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A New Electronic Load Controller for the Self-Excited Induction Generator to Decrease Stator Winding Stress

B. Nia Roodsari\textsuperscript{a}, E. P. Nowicki\textsuperscript{a}\textsuperscript{*} and P. Freere\textsuperscript{b}

\textsuperscript{a}Department of Electrical and Computer Engineering, University of Calgary, 2500 University Drive NW, Calgary, T2N 1N4, Alberta, Canada
\textsuperscript{b}Kathmandu Alternative Power and Energy Group, Kathmandu, Nepal

Abstract

Constant voltage and frequency can be generated by a Self-Excited Induction Generator (SEIG) driven with a fixed-speed low-head hydro-turbine when a constant electrical load is maintained by an Electronic Load Controller (ELC). In the Conventional-ELC (C-ELC), usually a chopper with a dump load is used in parallel with the consumer loads to provide regulation of voltage and control of frequency. In the C-ELC configuration a high degree of stress can be experienced by stator windings and excitation capacitors resulting from chopper operation, since in each chopping period the dump load is connected to the stator winding for a short period then disconnected. A new ELC topology is proposed to reduce this stress. Compared with the C-ELC, the main dump load has been divided into two separated parts. A part of the dump load can be connected in parallel with the consumer loads, resulting in less variation in the total load seen by the SEIG and less stress on the stator windings and excitation capacitors. This proposed topology can be utilized per-phase using bi-directional power switches, hence it can operate with unbalanced consumer loads. Simulation results demonstrate that even with unbalanced three-phase loads (assisted with bi-directional switches per-phase), the proposed topology has the capability to regulate voltage from no-load to full load. Moreover, the Total Harmonic Distortion (THD) analysis for output (stator) current shows a 9% improvement compared with the most recent results in the literature.

Keywords: Microhydro; Induction Generator (IG); Chopper; Insulated-Gate Bipolar Transistor (IGBT); Excitation Capacitors.

1. Introduction

Approximately one fourth of the world’s population live in homes without access to electricity, and a slightly higher fraction are dependent on traditional biomass for their daily energy requirements, such as cooking, heating and lighting [1]. Especially in developing countries, heavy reliance on traditional biomass, such as wood, may negatively impact average life expectancy due to the effects of different health problems [1]. This motivation, combined with increasing concern for the environment, ever-increasing electrical energy demand, limited access to conventional fuels, and advances in power electronics were the main reasons for the shift toward the use of non-conventional and renewable energy sources. Among renewable energy sources; wind, pico-hydro and microhydro turbines can be easily stabilised and are suitable in remote areas far from electrical generation utilities. These power plants without any connection to a large electrical grid are called stand-alone power generation units.

* Corresponding author. Tel.: +1-403-5006; fax: +1-403-6855.
E-mail address: Enowicki@ucalgary.ca.
It is known that the squirrel cage self-excited induction generator (SEIG) is appropriate for stand-alone generation units with a power rating less than 20kW driven by a constant speed uncontrolled turbine [2-4]. The self excitation phenomenon in induction generator was introduced by Besant and Potter in 1935 [5], with connection of a local capacitor bank across the generator output terminals. In remote areas the SEIG has several advantages over a DC generator or wound rotor induction generator, such as: 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]. A SEIG, however, suffers from poor voltage and frequency regulation capability. Therefore, in recent decades a considerable amount of research has been conducted to overcome these weaknesses [8].

Any fluctuation in consumer loads or in the delivered mechanical power by the prime mover results in output voltage and frequency variations of the SEIG. In hilly remote areas where the effect of fluctuations in delivered mechanical power has been mitigated by utilizing penstock supplied hydro turbines, voltage and frequency regulation can be achieved by constancy of load power. Constancy in the load power can be obtained by a variable or adjustable dump load. A variable or adjustable dump load should be connected in parallel with consumer loads to maintain the total load constant.

Electronic Load Controllers (ELCs) are utilized to maintain a near-constant total generated power from the hydro turbine. Although, voltage regulation can be obtained by utilising variable Volt-Ampere Reactive (VAR) sources [7-13], their extra cost and complexity prevents their utilization for pico or micro scale generation units. Hence, several different and simple types of ELCs for SEIGs have been reported in the past two decades [4, 14-23], which are now discussed in more detail.

In this regards Bonert and Hoops [14] were pioneers. They proposed an impedance controller approach. In this method voltage regulation can be achieved by utilising an uncontrolled three phase rectifier and a chopper switch connected in series with a dump load. In this proposed method the chopper has been synchronized to sixty degree conduction periods of the bridge to reduce voltage distortion. Later the feasibility of handling non-symmetrical loads and a control strategy for automatic start-up of the generator was reported by Bonert and Rajakaruna [15]. The transient analysis of this method has been done by Singh [16]. And finally a detailed design of the uncontrolled rectifier, chopper and dump load utilized in this approach was reported by Singh, Murthy and Gupta [2]. It is worth mentioning that, due to the single power switch, this system is simple, cheap and reliable, but it has a restricted capability to work with unbalanced three phase loads which are common in generating systems for small and remote communities.

Three different methods based on intrinsic characteristics of the induction generator were developed by Smith [17]. Voltage controller methods utilizing phase angle control techniques, binary weighted switched resistors, and a variable mark-space ratio chopping method were implemented. The phase angle control technique can be problematic for the SEIG due to a variable lagging power factor. Despite its conceptual simplicity, discrete control of output power and complexity associated with wiring of the power electronic switches are the main drawbacks of the binary weighted switched resistor method. A simplified model of the impedance controller approach [14] for a single phase system has been utilized in the variable mark-space ratio method.

