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Small Scale Wind Generation System: Part I–experimental Verification of Flux Reversal Generator Block

B. Vidhya, K. N. Srinivas
Department of Electrical and Electronics Engineering, B. S. Abdur Rahman University, Chennai, India

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ABSTRACT

This research work, titled Small Scale Wind Generation System, reported in part I and part II, proposes modeling, analysis and control of a small scale wind energy conversion system employing a direct driven Flux Reversal Generator (FRG) connected to the micro grid through a Quasi-Z-Source Inverter (QZSI). The application of QZSI using FRG to feed micro grid is proposed for the first time in this research work. The QZSI can realize buck/boost, inversion and power conditioning in a single stage with improved reliability. Also it features a wide range of voltage gain which is suitable for applications in wind systems, due to the fact that the wind generator output varies widely with wind velocity. In addition, the modified Space Vector PWM (SVPWM) technique is proposed in this paper to satisfy the shoot-through characteristic of QZSI. This also adds to the contribution of this research work. In this part I of this full research, modelling of the small scale FRG for wind system using Finite Element Analysis (FEA) is presented. The major parameter of FRG viz, voltage, current, torque and power are analyzed, validated and then represented in d-q model. The simulation results are validated with the analytical results. An experimental set-up to run the full procedure reported in this paper. These results form the basis for part II of this research work.

Corresponding Author:

K. N. Srinivas,
Department of Electrical and Electronics Engineering,
B. S. Abdur Rahman University,
Chennai, India.
Email: knsrinivas@bsauniv.ac.in

1. INTRODUCTION

Increasing exhaustion of conventional fuels and the severity of environmental pollutions navigate green energy installation by the renewable energy sources. In such kind of scenario renewable energy sources are providing good solution [1], [2]. Photovoltaic (PV) cell and wind energy system are available commonly and in plenty. In particular, wind energy is one of the fastest growing, cost effective, light weight, high efficiency and environmentally accepted mean of electric power generation. When micro grids are concerned, small-scale wind power is used more frequently. Researches on this are call of the day. The small scale wind power has turbine in smaller sizes. This reduces the cost of installation. Further, it is able to produce power at lower wind speeds. These saliencies allow small wind units to be a practical and workable option than their large counterpart. Various types of electrical machines are used in small scale wind generator in the past, including Permanent Magnet Synchronous Machine (PMSM) widely, [3]-[7]. The speed control of wind energy system is achieved by adoption of diode bridge rectifier and back to back pulse width modulation based voltage source inverter [8]-[10].

However, in recent years, flux reversal technology is occupying major place in wind power generation, [11]-[13]. Flux Reversal Motor (FRM), with its good efficiency, reliability, higher power density, compact small size and relatively light weight [14], has become an inseparable part in wind power generation within the last one decade. In particular, the electrical gear ratio (K) concept of FRM [12]-[15] made it a well suited candidate for low speed applications. In the scenario wherein conventional induction motors and synchronous motors can not appreciably handle the low speed low power applications, FRM has extended its helping hands to address this issue favorably.

Thus, the application of low speed FRM for possible integration with micro grids is presented in the first part of this research work. This part I presents a design of FRG for small scale wind connected to the micro grid via quasi-z-source inverter which uses modified SVPWM technique.

In conventional PMSG, the AC output is given to the grid through AC/DC converter for each power generation system (wind, solar, battery and so on). Then the output DC link voltage from all these sources is converted in to an AC through common Voltage Source Inverter (VSI). Here, input DC voltage of the VSI must be greater than the AC output voltage. Therefore, the VSI is to be designed to withstand the high stress and with high capacity devices. In order to avoid this, a buck boost circuit is used in the DC link to keep the DC voltage constant and to reduce the VSI stress [16]. This increases the cost of the system heavily. Also this causes a reduction in the overall efficiency of the system. To overcome the above mentioned issues, this research proposes as QZSI.

This inverter exhibits both buck and boost capability at a single stage. The QZSI is developed from the traditional z-source inverter and therefore the same control method which is used in ZSI can be used for QZSI. The SVPWM control methods are commonly used in industry to control ZSI [17-19] because of lower current harmonics, high modulation index and high voltage utilization efficiency. Applying this control method to QZSI does not only conserve the advantages of SVPWM but it also provides other performance benefits such as good buck/boost capability, lower component ratings, reduced source stress and reduced component count. This makes the structure in to a compact size and it becomes highly reliable with a low cost. Most of the research work is carried out on application of QZSI are of PV systems [20], and few publications are available in application of QZSI to PMSG wind generation [21].

