Performance of Synchronous Reluctance Generators with Series and Shunt Stator Connections

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Abstract *– This paper reports the performance of series- and shunt-connected self-excited reluctance generators (SERG). In addition to the two stator connections, an analysis was carried out on rotor configurations (with and without a cage) a combination resulting in four different generator topologies. The loss of load and transient characteristics of each generator configuration were studied for a combination of pure resistive and R-L loads. It is shown that for the same machine size, speed and exciting capacitor value, the generator with a cage preserves a better wave shape following a transient disturbance than the cageless machine. At unity power factor, shunt generator with cage can deliver 0.691pu output power, at 1.97% regulation; its series counterpart only delivers 0.589 pu at 2.05%. The study demonstrates that while shunt generators have better regulation and supports higher loads at different power factors, series generators show a superior performance in terms of damping out transients.*

Keywords*: synchronous reluctance generator, transient performance, voltage regulation, loss of load performance, series connection, shunt connection, exciting capacitor*

1. INTRODUCTION

Generating operation of the synchronous reluctance machine was first reported by Abdel-Kader in 1985 [1]. The machine has not found much industrial application in power generation because it produces an output power that is less than that of an induction generator of comparable size and much less than that of field-excited generators. A major advantage of this generator type is that for loads within its carrying capacity, the frequency of the voltage developed has a well-defined relationship with the number of poles and operating speed of the generator. Induction generators are more prominent than reluctance generators because for the same machine size, speed and terminal excitation capacitance, it produces higher terminal voltage and higher current at dropout-voltage [2] and hence higher maximum power than the reluctance generator. This is because it has a relatively higher magnetizing reactance. Unfortunately, frequency of induction generator voltages depends on load power factor and capacitor values and preservation of voltage wave shapes for all load conditions requires additional control circuitry which increases its cost. Reluctance generators are constant frequency devices. This has excited interest in research on SERG. In [3], the machine characteristics was reported; the steady state analysis has been performed [4-6] developing equations for the d-axis reactance and capacitance required or excitation in terms of load angle.

The stability and its response to small perturbations [7] and dynamic effects were presented in [8]. Boldea, *et al* [9] used a high reactance ratio axially-laminated anisotropic (ALA) machine and recommended its suitability as a source of controlled dc power. A series-connected generator was reported in stand-alone mode by Ben-hail and Rabin [10]. The impact of cross-saturation was presented by Vagati, *et al* [11] for a transverse-laminated (TLA) rotor configuration.

The performance of SERG with- and without rotor cage has been reported in [12]. A recent paper by Ibrahim and Pillay [13] that dwelt deeply on SERG excitation in stand-alone mode developed a hysteresis current characteristic from which the voltage build-up and loss of excitation due to short-circuits for shunt-excited generators can be predicted. The paper produced a hysteresis loop of the machine and gave a clearer insight into the collapse of residual magnetism. The saturation curves needed for simulation in SERG were studied in detail by Guha and Kar [14] and Hoffer, *et al* [15] by considering several models, yielding the stability limits of the generator. Wang and Bianchi [5], inserted magnets into the ALA barriers and reported improved performance than conventional SERGs. To initiate self-excitation, it was emphasized that even in the presence of sufficient residual magnetism a closed loop needs to exist between the windings and a capacitor [16, 17]. Even when a suitable capacitance is connected, the residual magnetism has to be sufficient not just for the initiation of self-excitation but to sustain it when there are seemingly tolerable load changes [18].

The paper by Sekdy, *et al* [19] reported a voltage and frequency control of SERG using adjustable (switching) capacitors connected in series and shunt to load in an existing and already connected conventional shunt excitation fixed capacitor resulting in an improvement on voltage regulation for optimal load capacitor values. The paper by Hong, *et al*, [20] described a unique cooling method, loss calculation and parameter sensitivity analysis for a high speed SERG assisted by permanent magnets for use in aviation applications.

