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Particle Swarm Optimization of Switched Reluctance Generator based Distributed Wind Generation

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Abstract— ***In this paper, basic particle swarm optimization (PSO) is proposed to find the optimal power generation of switched reluctance generator (SRG) for wind energy conversion in order to incorporate in power distribution system (PDS). SRGs are not commonly used in wind energy applications; however their high levels of robustness, efficiency, and speed range make them a good option. The control of the power delivered to the load is a constant challenge. Since wind speed is variable the excitation voltage must be controlled to make the generated power as constant as possible. Here, we present a PSO approach for optimizing performance of a Switched Reluctance Generator (SRG) intended for distributed wind power application. Phase voltage switching angles and DC bus voltage level have been identified as control variables affecting output power. Due to highly nonlinear characteristics of Switched Reluctance Generator, iterative simulation of the generator model on the range of control variables can be used for finding output power profile. Since it is a multidimensional search space, the number of iterations is very large. Therefore, we have used evolutionary algorithms to narrow the search space and reduce simulation time. A basic particle swarm optimization (PSO) algorithm has been introduced to find optimal firing angles and DC bus voltage level under multiple operating conditions. Optimization of the control variables is performed using a machine model based on measured characteristics. Selected operating points are experimentally tested using a 4 kW 1500 rpm SRG prototype. PSO algorithm is a viable alternative for generating optimal control in multi-dimensional optimization of SRG wind power conversion.***

Keywords— ***DC bus level, Optimization, Optimal firing angles, Particle Swarm Optimization, Power Distribution System, Switched Reluctance Generator***

I. INTRODUCTION

At present, due to the large global consumption of power, researches on renewable energy sources and integration into an electric power system, such as photovoltaic, wind power, biomass and others are being conducted. Among all the renewable energy sources, wind power presents the higher global growth in the last years. The synchronous and induction machines are nowadays dominating the market of wind energy applications. Wind powered generators must operate efficiently under variable speed conditions. Switched Reluctance Generator is proved to be a real alternative to conventional variable speed drives in the extraction of maximum energy in wind energy generation system. The rugged and simple construction, low-manufacturing cost, potential for high efficiency, fault tolerance, and support of both high-rotational speed and high-temperature operation are some attractive characteristics that enable the use of SRG in wind energy applications [1]. The objective of SRG control in wind energy application is to optimize the energy captured to produce maximum output power. Extensive ongoing research has been done on the low and medium speed range which studies the suitability of using SRG in wind power applications. Control strategy to keep the dc-link voltage at a desired value with optimal performance characterized by high-efficiency, low-torque ripple, and low-acoustic noise has been used in [2]. In [3], the turn-on and turn-off angles are continuously adjusted to successfully regulate the generator output voltage under varying loads. As to [4], under fixed optimal turn-off angle, the generator output power is controlled by regulating the turn-on angle using fuzzy control. To optimize the SRG performance by simulation, multidimensional tables representing the SRG performance in terms of torque ripple and energy efficiency are achieved in [5]. By superposing the generated tables, a multidimensional performance table is obtained representing the optimal operating zones over the speed and power ranges.

The relative difficulty to establish an analytical model for the SRG that can be used for this optimization, a detailed model of the machine, based on the magnetization characteristics obtained by measurements is used to simulate the system operation over the desired speed and power ranges. In order to narrow the search space and reduce simulation time, this paper introduces an optimization technique for SRM motivated by particle swarm approach. The main advantage of traditional PS based optimization algorithm over other modern heuristics is finding the true global minimum of a multi modal search space regardless of the initial parameter values, fast convergence, versatility, and use of few control parameters. The feasibility of the proposed method is demonstrated for an 8/6, four phases, 4 KW, 1500 rpm SRM and compared with Genetic Algorithm (GA) method. The results show that the proposed approach performs better in terms of solution quality, accuracy and convergence time. The organization of paper is as follows. In section II, the problem formulation is explained, while the wind energy conversion system is briefly introduced in Section III. The performance of the

PS algorithm is presented in Section IV. Section V provides the experimental testing of the SRG. Finally, conclusions are given in Section VI.