Application of QZSI for the wind power generation employing low speed FRG connected to AC micro grid proposed in this paper is new. This forms the contribution of this research work. In this focus, part I of this research paper discusses the machine modeling alone. The QZSI research is presented in its part II counterpart. This part I is organized in to the following sections: The design of 6/14 low speed FRG for wind generation is demonstrated in section II. The d-q model representation of FRG is derived in section III, which is essential for further modeling stages. Analytical proofs to validate the small speed FRG design are appropriately given. Finally, section IV concludes the part I of the paper.

2. ELECTROMAGNETIC CHARACTERIZATION AND ANALYTICAL VERIFICATION OF THE PROPOSED 6/14 FRG

The construction and principle of operation behind the flux reversal machines can be well understood in [22] and hence are skipped here. Depending up on the output power, the speed of the small scale wind turbine varies between 140 RPM to 300 RPM. The wind turbine speed decreases when the capacity of the machine increases. The rated speed of 1 kW machine is 214 RPM. For this rated speed, the suitable FRG configuration is 12/16 and 6/14 pole. The 6/14 pole has more power density than 12/16 pole machine because the stator flux linkage of 6/14 pole is twice that of 12/16 pole. Hence 6/14 pole configuration is selected for the proposed analysis.

The design specifications of 6/14 FRG at 1.8 KW, 50 Hz, 214 RPM is given in Table 1. Based on the design specifications main dimensions of 6/14 FRG was calculated using the design equation given in [23]. The dimensions are given in Table 2. Based on this dimensions, the proposed 6/14 pole FRG is modeled for electromagnetic finite element analysis.

The cross section of 6/14 FRG is shown in Figure 1. It has 6 stator pole and 14 rotor pole. Each stator pole consists of four Permanent Magnets (PM) and a main field winding. These two form the excitation system for stator. Rotor has no PMs and windings.

Table 1. Generator Specifications

parameter	value
Generator power	1*KW*
Rated voltage	170V
Rated current	3,7, *A*
Frequency	50 *Hz*
Generator speed	214, *RPM*

Table 2. Dimension of FRG

parameter	value
Stator outer diameter	270, mm
Stator bore diameter	240, mm
Stator inner diameter	166, mm
PM height (NdFeb)	2.45, mm
Air gap	0.5, mm
Rotor outer diameter	160, mm
Rotor inner diameter	100, mm
Shaft diameter	52, mm
Stack length	150, mm
Rotor pole arc	8.56, deg
Stator pole arc	12, deg
Coil type	Swg 25

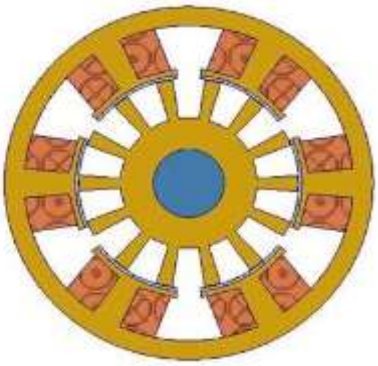

Figure 1. Cross section of FRG

2.1. Static characterization

The flux density distribution at no load is 1.4 Wb/m^2 as shown in Figure 2. The flux density along the periphery of the machine at the center of the stator pole is shown Figure 3. From the Figure 2 and 3, it is observed that the 6/14 pole FRG has 2 pole flux pattern. The phase flux linkages of FRG are shown in Figure 4. The flux linkages are sinusoidal, hence the induced voltage is also sinusoidal. The no load phase voltages are shown in Figure 5. Based on the flux linkage the total inductance is calculated as

$$L = \frac{\lambda_{load} - \lambda_{PM}}{i} \tag{1}$$

The quantities λ_{load} and λ_{PM} are the load and no load flux linkages of the coil. They are obtained from FEA based simulation. The total calculated self inductance is 0.05 H and the mutual inductance is 0.48 H.

The simulated results of this paper are validated through rigorous analytical approach [23] and are given as inference in each section.

Results and Discussions:

The flux density in the air gap is calculated by, $B_g = \dfrac{B_r}{1+\dfrac{\mu_{re}}{\mu_0}\left[\dfrac{(1+K_{st})g}{h_m}\right]}$, with B_r, the residual flux density as 1.3, T; μ_r, the recoil permeability as 1.05 μ_0; K_{st}, saturation factor as 0.05; h_m, the magnet thickness as $2.45mm$; and g, the air gap as $0.5mm$. The calculated air gap flux density B_g is 1.15, T.