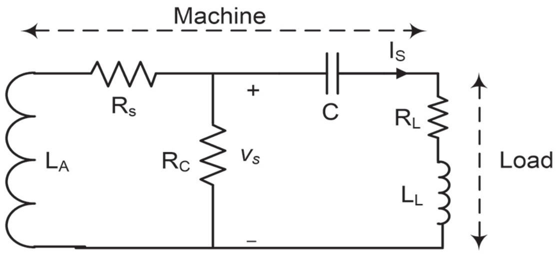
In [21], the electromagnetic design and analysis of a five phase reluctance generator with permanent magnet excitation with rectifier load was reported as having a higher power density than the conventional three phase machine. Grid applications of related generators have been explored in [22, 23].

From the foregoing, SERG with cage and with shunt capacitor connection appears to have received more attention [1-9, 12-19] than the series-excited machine cageless types [10, 11]. No attempt to the best of knowledge of the authors has been made to study both types and place their performance side-by-side and this forms the basis of this paper.

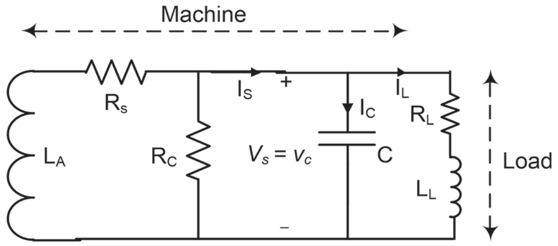
Section 2 deals with the general description of the stator connections and rotor configuration while section 3 details the mathematical modeling of the generator topologies. In section 4, the machine self-excitation process is presented and section 5 discusses the transient performance of the generators following the addition and removal of loads. Section 6 presents their voltage regulation and loadability characteristics while the study is concluded in section 7.

2. THE MACHINE UNDER STUDY

The connection diagram for both series and shunt-excited machines for one phase are shown in Fig. 1.



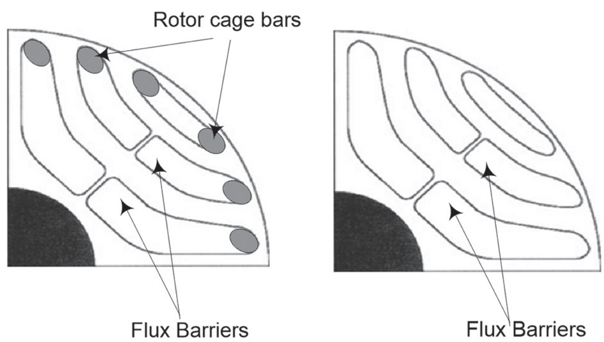
(a) Series connection



(b) Shunt connection

Fig. 1. Stator connections including core loss

The rotor shape is transverse-laminated (TLA) type. The stator winding is uniformly distributed around 36 slots of the machine and short-pitched 7/9 for all the generators to yield a more sinusoidal waveform. The stator winding layout over one pole is shown in Fig. 2.



(a) (b)

	Winding Layers	
Slot	Layer 1	Layer 2
1	A+	A+
2	A+	C –
3	A+	C –
4	C –	C –
5	C –	B+
6	C –	B+
7	B+	B+
8	B+	A –
9	B+	A –

(c)

Fig. 2. Machine under study; (a) rotor with cage, (b) rotor without cage, (c) Stator winding layout over one pole-pitch

3. 3. THE SYSTEM MODEL

3.1. MACHINE MODEL

The dynamic voltage equations of a SERG with distributed polyphase stator winding and with a short-circuited rotor cage winding is given by [12]:

$$\begin{aligned} v_{qs} &= -R_s i_{qs} + \omega_r \lambda_{ds} + \frac{d}{dt}\lambda_{qs} \\ v_{ds} &= -R_s i_{ds} - \omega_r \lambda_{qs} + \frac{d}{dt}\lambda_{ds} \\ v_{qr}' &= R_{qr}' i_{qr}' + \frac{d}{dt}\lambda_{qr}' \\ v_{dr}' &= R_{dr}' i_{dr}' + \frac{d}{dt}\lambda_{dr}' \end{aligned} \tag{1}$$

where, i_{qs}, i_{ds}, i_{qr}' and i_{dr}' are the stator and rotor q- and d-axis currents respectively, λ_{ds}, λ_{qs}, λ_{dr}' and λ_{qr}' are the stator and rotor flux linkages, ω_r is the rotor speed and R_{qr}' and R_{dr}' are the rotor winding resistances in the equivalent q- and d-axis respectively.

