Variable-Reluctance Generators in Wind-Energy Systems

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Abstract

This paper presents two approaches of incorporating the variable-reluctance generator (VRG) into advanced wind conversion systems at or above the 50 kW power level. The VRG is a synchronous generator which is compatible with variable-speed operation of advanced wind turbines. Operating through a power electronic interface to the utility, this generator offers simplifications of the utility/generator interface over adjustable-speed wind conversion systems based on the induction generator. In addition, analyses performed here using experimentally based data show that the VRG system is as much as 6% more efficient and up to 13% less expensive than a comparably-rated induction generator system. These analyses are based on a piece-wise linearization of the nonlinear VRG characteristics. At comparable power levels, it can offer superior utility power-quality relative to the induction generator systems presently under development. The VRG also offers a reduction in the operating, maintenance and energy costs associated with advanced wind-energy systems.

1 Introduction

Considerable resources have been committed to the development of practical wind generators in the last twenty years. References [1, 2, 3, 4, 5] document the developments in wind energy which have made the technology cost competitive with more conventional forms of energy. The current trend is to focus attention on the $100-500$ kW range, where the machines can retain much of the modular simplicity of smaller machines while incorporating selected innovations to enhance economic operation. Wind generating capacity in the United States now exceeds 1600 MW, and this number is expected to increase. Further, wind energy can be important to countries which do not have access to large interconnected power grids.

The induction generator (IG) has been the common energy converter used in wind systems. Variable-speed generator operation provides for greater energy capture through three mechanisms. First, energy can now be captured at wind speeds which are lower than those necessary to create generation at the utility frequency. Second, the dynamic control over the generator voltage and frequency allows for generator operation at maximum efficiency. Third, the dynamic voltage and frequency control allows the electrical excitation to track the wind speed, thereby reducing the loss of energy in the mechanical transmission.

This paper presents two ways to incorporate the variable-reluctance generator (VRG) into advanced wind conversion systems at or above the 50 kW power level. The first way employs a voltage-source inverter (VSI) to excite the VRG; the second way uses a current-source inverter (CSI) to excite the VRG. Analyses performed in Sec. 3 and 4 highlight the potential energy and cost benefits of a VRG, respectively.

2 The Variable-Reluctance Generator in Wind Energy Systems

The VRG is a synchronous generator which is compatible with variable-speed operation of advanced wind turbines. See [6, 7] for operational characteristics of the variable-reluctance motor (VRM). These characteristics carry over to the VRG.

2.1 Voltage-Source Excitation of a VRG

A VSI appropriate for interfacing the VRG with the utility is shown in Fig. 1, based on slight modifications of common VRM inverters [8, 9]. The magnetic analysis performed here assumes the piecewise-linear magnetic

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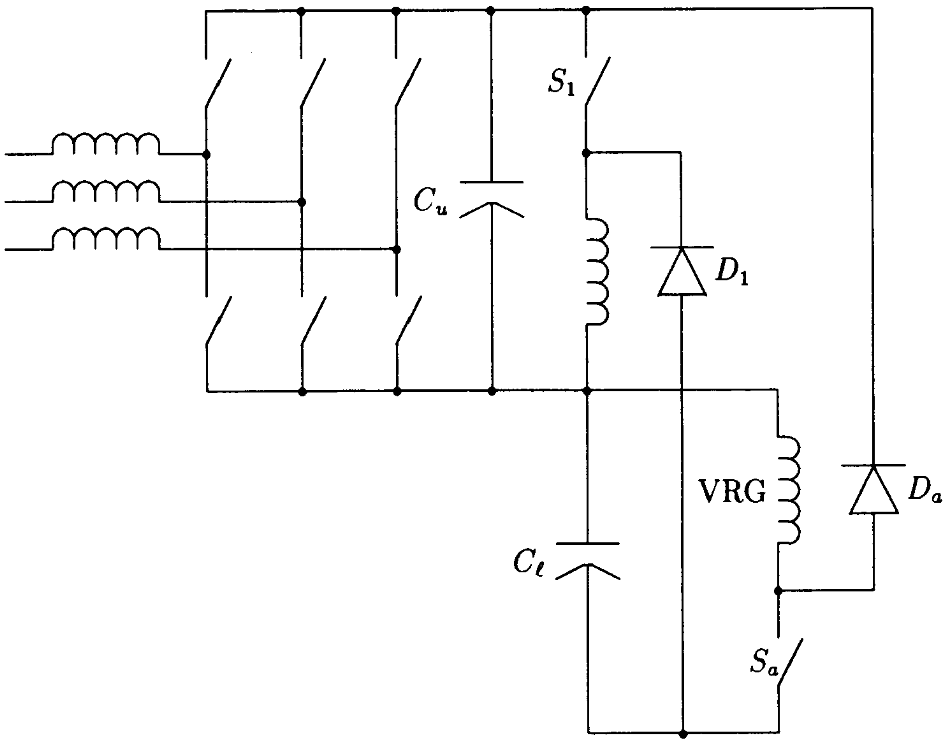