II. THE SWITCHED RELUCTANCE GENERATOR

Fig. 1 shows parts of the 8/6, 4 kW SRG prototype tested. The SRG has steel laminations on the rotor and stator. There are concentrated windings placed around each salient pole on the stator. The coils around the individual poles are diametrically connected to form the phase windings. There are no windings or permanent magnets on the rotor, making the structural integrity of the rotor compatible with operation at very high speeds. In the SRG there is a natural tendency to align the rotor and the stator active poles in order to maximize de inductance of that phase. When a prime mover forces the rotor to leave the stable equilibrium position, the electromagnetic torque produced results in a back electromotive force that increases the applied voltage. In this way the machine generates electrical power.

Fig. 1. Parts of the prototype Switched Reluctance Generator

A. Mathematical Model

The SRG under investigation is excited through a conventional asymmetrical bridge topology. Fig. 2 shows the driving circuit that delivers electric energy to a dc bus represented by a capacitor C. The system load is represented by a resistor R_L. The assumptions made are: 1) the magnetic saturation is ignored; 2) fringing effect is neglected; 3) mutual coupling among phases is neglected. The voltage equation for each phase of the SRG is given by:

$$V_{ph} = R_{ph} i_{ph} + L_{ph} \frac{di_{ph}}{dt} + \omega i_{ph} \frac{dL_{ph}}{d\theta} \tag{1}$$

Where $V_{ph}, R_{ph}, i_{ph}, L_{ph}, \omega,$ and θ stand for phase voltage, stator resistance, phase current, phase inductance, speed, and rotor position, respectively. The last member on the right side is back EMF, which depends on the first derivative of phase inductance with respect to the rotor position, phase current and rotor speed:

$$e = \omega i_{ph} \frac{dL_{ph}}{d\theta} \tag{2}$$

The generated electrical power is proportional to this back EMF. In SRG operation cycle, two main periods are defined: excitation period, during which phase winding is excited and act as field winding, and generation period, during which phase winding act as armature winding in which voltage is generated [6].

Equation (3) determines DC bus capacitor current which is a sum of all phase excited and generated currents, and also load current. Load current and DC bus voltage are given by equation (4) and (5) respectively.

$$i_C = \sum_{j=1}^{4} i_{gen\,j} - \sum_{j=1}^{4} i_{exc\,j} - i_{RL} \tag{3}$$

$$i_{RL} = \frac{V_{dc}}{R_L} \tag{4}$$

$$\frac{dV_{dc}}{dt} = \frac{i_C}{C} \tag{5}$$

Output power is proportional to DC link current (i_o) which is a sum of generated currents of all phases minus a sum of excited currents of all phases:

$$P_{out} = i_O V_{dc} \tag{6}$$

$$i_o = \sum_{j=1}^{4} i_{gen\,j} - \sum_{j=1}^{4} i_{exc\,j} \tag{7}$$

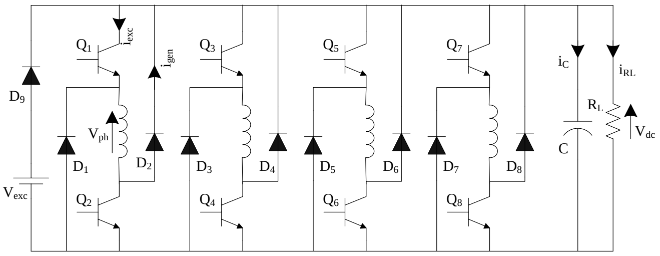

Fig. 2. Conventional SRG Converter

B. Magnetic Characteristics

An accurate SRG model needs a good knowledge of the magnetic characteristics of the machine to determine its electrical and mechanical behaviors [7]. The flux linkage of a stator phase and torque characteristic, are a function of the excitation current and the rotor position. The magnetic characteristics of the SRG are obtained with experimental measurement on the tested machine. Each phase has a periodicity of $2\pi/N_r$ that is equal to 90 mechanical degree for the 8/6 pole SRG. Fig. 3 shows the flux linkage characteristics according to current for different rotor positions from unaligned to aligned position. Fig. 4 shows the torque characteristics according to angle for different current values. Rotor position is changed from unaligned position (zero mechanical degree) to aligned position (45 mechanical degrees).