The resistance R_s appearing in the stator windings are values already accounted for by core loss resistance R_C according to $R_s=(R_a \times R_c)/(R_a + R_c)$ where R_c is the core loss and R_a is the stator winding resistance. The flux linkages are defined as:

$$\begin{aligned} \lambda_{qs} &= (L_{ls} + L_{mq}) i_{qs} + L_{mq} i_{qr}' \\ \lambda_{ds} &= (L_{ls} + L_{md}) i_{ds} + L_{md} i_{dr}' \\ \lambda_{qr}' &= (L_{lqr}' + L_{mq}) i_{qr}' - L_{mq} i_{qs} \\ \lambda_{dr}' &= (L_{ldr}' + L_{md}) i_{dr}' - L_{md} i_{ds} \end{aligned} \tag{2}$$

Here, L_{ls} is the leakage inductance in the stator while L_{lqr}' and L_{ldr}' are the rotor leakage inductances in q- and d- axis respectively, L_{mq} and L_{md} are the magnetizing inductances in the q- and d- axis respectively. The mechanical equation of the rotor is given by:

$$\begin{aligned} \omega_r &= \frac{p_r}{2J}\int (T_e - T_L) dt \\ T_e &= \frac{3}{4} p_r \left(i_{qs}(i_{ds} + i_{dr}') L_{md} - i_{ds}(i_{qs} + i_{qr}') L_{mq} \right) - T_L \end{aligned} \tag{3}$$

Equations (1) – (3) are also valid for a cageless machine if all the rotor quantities i_{qr}', i_{dr}', λ_{dr}' and λ_{qr}' are set to zero.

3.2 CAPACITOR AND LOAD MODELS

The loads on each of the generators will be loads of lagging power factor (R-L series type). Considerations were not made about leading power factors because such loads are not very common in practice. For a changing R_L, the corresponding inductance L_L can be calculated for a specified power factor load using:

$$L_L = \frac{R_L}{\omega_r} \times \sqrt{\left(\frac{1}{\cos\phi}\right)^2 - 1} \tag{4}$$

3.2.1. Capacitor and load model for the series generator

If the capacitor is connected to the generator as shown in Fig. 1(a), it will be easy to write both the capacitor and load voltage equation as seen by the machine terminal voltage, v_s as:

$$v_s = i_s R_A + \frac{1}{C}\int i_s dt + L_L \frac{di_s}{dt}. \tag{5}$$

It is obvious that the stator winding current i_S flows directly through the load. The resistance R_A appearing in (5) represents the stator winding resistance R_S and the load resistance R_L. Noting that R_L, L_L and C are constants and equal in each of the three phases, a transformation of (4) to the d-q reference frame fixed to the rotor yields:

$$\begin{aligned} v_{qs} &= R_A i_{qs} + \frac{i_{ds} - C\frac{dv_{dc}}{dt}}{\omega_r C} + L_L \frac{di_{qs}}{dt} + \omega_r L_L i_{qs} \\ v_{ds} &= R_A i_{ds} + \frac{i_{qs} + C\frac{dv_{qc}}{dt}}{\omega_r C} + L_L \frac{di_{ds}}{dt} - \omega_r L_L i_{ds} \end{aligned} \tag{6}$$

From (6), the volage across the load in Fig. 1(a) may be calculated.