Flux is given by $\phi = (1+K_{fr})B_g \tau l$, Wb, where l is stack length of the generator, and τ is pole pitch, which is given by $\tau = \frac{\pi}{28}(D_r + 2g)$. K_{fr} is a fringing factor (K_{fr}=0.4). D_r is diameter of the rotor and g is airgap (refer Table 2). The substitution gives, $\phi = 0.0049\ Wb$. Thus flux linkage, $N\phi = 0.53\ Wb - Turns$, where N is the number of turns per coil, which is obtained in the simulation result of Figure 4.

The induced EMF (per phase) of the FRG is given by $E_m = 2N\ (2\pi n) l \pi D_r . K_{fring} . \frac{n_p}{2} . B_{PM}$, V/ph, where n rotor speed in rad/sec. is n_p is the number of permanent magnet pair per stator pole as 2. This gives $E_m = 153\ V/ph.$ which is closely obtained in the simulation results of Figure 5.

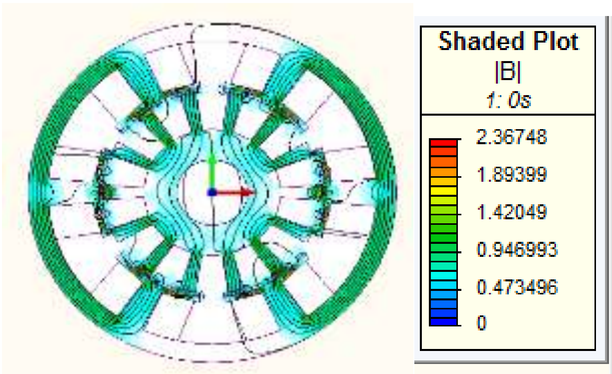

Figure 2. Flux distribution at no load

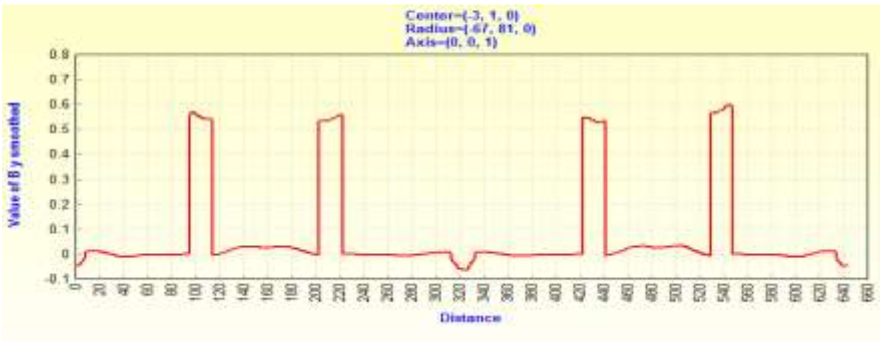

Figure 3. Flux density along the periphery of the machine at the center of the stator pole

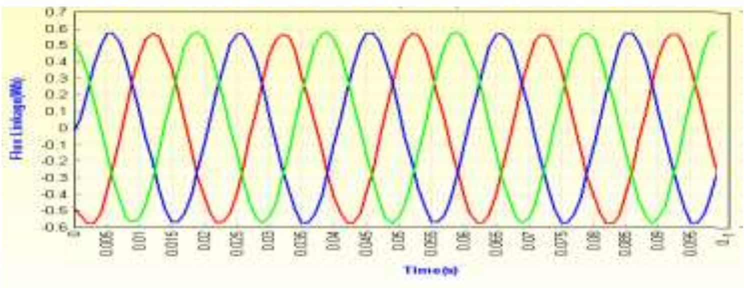

Figure 4. Flux linkages of the coil

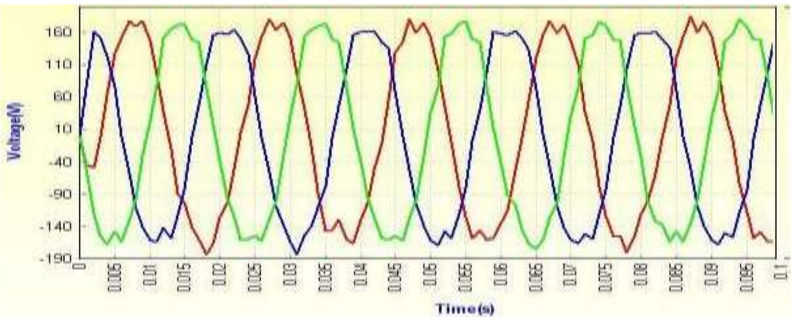

Figure 5. No load induced voltage

2.2. Dynamic characterization

Finite element dynamic analysis of FRG is carried out to find the voltage and current characteristics of the machine at 214 RPM. This simulates the actual practical run of the machine [24]. The speed characteristic in deg/sec is shown in Figure 6. In the graph 1284 deg / sec indicates 214 rpm.

