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Research Article

DC Voltage Output Control of a Hybrid Synchronous Generator-based Wind Turbine

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Abstract – This article discusses regulating a Wind Turbine (WT) that uses a Hybrid Excitation Synchronous Generator (HESG) to power an isolated load via a diode bridge rectifier. The HESG acts as a DC generator and supplies power to the DC load. The primary objective of the suggested control strategy is to maintain a steady DC voltage output, even when there are changes in rotor speed and/or load. The entire system is simulated and modelled in Matlab/Simulink, and the simulation results prove the effectiveness of the proposed method in delivering power to an isolated location.

Keywords –Hybrid Excitation Synchronous Generator (HESG), Diode Bridge Rectifier, Control, DC Bus Voltage, Isolated Load

I. Introduction

Permanent magnet machines are a popular choice for many applications due to their brushless and efficient nature. Nevertheless, regulating the excitation flux generated by the permanent magnets can be a challenge once the machine has been designed, making it difficult to achieve voltage regulation in generator mode and speed increase in motor mode. On the other hand, rotor wounded synchronous machines offer exceptional magnetic field regulation but use slip rings and brushes in their structure, resulting in low efficiency due to losses in the excitation winding.

The term " Hybrid Excitation" refers to structures that incorporate two types of excitation flow one created by permanent magnets and the other generated by excitation coils that regulate the flow in the air gap [1][2][3]. The secondary source of excitation is used to enhance or weaken the magnetic flux, enabling the benefits of permanent magnet machines to be combined with the ability to control the magnetic flux through excitation windings. In this context, the authors propose a model and control mechanism for a synchronous hybrid excitation machine (HESG) that is linked to a bridge rectifier with diodes and powered by a wind turbine.When used to supply power to an isolated load as a wind generator, this machine operates as a Hybrid Excitation Generator (HESG). Alternatively, when incorporated into an energy conversion system as a generator, it is referred to as a HESG.When used to supply power to an isolated load as a wind generator, this machine operates as a Hybrid Excitation Generator (HESG). Alternatively, when incorporated into an energy conversion system as a generator, it is referred to as a HESG.

II. Modelling of system elements

A. Model of the turbine

Eq. (1) provides the theoretical power input to the turbine, with ρ representing the air density, S representing the circular area swept by the turbine, β indicating the pitch angle of the blades, and v representing the wind speed in [m/s][4]

$$P_t = C_p P_v = \frac{1}{2}\rho \pi R^2 v^3 C_p(\lambda,\beta) \quad (1)$$

The ratio of turbine speed to wind speed is expressed by Eq. (2), where Ωm is the speed of the turbine; Rt is the radius of the blades

$$\lambda = \frac{R.\Omega_t}{v} \quad (2)$$

The power coefficient (Cp) has a theoretical limit of 0.475 called the "Betz limit". This limit is never reached in practice [6]. This coefficient can be estimated using Eq. (3)

$$C_p(\lambda,\beta) = 0.5\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)\exp\left(\frac{-21}{\lambda_i}\right) + 0.0068\lambda$$
$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (3)$$

The basic equation that describes the mechanical system's dynamics on the generator's mechanical shaft is referred to.

$$J\frac{d\Omega_g}{dt} = C_{méc} = C_g - C_{em} - C_f \quad (4)$$

B. Model HESM

The initial modelling of the HESM is based on the physical description presented in this part. This description highlights the stator wound inductor: in fact, it behaves as if it were placed on the rotor in the same way as the magnets. Thus, it is possible to propose a symbolic bipolar diagram of the MSDE in the form shown in Figure 1. This diagram shows a (fictional) rotor winding that represents the excitation stator winding [5].