3.2.2. Capacitor and load model for the shunt generator

For the connection of Fig. 1b, the voltage across the capacitor is also the voltage across the load. The equation of this voltage in stator variable is:

$$v_s = v_c = \frac{1}{C}\int (i_S - i_L)\, dt \tag{7}$$

When (7) is transformed to the rotor reference frame, we have:

$$\begin{aligned} v_{qs} &= \frac{1}{\omega_r C}\left(i_{dL} - i_{ds} + C\frac{dv_{ds}}{dt}\right). \\ v_{ds} &= \frac{1}{\omega_r C}\left(i_{qL} - i_{qs} - C\frac{dv_{qs}}{dt}\right) \end{aligned} \tag{8}$$

Equation (8) shows that the exciting current charging the capacitor and maintaining the stator flux is supplied by the difference between the winding currents and the load currents, hence only a fraction of the winding current is available to the load. The load currents are modeled as supplying a general R-L load and are given as:

$$\begin{aligned} i_{qL} &= \frac{1}{\omega_r L_L}\left(R_L i_{dL} - v_{ds} - L_L \frac{di_{dL}}{dt}\right) \\ i_{dL} &= \frac{1}{\omega_r L_L}\left(R_L i_{qL} - v_{qs} + L_L \frac{di_{qL}}{dt}\right) \end{aligned} \tag{9}$$

3.4. INDUCTANCE SATURATION AND CORE-LOSS MODEL

The d- and q- axis inductances calculated by finite element in the presence or absence of a cage gave similar saturation and core-loss data for both rotor structures on the ground that a constant speed operation is assumed. These similarities create a uniform basis for the comparative studies on the performance of the four generators studied here. Equation (10) is a third order polynomial fit showing the dependence of direct- and quadrature-axis inductances and core loss on the magnetizing flux linkage of the machine, obtained with finite element software FEMAG DC®.

$$L_d = -3.3\lambda_m^3 + 1.5\lambda_m^2 - 0.26\lambda_m + 0.231\,H$$
$$L_q = -2.2\lambda_m^3 + 2.5\lambda_m^2 - \lambda_m + 0.17\,H \quad (10)$$
$$R_c = -18800\lambda_m^3 + 13300\lambda_m^2 - 1980\lambda_m + 669\,\Omega$$

where $\lambda_m = \sqrt{\lambda_{qs}^2 + \lambda_{ds}^2}$

4. VOLTAGE BUILD-UP

A common requirement for self-excitation of SERG is the existence of appropriate values of magnetic remanence, capacitor, speed and saturation. The constraint in the choice of these initial conditions is to ensure that the thermal limits and current carrying capability of the stator windings are not exceeded and that the generated voltage and frequency is nominally a universal value. Theoretically a large range of voltages and frequency can be generated whenever self-excitation occurs. Nearly all the papers cited emphasized these and, in this paper, a common set of values were chosen for the four configurations to ensure a fair comparison. To achieve this, a remanent flux of 0.01wb is assumed in the core, a rotor speed of ω_r = 377 rads/sec and a constant excitation capacitor of 65μF were used.

The solution of the above equations is accomplished with Matlab Simulink®. In addition to (4) and (10) which must be used during the simulation of all the self-excited generator types, the following combination of equations and modifications were used for the simulation of the four generator topologies as shown in Table 1.

Table 1. Generator topologies under study

Assigned Code	Generator Topology	Equations for Simulation
RG1	Shunt stator connection with rotor cage	The whole of (1), (2), (8) and (9).
RG2	Shunt stator connection with cageless rotor	The first two equations of (1) and first two of (2) with i_{qr}' and i_{dr}' set to zero, and the whole of (8) and (9).
RG3	Series stator connection with rotor cage.	The whole of (1), (2) and (6).
RG4	Series stator connection with cageless rotor	The first two equations of (1) and first two of (2) with i_{qr}' and i_{dr}' set to zero, and the whole of (6).

When these sets of equations are separately solved under no-load conditions, Fig. 3 results as shown.

Since the equations are solved under no-load conditions, the voltage build up for both series and shunt connections are similar. The difference will arise only due the effect of rotor cage during the voltage build-up process as shown in Fig. 4, but in all cases the frequency of the generated voltage is 60Hz and peak no load voltage is 120V. It is seen that generators with rotor cage develop voltages gradually while a spontaneous voltage build-up with voltage overshoots occurs in the cageless machines.