The simulated results of the developed torque is shown in Figure 7 and Figure 8. The average value of the full load torque is 39 Nm.

The generator output phase voltage and current are shown in Figure 9 and 10. The simulated results of voltage regulation of the generator for varying resistive load are obtained at 241 RPM and are shown in Figure 11. It varies between 2% to 10%, which is in acceptable limit.

Results and Discussions:

The rated current is given by, $I = \dfrac{2\pi NT}{3E_m/\sqrt{2}}$ where N is the rotor speed in RPM; T is the torque as 39 Nm. This gives the I=3.4A which is closely obtained in the simulation results of Figure 5.

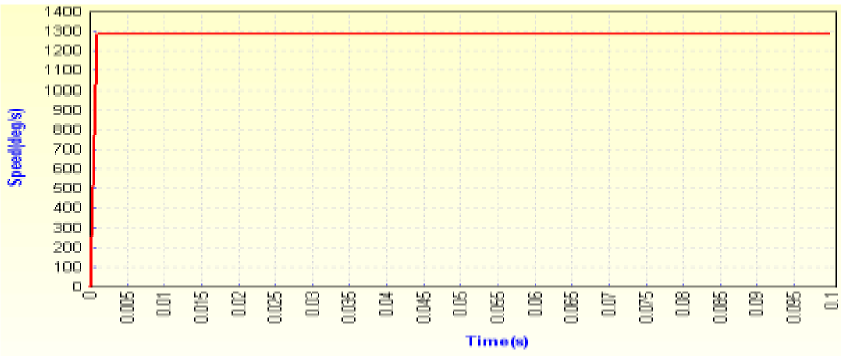

Figure 6. Speed of FRG

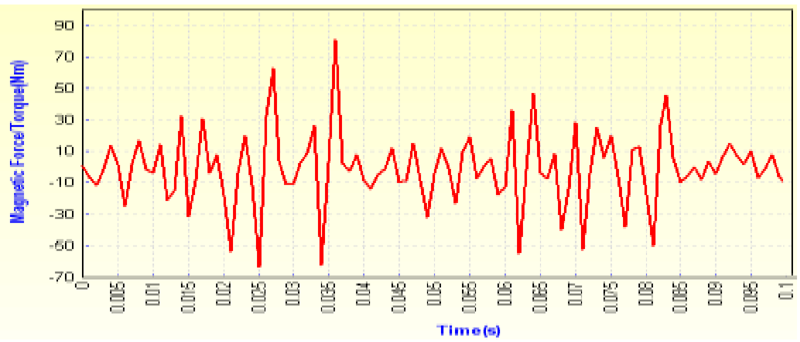

Figure 7. Developed torque

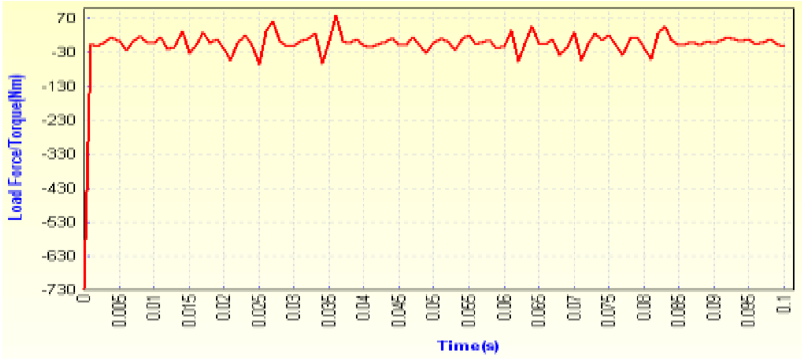

Figure 8. Developed torque–average

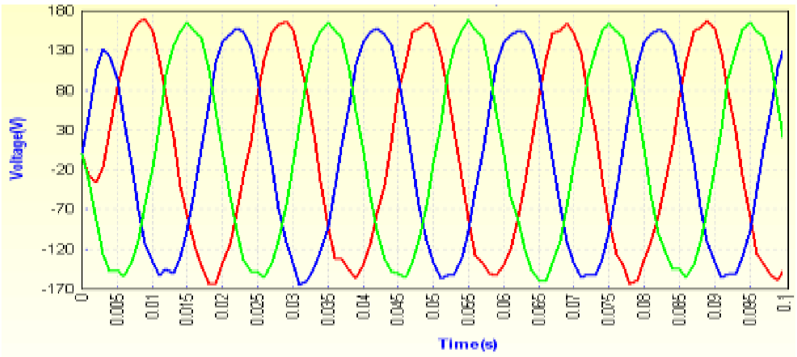

Figure 9. Induced phase voltage

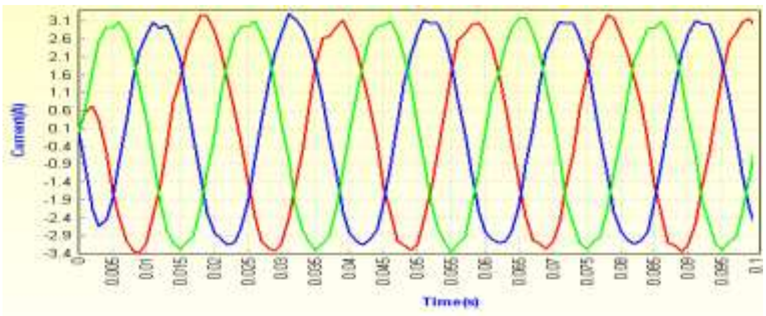

Figure 10. Phase current

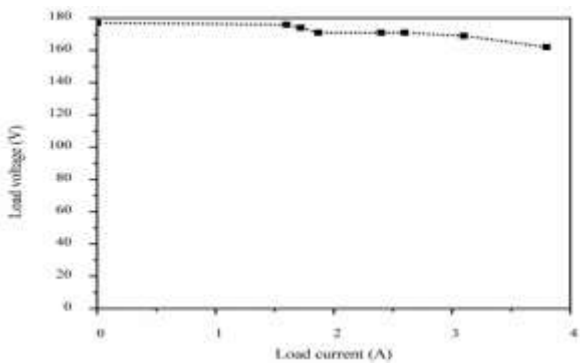

Figure 11. Voltage regulation of FRG

The simulated results of torque, flux linkages and inductances, which are obtained from the above electromagnetic finite element analysis of the machine, are carried over to the next section for d-q representation of the FRG.

3. FICTITIOUS ELETRICAL GEAR AND D-Q REPRESENTATION OF FRG

3.1. Fictitious electrical gear

The frequency and speed relationship for the FRG is given by

$$n = \frac{60\times f}{n_r} \tag{2}$$