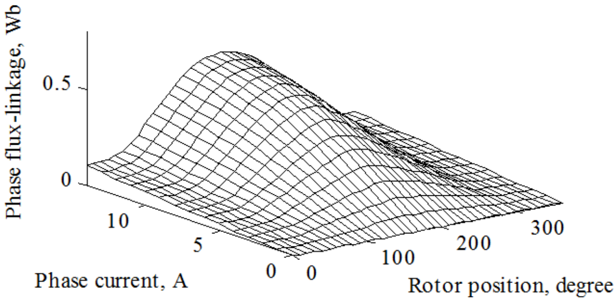

Fig. 3. Measured phase flux linkage

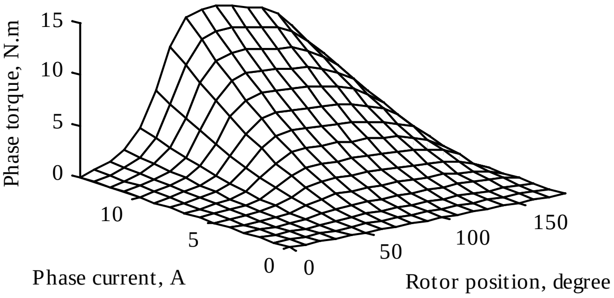

Fig. 4. Phase static electromagnetic torque

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C. Control Strategy

To avoid difficulties in obtaining analytical derivatives for the severely nonlinear SRG, numerical optimization techniques are preferred. Based on these equations and measured characteristics of flux linkage and static torque, we have developed a simulation subroutine $Power\_opt()$ in Matlab environment with M-file scripts [8]. The optimization work developed here delivers optimal power output as a function of the turn-on angle, turn-off angle, DC bus voltage level, reference current, winding resistance, angular velocity, and SRM measured characteristics in the form:

$$[P_{out}] = Power\_opt\left(\theta_{on}, \theta_{off}, V_{dc}, I_{ref}, R, \omega, SRM\_mc\right) \quad (8)$$

In order to achieve high performance, the SR generator should be operated with variable commutation angles [8]. As wind speed is variable, the excitation voltage must be controlled to make the generated power as constant as possible.

III. CONVERSION OF WIND ENERGY

Wind energy conversion systems convert the kinetic energy of the wind into electricity or other forms of energy. Wind power generation has experienced a tremendous growth in the past decade, and has been recognized as an environmentally friendly and economically competitive means of electric power generation. The kinetic energy (E) in air of mass *m* moving with speed *V* is given by:

$$E = \frac{1}{2} m V^2 \quad (9)$$

In a time Δt, the mass of the air that will flow through the area A is given by:

$$m = \rho A V \Delta t \quad (10)$$

Where ρ is the density of the air, if we put these two formulas together, we get that the kinetic energy of the air that passes through an area A in a time Δt is given by the formula:

$$E = \frac{1}{2} \rho A V^3 \Delta t \quad (11)$$

Since the energy per unit time is equal to the power, we get that the power in the wind moving through the area A is given by:

$$P = \frac{1}{2} \rho A V^3 \quad (12)$$

According to Albert Betz, we will get less than this maximum amount. Therefore, we often write the formula for the power from a wind turbine as:

$$P = \frac{1}{2} C_p \rho A V^3 \quad (13)$$

The power coefficient C_p is the fraction of the wind kinetic power that is captured by the wind turbine blades. It is also referred as the power coefficient of the rotor or the rotor efficiency. This coefficient changes from turbine to turbine and its value is given by:

$$C_p = \frac{\left(1 + \frac{V_o}{V}\right)\left(1 - \left(\frac{V_o}{V}\right)^2\right)}{2} \quad (14)$$

Where V_o is the downstream wind velocity at the exit of the rotor blades. This function is described in Fig. 5. It can be seem that this coefficient has a theoretical maximum value of 0.59. In practical designs, the maximum achievable *Cp* is between 0.4 and 0.5 for high-speed, two-blade turbines and between 0.2 and 0.4 for slow-speed turbines with more blades [9].