Figure 1: A VSI appropriate for interfacing a variable-reluctance generator to the utility. Only one phase of the VRG is shown.

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characteristic shown in Fig. 2 to represent the VRG. Parameters assumed for the model are given in Table 1; these values are taken as typical for a VRG at the 50 kW power level. The piecewise-linear model has been shown to do a good job of predicting average energy conversion, though the specific details of the phase currents could be in error [10].

Table 1: The parameters used to define the piece-wise linear model of Fig. 2 for the experimental VRG.

Parameter	Value
L_{max}	16.67 mH
L_{min}	0.667 mH
L_b	0.167 mH
I_{sat}	24 A

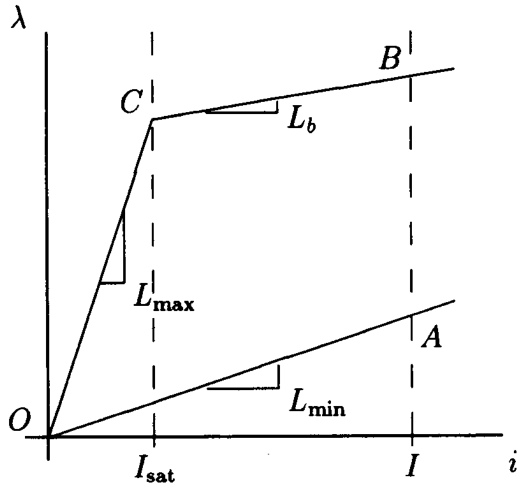

Figure 2: The piecewise-linear magnetic model used for VRG analysis, along with an idealized energy conversion cycle ($OCBAO$).

To begin, consider the operation of the VRG. When each phase switch is closed in turn, energy is taken from C_ℓ and put into the excited VRG phase. During this time the phase flux linkage and current are increasing. In terms of Fig. 2, we have traversed from O to C to B during this time.

When the phase current reaches a sufficiently high value (determined by some sort of controller), the controllable switch for that phase is turned off. The phase current is diverted at turn-off through the flyback diode and into C_u. Energy is delivered to the upper capacitor by virtue of the decreasing flux linkage as the phase current is returned to zero (via path BAO of Fig. 2).

From the geometry of the energy conversion characteristics summarized in Fig. 2, the ratio of energy (ER) supported by C_ℓ to the total energy converted is shown in Fig. 3 for the model parameters given in Table 1. The data in Fig. 3 show that the percentage of recirculated energy needed to support generation drops very abruptly with increasing current and generally remains well below 20% over most of the intended operating range. The recirculated energy that is supported by C_ℓ must be derived from C_u via switch S_1, an inductor, and D_1 which effectively places the lower capacitor in parallel with the inductor. These elements form a buck-boost converter which keeps C_ℓ charged.

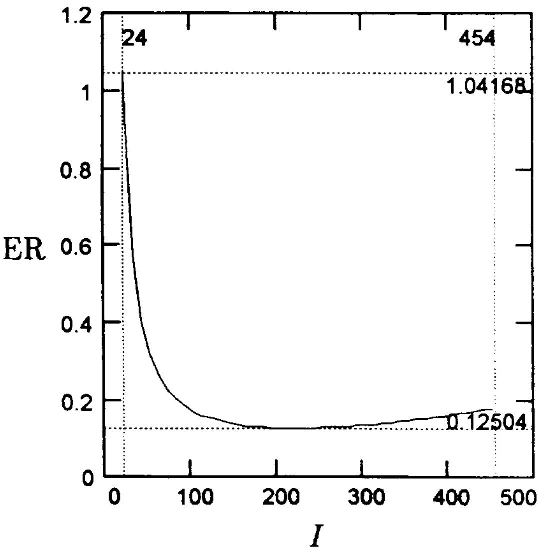

Figure 3: The ratio of recirculated to converted energy for the experimental VRG as a function of current, based on a piecewise linear model of the VRG.

