

Multi-Objective Optimization and Online Control of Switched Reluctance Generator for Wind Power Application

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Fossil fuel combustion in power plants is the world's most significant threat to people's health and the environment. Recently, wind power, as a clean, sustainable and renewable source of energy, has attracted many researchers. The present paper studies how to maximize the extraction of wind power and the efficiency of a switched reluctance generator (SRG) by firing angles control. The proposed scenario comprises the optimization of turn-on and turn-off angles in the offline mode using a particle swarm optimization algorithm to control the system in the online mode with linear interpolation. The present approach simultaneously investigates the firing angles; also, it has simple structure, low execution time, and efficient convergence rate that are independent of machine characteristics (regardless of high nonlinearity of SRG). Furthermore, copper losses, as well as switching and conduction losses of semiconductors, were considered in simulations to achieve a more realistic outcome. Ultimately, the simulation results of a typical three-phase 6/4 generator using Matlab confirmed the validity of the presented control strategy that can easily find applications in the future.

Article Info

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I. INTRODUCTION

Depletion of fossil fuels, current fuel economy, and environmental issues have made researchers search for clean sources of energy. Wind power is an important source of renewable energy that is capable of application in various regions, so it has appealed to scientists in recent years. Numerous pieces of wind power generation equipment have been designed and operated worldwide and their different aspects have been investigated so far.

In recent years, switched reluctance generators (SRG) have been introduced as new equipment for wind power generation. Its simple structure, low cost and maintenance, robustness, high efficiency, and wide range of velocity encourage researchers to contribute to SRG development [1].

Interestingly, considering a broad spectrum of SRG performance, it is possible to directly connect wind turbines to generators and eliminate the gearboxes. Simple structure and low cost make SRG not only to be economically feasible but also financially competitive with other machines available in the market. After three decades of progress, it is commercially applied in vacuum cleaners, washing machines [2], water pumps, automatic doors, hybrid electric vehicle [3], [4], automotive application [5], electrified powertrain [6], starter-generator [7], turbocharger application [8], gas turbine [9], textile machines, and many others [10], [11]. Linear switched reluctance motors (SRM) are also employed in the food industry, machine tools, and medical equipment [12]. They can also be utilized in sea wave electricity generation. Moreover, there are some fields, including aerospace or automobile industries, that can exploit the generator operation of linear SRM. Furthermore, as its application in low-speed ranges is currently under investigation, its commercial use in the wind

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industry seems to be in initial steps [13].

SRG application in wind generation has previously been addressed with the trial and error procedure to find optimum control parameters in most studies. Chang and Liaw [14] introduced a control strategy to fix a desirable DC-link voltage with optimum performance, high efficiency, minimum DC-link voltage ripples, and low acoustic noise. Sozer and Torrey [15] presented an approach for determining firing angles in order to achieve maximum efficiency in the single pulse mode through considering the turn-on and turn-off angles as control parameters. They found that the optimal efficiency and output power could be described as a function of the turn-off and turn-on angle, respectively. Optimization of excitation angles through minimizing root-mean-square (RMS) value of the phase current or through maximizing the average ratio of the output power per input power is focused on in [16]. In order to find the excitation angles based on the desirable DC-link current with a minimum current ripple, an online algorithm is suggested in [17]. The turn-on and conduction angles are determined under various speeds via finite element method in [18]. As the results are sensitive to the variations in system parameters as well as operating conditions, Wang and Chang [19] apply fuzzy control to determine firing angles that can reduce the effect of parameter changes. At higher speeds and single pulse mode, the turn-off angle is optimized using the fitted curve, which is a function of power and speed, followed by the determination of the turn-on angle to adjust the produced power [20].

In [21], controlling the optimal turn-on and turn-off angles for maximum output power is studied and the relation between exciting current and conducting time is investigated. Ziapour et al. [22] described the commutation angles and the output power relevance following with controlling output voltage at high speeds via choosing optimum commutation angles. A 12/8 three-phase switched reluctance generator and a digital controller are established for wind power generation in [23] in which switching signals are generated by a controller based on the rotor position, the phase current, and the DC-link voltage. In [24], optimal firing angles are determined for torque ripple reduction and acoustic noise minimization. In [25], a dsPIC30F microcontroller is utilized to investigate different strategies to control angles positions and current chopping for a three-phase 12/8 switched reluctance generator. The power generation procedure in the generator is studied as well. The performance of a single-phase 12/12 SRG with U-cores is analyzed in [26] by two methods: single pulse control method (SPCM) and SPCM adopting the freewheeling technique. The output power, efficiency, torque ripple, and DC current ripple of SRG are compared in these two control modes. Ivanov and Kalanchin [27] study the maximum power point tracking (MPPT) through the hill climb search (HCS) method by controlling the turn-on and turn-off angles of SRG while the rotational speed of the rotor and the current value is used as the

controller inputs. In [28], the output performance of a generator is evaluated by dynamic simulation where finite-element is used to analyze the magnetic field. A 1.5 kW three-phase 12/8 SRG is then designed for low speed micro-wind turbine optimally. SRG voltage control and voltage stabilization methods are discussed and compared in [29]. Considering core saturation, magnetic and windings losses, the mathematical model is improved and the adequacy of the model is established.

A passivity-based control of SRG for small-size wind energy systems is proposed in [30]. The main goals are maximum power point tracking and controlling the output voltage. An adaption scheme is included in the proposed adaptive controller to deal with the back-emf of SRG and time-varying inductance. The closed-loop stability is guaranteed by Lyapunov theorem. In [31], the DC voltage control of a stand-alone SRG is addressed using a robust controller based on discrete-time sliding mode control. A disturbance estimator is used to achieve robustness. The proposed controller is compared to a PI controller. The control of SRG based on firing angles and reference current is investigated by Sh. Jagwani et al. [32]. A single-phase grid-interactive inverter is utilized operating in both current control and voltage control modes. Robust power flow control for various case studies is also presented. In [33], a hierarchical Markov model is presented to evaluate the reliability of a double-sided linear switched reluctance generator. The equilibrium point of reliability evaluation accuracy and model complexity can be found using this model. Zhang et al. [34] report the design and optimization of an SR machine in terms of mathematical modeling of electromagnetic and thermal fields, efficiency, torque ripple, acoustic noise, and the application of SRM in wind generators. In [35], a direct instantaneous torque controller is utilized for SRG at low speeds in which the turn-on and turn-off angles are fixed in the negative slope of the inductance profile. A Cuk converter is applied to control the generated voltage. In [36], a fly-wheeling pulse train (FW-PT) control approach is suggested to decreasing voltage ripple besides achieving faster response as well as better dynamic behavior. Further techniques are also compared to the FW-PT approach. In order to reduce steady-state error and increase the generated power of asymmetric bilateral linear SRG, a dual-loop compensation voltage control scenario is proposed in [37].

Chen et al. [38] present a set of control strategies for small-scale wind power SRG connected to energy storage system in an off-grid mode. A step control scheme, merging MPPT with power balance control, is suggested to improve the SRG efficiency. In order to generate AC output, a two-stage inverter is established using a boost circuit in the front stage following with a PI controller in the second stage. A simple current-rise model is proposed to guesstimate the steady state peak-current in an SRG for the diversity of conditions. The turn-off current level and turn-off position are used to estimate the current rise

in a given generation interval. For better accuracy, the interval is subdivided into multiple sections to a certain extent. As the number of sections is increased, the accuracy of the proposed model is improved except near to unaligned position [39]. In order to control the SRG power, a proportional plus resonant (P+RES) controller is presented [40]. The proposed scheme consents to control the power delivered to DC link using turn-off angle. Additionally, the controller provides power ripple reduction in comparison with the PI controller. Moreover, the proposed control methodology is implemented on a digital signal processor (TMS320F2835).