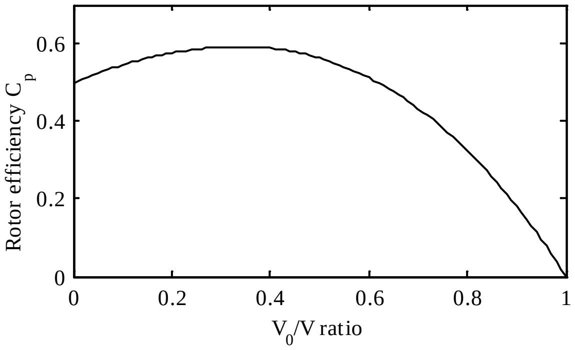

Fig. 5. Rotor power coefficient versus speed ratio

The power absorption and operating conditions of a turbine are determined by the effective area of the rotor blades, wind speed, and wind flow conditions at the rotor. Therefore, the output power of the turbine can be varied by effective area and by changing the flow conditions at the rotor system, which forms the basis of control of wind energy conversion system [10]. The tip speed ratio λ , defined as the ratio of the linear speed at the tip of the blade to the free stream wind speed and is given by:

$$\lambda = \frac{\omega R}{V} \quad (15)$$

Where R is the rotor blade radius and ω is the rotor angular speed.

Variable speed wind turbines typically use generator torque control for optimization of power output. They use blade pitch angle (β) to control the output power above their rated wind speed. Fig. 6 shows the turbine power-speed characteristics for various values of wind velocity at fixed pitch angle.

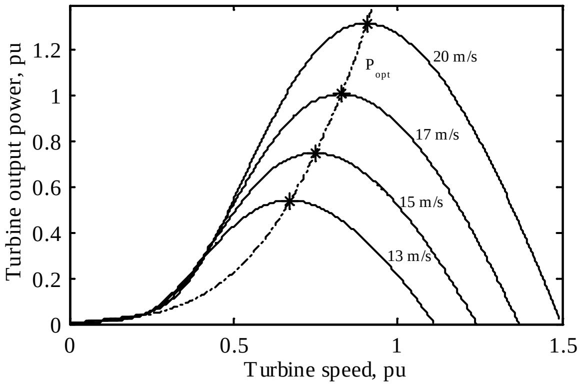

Fig. 6. Power-speed characteristics of the wind turbine

By eliminating wind speed from (15) when power coefficient is maximum:

$$P_{\max} = \frac{1}{2}\rho A\left(\frac{R\omega_{opt}}{\lambda_{opt}}\right)^3 C_{p,\max} \quad (16)$$

$\omega_{opt} = \frac{\lambda_{opt} V}{R}$ is a function of wind speed, then

$$P_{\max} = K\omega_{opt}^3 \quad (17)$$

Expression (17) shows that extracted maximum power from wind is a cubic function of the turbine optimum speed (figure 6). The wind profile shown by Fig. 7 is a real data measured in Haouaria wind energy village of Tunisia. For this wind speed characteristic, the average wind speed is $\overline{V} = 6.28 m/s$ with a dispersion coefficient of $\sigma_v = 2.32 m/s$. For this wind profile, the mean turbulence intensity, defined as $\frac{\sigma_v}{\overline{V}}$ is $\approx 37\%$.

