An Improved Electronic Load Controller for the Stator Windings of Self-Excited Induction Generators

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Abstract

When an Electronic Load Controller (ELC) maintains a steady electrical load, a Self-Excited Induction Generator (SEIG) operated by a fixed-speed low-head hydro-turbine may provide stable voltage and frequency. To regulate voltage and control frequency, a chopper with a dump load is often employed in parallel with consumer loads in the Conventional-ELC (C-ELC). Since the dump load is linked to the stator winding during each chopping period for a brief duration and then disengaged, the stator windings and excitation capacitors in the C-ELC arrangement may be subjected to significant stress as a consequence of chopper operation. To alleviate this pressure, a novel ELC topology is presented. When compared to the C-ELC, the primary dump load now consists of two distinct sections. The SEIG will observe less change in the total load and the stator windings and excitation capacitors will be subject to less stress if a portion of the dump load is connected in parallel with the consumer loads. Using bidirectional power switches, the suggested architecture may be implemented on a per-phase basis, allowing it to function with imbalanced consumer loads. The suggested topology has been shown to be capable of regulating voltage from no-load to full-load in simulations using unbalanced three-phase loads (aided by bi-directional switches per phase). In addition, compared to the most recent findings in the literature, the Total Harmonic Distortion (THD) study for output (stator) current demonstrates a 9% improvement.

Keywords:

Micro hydro; Insulated-Gate Bipolar Transistor (IGBT); Chopper; Exit Capacitors.

Introduction

About a quarter of the global population does not have access to electricity, and an even larger percentage uses traditional biomass for their daily energy needs including cooking, heating, and lighting [1]. Heavy dependence on conventional biomass, such as wood, may reduce average life expectancy owing to the impacts of various health issues, especially in poor nations [1]. This impetus, together with rising environmental consciousness, rising electrical energy consumption, shrinking supplies of traditional fuels, and technological improvements in power electronics, drove a paradigm shift toward the use of alternative and renewable energy. Wind, pico-hydro, and micro-hydro turbines are among the renewable energy sources that can be readily stabilized and are well-suited for use in outlying regions without ready access to grid-scale electrical production services. Stand-alone power production units are power plants that operate independently of the national electrical grid.Standalone generating units with a power rating of less than 20kW powered by a constant speed uncontrolled turbine are ideal candidates for the squirrel cage self-excited induction generator (SEIG) [2-4]. Besant and Potter [5] first described the self-excitation phenomena in an induction generator by connecting a local capacitor bank across the generator's output terminals. Reduced unit cost per generated kilowatt, ruggedness, absence of a DC-source for excitation, absence of brushes, simplicity of maintenance, and self-protection under fault conditions [6,7] are just a few of the advantages of the SEIG over a DC generator or wound rotor induction generator in remote areas. However, an SEIG's voltage and frequency control abilities are subpar. As a result, a great deal of study has been done in recent decades to address these limitations [8]. The SEIG's output voltage and frequency will change in response to changes in consumer loads or the prime mover's provided mechanical power. Voltage and frequency control may be attained by constant load power in mountainous, isolated places where the influence of changes in delivered mechanical power has been reduced by using penstock fed hydro turbines.