Direct search algorithms have been vastly used in scientific and industrial optimizations that can be simply coded [41]. Such methods like downhill simplex [42] or Hooke and Jeeves approach [43] appear to be suitable when the cost function is nonlinear, non-differentiable, and non-smooth. Population-based methods including the controlled random search algorithm [44], the genetic algorithm (GA) [45], and also the evolutionary algorithms [46], [47] are some other methodologies to tackle multimodal problems. These techniques outperform the gradient-based algorithms due to their capability in searching for an optimum point of multimodal functions as well as efficient performance in non-continuous feasible regions. In an attempt to attain an optimum firing angles range to control the maximum torque in various circumstances through GA, Fisch et al. [48] select the turn-on angles according to the optimization of generator efficiency. Moreover, in [49] the fuzzy logic is applied to control the DC-link voltage. The conduction angle is calculated based on the error signal of the output voltage via a fuzzy controller, and the turn-off angle is then computed from the linear relationship of velocity. The optimum design of a 1 kW SRG is addressed for wind applications using GA [50]. This optimization approach uses the design variables based on the main model and exploits LHS¹ for variable sampling. In [51], the optimization of a linear switched reluctance generator is explored based on energy efficiency. A genetic algorithm is used as the optimization method while the generator's magnetic field proceeded by the finite element method. In [52], two of the most important problems in wind conversion systems are addressed. A new MPPT scheme to improve the HCS technique as well as the modified torque ripple minimization method for a four-phase 8/6 SRG based on the artificial neural network is proposed. An experimental methodology is presented to control the SRG voltage using a fuzzy logic system [53]. The turn-on angle is fixed while the turn-off angle is varied. The suggested method is executed using a high processing capacity DSP/FPGA.

To avoid complex analytical calculations of cost functions, numerical optimizations provide an efficient route to find optimum local points. Accordingly, in the present work, a

particle swarm optimization (PSO) algorithm is employed due to the extreme nonlinearity of the generator, the prevention of the nonlinear analytical equations, simplicity, and the lower execution time of the simulation. The main advantages of this technique include well-organized memory usage, cooperation and information sharing between particles, high conversion speed, and simple establishment and execution. In contrast to the aforementioned works, simultaneous investigations of firing angles are presented in this paper. It should be noted that some of the similar works have investigated the effect of both firing angles separately. For instance, the first objective function is optimized using one firing angle, and the other objective function is then optimized using another one. However, each angle affects both objective functions. Therefore, it is more efficient to investigate them simultaneously. In this regard, a 60 kW three-phase 6/4 SRG was considered that supplied local load by an inverter in an off-grid mode, which was poorly addressed. Moreover, the excess generated power was stored in a battery bank. In order to eliminate the harmonics, the inverter was equipped with an LC filter. Contrary to the related works, where a linear model of SRG is used, this paper applies an actual nonlinear model of real SRG considering the effect of losses in simulations to approach reality. This model is based on the magnetization curves of an actual SRG where the saturation effect is included. On the other hand, an online control scheme is finally presented in this study whereas all the similar works have proposed offline methods. In this approach, the best offline obtained control variables are collected in a lookup table. Then, using this table, the online controller employs linear interpolation to achieve the maximum power generation. All parts of the system and their relations are presented in detail in Fig. 1.

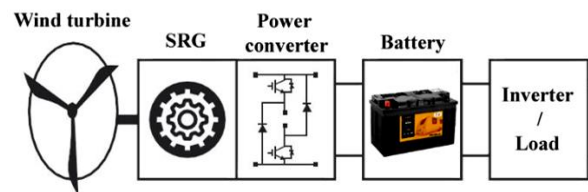


Fig. 1. The relationship between different parts of the system.

Section II focuses on a wind turbine, mathematical relations, and control strategies. The remaining of the paper is organized as follows. Section III describes the SRG structure, principles of its performance, nonlinear model, and power losses in this machine. Section IV explains the proposed methodology. Simulation results are shown in Section V. Finally, Section VI concludes the paper.

¹ Latin hypercube sampling (LHS)

II. WIND TURBINE

Wind turbines convert the kinetic energy of wind to electrical power. The maximum power generation depends on not only mechanical constraints but also wind speed [54]. The capacity of a turbine for power generation is often presented by companies as a curve in which power is plotted versus wind speed, called an ideal power curve [1]. An example of such curves is shown in Fig. 2.

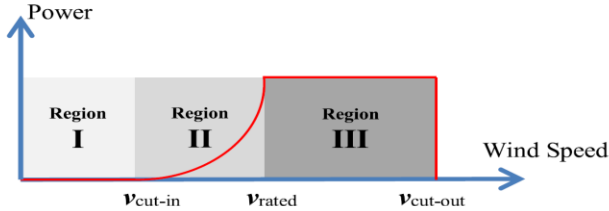


Fig. 2. The power curve of a variable-speed wind turbine [55].

Mechanical power generation (P_{aero}) follows a nonlinear relationship with air density, wind speed, and power coefficient (C_p) as:

$$P_{aero} = \frac{1}{2} \cdot \rho \cdot \pi \cdot R^2 \cdot v^3 \cdot C_p \quad (1)$$

where R is the radius of the area covered by the blades, v is the wind speed and ρ is the air density. The power coefficient obeys a non-linear function of the blade pitch angle (β) and the tip speed ratio (λ), which is the ratio between the tip speed of the blades and the wind speed [56]. It can be formulated as:

$$C_p \propto (\lambda, \beta) \quad , \quad \lambda = \frac{\omega_t R}{v} \quad (2)$$

where ω_t is the rotational speed of the turbine axis. This coefficient is an especial factor for each turbine and plays an important role in control purposes. It also gives information upon the aerodynamic efficiency of the turbine [57].

$$C_p(\lambda, \beta) = c_1 \cdot \left(\frac{c_2}{\lambda_i} - c_3 \cdot \beta - c_4 \right) \cdot e^{\frac{-c_5}{\lambda_i}} + c_6 \cdot \lambda \quad (3)$$

The coefficients c_1 to c_6 are: $c_1 = 0.5176$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 5$, $c_5 = 21$, $c_6 = 0.0068$, and:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08 \cdot \beta} - \frac{0.035}{\beta^3 + 1} \quad (4)$$

The variation of C_p with β and λ is illustrated in Fig. 3.

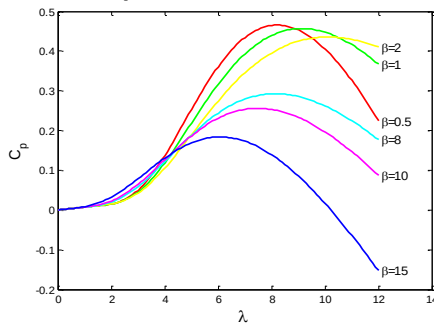


Fig. 3. Power coefficient of a variable speed wind turbine.

As can be seen in Fig. 2, the wind turbine power curve is divided into three regions. The first one is associated with the time when wind speed is less than a cut-in speed and the

turbine is in standby mode. The generated power of the turbine in this region can often be ignored in comparison with its dissipations. Hence, there is not any power exchange and the turbine fails to operate. In the second region, wind speed falls between cut-in and rated speed and the main goal is to obtain the highest power via an MPPT algorithm. According to Equ. (1), C_p needs to be maximized to attain MPPT in various wind speeds which is possible if β is set to be minimized, as evident in Fig. 3. Therefore, $\beta=0$, and C_p shrinks to a function of λ , which is a function of the rotor speed. The received wind power would then be regulated by varying the rotor speed. Fig. 4 shows the turbine power versus the rotation speed of its axis in a range of wind speed. The maximum power can be obtained by the turbine speed of 1 pu and the wind speed of 14 m/s [13], [58]. At other wind speeds, the optimum rotation speed of the turbine axis that can be attained from the turbine power curve must be less than the nominal speed to generate the maximum wind power.

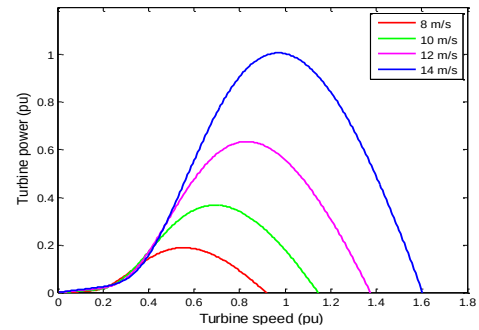


Fig. 4. Power curve of a variable-speed wind turbine.

The third region covers wind speeds of higher than the rated speed. Due to electrical constraints, to diminish mechanical stresses and also to avoid turbine damages in this region, the output power ought to be constant in the rated value. Accordingly, one can keep the power constant at the rated value by increasing the blade pitch angle that decreases the power coefficient. Actually, the turbine must be tuned to lose some of the wind energy. Hence, the control objective involves adjusting the rotor speed in nominal value and fixing the power in nominal value by controlling the blade pitch angle [55], [59]. This paper investigates the SRG performance in the second region.

III. SWITCHED RELUCTANCE GENERATOR

Switched reluctance generators (SRG), which have attracted the interests of researchers in recent years, are synchronous generators with a salient pole in rotor and stator and can be excited by stator like an induced machine. SRG benefits from its solid structure, simple performance, low cost, high assurance capability, and wide speed range (which is capable of eliminating the gearbox at low speed). Showing efficient performance in a broad spectrum of speed, SRG seems to be competitive with an induced machine regarding the required investment. Moreover, its converter is less expensive and

enjoys more reliability and efficiency in terms of torque response, torque per unit volume, and torque per unit weight [10].

