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Optimal capacitance selection for a wind-driven self-excited reluctance generator under varying wind speed and load conditions

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HIGHLIGHTS

- We determined & selected suitable excitation capacitance value for WDSERG.
- This ensured a constant output voltage under changing wind speed & connected load.
- Mathematical model of WDSERG has been developed from the dynamic model of SERG.
- We developed an algorithm that searches for the optimal excitation capacitance.
- There is an optimal capacitance value that would produce a constant output voltage.

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ABSTRACT

This paper presents a methodology to determine and select a suitable excitation capacitance value for a wind-driven self-excited reluctance generator (WDSERG), which would produce a constant output voltage under changing wind speed and connected load. A steady state mathematical model of WDSERG is developed from the dynamic model of self-excited reluctance generator (SERG) and phasor diagram. This model is used to develop an algorithm that searches for the optimum excitation capacitance which produces a desired output voltage level for any given wind speed and load within the operating limits of the WDSERG. Different scenarios of variable speed, load and power factor are considered and an optimal capacitance value is determined and selected for each cases. Published experimental data was utilised to validate the developed model. The results show that there is a distinct capacitance value that would produce a constant output voltage under any given operating conditions of wind speed and terminal load. The procedure presented can form a basis for the design of a variable excitation capacitor to maintain a constant output voltage under varying wind speed and load, which will invariably offer an effective and low-cost solution for output voltage control of WDSERG.

1. Introduction

The rise in energy demand and the need to mitigate the effects of climate change due to global warming has informed various research interests to harness renewable energy sources in recent years. Viable renewable energy sources such as hydro, wind, solar, and geothermal resources are receiving concentrated attention in various parts of the world particularly in developed countries [1]. Moreover, the inadequate and erratic supply of electricity in most developing countries has raised concern with increasing efforts geared toward the exploration of available renewable sources [2]. Thus the perennial exploitation of fossil fuel for power generation is gradually being phased out for a more environmentally friendly renewable energy sources.

Wind Energy Conversion Systems (WECS) are becoming popular as a viable renewable alternative [1,3]. This is because of wind availability in several parts of the world [4,5]. Cheng and Zhu [6] presented a review of the modern wind energy conversion technologies, with particular focus on the various wind power generators and the control schemes. The authors compared different types of wind energy conversion systems and the most commonly used maximum power point tracking (MPPT) control to achieve the optimal generator speed which would produce maximum energy.

Permanent Magnet Synchronous Generator (PMSG) has received considerable attention for wind energy conversion both in direct-driven mode and with single or multi-stage gearboxes [6–9]. Due to the presence of the permanent magnet in the rotor

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of PMSG, it offers a high energy conversion efficiency, reduced rotor thermal stress and high torque density [10,11]. However, the major limitations of PMSG includes demagnetisation of the permanent magnet material at high temperature, high cost of permanent magnet, and cogging torque effects [12]. The authors of reference [8] evaluated the electromagnetic losses in PMSG-based WECS, putting into consideration the stochastic nature of wind speed. Losses and overload capabilities of different generators with the same rated power but different rated voltage were compared. It was shown that an optimum efficiency and a high overload capability can be achieved by adjusting the rated voltage level. In [7], the authors presented the analysis of speed and torque control structures for variable speed, fixed pitch wind energy conversion systems with a view to determining the most suitable structure which would improve the generator's reliability and robustness. More information on grid-connected PMSG is presented in [13], where the authors discussed different power converter topologies presently adopted in PMSG-based WECS, various control strategies and the important grid integration requirements.

Furthermore, the design and application of Doubly-Fed Induction Generator (DFIG) has also been found to be an attractive choice for variable speed constant frequency WECS due to its significant advantages [14,15]. DFIG has double output capability through both the stator and the rotor. It requires reduced rating of power converters and harmonic filters and does not require external reactive power compensation due to the flexibility of its stator excitation from the rotor circuit [16]. Also, its active and reactive power can be independently controlled [17]. However, the presence of slip rings and brushes on the DFIG rotor necessitates the need for regular maintenance. This makes the application of DFIG for remote and off-shore applications less reliable and more costly [12,18]. Also, the difficulty associated with grid fault ride-through control of DFIG in grid-connected applications poses a major challenge to manufacturers of wind turbine since both the stator and rotor of the DFIG are connected to the grid [19]. In addition, the large size, enormous complexity and high cost associated with the design, assembly and control of DFIG makes it unsuitable for small stand-alone applications where low-cost is of primary consideration [12].