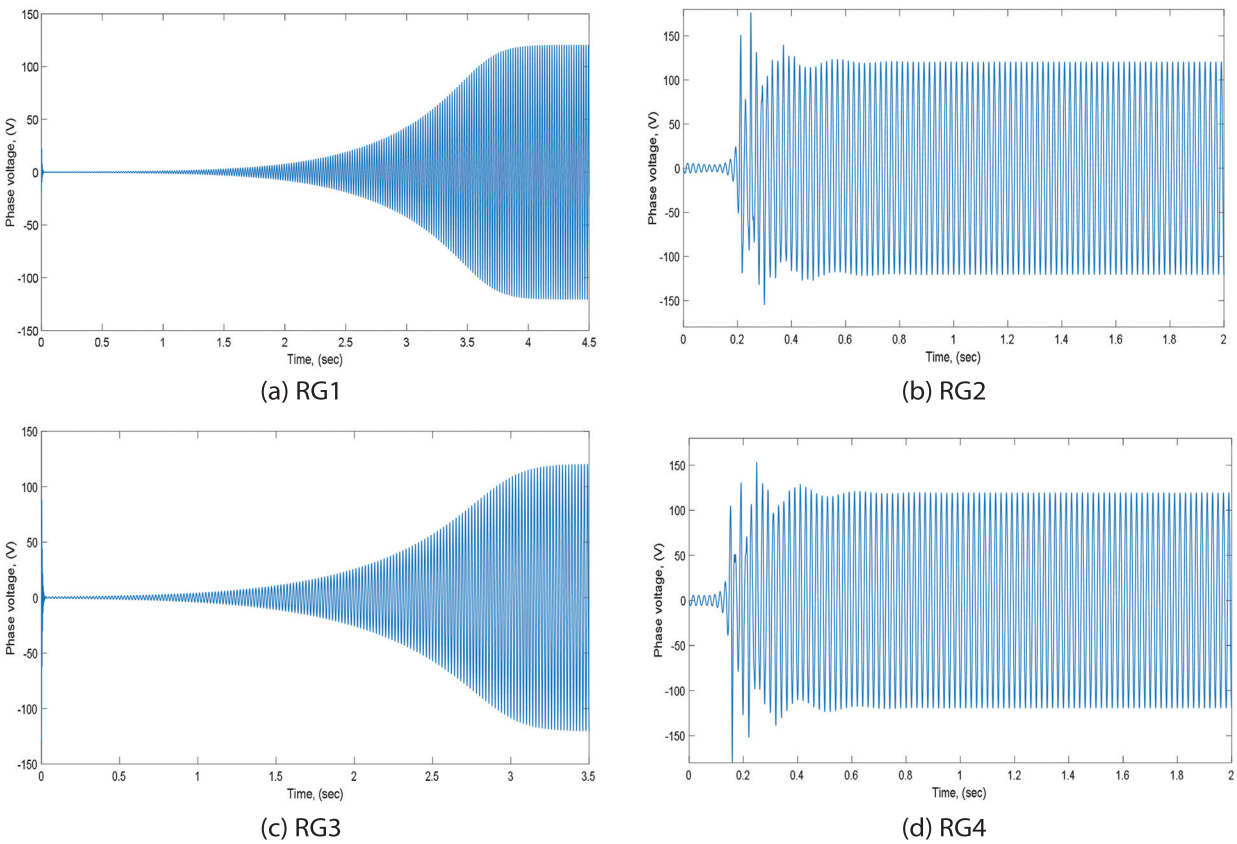


Figure 3. Voltage build up on phase A under no-load condition

5. TRANSIENT PERFORMANCE

The transient performance due to adding and removing of loads are now considered. The unloaded generator is operating at open circuit voltage when load is added at t=7.0secs. This leads to some voltage oscillations and then the voltage settles to a new voltage value less than the open circuit value. Then the load is removed at t=9.0secs. For a pure resistance (upf) load, the inductive loads are set to zero in the respective model equations. The variation in the values of voltages is used for assessing the loss of load performances. Results of plots from the four generator topologies are presented in Fig. 4 for unity power factor (pure resistive) loads. Fig. 5 shows the corresponding results obtained for an RL load of 0.85 power factor.