A. Switched Reluctance Generator Structure

Rotor and stator pole of SRG are made of solid steel plates. The machine coils wound around the stator poles and there is no magnetic material embedded in the machine structure. The rotor also lacks any magnetic material, coil, and brush and consequently it is called a cold rotor [60].

Considering the number of poles in rotor and stator, different machine arrangements emerge such as three-phase 6/4 or 12/8 and four-phase 8/6 or 16/12 in which the right and left numbers show the rotor poles and the stator poles, respectively. Examples of four-phase 8/6 and three-phase 12/8 are represented in Fig. 5 [61].

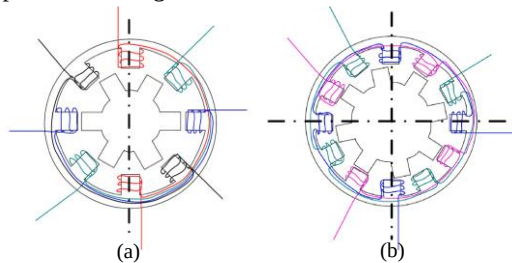


Fig. 5. Switched reluctance generator structure (a) four-phase 8/6, (b) three-phase 12/8 [61].

B. Principles of SRG Performance

In order to explain the SRG performance, it is vital to elucidate how a phase inductance changes. In a situation where the stator pole and the rotor pole are aligned, the air gap turns out to be minimum and the magnetic reluctance will then be minimum, resulting in the maximum inductance. Conversely, when the poles are non-aligned, the air gap and the magnetic reluctance will be maximum while the inductance drops to its minimum level. Clearly, the more the rotor pole approaches the stator pole, the more the inductance will be and vice versa. The inductance profile variations versus rotor position for one phase are illustrated in Fig. 6.

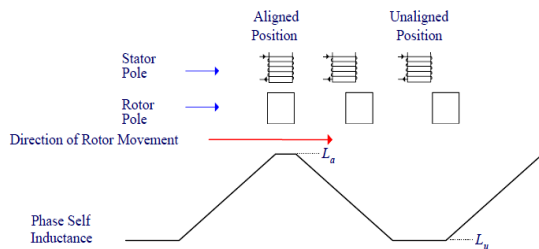


Fig. 6. Inductance variations versus rotor position [62].

The SR motor performance matches its generator performance in some aspects; however, they vary in some other aspects. As shown in Fig. 7, in the motor performance, phase excitation occurs in the positive slope of the inductance profile whereas in the generator mode, it takes place in the negative slope of the inductance profile. In an SR motor, with phase excitation, the rotor tends to position in a way that

minimum magnetic resistance happens [62], [63].

In the generator operation mode, the rotor is rotated by a prime mover and the phase excites in the negative slope of the inductance profile. At this stage, the energy is supplied to the phase winding by a converter from a DC source, and the current of this winding gradually starts to increase (due to high inductance) and the energy is saved in the magnetic field. The opposing torque in the prime mover increases the saved energy.

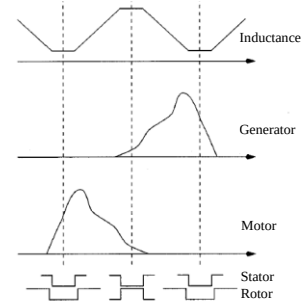


Fig. 7. Phase excitation period in motor and generator operation modes [64].

After reaching the turn-off angle in the negative slope of the inductance profile, the electromotive force (EMF) reverses and the phase current increases with a decrease in the inductance. At the end of the production period (reaching the minimum inductance), the saved energy in the field is transferred to the DC source or the load through a converter [65]. The phase excitation procedure of the generator is depicted in Fig. 8. At high speeds, due to shortness of the rotor position period (sum of excitation and production cycle when the rotor pole is moving away from the stator pole), the flux and current may fail to sufficiently grow. After terminating the excitation period, not only is there no production, but the received energy from the machine is also less than the delivered energy due to dissipation as shown in Fig. 8(b). In order to avoid such situations at high speeds, the phase is often excited sooner (in the positive inductance profile) to ensure sufficient current generation in the short period of the rotor position, considering the time constant of the system, as shown in Fig. 8(a) [64], [65].

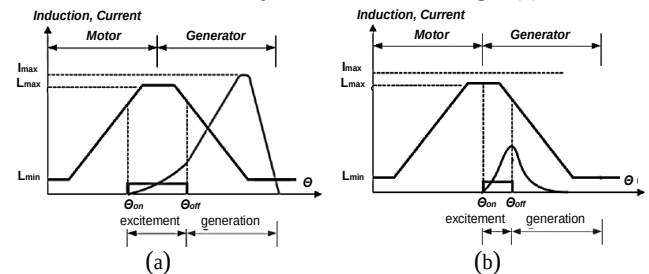


Fig. 8. The phase excitation procedure of the generator with (a) production (b) no production [65].

The SRG generated power is of DC type and an inverter is needed for AC load. Schematic of the asymmetric half bridge converter (AHBC) circuit and excitation/production mode are represented in Figs. 9 and 10, respectively. The AHBC appears to be of the most commonly used converter applied to operate SRG. As shown in Fig. 10, each phase of the converter consists

of two IGBTs and two diodes. As the DC-link voltage has to be remained constant with low ripple, the filter capacitor must be large enough.

The phase inductance in an SRG is shown with L_a, L_b, L_c and the coil resistance for each phase is represented with r . As observed in Fig. 9, two transistors in each phase turn on and off simultaneously. Moreover, in each moment only one phase is on and according to Fig. 10(a) only one phase is connected to the DC source and the coil of that special phase is excited.

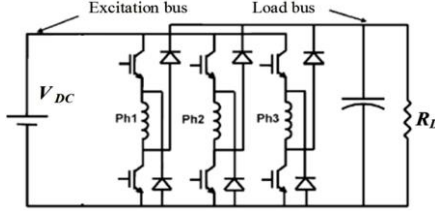


Fig. 9. The schematic of an asymmetric half bridge converter circuit [22].

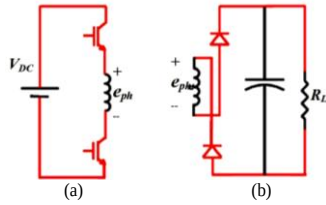


Fig. 10. The converter circuit in (a) excitation mode and (b) generation mode [22].

Eqs. (5)-(8) show the relationship of the corresponding phase dynamics.

$$V_{DC} = e_{ph} + r \cdot i_{ph} \quad (5)$$

where e_{ph} and i_{ph} are the voltage and current of the corresponding phase, respectively.

$$e_{ph} = -N_{ph} \frac{d\phi_{ph}}{dt} \quad (6)$$

where ϕ_{ph} is the phase flux and N_{ph} is the number of phase windings. Since $\phi_{ph} = L_{ph} \cdot i_{ph}$ then:

$$e_{ph} = -N_{ph} \frac{d(L_{ph} \cdot i_{ph})}{dt} = -N_{ph} \cdot \left(L_{ph} \frac{di_{ph}}{dt} + i_{ph} \frac{dL_{ph}}{d\theta} \cdot \omega \right) \quad (7)$$

Substituting (7) in (5), we have:

$$V_{DC} = -N_{ph} \cdot i_{ph} \frac{dL_{ph}}{d\theta} \cdot \omega - N_{ph} \cdot L_{ph} \frac{di_{ph}}{dt} + r \cdot i_{ph} \quad (8)$$

where $d\theta/dt = \omega$ is the angular velocity of the rotor. Equ. (5) explains the main relationship for the voltage of an excited generator phase and the first term from the right-hand side of Equ. (8) is called the back EMF which is proportional to the generated electrical power. The equivalent circuit of a generator phase is depicted in Fig. 10(b) while its switches are off. In this situation, the phase inductance current gradually reaches zero and the load resistance is provided via diodes. Eqs. (9)-(11) show the relationship of the SRG phase dynamics concerning Fig. 10(b) [66].

$$e_{ph} = r \cdot i_{ph} + R_L \cdot i_{ph} \quad (9)$$

Substituting e_{ph} from Equ. (6), it can be rewritten as:

$$N_{ph} \frac{d\phi_{ph}}{dt} = r \cdot i_{ph} + R_L \cdot i_{ph} \quad (10)$$

and substituting ϕ_{ph} from Equ. (7) in Equ. (10):

$$N_{ph} \cdot i_{ph} \frac{dL_{ph}}{d\theta} \cdot \omega + N_{ph} \cdot L_{ph} \frac{di_{ph}}{dt} = r \cdot i_{ph} + R_L \cdot i_{ph} \quad (11)$$

C. Nonlinear Model of Torque and Flux Production

Unsaturated (linear) switched reluctance machines suffer from an insufficient energy conversion ratio and their drive characteristics are not fully exploited. But, real switched reluctance machines are nonlinear with satisfactory efficiency. Understanding electromagnetic energy conversion needs a nonlinear analysis in which the saturation effect is included. One of those analyses is based on magnetization curves in which induced flux is considered proportional to the current in specific rotor positions. The magnetization curves of a 6/4 SR machine are shown in Fig. 11. The relationship of flux, inductance, and current can be expressed via Equ. (12) where λ , L , i , and θ denote linkage flux, phase inductance, phase current, and rotor position, respectively. Therefore, machine behavior can be expressed using linkage flux [67].

$$\lambda(i, \theta) = L(i, \theta) \cdot i \quad (12)$$

The torque characteristic curves of a 6/4 SR machine calculated from the magnetization curves are also depicted in Fig. 12.