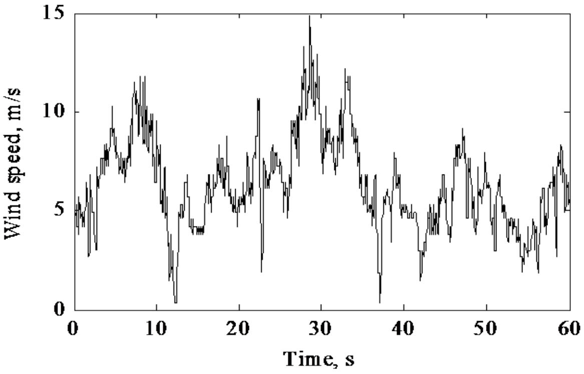

Fig. 7. Wind profile

IV. PARTICLE SWARM OPTIMIZATION

Particle Swarm Optimization (PSO) is a heuristic method inspired of the social model of bird swarms and fish schooling [11]. PSO, designed for the solution of nonlinear problems with continuous variables, was developed by J. Kennedy and R. Eberhart in 1995. Each individual, which corresponds to a candidate solution, is referred as a particle in a multidimensional search space. The particles in the search space adjust their location and velocity according to their own experience and the experience of neighbors. The particle swarm optimization concept consists of, at each time step, changing the velocity of accelerating each particle toward its *pbest* and *lbest* locations (local version of PSO). Acceleration is weighted by a random term, with separate random numbers being generated for acceleration toward *pbest* and *lbest* locations. PSO has been successfully applied in many research and application areas. It is demonstrated that PSO gets better results in a faster and cheaper way compared with other methods.

Another reason that PSO is attractive is that there are few parameters to adjust. One version, with slight variations, works well in a wide variety of applications. Particle swarm optimization has been used for approaches that can be used across a wide range of applications, as well as for specific applications focused on a specific requirement [12].

The position and velocity vectors of a particle in an *N*-dimensional search space are expressed in the equations (18) and (19):

$$X_i = (x_{i1}, x_{i2}, ..., \mathrm{x}_{in}) \quad (18)$$

$$V_i = (v_{i1}, v_{i2}, ..., v_{in}) \quad (19)$$

Where x_{ii} and v_{ii} are position and velocity of particle i^{th} in a search space with n particles respectively.

The best position obtained by a particle is expressed as:

$$Pbest_i = (x_{i1}^{best}, x_{i2}^{best}, ..., x_{in}^{best}) \quad (20)$$

The particle that has the best position all among the other particles in the population is expressed as:

$$Gbest_i = (x_{i1}^{best}, x_{i2}^{best}, ..., x_{in}^{best}) \quad (21)$$

The velocity and position of each particle updated after *(k+1)* steps is formulated as:

$$X_i^{k+1} = X_i^k + V_i^{k+1} \quad (22)$$

The velocity of i^{th} individual at *(k+1)* iteration is calculated using equation (23):

$$V_i^{k+1} = \omega V_i^k + c_1 rand_1 \times (Pbest_i^k - X_i^k) + c_2 rand_2 \times (Gbest_i^k - X_i^k) \quad (23)$$

Where

k : number of iterations

V_i^k : velocity of particle i^{th} at iteration k

X_i^k : position of particle i^{th} at iteration k

c_1 and c_2 : acceleration coefficients

ω : inertia weight parameter

$rand_1$ and $rand_2$: random numbers between [*0*, *1*]

Particles velocities on each dimension are clamped to a maximum velocity v^{max}. If the sum of accelerations would cause the velocity on that dimension to exceed v^{max}, Then the velocity on that dimension is limited to v^{max} given by equation (24) as:

$$v^{max} = (x^{max} - x^{min}) / N, \quad \text{N : number of intervals} \quad (24)$$

PSO flow chart is shown in Fig. 8:

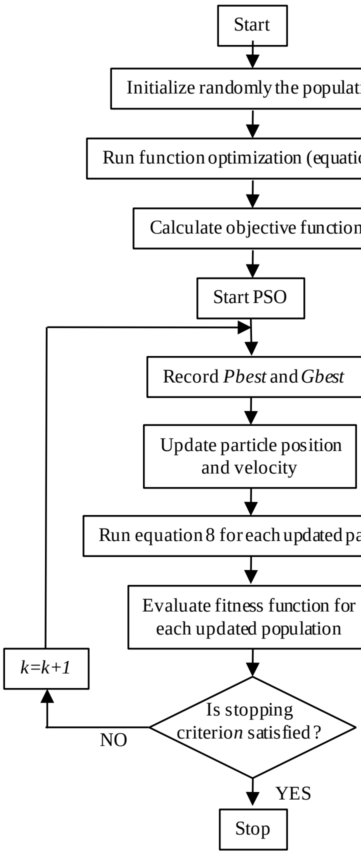

Fig. 8. PSO flow chart

The optimization problem is considered of the form:

Maximize

$$f = P_{out}(\theta_{on}, \theta_{off}, V_{exc})$$

Three decision variables namely, turn-on angle, turn-off angle, and DC bus excitation are considered for optimization. Their bounds are:

$$150° \le \theta_{on} \le 250°$$

$$50° \le \theta_{off} \le 150°$$

$$50 \le V_{exc} \le 250 \text{ V}$$

One constraint is also considered for optimization:

$$\theta_{on} \langle \theta_{off}$$

The following parameters are used with PSO algorithm. The number of particles was set to 50, number of maximum of inertia weight is *0.5*, coefficients for acceleration $c_1 = 0.1$ and $c_2 = 0.9$, and maximum number of iterations = *100*.

The performance of the proposed PSO is tested on a 4 kW SRG and compared to Genetic Algorithm (GA). Fig. 9 shows the performance of the optimization technique in terms of cost with PSO, and GA where the mean for the run out of 30 trials are plotted at each generation. Therefore, according to the presented results, the proposed PSO converges quickly for the global minimum than GA, as well as obtained better solutions than the GA. It is clear to see that PSO obtains better results than

GA. PSO gives smaller mean function value than GA, and hence its mean solution quality is better. In addition, PSO is able to obtain smaller standard deviation of function value; it means that the solution quality is more stable than GA.

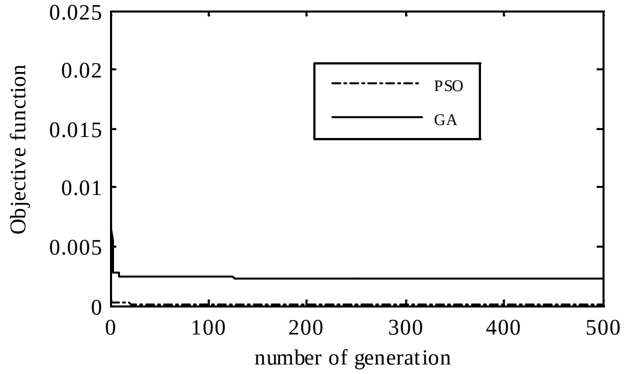

Fig. 9. Convergence curves of PSO and GA

V. SIMULATION AND EXPERIMENTAL RESULTS

A. SRG Output Power Optimization based PSO

Depending on the prime mover and application of SRG, the effect and the range of control variables on output power will change. In this work, we are interested only with variable speed wind turbine application.

When SRG is connected to a variable speed wind turbine and connected to utility line, DC bus voltage is constant. In this case, output power is a function of switching angles and shaft speed. Two decision variables are used for this optimization characteristic. In isolated network application, the effect of DC bus voltage changes was been added. Output power is a function of switching angles, DC bus voltage, and shaft speed. Three decision variables are used for this optimization case. Output power-speed characteristic with constant DC bus voltage is optimized and is compared to output power-speed characteristic with DC bus voltage changes in Fig. 10. Output power generation increases with optimal adjusting DC bus voltage level.

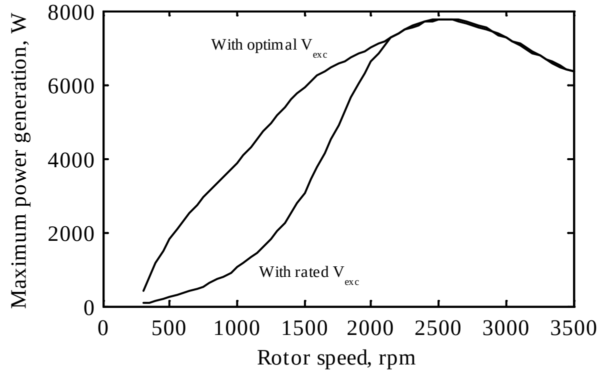

Fig. 10. Comparison of the power generation for constant and variable excitation voltages