where n is the rotor speed in RPM, f is frequency in Hz and n_r number of rotor poles. The Figure 2 and 3 shows that 6/14 pole FRG has 2 pole pattern. Hence the speed of the flux pattern (n_{fp}) is represented as $n_{fp} = \frac{120\times f}{n_r} = 60\times f$. It shows that speed of the rotor and speed of the flux pattern is different. This difference of rotor speed and flux pattern speed is represented in fictitious electrical gear ratio (K), which is represented as

$$K = \frac{n_r}{p_{eq}/2} \tag{3}$$

where p_{eq} is the number of flux pole pattern which is 2 for 6/14 pole FRG. Hence the gear ratio for 6/14 pole FRG is 14.

3.2. d-q model of FRG

The 6/14 pole FRG considered as a 2 pole PMSG. The d-q representation of the FRG is given by,

$$v_d = Ri_d + P_{eq}\lambda_d - K\omega_r\lambda_q \tag{4}$$

$$v_q = Ri_q + P_{eq}\lambda_q - K\omega_r\lambda_d \tag{5}$$

$$\lambda_d = L_q i_q \tag{6}$$

$$\lambda_q = L_d i_d + \lambda_{af} \tag{7}$$

The electrical torque is given by

$$T_e = \frac{3}{2}\times\frac{P_{eq}}{2}\times K(\lambda_{af} i_q + (L_d - L_q) i_d i_q) \tag{8}$$

where, R is the stator resistance in ohm , L_d and Lq are the *d* and *q* axis inductance in *H*, λ_d and λ_q are the *d* and *q* axis flux linkages (*Wb*). The ω_r is the rotor speed in rad/sec. i_d and i_q are the *d* and *q* axis stator current in Amps. i_d is zero in this machine and the value of i_q is obtained in Figure 10. By maintaining the *d* axis current to zero, FRG is controlled with constant flux up to base speed and q axis current is maintained in phase with back emf of the machine. All these parameters are obtained using FEA simulations as explained in the previous section, and are listed in Table 3.