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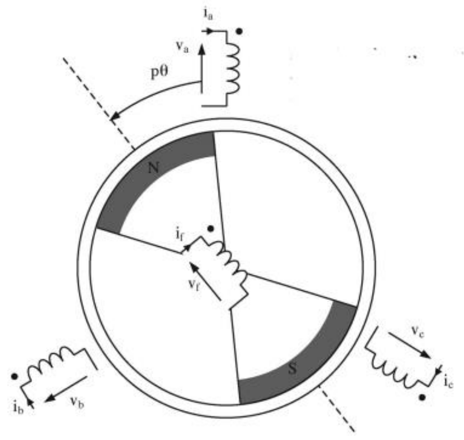

Fig. 1 Symbolic bipolar scheme of HESM

Equation (5) illustrates the dynamic model of the HESM in the dq frame [1]

$$\begin{cases} \frac{di_\mu}{dt} = \frac{1}{L_d}\left(V_d - R_s i_\mu + mR_s i_f + p\Omega\left(L_q i_q - \psi_{pm}\right)\right) \\ \frac{di_q}{dt} = \frac{1}{L_q}\left(V_q - R_s i_q - p\Omega\left(L_d i_\mu\right)\right) \\ \frac{di_f}{dt} = \frac{1}{\sigma L_f}\left(V_f - R_f i_f - me_\mu\right) \\ \frac{d\Omega}{dt} = \frac{1}{J}\left(C_{em} - C_r - f_v\Omega\right) \end{cases} \quad (5)$$

C. Model of the converters

The model of the rectifier is given by (6) [6]

$$\frac{C.dVc}{dt} = fa.ia + fb.ib + fc.ic - ich \quad (6)$$

For the control, we use the following method shown in Figure 2

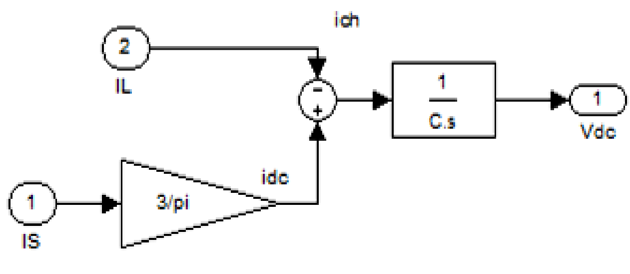

Fig. 2 Rectifier control

The model of the DC-DC converter (chopper)

Static chopper converters are mainly used to control electric power in circuits operating in direct current and to control energy transfer between a source and a load.

is given by Eq. (7)

$$\begin{bmatrix} I_L \\ V_C \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} I_L \\ V_C \end{bmatrix} + \begin{bmatrix} 0 & \frac{1}{L} \\ -\frac{1}{C} & 0 \end{bmatrix} \begin{bmatrix} I_L \\ V_C \end{bmatrix} u + \begin{bmatrix} \frac{E}{L} \\ 0 \end{bmatrix} \quad (7)$$

III. Principle of HESG Control

The objective of this instruction is to control the output voltage Vdc of the HESG, which requires a rectifier between the machine and the DC bus. A diode bridge rectifier is the preferred option due to its low cost and high reliability. The main advantage of using the HESG is its good efficiency and the possibility of combining it with a diode rectifier, which reduces the cost and losses of power electronics [7]. This solution has an indisputable advantage in terms of structural complexity [8]. Figure 3 presents the diagram of the proposed structure:

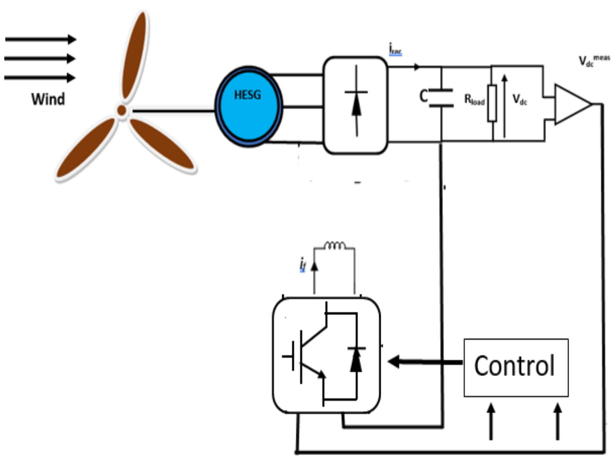

Fig. 3 The configuration of a wind turbine generator that utilizes an HESG coupled with a diode bridge rectifier is being discussed.

IV. HESG Based Wind Conversion System Description

To start, we will introduce the principle behind the proposed control. Initially, the aim is to regulate the current in the excitation winding [4]. By controlling this current, the excitation flux which comprises of the magnet's fixed flow and that of the coiled excitation can be precisely managed []. Figure 4 displays the structure of the conversion system and its control.

