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Study on different loading topologies of a six-phase self excited induction generator

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ABSTRACT

High number of phases of a multi-phase machine equip it with greater operational versatility. Due to the presence of dual 3-phases, a six-phase self excited induction generator (6φ-SEIG) is considered very convenient for grid connected as well as off-grid renewable energy based electricity generation systems. Besides, the multi-phase induction generators have been proposed as starter/generator for aero-engines in the aviation industry as more electric aircrafts (MEAs) gain prominence. In this paper six-phase simultaneous loading and three-phase loading at a time of a 6φ-SEIG are investigated. Terminal capacitors provide the reactive power for exciting the SEIG windings. Series capacitances are employed in short shunt connection for self- voltage correction of 6φ-SEIG. A dual d-q mathematical model of short shunt, symmetrical, 6φ-SEIG in dual-stator configuration is developed for the study. All the steady state and transient results are obtained through simulation model. Verification of simulation results is achieved with good accuracy on a prime mover driven open-end stator winding induction machine operated as 6φ-SEIG. For both loading configurations, the full load voltage regulation is maintained within 2% across all phases with optimum excitation and series capacitances of 4 μF/phase and 19 μF respectively.

1. Introduction

Escalation in global renewable energy capacity has motivated the researchers to strive for better power equipments giving higher yields [1,2]. This has also lead to the introduction of many contemporary electric power drives for renewable energy applications. A Self excited induction generator (SEIG) is considered most suitable for standalone wind and mini/micro hydro applications [3,4]. Integration of the Multi-phase technology [5,6] with SEIGs results in high degree of ruggedness and fault tolerance to these machines [7].

Multi-phase induction generators are being proposed for both grid connected [8] as well as standalone [9,10] wind energy applications. They offer a number of operational advantages over their three-phase counterparts [9]. One of these is the ability of multi-phase SEIGs to cope with phase outages more conveniently than three-phase SEIGs. For instance, when supplying a given load the outage of a phase in a three-phase SEIG shall restrict its capacity by more than 30% requiring an immediate de-rating of load. On the other hand, if the same load is supplied by, say, a six-phase SEIG (6φ-SEIG), the continuity could be maintained with almost no or negligible self adjustments in the currents the of healthy phases [9].

Increasing emphasis towards engagement of the multi-phase induction machines for renewable energy systems is quite evident [8,9,11–14]. Classical studies on the control of multi-phase induction generators presented in [11,12] are useful for developing good understanding on them. In Ref. [13] a controlling mechanism is proposed to mitigate the effects of phase opening on the output power of a six-phase symmetrical induction generator for renewable energy applications. Recent developments and advancements on multi-phase induction generator research could be found in [14].

Choice of 6φ-SEIGs for renewable energy applications is quite relevant as it offers more operational flexibility, fault tolerance and ruggedness [12,13]. Moreover, the presence of multiple of 3 phases enables its seamless integration to practical loads. Also, the power apparatus for 6 × 3 conversion can be easily procured

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Nomenclature

Symbol	Description
R_s, R_r, R_L	stator, rotor and load resistances, Ω
L_{sl}, L_{rl}, L_{lm}	stator, rotor and inter winding leakage inductances, H
Ψ_{sd}, Ψ_{sq}	d and q axes stator flux, Wb
Ψ_{rd}, Ψ_{rq}	d and q axes rotor flux, Wb
Ψ^0_{rd}, Ψ^0_{rq}	d and q axes initial rotor flux, Wb
$v_{dcap1,2}$, $v_{qcap1,2}$	d and q axes instantaneous voltages across excitation capacitances of winding sets ABC(subsc_1) and XYZ(subsc_2), Volts
$v_{Ldcap1,2}$, $v_{Lqcap1,2}$	d and q axes instantaneous load voltages of winding sets, V
$v_{dcse1,2}$, $v_{qcse1,2}$	d and q axes instantaneous voltages of series capacitances, V
$i_{dcap1,2}$, $i_{qcap1,2}$	d and q axes capacitor currents, A
$i_{sd1,2}$, $i_{sq1,2}$	d and q axes stator currents, A
i_{rd}, i_{rq}	d and q axes rotor currents, A
$i_{Ld1,2}$, $i_{Lq1,2}$	d and q axes instantaneous load currents, A
$V^0_{dcap1,2}$, $V^0_{qcap1,2}$	d and q axes voltages due to initial charge on excitation capacitances of ABC and XYZ winding sets, V
M^0_{rd}, M^0_{rq}	d and q axes rotor induced voltages due to remnant flux, V
I_L, I_m	load and magnetizing currents, A
C_{ex}	per phase excitation capacitance, μF
C_{se}	series capacitance, μF
ω_r	rotor electrical speed, rad/s
L_m	magnetizing inductance, H
Ψ_m	magnetizing flux, Wb
V_{NL}, V_L	no-load and load voltages, V
φ	phase
T_m	mechanical torque, Nm
T_e	electromagnetic torque, Nm
P	no. of poles
J	moment of inertia, kg-m^2