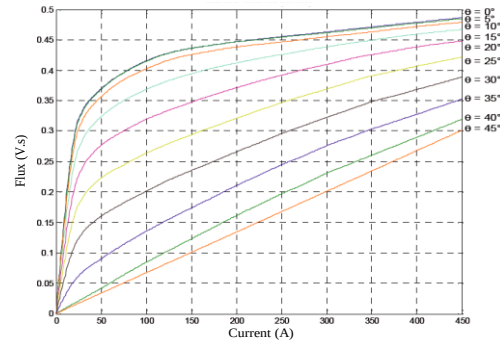


Fig. 11. The 6/4 SRG magnetization curves [68].

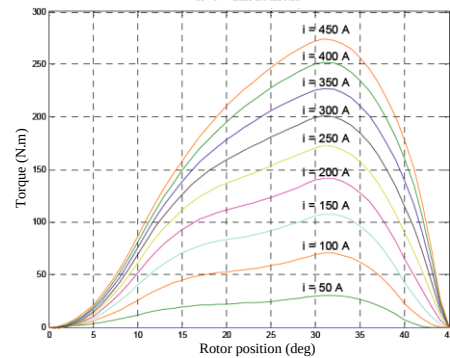


Fig. 12. The 6/4 SRG torque characteristic curves [68].

The SRG generated power is hardly introduced by an analytical relation due to its switching and nonlinear behavior of produced current [69]. Regardless of losses, the average output power of an SRG can be represented as follows, using some simplifications [62]:

$$P_{out} = \frac{N_s N_r V_{DC}^2}{\omega} \left(\int_{\theta_{on}}^{\theta_{off}} \frac{(\theta - \theta_{on}) d\theta}{L(\theta)} - \int_{\theta_{off}}^{\theta_e} \frac{(\theta_{off} - \theta_{on} - \theta) d\theta}{L(\theta)} \right) \quad (13)$$

where N_r and N_s are the number of rotor and stator poles, respectively, and θ_e stands for the extinction angle that represents the position where the current falls to zero after θ_{off} and it equals to:

$$\theta_e = 2\theta_{off} - \theta_{on} \quad (14)$$

Ignoring the saturation of SRG, the instantaneous electromagnetic torque per phase is defined as:

$$T(i, \theta) = \frac{1}{2} i^2 \frac{dL}{d\theta} \quad (15)$$

Torque ripple damages the generator and shortens its life. It can be expressed as:

$$T_{ripple} = \frac{T_{max} - T_{min}}{T_{ave}} \quad (16)$$

where T_{max} and T_{min} are the instantaneous maximum and minimum value of torque, respectively, and T_{ave} is the average torque. The level of torque ripple suppression can be achieved via torque smoothness factor defined as:

$$T_{SF} = \frac{1}{T_{ripple}} \quad (17)$$

The battery is charged via SRG DC link current. Since excessive current ripple decreases the battery life, it necessarily must be reduced. Accordingly, the current smoothness factor is defined as:

$$I_{SF} = \frac{I_{ave}}{I_{max} - I_{min}} \quad (18)$$

where I_{max} , I_{min} and I_{ave} are the maximum instantaneous DC link current, the minimum instantaneous DC link current, and the average DC link current, respectively. The efficiency of SRG is given by:

$$\eta = \frac{P_{out}}{P_{in}} \times 100 \quad (19)$$

where P_{out} is the generated electrical power and P_{in} is the mechanical input power provided by the wind turbine [62], [69].

D. Power Losses in SRG

The SRG efficiency is diminished because of losses, which are categorized into machine and power converter losses. Machine losses are divided into copper and iron losses, depending on the RMS stator current and the peak of the magnetic flux, respectively. Given the fact that all phases carry identical current, the average copper losses can be easily expressed as:

$$P_{Cu} = n r I_{rms}^2 \quad (20)$$

where n and I_{rms} are the number of phases and RMS value of phase current, respectively. The iron loss is approximately formulated based on Steinmetz equation as follows:

$$P_{Fe} = c_h f B^{a+bB} + c_e \left(\frac{dB}{dt} \right)^2 \quad (21)$$

where f is the stroke frequency, c_h and c_e are the hysteresis and

eddy-current loss coefficients, respectively, a and b are the coefficients that could be extracted from the loss curves, and B is the flux density.

Power converter losses are mostly composed of switching loss and conduction loss. The switching loss, which is affected by switching frequency, is usually higher than the conduction loss. The control strategy and the number of machine phases play an important role in determining switching frequency [2]. Modeling of switching loss based on the lookup table is of the most efficient routes describing the turn-on and turn-off energy losses as a function of device parameters such as voltage and current among others. The power of switching loss can consequently be estimated via multiplying the energy loss by the switching frequency [70]. The conduction losses of a power converter are calculated as follows:

$$P_{con} = \frac{2}{T} \left[\int_0^T v_{ce} i_c dt + \int_0^T v_D i_D dt \right] \quad (22)$$

where v_{ce} shows the collector-emitter voltage of the transistors, v_D represents the forward voltage of the diodes, i_c and i_D are the transistor and diode currents respectively [71].

IV. METHODOLOGY

The present paper introduces a robust strategy in which the firing angles of a SRG are controlled to maximize the efficiency as well as the wind power generation. In this approach, the controller of the converter circuit is initially trained via the particle swarm optimization algorithm in the offline mode and it is then applied for maximum power generation in the online mode using the obtained results and linear interpolation. The first step includes the PSO algorithm with accelerated coefficient to search the optimum control variable (firing angles). Unlike most previous studies in which the effect of only one of those angles has been considered, the simultaneous exploration for optimum firing angles is represented. Moreover, the turn-on and turn-off angles are examined simultaneously and the SRG performance is assessed based on the evaluation parameters. The flowchart of the PSO algorithm and the block diagram of the SRG control are shown in Figs. 13 and 14, respectively.

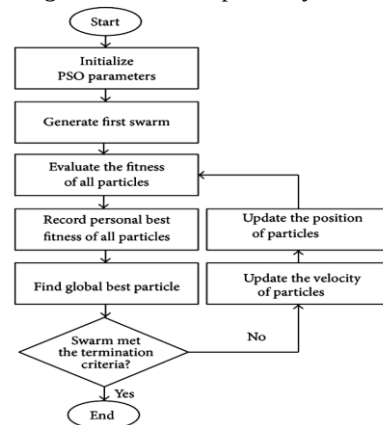


Fig. 13. The particle swarm optimization algorithm [72].

As shown in Fig. 14, to reach a desirable current level, the current error signal is passed through a hysteresis regulator located in the controller.

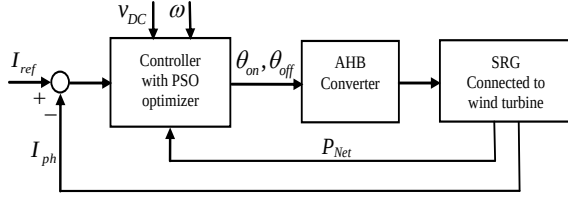


Fig. 14. The block diagram of an SRG control.