B. Experimental Results

The performance of the PSO strategy is experimentally verified on 4 kW SRG test-bench. The proposed control of the optimal generation follows the standard practice to utilize Matlab/Simulink and related toolboxes as the design framework to develop a rapid prototype system in a reliable procedure. The generated and self-developed codes are implemented using dsPic 30F4011 [13]. The SRG is coupled to a separately excited dc motor, which emulates the variable speed wind turbine using a speed control. The tests were performed with a resistive load $R = 200\,\Omega$ in parallel with a capacitor $C = 470\,\mu F$. A shaft incremental encoder provides direct, quadrature, and index pulses to the Quadrature Encoder Interface (QEI) unit of the dsPic. For a given reference speed and reference power selected from the optimal output power-speed characteristic by the user, the controller finds appropriate switching angles and DC bus level from a look-up table filled from the results of PSO approach based output power optimization.

In order to test the performance of the system for variable speed wind energy conversion, the wind profile of the Fig. 7 has been applied to the wind turbine emulator and the effective inertia of the 0.5 Kg m^2 has also been selected. Fig. 11 shows the wind profile of 60 s duration with relatively high turbulence and the corresponding rotational speed for the emulated turbine.

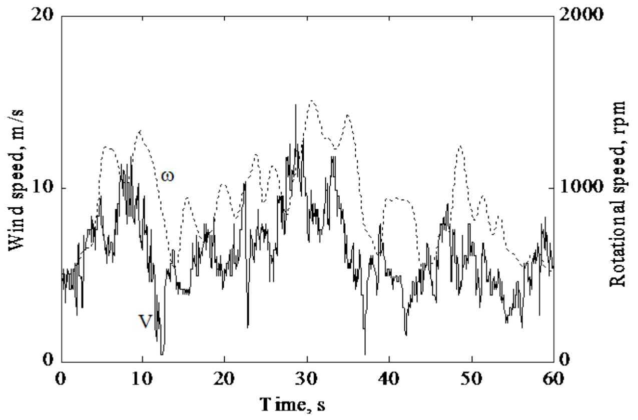

Fig. 11. Wind profile and rotational speed

Output power of SRG, and excitation voltage corresponding to variation in rotational speed between 500-1500 rpm, have been measured on the test bed and depicted by Fig. 12. The excitation voltage is optimized for each test point in order to achieve single pulse mode of operation.

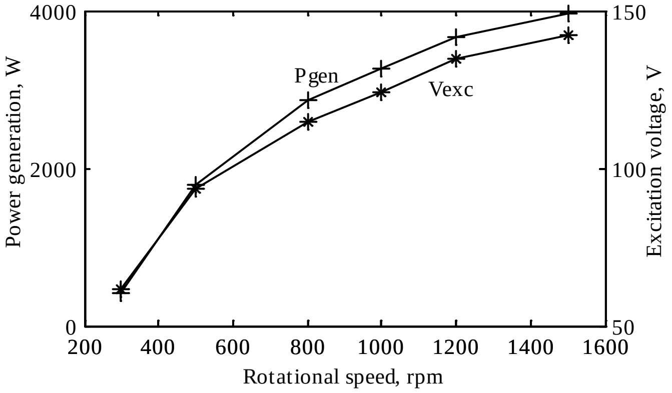

Figure 12 Experimental results of output power and the average excitation voltage.

VI. CONCLUSION

The power generation characteristics of a SRG are affected by many control variables. In this paper, the Classical PS strategy for optimizing SRG wind energy conversion projected to integrate power system distribution has been presented. Phase voltage switching angles and excitation voltage has been identified as control variables affecting output power. For this purpose, an experimental SRG model is used to reveal the potential of PS algorithm in multi-dimensional optimization. The SRG model has been simulated on the range of control variables to find optimal power generation. At each shaft speed, there is a triplet of turn-on angle, turn-off angle, and DC bus voltage level which maximize the output power. The comparison of simulation characteristics with experimental results are shown to verify the proposed PS strategy. The work demonstrates that the proposed method can be used to aid in selecting the best/optimal operation of SRG for wind energy based distributed source application.

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