As MATLAB has no ready-made FRG model, the above equations of voltages and torque in d-q frame are derived. They are separately modelled in simulink block where as shown in Figure 12.

Table 3. Parameters of FRG

S.NO	Parameters	Value
1	K	14
2	ω_r *rad/sec*	22.4
3	R *ohm*	0.174
4	$L_d = L_q$, *H*	0.05
5	i_q (*A*)	3.2

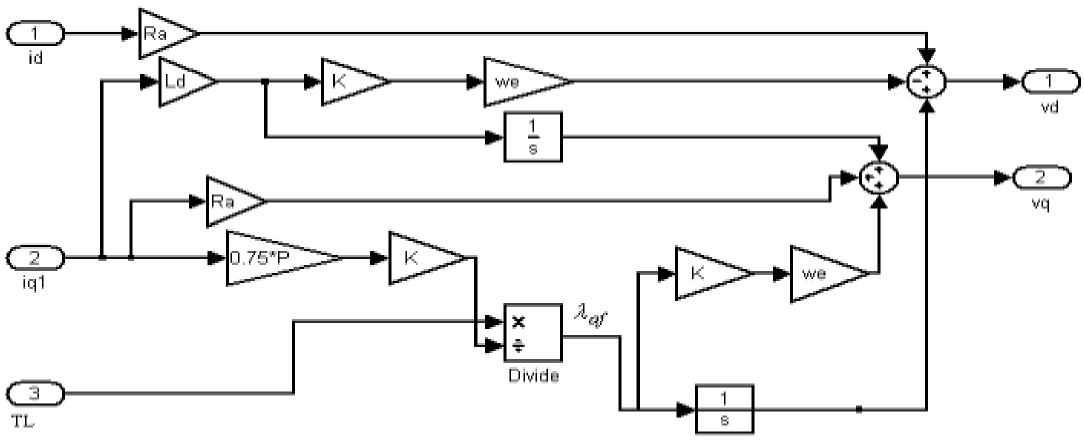

Figure 12. FRG d-q model

The input to the rectifier is V_{abc}. But the above designed sub system of FRG has V_d and V_q as the outputs, that is in d-q frame. So, for a transformation of d-q to abc, the subsystem of FRG d-q model is interfaced with *dq* to *abc* transformation block and then the 3-phase voltage is connected to rectifier block through the coupler. It is used to couple the transformation block (*dq0-abc*) to simscape rectifier. The controlled voltage source block of coupler converts the simulink input signal into an equivalent voltage source. These are as shown in Figure 13. The subsystem of coupler is shown in Figure 14. The FRG 3 phase output voltage is shown in Figure 15.

It is to be noted that the FEA simulated 3 phase voltage of FRG as shown in Figure 9 and the d-q modelled 3 phase voltage of FRG as shown in Figure 15 are the same, and they tally with the analytical inference.

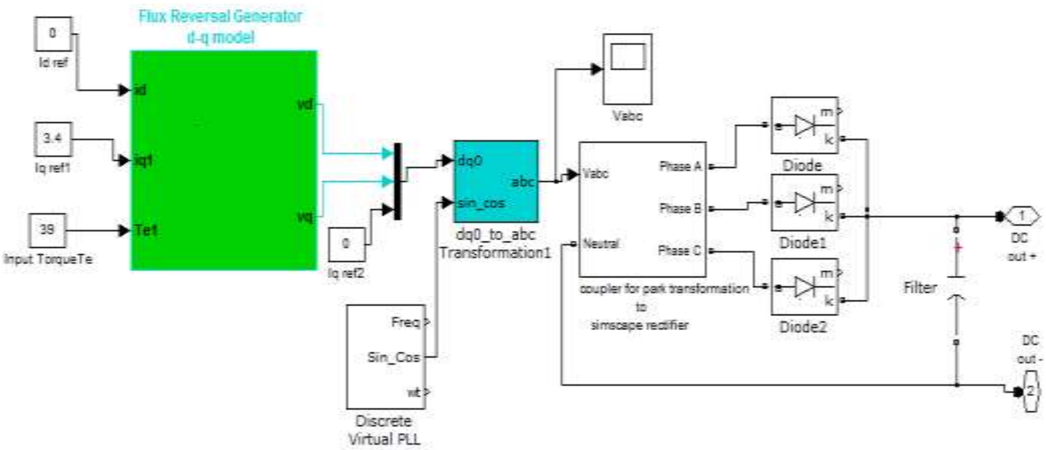

Figure 13. *d-q* voltages of FRG converted to *abc* voltages.