A variable or movable dump load may be used to maintain a constant load power. Connecting a variable or adjustable dump load in parallel with consumer loads is recommended for keeping the overall load steady. To keep the overall amount of power produced by the hydro turbine relatively constant, electronic load controllers (ELCs) are used. Regulating voltage via variable Volt-Ampere Reactive (VAR) sources [7-13] is possible, but these sources are too expensive and complicated to be used in pico or micro size generating units. Therefore, throughout the last two decades [4, 14–23], researchers have documented a variety of ELCs for SEIGs, each of which is explored in further depth below. When it comes to this topic, Bonert and Hoops [14] were forerunners. An impedance controller strategy was presented. Using a chopper switch in series with a dump load and an uncontrolled three-phase rectifier allows for voltage regulation. The voltage distortion is minimized by synchronizing the chopper with the bridge's sixty degree conduction intervals. Later, Bonert and Rajakaruna [15] reported on the practicability of managing asymmetrical loads and a control method for automated start-up of the generator. Singh [16] has performed a transient examination of this technique. Finally, Singh, Murthy, and Gupta [2] provided a thorough design of the unregulated rectifier, chopper, and dump load used in this method. The single power switch makes this system easy to use, inexpensive, and dependable, but it limits its adaptability to the often-unbalanced three-phase loads seen in generators for rural or suburban areas with fewer residents. Smith [17] suggested three approaches based on the induction generator's inherent properties. Methods for controlling voltage were developed, including those based on phase angle control, binary weighted switching resistors, and a chopping scheme with a configurable mark-space ratio.

The SEIG may have difficulties when using the phase angle control method because of its changeable lagging power factor. The primary downsides of the binary weighted switched resistor approach are the discrete control of output power and the complexity involved with connecting the power electronic switches. The variable mark-space ratio technique makes use of a reduced form of the impedance controller methodology [14] designed for a single-phase system. According to Singh [18], mathematical modelling of SEIGs with an enhanced ELC has been published. The upgraded ELC is the result of combining a current controlled voltage source inverter based on three Insulated Gate Bipolar Transistors (IGBTs) with a high frequency DC chopper. The upgraded ELC generates compensating currents for imbalanced loads, allowing the generator currents to be balanced. The suggested control technique was quite complex; nonetheless, the enhanced ELC may be used as a voltage regulator for unbalanced three phase loads. A voltage source converter without a chopper and a freshly built phase locked loop circuit are employed for a somewhat different method in [19]. The control technique, which included the magnetizing curve of the induction machine, allowed for more precise determination of the rotor flux location. Based on the framework described in [19], a number of somewhat different control mechanisms have been published in [20-22]. One such approach is suggested in [20], whereby the terminal voltage is controlled by adjusting the converter's modulation index in response to fluctuations in DC capacitor voltage caused by changing consumer loads.

System and Induction Generator

Modelling Figure 1 depicts the equivalent circuit of a d-q frame induction generator (IG). Based on the modelling strategy of [25], a modular Simulink model is developed in the stationary reference frame using MATLABSIMULINK from MathWorks. A common matrix formulation, based on the approach provided in [26], has been used to streamline the simulation process. For transient analysis of the three-phase SEIG, the following matrix equations in the form of state space equations are used.

$$\dot{x} = Ax + By$$

where $x = [i_{ds}, i_{qs}, i_{dr}, i_{qr}, V_{dL}, V_{qL}, i_{dL}, i_{qL}]^T$, $y = [V_{ds}, V_{qs}, V_{dr}, V_{qr}]^T$, $\dot{x} = \frac{dx}{dt}$

$$A = K\begin{bmatrix} R_sL_r & -\omega_rL_m^2 & -R_rL_m & \omega_rL_rL_m & L_r & 0 & 0 & 0 \\ \omega_rL_m^2 & R_sL_r & \omega_rL_mL_s & -R_rL_m & 0 & L_r & 0 & 0 \\ -R_sL_m & \omega_rL_rL_m & R_rL_s & \omega_rL_sL_r & -L_m & 0 & 0 & 0 \\ -\omega_rL_mL_s & -R_sL_m & -\omega_rL_sL_r & R_rL_s & 0 & -L_m & 0 & 0 \\ 1/CK & 0 & 0 & 0 & 0 & 0 & -1/CK & 0 \\ 0 & 1/CK & 0 & 0 & 0 & 0 & 0 & -1/CK \\ 0 & 0 & 0 & 0 & 1/LK & 0 & -R/LK & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/LK & 0 & -R/LK \end{bmatrix}, B = K\begin{bmatrix} -L_r & 0 & L_m & 0 \\ 0 & -L_r & 0 & L_m \\ L_m & 0 & -L_s & 0 \\ 0 & L_m & 0 & -L_s \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$K = \frac{1}{(L_m^2 - L_rL_s)}$$