The energy flow through the switch S_1 in support of the recirculated energy is generally smaller than the energy which must be supported by each phase switch. In terms of the energy converted by one phase, the total recirculated energy of the VRG is

$$W_{\text{recirculated(total)}} = q \text{ ER } W_{\text{converted(phase)}} \quad , \tag{1}$$

where q is the number of phases. It follows that the ratio of average switch currents is

$$\frac{I_{\text{avg},S_1}}{I_{\text{avg},S_a}} = q \text{ ER} \tag{2}$$

Equation 2 shows that under most operating conditions S_1 must support less average current than each phase switch. This average current imbalance is perhaps more significant than implied by Eq. 2, because the peak phase current could be as much as three times greater than the average phase current because of the large amount of ripple. The ripple current through S_1 can be made relatively small through appropriate design. The implications of the switch ratings on cost is analyzed below in Sec. 4.

The VRG system must be considered to be more reliable than the IG system. First, the VRG system requires ten controllable switches; the IG system requires twelve. Second, the VRG does not have any windings on the rotor which can fail. Third, each phase winding in the VRG is physically isolated from the other phase windings. In an induction generator, winding slots are occupied by two phase windings.

2.2 Current-Source Excitation of a VRG

A current-source inverter system has the potential to dramatically simplify the control of the VRG, particularly at the low speeds associated with wind turbines. In addition, it can be used to economically interface the VRG to the utility with high power-quality. Figure 4 shows a CSI for VRG excitation and two utility interfaces. The operation of the total converter can be understood by separately considering its constituent components.

Referring to Fig. 4, the current source inverter is comprised of the VRG, the controllable switch in series with each phase (S_a), the flyback diode for each phase (D_a), the capacitor (C), and the controllable switch in parallel with the VRG (S_1). Switch S_1 is used to ensure continuity of energy in the current-source inductor, and would be used when warranted by the operating mode of the VRG.

Excitation of phase a begins when S_a is closed and S_1 (or S_b or S_c) is opened. After an initial transient, the phase current becomes I_{dc} ($OCBA$ in Fig. 2). The phase is deenergized by turning off S_a, diverting the phase current to C via D_a. The capacitor provides the negative Volt-seconds necessary to drive the phase current back to zero (AO in Fig. 2). The magnetizing energy is shown in Fig. 5 for the model of Table 1. The nonlinear relationship between magnetizing energy and phase current is due to magnetic saturation.

Figure 6 shows the equivalent linear inductance needed to store the magnetizing energy, and gives valuable design