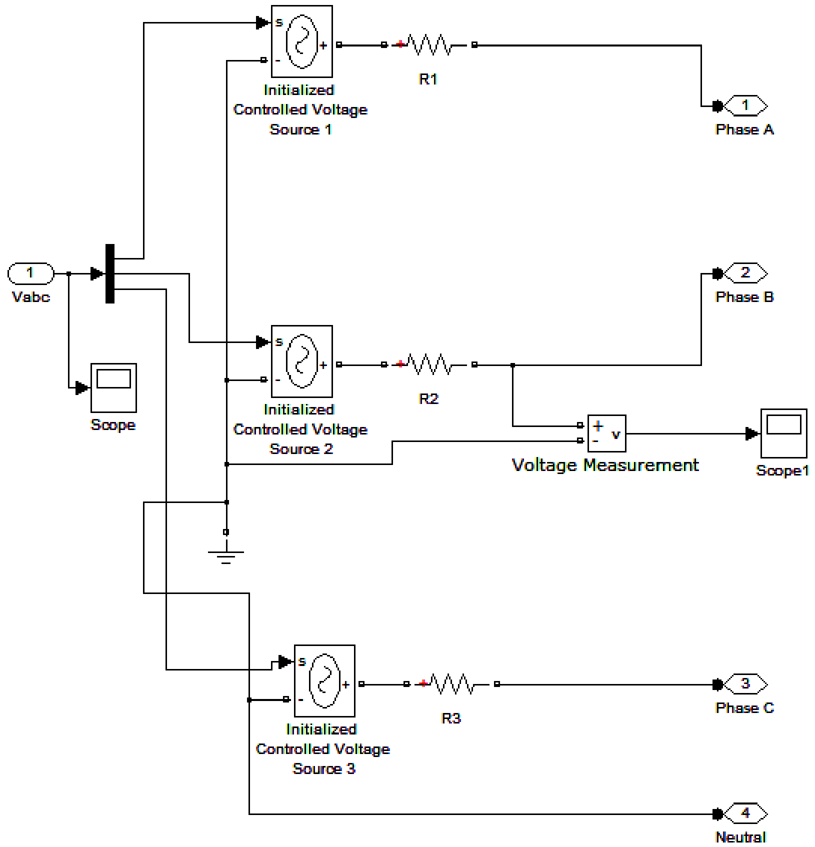

Figure 14. Coupler for transformation (*dq0-abc)* to simscape rectifier

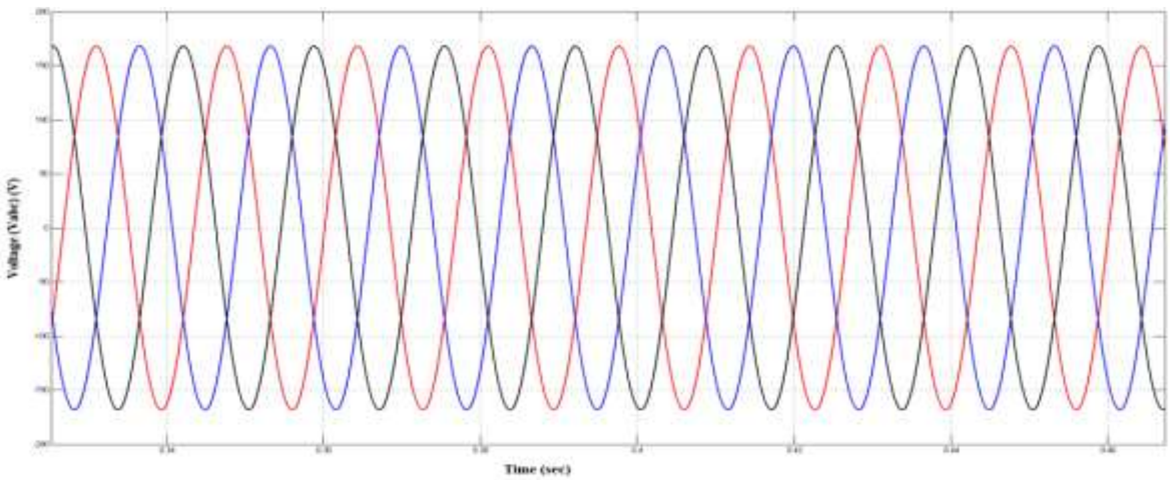

Figure 15. V_{abc} voltage

4. RESULTS AND DISCUSSIONS

The torque from small turbine which works as the prime mover to FRG is the machine's input. The performance of FRG under this condition was modeled and simulated in section II. The relevant machine parameters thus obtained are used in simulink modeling to interface the machine with the rectifier. This interfacing of FRG with rectifier is shown in Figure 13, and the simulated results of the DC output voltage is shown in Figure 16.

