slip-ring induction motor drives. His work has led to a number of publications in leading journals, as well as patents. He is also active as a consultant to industry and has participated in a number of research and development projects in various areas, such as industrial drives, servo drives, traction drives, wind energy, and automotive applications. His research interests are in the area of power electronics and motor drives.

Prof. Ranganathan is a Fellow of the Indian National Academy of Engineering and the Institution of Engineers, India. He was the recipient of a Prize Paper Award from the Static Power Converter Committee of the IEEE Industry Applications Society (1982), the Tata Rao Prize of the Institution of Engineers India (1991 − 1992), the VASVIK Award in Electrical Sciences and Technology (1994), and the Bimal Bose Award of the Institution of Electronics and Telecommunication Engineers, India (2001), the C.V.Raman Young Scientist Award of the Government of Karnataka (2002), and the Rustom Choksi Award for Excellence in Engineering Research (2005) of the I.I.Sc.

K. Vijaykumar was born in Andhra Pradesh in 1985. He received his B.Tech degree in Electrical and Electronics Engineering from Jawaharlal Nehru Technological University and M.Tech (power electronics and Drives) from NIT Warangal in 2008.

He is working in IE Power Technologies Pvt. Ltd., Bengaluru. His research interest is in the area of Drives and control.

G. Guruswamy was born in Tamilnadu, India in 1967. He received the B.E Degree in Electronics and Communication Engineering from Bharathiyar University, Tamilnadu, India in 1988.

He is currently working in IE Power Technologies Pvt. Ltd, Bengaluru. His major responsibilities include project development, Design and development of standard and application specific variable speed drives. His research interest is in the area of Motor control.