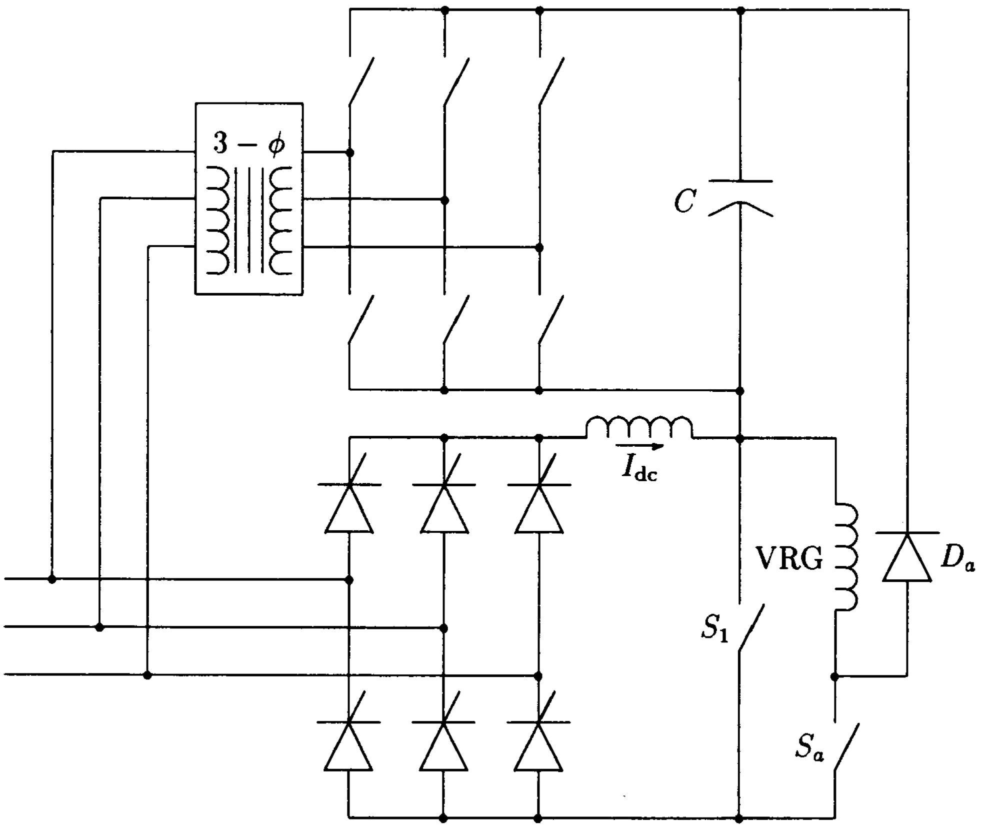

Figure 4: A CSI appropriate for interfacing a variable-reluctance generator to the utility. Only one phase of the VRG is shown; additional phases would be placed in parallel with the one shown.

information for the link inductor. For a small amount of ripple in the source current during commutation between phases, we want $L_{dc} \gg L_{equivalent}$. This must be considered carefully in conjunction with the dynamic performance of the phase-controlled converter.

The energy which is transferred from the phase to C is

$$W_{capacitor} = \frac{1}{2} L_{min} I^2 \tag{3}$$

The fraction of the total energy converted which must be supported by the capacitor is shown in Fig. 7 as a function of phase current for the VRG model.

The upper utility interface shown in Fig. 4 is used to regulate the voltage across the capacitor, and to function as an active power filter which compensates for the distortion and the reactive power drawn by the lower utility interface. The active power filter is still available for distortion filtering and reactive power support when the VRG is not operating.

The reliability of the CSI system is difficult to assess in comparison to either the VSI system or the IG system. The number of fully controllable switches required for the CSI system are the same as for the VSI system, though some of these switches are at reduced power ratings. The CSI has the additional need for six thyristors. It is fair to conclude that the VSI-based system is the most reliable of the three systems discussed, followed by the CSI-based system, then the IG system.

3 Energy Benefits

The energy benefits offered by either the VSI- or CSI-based VRG system are significant. This section compares the efficiency of the IG system, the VSI-based system of Fig. 1 and the CSI-based system of Fig. 4. At the outset, it is recognized that all three systems support variable-speed operation of the wind turbine, which has been doc-

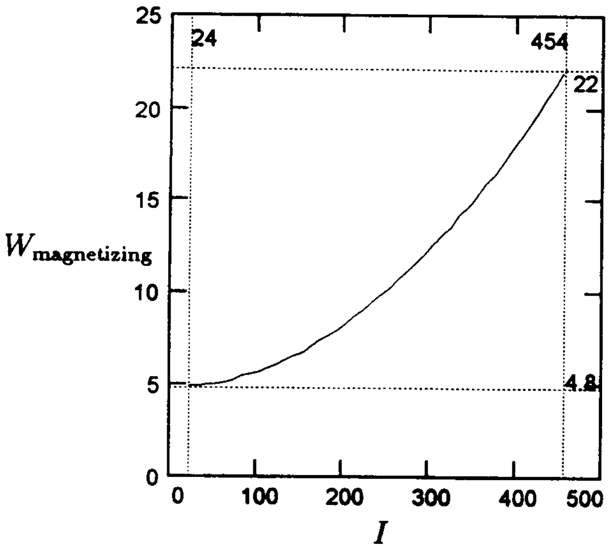

Figure 5: The magnetizing (recirculated) energy requirements of the experimental VRG as a function of phase current.