The presented strategy mainly aims to maximize power generation from wind, maximize generator efficiency, and minimize current ripple and torque ripple. Simultaneous speed and voltage feedbacks are used to generate maximum power. Accordingly, the generator is posed to a special voltage source and constant speed –via a wind turbine with extremely high inertia– and the firing angles (or the particles) that are generated accidentally under special constraints are transferred to the simulation part. For each couple of the turn-on and turn-off angles, the evaluation parameters including net output power (the difference between the power of load and the excitation power), the RMS current of each phase, torque ripple, and DC link current ripple are measured, and the best control variables (particles) of each group and the best general control variables (best particle) of the whole complex are selected. Having estimated the new variables (new position of the particles), the PSO algorithm transfers them to the simulation section and this procedure continues until the algorithm terminates. The objective function (F) for the optimization problem is considered:

$$\text{Max. } F(\theta_{on}, \theta_{off}) = \omega_1 \frac{P_{Net}}{P_{max}} + \omega_2 \frac{I_{rms \min}}{I_{rms}} + \omega_3 \frac{T_{SF}}{T_{SF \max}} + \omega_4 \frac{I_{SF}}{I_{SF \max}} \quad (23)$$

$$\text{subject to: } \theta_{on} \in [75, 110]$$

$$\theta_{off} \in [95, 135]$$

$$\theta_{on} < \theta_{off}$$

where $P_{net} = P_{load} - P_{excitation}$, P_{load} is the power of load, $P_{excitation}$ is the power of excitation source, and $\omega_1, \omega_2, \omega_3$, and ω_4 are weight coefficients considered to efficiently raise the importance of each term, which are selected as to be 0.5, 0.3, 0.1, and 0.1, respectively. The parameters of the PSO algorithm are the number of particles, the maximum number of iterations, and the inertia that are set to 20, 20 and 0.6, respectively. The best control variables obtained at the end of the first step are collected in a lookup table for each speed and nominal voltage. Then, using this table, the online controller employs linear interpolation to generate maximum power and efficiency for the variable-speed wind turbine.

V. SIMULATION RESULTS AND DISCUSSION

This paper proposes an efficient approach to generating maximum wind power as well as the maximum efficiency of SRG. Simulation in MATLAB is presented in this section to

assess the validity of the present methodology. The simulation has performed on a three-phase 6/4 generator with realistic conditions based on the information given in Table I.

TABLE I
THREE-PHASE 6/4 SR GENERATOR PARAMETERS [67]

Parameter	Value
Nominal power	60 kW
Nominal speed	5500 rpm
Max. coil current	450 A
Reference current	200 A
Stator coil resistance	0.05 Ω
Coefficient of inertia	0.05 kg.m ²
Coefficient of friction	0.02 N.m.s

The simulation and optimization procedure for the SRG control system is schematically illustrated in Fig. 15. It is composed of two parts: a Stateflow control chart and an SRG simulator.

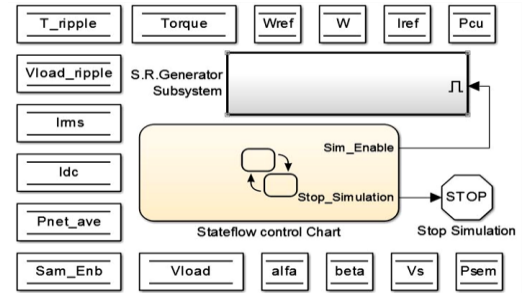


Fig. 15. The simulation of the system in MATLAB.

In the SRG simulator subsystem, the generator model is simulated according to the fundamental mathematical relations of an actual generator and also magnetic flux curves and torque. According to Fig. 16, the output of the generator is connected to a battery and a local load through a D/A inverter and a filter.

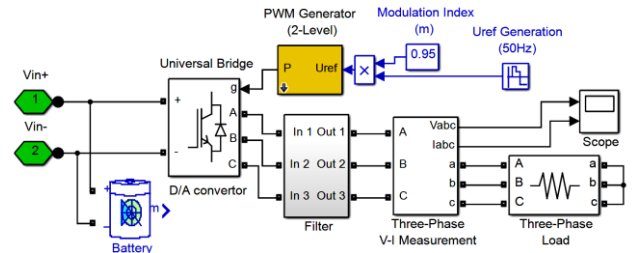


Fig. 16. The simulation of a battery and the load connected to the generator output in MATLAB.

Before controlling the generator, the effect of firing angles, as factors underpinning the output power, was investigated. Therefore, the generator model was executed for all of the possible arrangements of firing angles when the speed was 5000 rpm, the excitation voltage was 240 V, and the current was 200 A. The results are depicted in Fig. 17. As is evident, there is a pair of firing angles at which the corresponding generator power maximizes.

Prior to executing the SRG subsystem, the firing angles were randomly generated in Stateflow subject to system constraints, in the control chart subsystem. Meanwhile, the evaluation parameters were fed back to the Stateflow. The optimum particle was then selected based on the objective

function defined in Equ. (23). After assessing the results, considering the parameters (particles) and also the coefficient of inertia, new firing angles (new position of particles) were selected and transferred to the SRG subsystem again for evaluation. This procedure continued until the end of the PSO algorithm and the methodology was extended such that the run time decreased in accordance with the rotor speed increase.

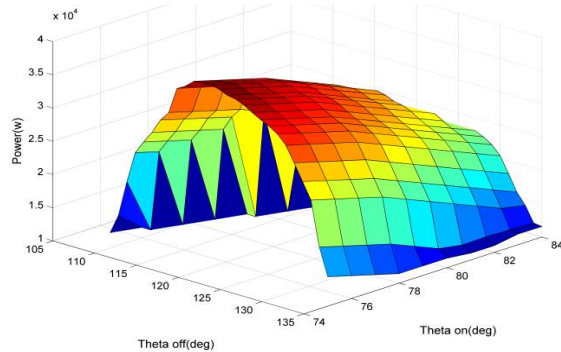


Fig. 17. The generator power versus the firing angles.

Consequently, the firing angles controller was initially learned in the offline mode. The optimum control variables for each speed and nominal voltage were then stored in a lookup table located in the controller part of the converter to be used to obtain the maximum power in the online mode. The offline calculation results of the proposed methodology for a voltage of 240 V and various speeds are summarized in Table II.

TABLE II

THE OFFLINE CALCULATION RESULTS OF THE METHODOLOGY

ω (rpm)	θ_{on} (deg)	θ_{off} (deg)
1000	87.4	107.2
2000	85.8	115.4
3000	83.2	125.8
4000	80.2	126.9
5000	77.9	122.5
5500	74.98	115

The convergence curves of the optimum firing angles, as well as the generator net power for several executions of the PSO algorithm in the offline mode, are illustrated in Figs. 18 and 19 where voltage and speed were 240 V and 5500 rpm, respectively. As can be seen, the minimum and maximum growth rates of the algorithm are 5 and 28 percent, respectively.

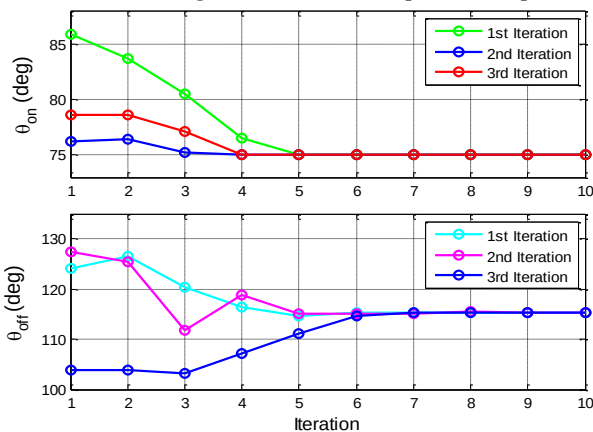


Fig. 18. The convergence curve of the proposed method for the

SRG firing angles in the offline mode.

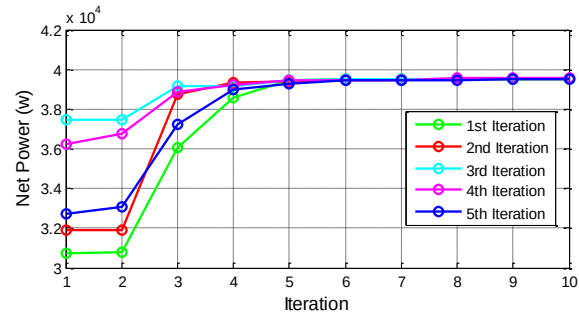


Fig. 19. The convergence curve of the proposed method for the generator net power.

The net power of the generator, as well as the efficiency for an exciting voltage of 240 V and various speeds, are obtained and presented in Table III.

TABLE III

THE GENERATOR NET POWER AND EFFICIENCY

ω (rpm)	Net power (kW)	Efficiency (%)
1000	1.5	21.5
2000	14.9	50.6
3000	21	68
4000	29.8	73.5
5000	32.9	82.4
5500	39.75	84.2

The average copper losses and power converter losses are calculated according to Table IV.