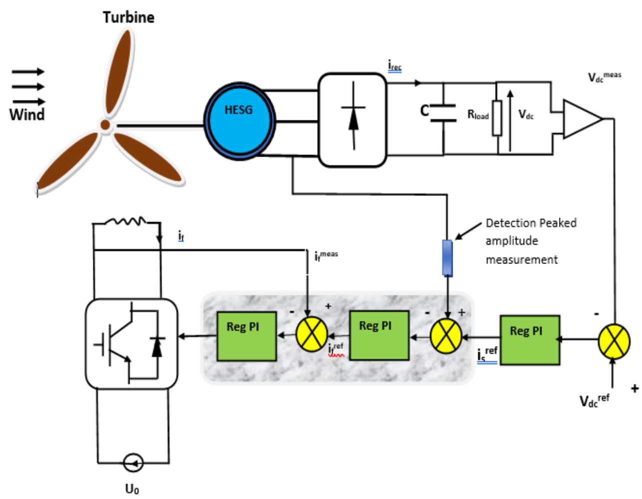

Fig. 4 The principal diagram of the HESG control driven by a wind turbine

It is not possible to regulate the stator currents using a resonant controller as the input of the chopper must be in direct current to regulate the current in the exciter winding.

The magnitude of the stator current is modulated via the excitation current by a regulator. Its reference is calculated by the outer loop of the output voltage Figure 5.

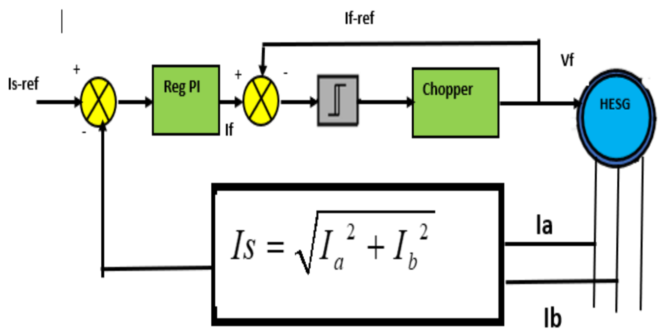

Fig. 5 The inner loop involves regulating the amplitude of the stator current.

V. Results & Discussions

The HESG is driven by a wind turbine, with a reference voltage equal to 150 V.

For the simulations. Figure 4 presents the block diagram of this command under the Matlab/Simulink environment. Figure 6 represents the applied wind profile. The wind velocity fluctuates between 1.25 m/s and 14.75 m/s, with an average value of 8 m/s.. Figure 7 represents the mechanical speed of the HESG and the corresponding aerodynamic power obtained according to the profile of the applied wind.