Proposed Electronic Load Controller

Proposed ELC topology

In Fig. 3a, we see a typical system, which includes a prime mover, an induction generator, an excitation capacitor bank, three-phase unbalanced loads, electronic load controllers, and their associated control circuits, all of which work together to provide gate signals for the used IGBT switches. Figure 3b depicts the planned ELC structure throughout all phases. The topology shown in Fig. 3c may be compared to that in [4]. In the suggested architecture, a chopper switch is the primary component of the ELC. In the diagrams, the chopper switch has been swapped out with a more perfect switch (). Note that bidirectional IGBT switches should be used instead of this ideal switch in experimental and simulation studies [4, 23]. Two series resistances and a chopper switch make up the ELC in the proposed architecture. A part of the dump load may be connected in parallel with the consumer loads while the chopper switch is in the closed position. The chopper switch condition equivalent circuit of this setup is shown in Fig. 4 for ease of understanding. In this case, the total dump load is equal to while the chopper switch is off, and it increases to when the chopper switch is on and the ELC is connected to the system. Both of these scenarios are shown in Fig. 4a and b. Fig. 4c and d represent the analogous circuit diagram of the suggested approach in [4]. When the chopper is off, the dump load is not connected to the induction generator (Fig. 4c) in the proposed method by

Ramirez [4, 23] and generally in all ELC approaches based on chopper and dump loads, but in the proposed topology a small non-zero dump load is connected to the system (Fig. 4a), resulting in a more uniform generated power from the generator, decreasing the machine stress. The method used to create the proposed ELC is described below.

Experiment Outcomes

Here, we show the simulation findings from an exploration into the practicability and performance of the suggested ELC. Voltage regulation for a 3 kW, 220V Donly IG was simulated in MATLABSIMULINK using the suggested ELC architecture. Using a 60 three-phase star-connected excitation capacitor bank charged to a starting voltage of 10V, 10V, and -20V, the chosen IG was driven at a speed of 316, rad/s. At , the generator's output voltages and frequency stabilize. Table 1 summarizes the two abrupt (step) adjustments in the three-phase used unbalanced consumer loads used in this simulation. At , the generator is linked to both the consumer load and the projected ELC. At and , two distinct abrupt (step) adjustments in consumer loads are implemented. Magnetizing inductance, magnetizing current, root-mean-square (RMS) value of the regulated output voltage with the aid of the proposed ELC, instantaneous produced power with and without ELC, and instantaneous output voltage are all shown in Fig. 5. Parts (a) and (b) of this figure illustrate the magnetic inductance and current, respectively. Figure 5c shows the RMS output voltage with and without the ELC. The suggested ELC reduces voltage fluctuations in the system to around 4 V RMS, or 1.8%. The amplitude of the transient voltage is shown in Fig. 5c. The RMS variation of the output voltage is less than 1% under steady-state settings. Without active load regulation (ELC), the standard deviation of the output voltage is 31 V RMS (248 minus 217). In Fig. 5d, the black lines depict the three-phase output power with the proposed ELC and the gray lines depict the power without it. Due to the three-phase imbalanced load pattern shown in Table 1, the output power of the IG without ELC ranges between 0.2 and 3.05 kW even while operating at steady state. These findings show that even with an imbalanced system, the suggested ELC design is able to regulate voltage, control frequency, and draw the rated power from the IG. Three-phase instantaneous currents, comprising the consumer current and three independent ELCs, are shown in Figs. 6 and 7. In Fig. 7, three distinct load circumstances are shown, and one complete cycle of the ELC current is displayed for each. Figure 8 shows the average power for each phase, accounting for dumped power, total power, and unbalanced consumer loads. Each phase uses around 1 kilowatt of electricity in total.

Table 1. The considered consumer load pattern with two step changes at 5.5 seconds and 8.5 seconds.