off the shelf as it is readily available in the open market, thereby requiring no customization in associated transformers, converters, etc.

Concept of more electric transportation has opened new areas of applications for electric power drives. A 6φ-induction generator is proposed as a starter/generator for an aero-engine in [15]. Developed prototype is specifically tested for over load capability and post fault operation. Both these aspects are crucial for the safety critical application in aircrafts or more electric aircrafts (MEAs).

Numerous issues of multi-phase SEIGs have been quite aptly treated in the available literature. However, it is observed that some of the fundamental attributes of multi-phase concept are still to be tested for a multi-phase SEIG. Presence of dual-three phase loading terminals in a six-phase SEIG [16,17] can be utilized for different loading topologies. This paper is initiated from this basic premise to further develop into a full scale investigation on different loading topologies for multi-phase SEIGs.

2. Significance and methodology of proposed study

Loading modes investigated in this analysis are (i) six-phase simultaneous loading and (ii) three-phase loading at a time. Choice of loading configurations is motivated by their practical suitability to a 6φ-SEIG. When supplying three-phase power to either a grid or an isolated load through a 6×3 converter, a six-phase SEIG offers better stability and fault tolerance than its three-phase counterpart [9]. Alternately, three-phase load supplied by the 6φ-SEIG from its three terminals displaced by 120° offers an opportunity to assess its performance under this extreme case of unbalanced loading.

To achieve the objectives of proposed study a dynamic model of symmetrical 6φ-SEIG in dual d-q axes is derived and duly implemented in terms of its simulation model on MATLAB/SIMULINK platform. All the analytical results are verified experimentally on a 6φ-SEIG test-rig developed in the laboratory.

Winding configuration of the 6φ-SEIG with symmetrical phase displacement is depicted in Fig. 1. For simultaneous six-phase loading, the rated load is evenly distributed on all the phases of 6φ-SEIG. However, to facilitate three-phase

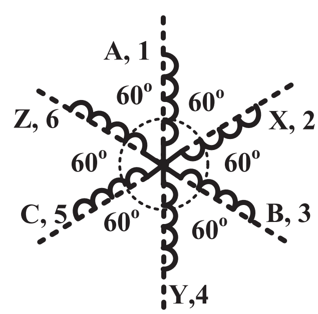

Fig. 1. 6φ-SEIG winding configuration.

loading at a time, three output terminals of 6φ-SEIG i.e., either ABC or XYZ (to draw balanced three-phase power) are loaded with 50% of the rated load leaving the other set un-loaded. This allows balanced three-phase power to be drawn from three output terminals of 6φ-SEIG and also represents a classical case of unbalanced loading. Both loading configurations are implemented without any interfacing transformer which makes the scheme simple there by not compromising on the inherent attributes of ruggedness and fault tolerance of SEIGs.

Reactive power for the implemented 6φ-SEIG is supplied with the combination of excitation (shunt) and compensation (series) capacitances [7] evaluated through experimental tests. Self-voltage regulating 6φ-SEIG configuration so obtained is often referred as the short-shunt [18] voltage compensation connection for SEIGs.

3. Mathematical Modeling of short shunt Six-phase SEIG

An integrated dual d-q model of short shunt 6φ-SEIG in stationary reference frame is given by Fig. 2 [9,16,17].

Dual d-q SEIG model of Fig. 2 consists of the parameter L_{lm} [19,20] which represents mutual coupling between dual three-phase windings ABC and XYZ of dual-stator SEIG. Entire machine model may be represented by (1) [9].

$$\omega_r[K][i]^T + [L]p[i]^T + [v]^T = 0 \quad (1)$$

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