This DC voltage will form the input for the next stage that is QZSI stage.

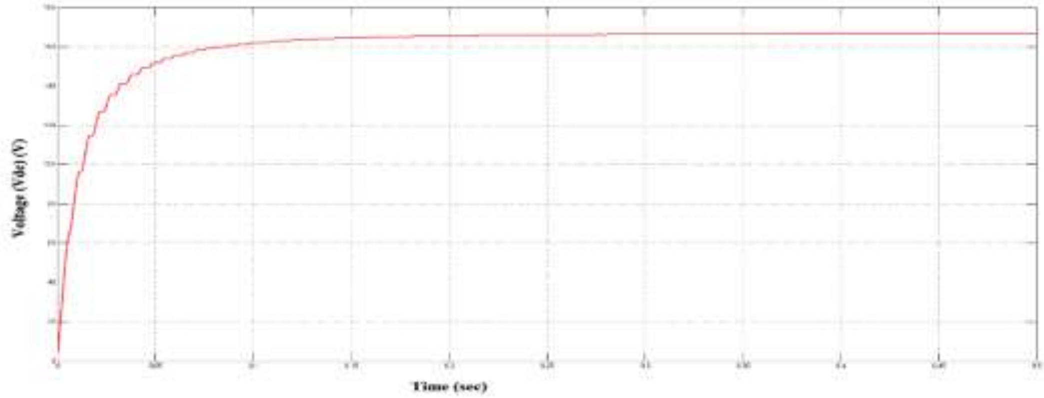

Figure 16. Rectifier output voltage (V_{dc})

The complete simulation and analytical works carried out on the FRG part of this wind energy system has been experimentally set-up and verified. The part-II part of this paper makes use of all the experimentally obtained results of FRG. The experimental set-up showing all the accessories are shown in Figure 17.

Figure 17. Prototype of Small scale FRG fit for wind energy system

4. CONCLUSION

In this part I research paper on 'small scale wind generation system' using flux reversal technology connected to micro grid through quasi-z-source inverter, the FRG has been designed, modeled and analyzed to give the rectified V_{dc} input voltge to the QZSI. For wind power generation and for its inter-connection with the micro grid, the suitability of FRG has been brought out. The rudiments of FRG modeling and analysis for the same purpose, which is a new addition in FRG literature, has been presented. Figure 17 shows the entire prototype of the small speed FRG and its generator voltage comparisons made at the university using its research funding. The other major part of this research are QZSI analysis and final interconnection with micro grid, which are presented in part II of this research.

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BIOGRAPHIES OF AUTHORS

Ms.Vidhya.B was born in the year 1988. She obtained B.E Electrical and Electronics Engineering from Anna University in 2009. M.Tech (Power System Engineering) from B.S.Abdur Rahman University in 2011.She is currently pursuing Ph.D in Electrical Machinesin the Department of Electrical and Electronics Engineering at B.S.Abdur Rahman University. Her areas of interest include Electrical machines–design, modeling and analysis, in which she is pursuing her Ph.D., Her other research interests are Power systems and load frequency control.

K.N. Srinivas was born in the year 1967. He obtained (i) D.E.E.E. (Diploma in Electrical & Electronics Engineering) from Chenkalvarayan Polytechnic, Chennai - 7 in the year 1985, (ii) A.M.I.E., from I.E. India in Electrical Engineering branch in 1989, (iii) M.E. (Power Systems) from Annamalai University in 1993 and (iv) Ph.D in Electrical Engineering from Anna University in 2004.

- He is a recipient of *IEEE Best Paper* awards in the *IEEE* international conferences IECON 2000 (held at Japan) and IECON 2003 (held at USA).
- He has more than 50 international journal and international conference publications.
- He has authored 3 text books for engineering students.
- He has executed 2 funded projects from TNSCST and has completed a project on 3D magnetic field sensor Sensor project for DRDO, an Indian government defence organization.

Member of IEEE and I E (India), Dr K N Srinivas is currently Professor and Head in the department of Electrical and Electronics Engineering, B S Abdur Rahman University, Chennai 48, Tamilnadu. His areas of research interests are electrical and mechanical design, modeling and analyses of electric machines and power system contingency analysis