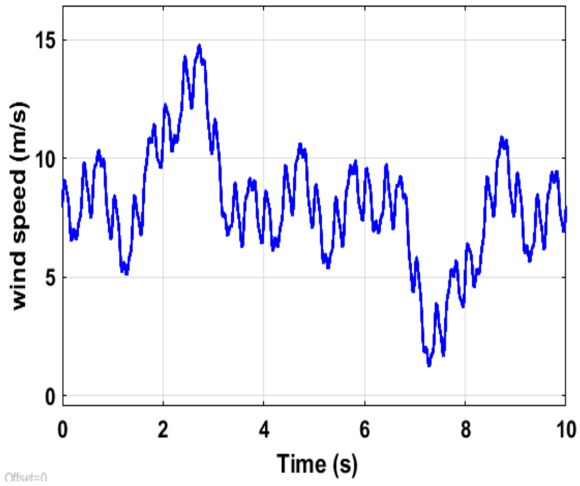

Fig. 6 Applied wind profile

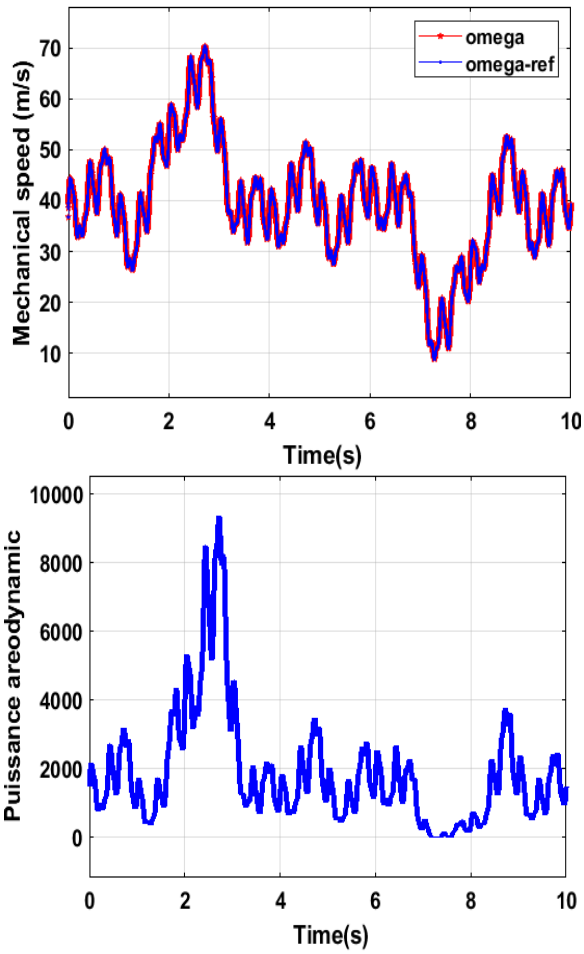

Fig. 7 Mechanical speed of the HESG and the corresponding aerodynamic power

Simulation results for a load R=12Ω and L=0.05

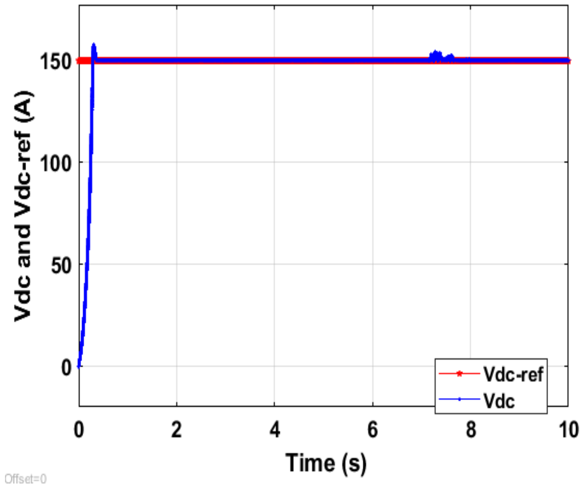

Fig. 8 Vdc and Vdc-ref

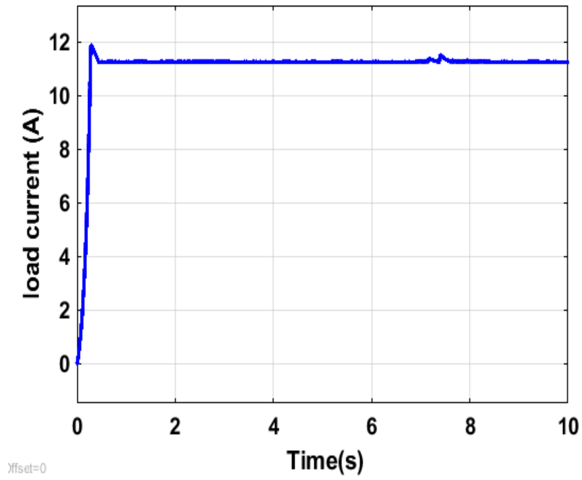

Fig. 9 load current

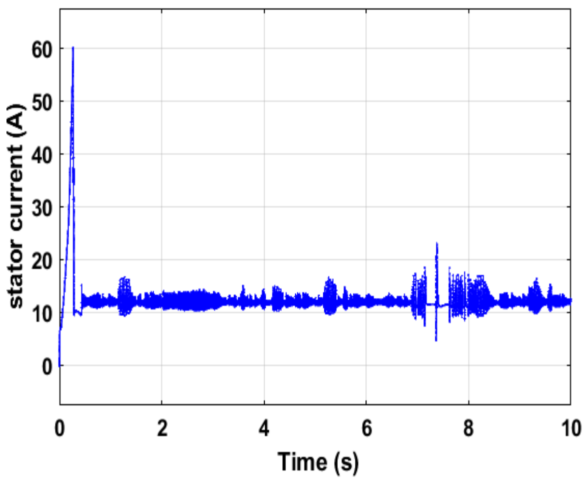

Fig. 10 stator current

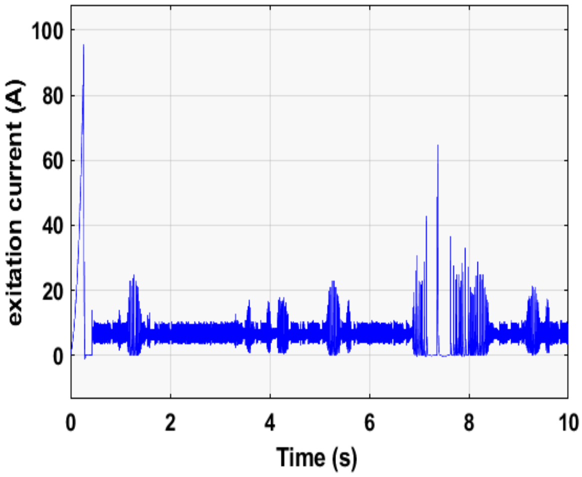

Fig. 11 excitation current

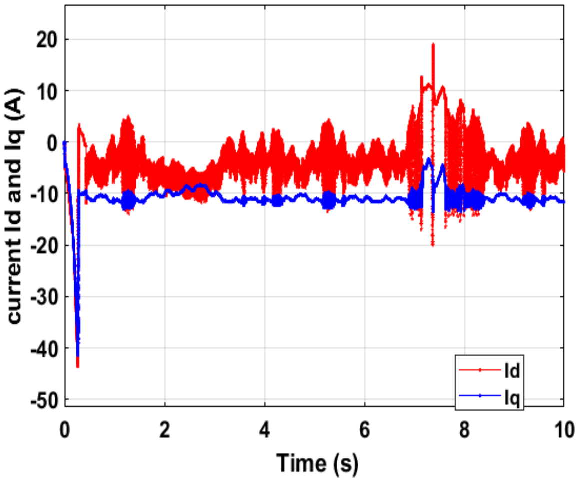

Fig. 12 Id and Iq current

Simulation results for a load R=10Ω

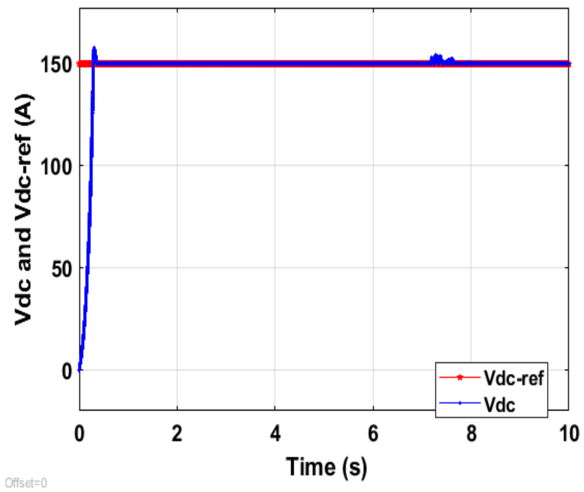

Fig. 13 Vdc and Vdc-ref

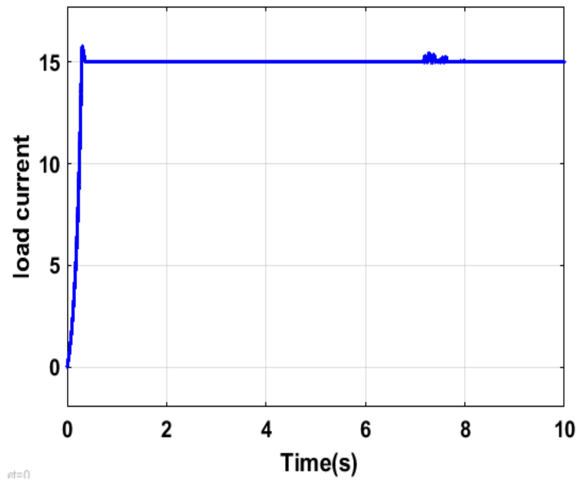

Fig. 14 load current

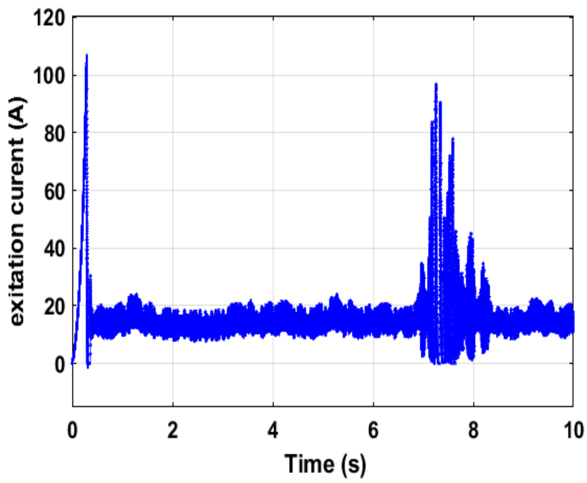

Fig. 15 excitation current

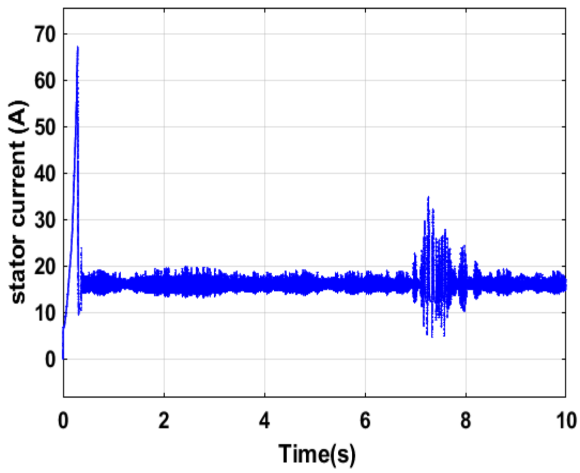

Fig. 16 stator current

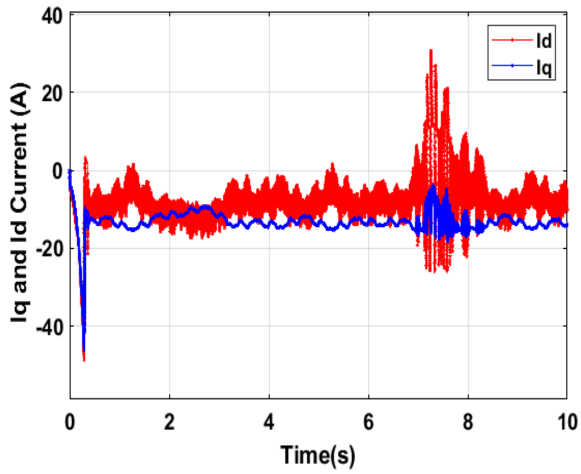

Fig. 17 Id and Iq current