Consumer loads				
Connection Time (S)	0-1.5	1.5-5.5	5.5-8.5	8.5-12
Phase "a" load (Ω)	NL	1000	230	75
Phase "b" load (Ω)	NL	1200	300	63
Phase "c" load (Ω)	NL	800	160	61.5

To compare the proposed ELC and that in [4], typical dump load currents for these two topologies with more details are depicted in Fig. 9. The first column shows the dump load current based on the proposed topology, and the figures illustrated in second column (right hand side) are simulation results based on [4]. The selected consumer loads in this investigation are three phase star-connected loads equal to 55, 95, 150, and 300 Ω. In the proposed method the dump load current has been restricted between two sinusoidal waveforms. But for the method in [4] the corresponding boundaries are the upper sinusoidal waveform and zero (Fig.9e to Fig.9h). The harmonic content of the stator current based on the proposed method and that in [4] is depicted in Fig. 10 (with similar arrangement of Fig.9). The Total Harmonic Distortion (THD) for each case is shown. The THD for the proposed topology is less than the topology in [4]. It may be noted that the proposed topology in [4] had the lowest THD level compared with other previously proposed topologies. Decreasing the dump load current fluctuations is the main reason for decreasing the THD level in our proposed method. A comparison between THD level for the proposed ELC topology and that in [4] is depicted in Fig. 11. The THD has been depicted with respect to per phase consumed load current. The stator current THD is shown in part (a) and the output voltage THD is shown in part (b). Maximum THD for the output current of the proposed topology is about 36% compared with 45.5% for the THD in [4]. The calculated THD for the output voltage of both topologies is approximately equal.

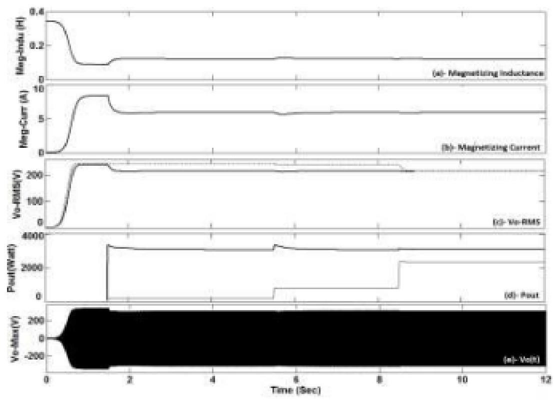

Fig. 1. Typical system characteristics, (a) magnetizing inductance, (b) magnetizing current, (c) RMS output voltage (dashed line: no ELC; black line: with proposed ELC) , (d)

output power with (gray) and without ELC (black), and (e) instantaneous output voltage with proposed ELC.

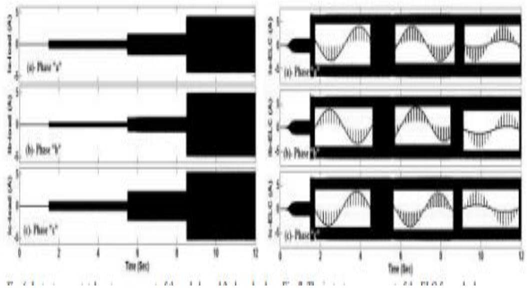

Fig. 2. Instantaneous total customer current of the unbalanced 3-phase load Fig. 7. The instantaneous current of the ELC for each phase.

Conclusion

In this study, we provide a unique and easy-to-implement Electronic Load Control setup for micro hydro power plants. They use an induction generator. Reducing strain on the stator windings of the generator is the primary focus of the suggested technique. To accomplish this, a novel chopper circuit architecture was developed. The simulation findings show that the proposed ELC works well even with unbalanced three phase loads over the whole spectrum of consumer loads. It is more cost efficient and dependable than ELC topologies based on rectifier or converter architectures because fewer power switches are required (3 bi-directional power switches compared to 7 uni-directional power switches). Longevity of the induction generator may also be improved by reducing the stress on the stator.

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