In the four topologies considered, addition of load results less and quicker damping than when the same load is disconnected. This is akin to what happens in field-excited alternators [28]. Expectedly, machines with cage possess better damping characteristics than the cageless types. For the same magnitude of load, the resistive load yields a lower voltage drop but with more oscillations than the RL loads (Figs. 4a and 5a). Series connected machines are faster in damping than shunt-connected machines for similar loading conditions.

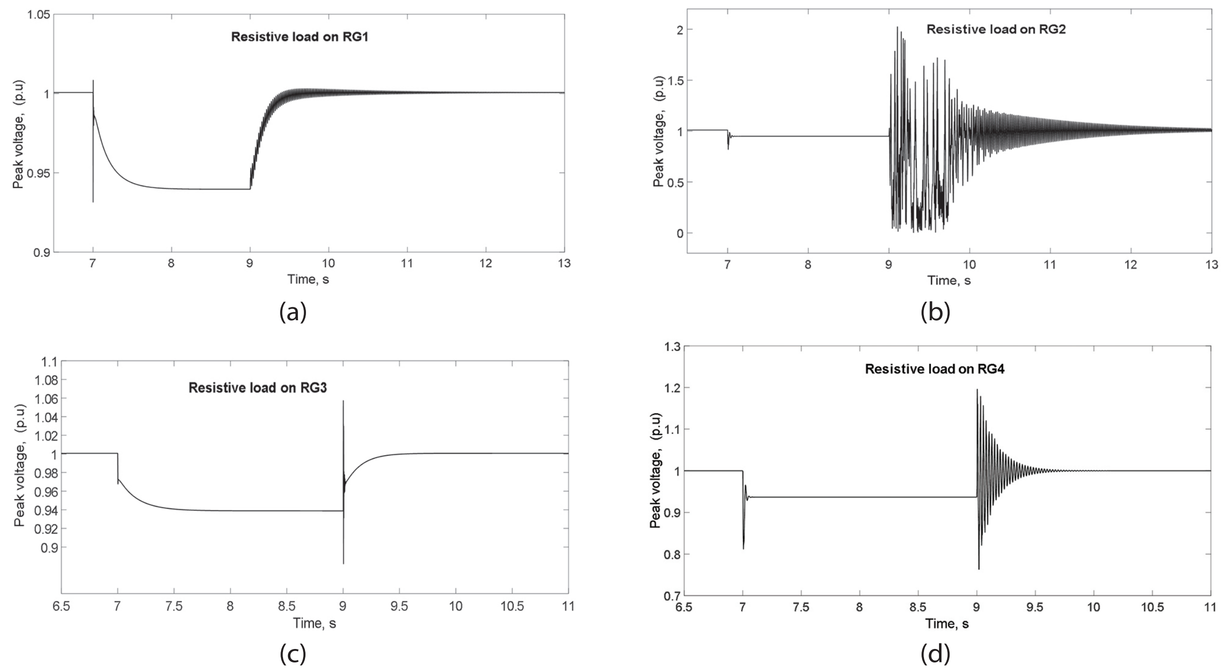


Fig. 4. Transient responses of phase A voltage following sudden switching and loss of pure resistive load on the generators