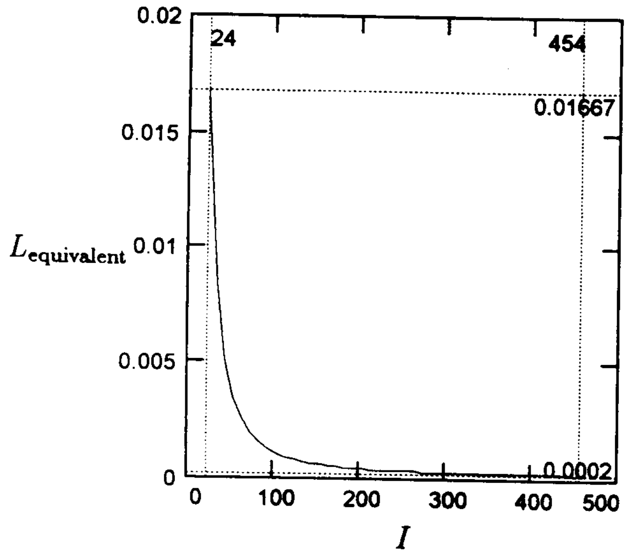

Figure 6: The equivalent inductance as a function of phase current. This inductance is the linear inductance needed to support the magnetizing energy requirements of the experimental VRG as a function of phase current.

umented to yield a 10 – 15% improvement in energy capture over constant-speed turbines [5]. This discussion of energy benefits focuses on the relative efficiency of the three systems.

The fundamental assumptions on component efficiency are given in Table 2. The entries are based on documented performance in the case of the VSI-based VRG (assuming equality with VRM performance [10, 11]), on a conservative approximation based on similar performance data for the CSI-based VRG, on industry rules of thumb for the phase-controlled rectifier and IGBT inverters, and on manufacturer data for the induction generator. The efficiency calculations are summarized in Table 3.

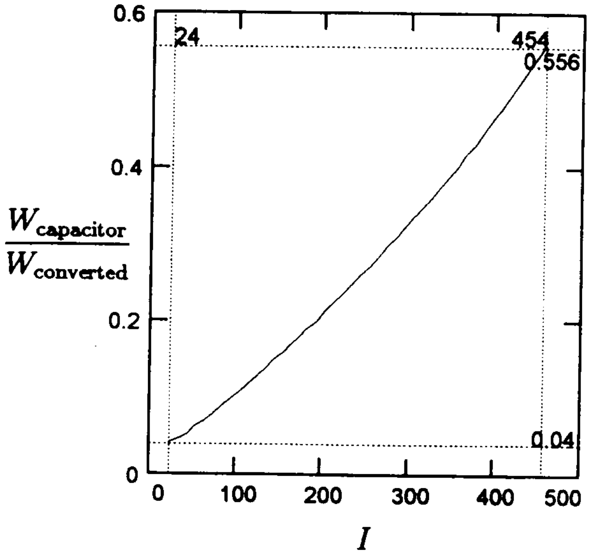

Figure 7: The percentage of the converted energy which must be supported by the capacitor in Fig. 4 as a function of phase current.

Table 2: The achievable efficiencies assumed as the starting point of the energy benefit analysis.

System Component	Assumed Eff. (%)
VSI-VRG Combination	95
CSI-VRG Combination	94
Phase-Controlled Rectifier	98
50 kW IGBT Inverter	97
20 kW IGBT Inverter	97
Induction Generator	92

The induction generator is assumed to be interfaced to the utility through two 50 kW IGBT inverters. The VSI-based VRG is assumed to be interfaced to the utility through a 50 kW inverter. The CSI-based VRG is assumed to be interfaced to the utility through a 30 kW phase-controlled rectifier and a 20 kW IGBT inverter. The effective efficiency of the utility interface is taken to be the weighted average of the phase-controlled rectifier and IGBT inverter efficiencies based on energy flow.

The potential efficiency improvements offered by the VRG system are significant. As with all efficiency numbers, however, they do not by themselves tell the entire

Table 3: A summary of the energy benefits offered by the VRG systems, based on 50 kW of shaft power delivered to the generator.