TABLE IV

THE AVERAGE COPPER LOSSES AND POWER CONVERTER LOSSES OF THE GENERATOR

ω (rpm)	P_{cu} (kW)	$P_{converter}$ (kW)
1000	0.54	0.16
2000	1.12	0.26
3000	2.05	0.47
4000	2.78	0.52
5000	3.23	0.69
5500	3.93	0.72

To reveal the productivity of the proposed methodology, the generator efficiency results of the PSO technique are compared to GA, as shown in Fig. 20. The initial population is set to be the same for both methods, and the results are plotted for 100 iterations. Consequently, the PSO enjoys a better convergence rate and better outcomes than the GA.

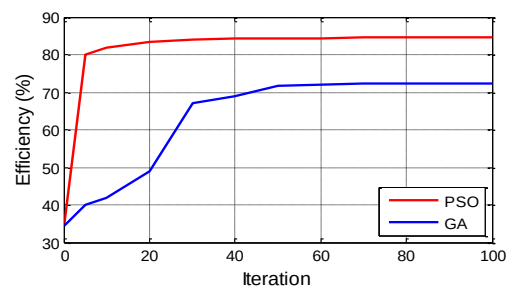


Fig. 20. The convergence curves of the proposed method vs the GA for the SRG efficiency.

In order to assess the proposed methodology, a hypothetical worst case of wind profile like Fig. 21 with a variable speed

was applied to a turbine while the performance of the system was investigated in a rough situation. It is obvious that if the controller overcomes these instant changes, it will definitely show a good response to actual wind profiles.

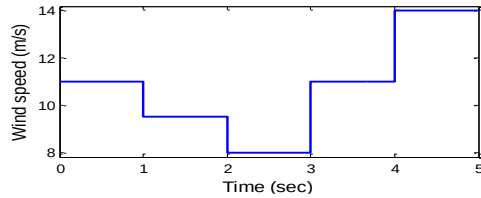


Fig. 21. A hypothetical variable-speed wind profile.

Since the nominal wind speed is 14 m/s, the turbine performance falls in the second region. Therefore, the maximum turbine power occurs in the nominal wind speed and the pitch angle of zero.

To achieve MPPT, the reference value of the rotor speed is selected equivalent to its optimum value based on the turbine power curve (Fig. 4) and instantaneous wind speed. Fig. 22 shows the optimum rotor speed (reference value) and also its actual speed after applying the methodology.

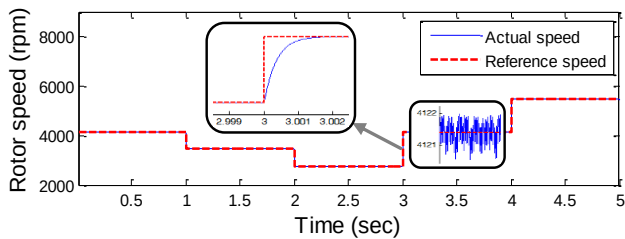


Fig. 22. The rotor speed corresponding to the wind profile.

Obviously, the presented approach efficiently pursues the optimum speed and the actual speed approximates to its reference value. Variations in the firing angles leading to the maximum power and the generator efficiency are illustrated in Figs. 23 and 24, corresponding to the wind profile and the rotor speed.

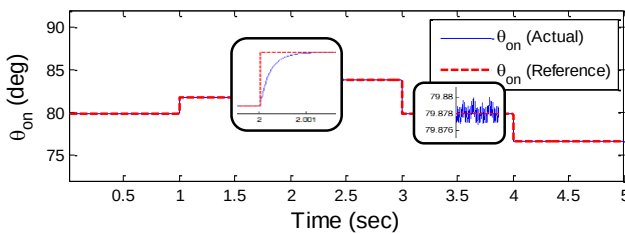


Fig. 23. The turn-on angle control corresponding to the rotor speed.

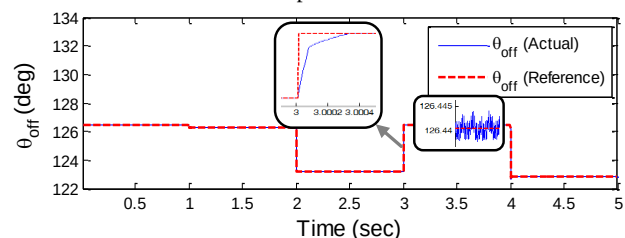


Fig. 24. The turn-off angle control corresponding to the rotor speed.

As observed, both firing angles were simultaneously varying with the changes in wind speed that accurately follow the reference firing angles in the offline mode (Table II). Since the first column of Table II fails to cover the entire range of generator axis speeds, linear interpolation is used if necessary. As evident in Fig. 22, for a rotor speed of 4121.5 rpm, the turn-on and turn-off angles were interpolated as 79.878 and 126.44, respectively, which are consistent with the simulation results in Figs. 23 and 24.

Fig. 25 shows inductance, phase current, linkage flux, and generator torque in optimum firing angles. The voltage and current of the three-phase load are also depicted in Fig. 26.

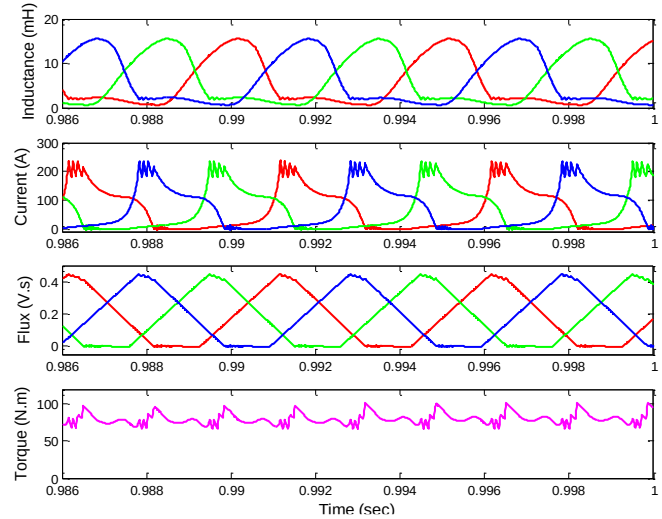


Fig. 25. The inductances, phases currents, linkage fluxes, and generator torque in optimum firing angles.

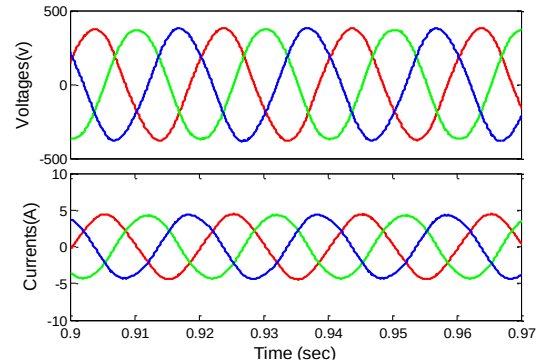


Fig. 26. The voltage and current of 3-phase local load.

VI. CONCLUSION

The present paper used a switched reluctance generator to generate maximum electrical power from wind to supply the local load demand, followed by a battery bank to store the excess generated power. As the firing angles appeared to be of importance in generator control, they were firstly optimized via a PSO algorithm in the offline mode according to the maximum wind power generation, maximum generator efficiency, and minimum ripple of torque and current. The optimum firing angles were stored in a lookup table for some speeds and nominal voltage to be employed for various speeds

and voltages in the online mode. The PSO algorithm was launched in the Stateflow toolbox. Accordingly, the methodology was developed such that the execution time decreased as the rotor speed increased. Consequently, the execution time was different for various speeds. Moreover, the required signals were sampled precisely. In contrast to the previous works in which the effect of each firing angle was studied separately, our contribution scrutinizes the simultaneous optimization of both firing angles resulting in a substantial reduction in computation and simulation time as well. Consequently, the algorithm provided a precise outcome. Some other major features of the present work include simple structure, reasonable convergence rate that is independent of machine characteristics, and utilizable methodology for any other SRG machine. Additionally, an actual nonlinear model of SRG considering copper losses, switching and conduction losses of semiconductors were included in the simulations to approach real conditions, which has poorly been addressed before. Ultimately, unlike similar works that have considered the offline mode, this study presented an online control scheme. Matlab was used to apply the proposed method to a typical 60 kW three-phase 6/4 generator and the results confirmed the validation of the proposed method.