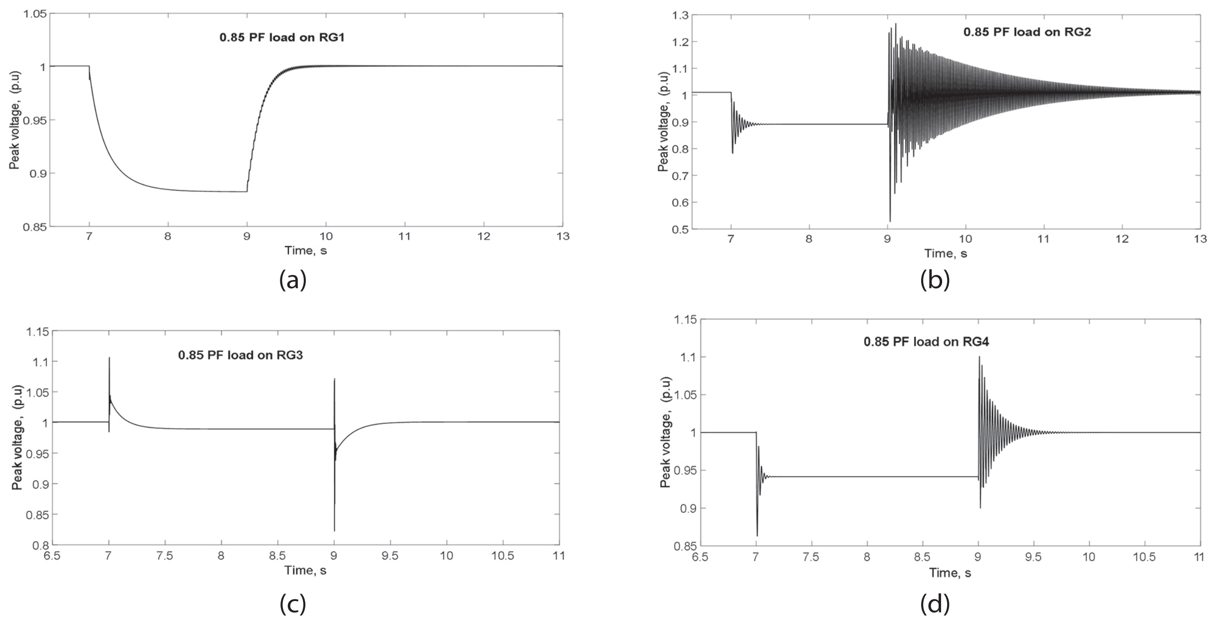


Fig. 5. Transient responses of phase A voltage following sudden switching and loss of 0.85 power factor load on the generators

Series generators (RG3 and RG4) are more capable of withstanding load transients than shunt generators (RG1 and RG2) for similar load combinations. In fact, the series generator with cage offers better damping of transients than the corresponding shunt machine.

6. VOLTAGE REGULATION CHARACTERISTICS

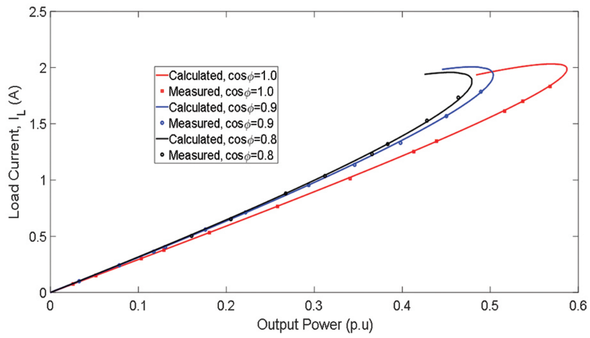
The non-linearity of L_d, L_q and R_c necessitates that the steady-state solution of self-excited generators be performed numerically. This can be accomplished by setting all the time derivatives of state variable to zero and then using either look up tables or quasi-Newton's iterative techniques (or similar algorithms) to solve the resulting set of equations with preset initial conditions. These have been reported severally in literature [2–5, 10, 11, 13] and it is not the intention of this paper to repeat such a study. In this study, the regulation is studied by loading each of the four generator types gradually from no load to full load and the peak value of the generator voltage observed. A full load point here is determined as the point where the voltage collapses or self-excitation is lost. Table 2 is obtained for each generator topology by gradual loading from no load to full load determined by a load angle of 43° and shows the results for three different load power factors.

The regulation shows that the shunt generators are better power converters than series generators since they can deliver more power at every power factor. This is because for a series machine, the sum of leakage plus load inductance should not be higher than the value of the saturated q-axis inductance, otherwise system will fail to excite or if already excited, voltage collapse will result. All the topologies have their best voltage regulation and power carrying capacity at unity power factor.