System	Efficiency (%)	P_{out} (kW)	$P_{\text{out}}/P_{\text{out,IG}}$	Improvement (%)
IG	86.5	43.25	1.00	--
VSI-VRG	92	46	1.063	6.3
CSI-VRG	91.7	45.85	1.06	6.0

story. Another part of the story is price performance, and this is discussed in the next section. An important issue which has not been taken into account in this analysis is the effect of operating point on system efficiency. That is, system efficiency is not constant for all rotor speeds.

For all of the systems discussed here, efficiency drops with speed. This is a natural consequence of the definition of efficiency and the fact that power throughput depends linearly on shaft speed. The overhead of supporting torque production at low speeds erodes the efficiency as the shaft speed is reduced. For the VRG, the drop in efficiency as the speed is reduced can be precipitous for the VSI-based system because the inverter must work hard to regulate the phase currents, causing inverter losses to rise dramatically. The efficiency of the CSI is much less volatile because the responsibility of regulating phase currents is placed on the current source, not on the individual inverter phases. This could make the CSI-based system more attractive despite the numbers reported in Table 3.

4 Cost Benefits

This section provides a cost/benefit analysis for the IG system and the two VRG systems. At the outset, it is assumed that the price difference between the induction and variable-reluctance generators is negligible. (If manufactured in comparable quantities, the VRG would be slightly less expensive than the IG.) Thus, the cost benefits are to be achieved through the power electronic converters which interface the generators with the utility. The comparison is made for 50 kW wind systems. The relative results should hold at higher power levels.

The analysis performed here makes use of industry rules of thumb, which are summarized by *cost factors*. Each functional component of the power electronics equipment carries a cost factor. The list price of the equipment is then determined by multiplying the total cost factor by a price/cost factor conversion ratio. The conversion ratio is a nonlinear function of power level.

The major cost factors include the control board, the drive electronics, the semiconductor devices, and ancillary things such as the enclosure, wiring, hardware, etc. The cost factors for the drive electronics and semiconductor devices scale with the power level and the type of device; the cost factors for the control board and the ancillary parts are essentially independent of power level. Table 4 gives the cost factors used as the basis of comparison; Table 5 summarizes the relative cost calculations.

Both VRG power electronic converters offer significant cost savings over the power electronics needed to support variable-speed operation of the induction generator. These cost savings, coupled with the energy benefits make a very persuasive argument for the development of advanced wind energy systems based on the variable-reluctance generator.

5 Conclusions

This paper has presented arguments for incorporating the variable-reluctance generator in advanced variable-speed wind turbines. The central factors in these arguments are the generator simplicity, the flexibility of the utility interfaces, the improved energy efficiency and the less expensive utility interface.

It has been shown that both the VSI- and the CSI-based VRG systems offer improved efficiency and reduced cost over the conventional induction generator. The improved efficiency is tied to the improved efficiency of the VRG over the induction generator. The lower cost is a reflection of the fewer controllable switches that are required to interface the VRG with the utility.

Acknowledgements

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Table 4: The cost factors used to evaluate the cost benefits of the VRG systems.

Item	Cost Factor
Control Board	1.0
Ancillary Parts	1.0
Drive Electronics (Controllable Switches, 20 kW)	0.2
Drive Electronics (Controllable Switches, 50 kW)	0.25
Drive Electronics (Thyristors, 50 kW)	0.125
Devices (Controllable Switches, 20 kW)	0.325
Devices (Controllable Switches, 50 kW)	0.41667
Devices (Thyristors, 50 kW)	0.04167

Table 5: A summary of the cost calculations.

	IG System	VSI-VRG System	CSI-VRG System
Drive Electronics:	12 x 0.25 = 3.0	10 x 0.25 = 2.5	4 x 0.25 = 1.00 6 x 0.2 = 1.20 6 x 0.125 = 0.75
Devices:	12 x 0.41667 = 5.0	10 x 0.41667 = 4.2	4 x 0.41667 = 1.67 6 x 0.325 = 1.95 6 x 0.041667 = 0.25
Control:	1.00	1.00	1.00
Ancillary:	1.00	1.00	1.00
Total:	10.0	8.7	8.82

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