In stand-alone, off-grid WECS, the key considerations in the choice of wind turbine generators include cost and simplicity of control. In this regard, self-excited generators has been identified as a low-cost alternative to PMSG and DFIG. Therefore, significant research and development of self-excited generators has been on the increase in recent years [1]. The most commonly investigated self-excited generator is the Self-Excited Induction Generator (SEIG) with squirrel-cage rotor [12]. SEIG has been applied in stand-alone wind energy conversion because of its inherent advantages over the conventional synchronous generators. Its simplicity, as well as its rugged construction makes it relatively inexpensive and is therefore popular in isolated wind energy conversion system applications. Furthermore, it is self-protected against excessive overload and short-circuit contingencies [20,21], it requires no external direct current (DC) supply for excitation and voltage regulation and has better transient performances [22]. However, it suffers from poor voltage and frequency regulation with changes in load and prime-mover speed, with an attendant need for voltage and frequency stabilizing circuits. This invariably increases the installation cost [23–25].

In order to overcome the aforementioned challenges of SEIG, Self-Excited Reluctance Generator (SERG) has been explored as alternative choice for use in isolated wind energy conversion system. SERG has additional advantages of constant output frequency in spite of variation in load and excitation capacitances as well as enhanced steady state performances over a wide range of operation [23,26–30]. This makes SERG suitable for wind energy conversion.

Although, an SERG will operate at constant output frequency with load variations at its output terminals, however, in a similar way to the SEIG, the generated voltage of the SERG falls with increasing load and therefore requires an increase in excitation capacitance within the stable operating limits of the machine to maintain the output voltage within acceptable limits. Also, the output voltage changes considerably with variation in prime-mover speed. Therefore, a leading VAR is required to continuously regulate the output voltage under changing speed and/or load. This can be accomplished using variable excitation capacitors.

Since it is desirable to obtain an efficient energy production with constant output voltage from a generator for most practical applications, there is a need to keep the output voltage constant at a desired level under changing speed and/or load. This paper therefore presents a method for the selection of an optimal excitation capacitance for SERG, which can be implemented in a controller in order to maintain an efficient energy production at the desired output voltage within predetermined limits.

Different approaches have been adopted to regulate the output of wind turbine-based systems. For instance, the authors of reference [31] proposed the use of a supercapacitor bank as a dynamic regulation system in a wind-powered small-scale seawater reverse osmosis desalination plant. The system was designed to continuously adjust its energy consumption as the generated wind power varies. For this particular application, the authors illustrate the possibility of using supercapacitors to regulate the energy consumption of the system in spite of the varying wind speed and wind power.

In the case of SEIG, different methods for determining the excitation capacitance requirement for a regulated output voltage of SEIG have been presented in several works [32–36]. A general analysis to determine the steady state performance of an isolated SEIG feeding a balanced R-L load was presented in [33]. The analysis included the machine core losses and their variation with air gap flux. Predictions of the minimum value of excitation under no load, resistive and inductive load were made as well as the capacitance value required to maintain a constant terminal voltage under varying load, power factor and speed. The authors also show a mathematical basis for the design of a static exciter which utilises a Fixed Capacitor Thyristor-Controlled Reactor (FCTCR) to provide the variable excitation capacitance. The results depict that the capacitance requirement increases significantly with decreasing speed, load impedance and power factor for a lagging load. The authors of Ref. [32] presented a controlled shunt capacitor SEIG, which is continuously adjusted in order to maintain a constant output voltage over a relatively wide range of load and rotor speed. The method employed Insulated Gate Bipolar Transistor (IGBT) switches connected back to back across the fixed excitation capacitors to achieve variable excitation. It was shown that the proposed method can achieve a high level of voltage regulation for a wide range of load.

However, there is paucity of literature on the use of SERG for stand-alone WECS since most works on stand-alone WECS are based on PMSG and SEIG [6,13]. Moreover, most of the literature works on capacitance requirement of SERG are concerned with the determination of minimum excitation capacitance required for self-excitation and voltage build up [20,26,37]. Therefore, this present work advances the existing literature by proposing a methodology to determine and select the optimal capacitance required to maintain a constant air-gap flux, and hence, a constant output voltage for a Wind Driven Self Excited Reluctance Generator (WDSERG) under conditions of varying wind speed and changing load.