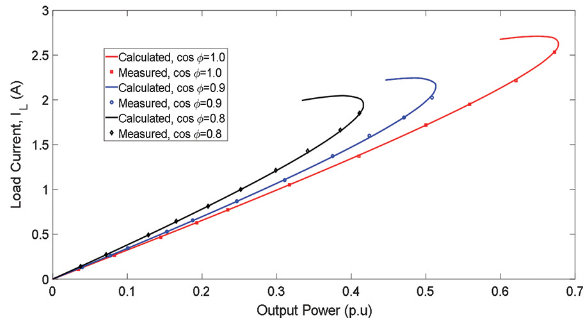
Table 2. Maximum power deliverable and voltage regulation at δ=43° electrical for the generators at different load power factors.

Load Power factor → Gen. Topology↓		cosϕ=0.8	cosϕ=0.9	cosϕ=1.0
RG1&RG2 (shunt connection)	Max. Power (p.u)	0.466	0.579	0.691
	Voltage Reg. (%)	2.44	2.39	1.97
RG3&RG4 (series connection)	Max. Power (p.u)	0.453	0.511	0.589
	Voltage Reg. (%)	2.50	2.45	2.05

Measured and calculated values of load current plotted against the output power are shown in Fig. 6 for both the series and shunt generator. These again re-emphasizes that shunt generators are better in terms of energy-conversion than series generators. Fig. 7 shows the voltage of the SERG under steady state conditions with loads of difering power factors. The shunt generator exhibits better voltage regulation and is seen to be capable of supporting more load than the series machine at all corresponding power factors. However, seris gnerators are less sensitive to power factor variations than shunt generators

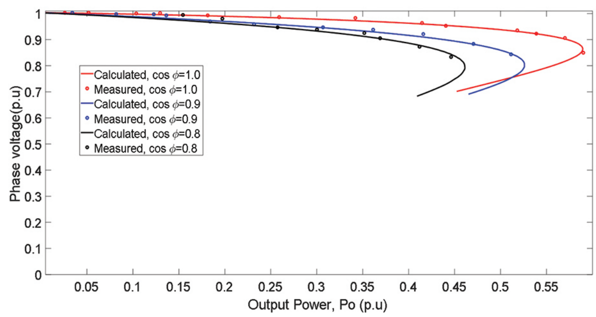


(a) Series generators



(b) Shunt generators

Fig. 6. Load current plots



(a) Series generators

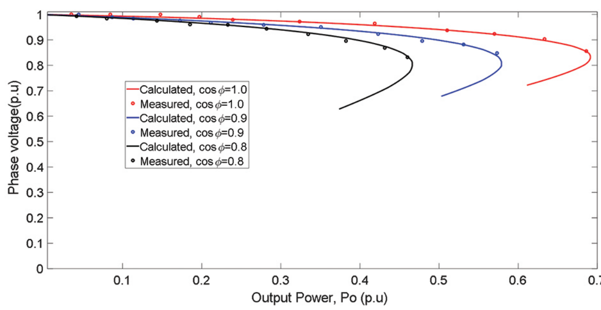


Fig. 7. Power vs Voltage plots

7. CONCLUSIONS

The seeming advantage of series connection is that both the excitation and load current flow in the connected load while only a fraction of the current in the stator winding is available to the load for shunt connection. It would have then been easily presumed that series connection can support a larger load than shunt connection since all the winding current flows through the load, but results presented here has shown otherwise. This is because, for series connection, the load must be matched to the generator such that it fulfils the condition for self-excitation before a voltage can be produced.

The dynamics and voltage regulation characteristics of four stand-alone reluctance generator configurations has been studied. Expectedly, machines with damping cage are better in delivering a better voltage waveform than the cageless machine, even though the later are faster in excitation. Shunt generators are also seen to be better in terms of both voltage regulation and power conversion ability. Following sudden addition and loss of loads, series generators offer the advantage of having better damping characteristics than the shunt generators. Loss of load for cageless generator with shunt connection (RG2) leads to very large drop in voltages which may not be tolerable in some applications. Based on these results, the study recommends that a cageless rotor machine be used with series connection while a shunt generator requires a rotor cage.

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