The simulation results of the HESG connected to a diode bridge rectifier supplying an isolated load (R then R, L) are presented in Simulation results for a load R=10Ω and for a load R=12Ω and L=0.05 These figures demonstrate that the output voltage can be controlled by regulating the stator current magnitude, as seen from the graphs. To ensure the reliability of this operation, the regulation of the output voltage is tested by changing the value of the resistance and adding a load RL (R = 12 Ω, L=0.05H) to the existing load R = 10 Ω. Despite the variation in the speed of the HESG due to wind speed fluctuations, the setpoint tracking is achieved with a very short response time. The curves of the output voltage, stator currents on the axes q, d, and the excitation current are also presented in Figures 10, 11 and 15 and 16. The curves exhibit distortions that result from the diode rectifier and the high-frequency switching of the chopper connected to the excitation winding. The system also provides good usable power, and it is essential to assess the machine's capacity to operate as a generator with a diode rectifier in such a system.

VI. CONCLUSION

The article introduces the HESG as a self-contained DC load in power supply system's when connected with a diode bridge rectifier. This machine shows promise in replacing the current complicated structure consisting of three machines used in electric power generation. The paper describes the machine's model, the modelling of the diode bridge rectifier, and the analysis of DC bus voltage regulation. The control system, consisting of two loops, is then discussed, with the field current controller (inner loop) and DC voltage controller (outer loop) having only one degree of freedom. The simulation results show that the generator can operate efficiently with the DC bus voltage remaining stable, even under varying loads or speeds.

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