REFERENCES

- [1] P. Carlin, A. Laxson, and E. Muljadi, "The History and State of the Art of Variable-Speed Wind Turbine Technology," *Wind Energy*, vol. 6, pp. 129–159, Apr. 2003.
- [2] M. Farshad, "Modeling and Intelligent Control of Switched Reluctance Motor in Washing Machine," Ph.D. Dissertation, University of Tehran, Iran, 2006.
- [3] M. Takeno, A. Chiba, N. Hoshi, S. Ogasawara, M. Takemoto, and M. A. Rahman, "Test Results and Torque Improvement of the 50-kW Switched Reluctance Motor Designed for Hybrid Electric Vehicles," *IEEE Trans. Ind. Appl.*, vol. 48, no. 4, pp. 1327–1334, 2012.
- [4] F. L. M. dos Santos, J. Anthonis, F. Naclerio, J. J. C. Gyselinck, H. Van der Auweraer, and L. C. S. Góes, "Multiphysics NVH Modeling: Simulation of a Switched Reluctance Motor for an Electric Vehicle," *IEEE Trans. Ind. Electron.*, vol. 61, no. 1, pp. 469–476, 2014.
- [5] D.-M. Nguyen, I. Bahri, G. Krebs, E. Berthelot, and C. Marchand, "Vibration study of the intermittent control for a switched reluctance machine," *Math. Comput. Simul.*, vol. 158, pp. 308–325, 2019.
- [6] H. Cheng, L. Wang, G. Han, and H. Chen, "The Design and Control of an Electrified Powertrain with Switched Reluctance Machines for Series Hybrid Electric Vehicle," in *2019 IEEE Vehicle Power and Propulsion Conference (VPPC)*, 2019, pp. 1–5.
- [7] J. A. Domínguez-Navarro, J. S. Artal-Sevil, H. A. Pascual, and J. L. Bernal-Aguistín, "Fuzzy-logic strategy control for switched reluctance machine," in *2018 Thirteenth International Conference on Ecological Vehicles and Renewable Energies (EVER)*, 2018, pp. 1–5.
- [8] A. El-Shahat, A. Hunter, M. Rahman, and Y. Wu, "Ultra-High Speed Switched Reluctance Motor-Generator for Turbocharger Applications," *Energy Procedia*, vol. 162, pp. 359–368, 2019.
- [9] D. Pham, A. Klein-Hessling, and R. W. De Doncker, "Control of a DC-DC Converter as an Active Filter in Combination with Switched Reluctance Generators for Gas Turbine Applications," in *2019 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS)*, 2019, pp. 1–17.
- [10] A. M. S. Arifin, "Switched reluctance generator drive in the low and medium speed operation : modelling and analysis," Ph.D. Dissertation, Massey University, New Zealand, 2013.
- [11] T. J. E. Miller, *Electronic Control of Switched Reluctance Machines*, Jan. 2001.
- [12] J. Llibre, N. Martinez, P. Leprince, and B. Nogarede, "Analysis and Modeling of Linear-Switched Reluctance for Medical Application," *Actuators*, vol. 2, pp. 27–44, Jun. 2013.
- [13] O. Anaya-Lara, N. Jenkins, J. Ekanayake, P. Cartwright, and M. Hughes, "Wind Energy Generation: Modelling and Control," in *John Wiley & Sons*, 2009.
- [14] Y. Chang and C. Liaw, "On the Design of Power Circuit and Control Scheme for Switched Reluctance Generator," *IEEE Trans. Power Electron.*, vol. 23, no. 1, pp. 445–454, 2008.
- [15] Y. Sozer and D. A. Torrey, "Closed loop control of excitation parameters for high speed switched-reluctance generators," *IEEE Trans. Power Electron.*, vol. 19, no. 2, pp. 355–362, 2004.
- [16] H. Chen, "Implementation of a Three-Phase Switched Reluctance Generator System for Wind Power Applications," in *2008 14th Symposium on Electromagnetic Launch Technology*, 2008, pp. 1–6.
- [17] K. Ogawa, N. Yamamura, and M. Ishida, "Study for Small Size Wind Power Generating System Using Switched Reluctance Generator," in *2006 IEEE International Conference on Industrial Technology*, 2006, pp. 1510–1515.
- [18] R. Cardenas, R. Pena, M. Perez, J. Clare, G. Asher, and P. Wheeler, "Control of a switched reluctance generator for variable-speed wind energy applications," *IEEE Trans. Energy Convers.*, vol. 20, no. 4, pp. 781–791, 2005.
- [19] Q. Wang and L. Chang, "An intelligent maximum power extraction algorithm for inverter-based variable speed wind turbine systems," *IEEE Trans. Power Electron.*, vol. 19, no. 5, pp. 1242–1249, 2004.
- [20] A. Fleury, D. A. de Andrade, F. d. S. e Silva, and J. L. Domingos, "Switched Reluctance Generator for complementary Wind Power Generation in Grid Connection," in *2007 IEEE International Electric Machines & Drives Conference*, 2007, vol. 1, pp. 465–470.
- [21] N. Sun, D. Choi, J. Li, and Y. Cho, "The Angle Control of Switched Reluctance Generator for Maximum Output Power," in *2012 Sixth Int. Conf. on Electromagnetic Field Problems and Applications*, 2012, pp. 1–4.
- [22] M. Ziapour, E. Afjei, and M. Yousefi, "Optimum commutation angles for voltage regulation of a high speed switched reluctance generator," in *4th Annual International Power Electronics, Drive Systems and Technologies Conference*, 2013, pp. 271–276.
- [23] X. Deng et al., "Design of switched reluctance generator system for wind power maximization," in *2015 IEEE NW Russia Young Researchers in Electrical and Electronic Engineering Conference*, 2015, pp. 306–310.
- [24] M. V Zaharia, A. A. Laczko, A. A. Pop, M. M. Radulescu, and F. Gillon, "Optimal commutation angles of a switched reluctance motor/generator," in *2015 Tenth International Conference on Ecological Vehicles and Renewable Energies (EVER)*, 2015, pp. 1–8.

- [25] W. Wang *et al.*, "Control system of switched reluctance generator," in *2017 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus)*, 2017, pp. 1064–1069.
- [26] L. Ling, L. Dong, and X. Liao, "Comparison of two control methods of switched reluctance generator," *2017 12th IEEE Conf. Ind. Electron. Appl.*, pp. 792–796, 2017.
- [27] A. Ivanov and I. Kalanchin, "Application of maximum power point tracker method in wind energy conversion system based on the switched reluctance generator," in *2017 International Multi-Conference on Engineering, Computer and Information Sciences (SIBIRCON)*, 2017, pp. 472–476.
- [28] M. A. Dranca and M. M. Radulescu, "Comparative Design Analysis of Three-Phase Switched Reluctance Generators for Micro-Wind Power Applications," in *2018 XIII International Conference on Electrical Machines (ICEM)*, 2018, pp. 597–601.
- [29] M. O. Shykhnenko, L. I. Mazurenko, O. V. Dzhura, and O. A. Bilyk, "Mathematical Model, Research and Improvement of the Switched Reluctance Generator Voltage Stabilization Methods," in *2018 IEEE 3rd International Conference on Intelligent Energy and Power Systems (IEPS)*, 2018, pp. 338–342.
- [30] M. M. Namazi, S. M. S. Nejad, A. Tabesh, A. Rashidi, and M. Liserre, "Passivity-Based Control of Switched Reluctance-Based Wind System Supplying Constant Power Load," *IEEE Trans. Ind. Electron.*, vol. 65, no. 12, pp. 9550–9560, 2018.
- [31] H. Ačkar, S. Huseinbegović, Š. Mašić, S. Smaka, and A. Tahirbegović, "Voltage Control of a Switched Reluctance Generator Using Discrete Sliding Mode Technique," in *2018 XIII International Conference on Electrical Machines (ICEM)*, 2018, pp. 1731–1737.
- [32] S. Jagwani, G. K. Sah, and L. Venkatesha, "MPPT Based Switched Reluctance Generator Control for a Grid Interactive Wind Energy System," in *2018 7th International Conference on Renewable Energy Research and Applications (ICRERA)*, 2018, pp. 998–1003.
- [33] H. Chen, S. Xu, W. Wei, J. Yang, and R. Nie, "Reliability Assessment of Double-Sided Linear Switched Reluctance Generator System Based on Hierarchical Markov Model," *IEEE Trans. Ind. Electron.*, vol. 66, no. 6, pp. 4901–4911, 2019.
- [34] S. Li, S. Zhang, T. G. Habetler, and R. G. Harley, "Modeling, Design Optimization, and Applications of Switched Reluctance Machines—A Review," *IEEE Trans. Ind. Appl.*, vol. 55, no. 3, pp. 2660–2681, 2019.
- [35] E. H. Catata, D. B. Luque, J. L. Azcue-Puma, and E. R. Filho, "Direct Instantaneous Torque Control of Three Phase 6/4 Switched Reluctance Generator Operating at Low Speeds," in *2019 IEEE XXVI International Conference on Electronics, Electrical Engineering and Computing (INTERCON)*, 2019, pp. 1–4.
- [36] X. Zan *et al.*, "A New Control Strategy for SR Generation System Based on Modified PT Control," *IEEE Access*, vol. 7, pp. 179720–179733, 2019.
- [37] P. Xiao, J. Pan, C. Wang, R. Huang, and P. Fu, "Dual-Loop Compensation Voltage Control for Linear Switched Reluctance Generators," in *2019 22nd International Conference on Electrical Machines and Systems (ICEMS)*, 2019, pp. 1–5.
- [38] H. Chen, D. Xu, and X. Deng, "Control for Power Converter of Small-scale Switched Reluctance Wind Power Generator," *IEEE Trans. Ind. Electron.*, p. 1, 2020.
- [39] A. Kushwaha and R. Kanagaraj, "Peak-current estimation using simplified current-rise model of switched reluctance generator operating in single-pulse mode," *Int. J. Electr. Power Energy Syst.*, vol. 120, p. 105971, 2020.
- [40] K. Chirapo, A. Oliveira, A. Sguarezi, A. Pelizari, S. Di Santo, and E. Costa, "P+RES Controller Applied to the Direct Power Control of Switched Reluctance Generator," *J. Control. Autom. Electr. Syst.*, vol. 31, Jan. 2020.
- [41] M. M. Ali, C. Storey, and A. Törn, "Application of Stochastic Global Optimization Algorithms to Practical Problems," *J. Optim. Theory Appl.*, vol. 95, no. 3, pp. 545–563, 1997.
- [42] J. A. Nelder and R. Mead, "A Simplex Method for Function Minimization," *Comput. J.*, vol. 7, no. 4, pp. 308–313, Jan. 1965.
- [43] B. S. A. Gottfried and J. A. Weisman, *Introduction to Optimization Theory*. Prentice-Hall, 1973.
- [44] W. L. Price, "Global optimization by controlled random search," *J. Optim. Theory Appl.*, vol. 40, no. 3, pp. 333–348, 1983.
- [45] D. E. Goldberg, *Genetic Algorithms in Search, Optimization and Machine Learning*, 1st ed. Boston, MA, USA: Addison-Wesley Longman Publishing Co., Inc., 1989.
- [46] R. Yang and I. Douglas, "Simple Genetic Algorithm with Local Tuning: Efficient Global Optimizing Technique," *J. Optim. Theory Appl.*, vol. 98, no. 2, pp. 449–465, 1998.
- [47] J. Ronkkonen, S. Kukkonen, and K. V. Price, "Real-parameter optimization with differential evolution," in *2005 IEEE Congress on Evolutionary Computation*, 2005, vol. 1, p. 506–513 Vol.1.
- [48] J. H. Fisch, Y. Li, P. C. Kjaer, J. J. Gribble, and T. J. E. Miller, "Pareto-optimal firing angles for switched reluctance motor control," in *Second International Conference On Genetic Algorithms In Engineering Systems: Innovations And Applications*, 1997, pp. 90–96.
- [49] K. Liu and M. Stiebler, "Voltage Control Of A Switched Reluctance Generator By Means Of Fuzzy Logic Approach," in *Proceedings of the 6th International Conference on Optimization of Electrical and Electronic Equipments*, 1998, vol. 2, pp. 443–446.
- [50] H. Shin and K. Lee, "Optimal design of a switched reluctance generator for small wind power system using a genetic algorithm," in *2015 9th International Conference on Power Electronics and ECCE Asia (ICPE-ECCE Asia)*, 2015, pp. 2209–2214.
- [51] M. Tchavychalov and V. A. Detistov, "Optimum Design of Linear Switched Reluctance Generator," in *2018 X International Conference on Electrical Power Drive Systems (ICEPDS)*, 2018, pp. 1–4.
- [52] N. H. Saad, A. A. El-Sattar, and M. E. Metally, "Artificial neural controller for torque ripple control and maximum power extraction for wind system driven by switched reluctance generator," *Ain Shams Eng. J.*, vol. 9, no. 4, pp. 2255–2264, Dec. 2018.
- [53] G. P. Viajante, E. N. Chaves, L. C. Miranda, M. A. A. Freitas, C. A. Queiroz, and J. A. Santos, "Design and Implementation of a Fuzzy Control System Applied to a 6x4 SRG," in *2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, 2019, pp. 1–6.
- [54] H. E. M. Lopez, "Maximum power tracking control scheme

for wind generator systems,” M.S. Thesis, Texas A&M University, 2007.

- [55] H. Moodi and D. Bustan, “Wind turbine control using T-S systems with nonlinear consequent parts,” *Energy*, vol. 172, pp. 922–931, Apr. 2019.
- [56] M. Heidari, “Maximum Wind Energy Extraction by Using Neural Network Estimation and Predictive Control of Boost Converter,” *Int. J. Ind. Electron. Control Optim.*, vol. 1, no. 2, pp. 115–120, 2018.
- [57] A. Pintea, D. Popescu, and P. Borne, “Robust control for wind power systems,” in *18th Mediterranean Conference on Control and Automation, MED’10*, 2010, pp. 1085–1091.
- [58] E. Rahmadian, H. Akbari, and H. Sheisi, “Maximum Power Point Tracking in Grid Connected Wind Plant by Using Intelligent Controller and Switched Reluctance Generator,” *IEEE Trans. Sustain. Energy*, vol. 8, p. 1, Jul. 2017.
- [59] L. Y. Pao and K. E. Johnson, “A tutorial on the dynamics and control of wind turbines and wind farms,” in *2009 American Control Conference*, 2009, pp. 2076–2089.
- [60] Ji.-W. Ahn, “Switched Reluctance Motor,” in *Torque Control*, Rijeka: IntechOpen, 2011, p. Ch. 8.
- [61] A. Arifin and I. Al-Bahadly, “Switched Reluctance Generator for Variable Speed Wind Energy Applications,” *Smart Grid Renew. Energy*, vol. 2, pp. 27–36, Jan. 2011.
- [62] P. Asadi, “Development and application of an advanced switched reluctance generator drive,” Ph.D. Dissertation, Texas A&M University, 2006.
- [63] Y. Gao, “Speed control of switched reluctance motors,” Hong Kong University of Science and Technology, 2000.
- [64] D. A. Torrey, “Switched reluctance generators and their control,” *IEEE Trans. Ind. Electron.*, vol. 49, no. 1, pp. 3–14, 2002.
- [65] T. Sawata, P. C. Kjaer, C. Cossar, and T. J. E. Miller, “A control strategy for the switched reluctance generator,” in *international conference on Electrical Machines*, 1998, pp. 2131–2136.
- [66] N. Faridnia, “Voltage Control of a 12/8 Pole Switched Reluctance Generator Using Fuzzy Logic,” *Int. J. Mod. Nonlinear Theory Appl.*, vol. 1, pp. 107–112, Jan. 2012.
- [67] D. A. Torrey, X. Niu, and E. J. Unkauf, “Analytical modelling of variable-reluctance machine magnetisation characteristics,” *IEE Proc. - Electr. Power Appl.*, vol. 142, no. 1, pp. 14–22, 1995.
- [68] H. Le-Huy and P. Brunelle, “A versatile nonlinear switched reluctance motor model in Simulink using realistic and analytical magnetization characteristics,” in *31st Annual Conference of IEEE Industrial Electronics Society, 2005. IECON 2005.*, 2005, p. 6 pp.-pp.
- [69] P. J. d. S. Neto, T. A. d. S. Barros, M. V. de Paula, R. R. de Souza, and E. R. Filho, “Design of Computational Experiment for Performance Optimization of a Switched Reluctance Generator in Wind Systems,” *IEEE Trans. Energy Convers.*, vol. 33, no. 1, pp. 406–419, 2018.
- [70] A. Bryant *et al.*, “A Fast Loss and Temperature Simulation Method for Power Converters, Part I: Electrothermal Modeling and Validation,” *IEEE Trans. Power Electron.*, vol. 27, no. 1, pp. 248–257, 2012.
- [71] J. Faiz and R. Fazai, “Optimal Excitation Angles of a High Speed Switched Reluctance Generator by Efficiency Maximization,” in *2006 12th International Power Electronics and Motion Control Conference*, 2006, pp. 287–291.
- [72] K. Lee, *Modern Heuristic Optimization Techniques: Theory and Applications to Power Systems*. 2008.



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