The mathematical modeling of SEIGs with an improved ELC has been reported by Singh [18]. The improved ELC has been constructed by a combination of a three phase Insulated Gate Bipolar Transistor (IGBT) based current controlled voltage source inverter and a high frequency DC chopper. For unbalanced loads, compensating currents have been generated by the improved ELC to balance the generator currents. Although the proposed control strategy was very complicated, the improved ELC could be utilized for unbalanced three phase loads as a voltage regulator.

Taking a slightly different approach, a voltage source converter without chopper and with a newly designed phase locked loop circuit has been used in [19]. In this method field oriented control gave higher accuracy in calculating the rotor flux position from the magnetizing curve of the induction machine which was included in the control strategy. Several slightly modified control approaches based on the proposed structure in [19] have been reported in [20-22]. Among them, the method proposed in [20] allows DC capacitor voltage to change with the consumer loads and the terminal voltage is regulated by variation of the converter modulation index.

A simple, inexpensive and reliable ELC method based on use of the anti-parallel IGBT switch was proposed by Ramirez [4, 23]. The rectifier circuit was eliminated and with help of the bi-directional switch and dump load resistor control is achieved based on the AC current instead of the DC current. The result is a simple and more reliable configuration with voltage regulation capability from no-load to full load under balanced or unbalanced load conditions. Although the injected harmonic content in the stator windings and in the excitation capacitors is reduced compared to all previous methods based on rectifier or voltage source converters [4], there is still concern that the high harmonic content could cause several problems for the induction generator and capacitor bank. Among these problems are an increase in heat losses, increase in stator losses, higher operating temperature, additional magnetic flux, increase in the number of
failures of the machine, and increase in noise generated. Among these negative effects, heat losses in the machine are the main cause of insulation weakness and a decrease in the life expectancy [24].

The contribution of this paper is to propose a new, simple, and reliable ELC switching configuration using bi-directional IGBT switches. The proposed approach provides voltage regulation and frequency control and does so with decreased stator winding stress which is achieved by a significant decrease in stator harmonic current content. In addition, voltage regulation is achieved for unbalanced three phase loads from no-load to full load.

The remainder of this paper is organized as follows. A brief explanation of the d-q model matrix formulation (well accepted by electromagnetic machine designers) for transient analysis of the SEIG is presented in Section 2. The proposed ELC topology and underlying mathematical calculation for voltage regulation are provided in Section 3. Simulation results are presented in Section 4. Section 5 provides conclusions.

### 2. Induction Generator and System Modeling

The Induction generator (IG) equivalent circuit diagram in the d-q frame is depicted in Fig. 1. A modular Simulink model (i.e. MATLAB SIMULINK from MathWorks) in the stationary reference frame is designed based largely on the modeling approach of [25]. To simplify the simulation procedure a standard matrix formulation, based on the proposed idea in [26], has been utilized. The matrix equations in the form of state space equations, appropriate for transient analysis of the three phase SEIG are:

\[
\dot{x} = Ax + By
\]

where \( x = [i_{ds}, i_{qs}, i_{dr}, i_{qr}, V_{dl}, V_{ql}, i_{dl}, i_{ql}]^T \), \( y = [V_{ds}, V_{qs}, V_{dr}, V_{qr}]^T \), \( \dot{x} = \frac{dx}{dt} \),

\[
A = K \begin{bmatrix}
R_{dL} - \omega_L L_m^2 & -\omega_L L_m & L_r & 0 & 0 & 0 \\
\omega_L^2 L_m & R_{dL} & \omega_L L_m L_s & -R_L L_m & 0 & L_r & 0 & 0 & 0 \\
-R_L L_m & \omega_L L_r L_m & R_{rL} & \omega_L L_r L_r & L_m & 0 & 0 & 0 & 0 \\
-\omega_L L_m L_s & -\omega_L L_s L_r & R_{rL} & L_m & 0 & -L_m & 0 & 0 & 0 \\
1/CK & 0 & 0 & 0 & 0 & 0 & -1/CK & 0 & 0 \\
0 & 1/CK & 0 & 0 & 0 & 0 & 0 & -1/CK & 0 \\
0 & 0 & 0 & 0 & 0 & 1/LK & 0 & -R/LK & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1/LK & 0 & -R/LK \\
\end{bmatrix}, \quad B = K \begin{bmatrix}
-L_r & 0 & L_m & 0 \\
0 & -L_r & 0 & L_m \\
0 & 0 & -L_s & 0 \\
0 & L_m & 0 & -L_s \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\end{bmatrix}
\]

\[K = \frac{1}{(L_m^2 - L_r L_s)}\]

where \( \omega_r \) is the electrical rotor speed, \( i_{ds}, i_{qs}, i_{dr}, i_{qr}, i_{dl} \) and \( i_{ql} \) are stator, rotor and load currents, \( V_{ds}, V_{qs}, V_{dr}, V_{qr}, V_{dl} \)

and \( V_{ql} \) are stator, rotor and load voltages, \( R_s \) and \( R_r \) are stator and rotor resistance, \( L_s \) and \( L_r \) are stator and rotor self inductance and \( L_m \) is mutual inductance between stator and rotor.

Due to operation of the SEIG near the saturation region, the magnetizing characteristics are non-linear. Therefore in any step of the simulation the magnetizing current should be calculated based on rotor and stator currents [27]. The magnetizing current \( (i_m) \) in the d-q model is given by the well known equation:

\[
i_m = \sqrt{(i_{ds} + i_{dr})^2 + (i_{qs} + i_{qr})^2}
\]

\[
i_m = \sqrt{I_{d}^2 + I_{q}^2}
\]

![Fig. 1. Dynamic or d-q equivalent circuit of an induction generator (in stationery reference frame \( \omega_e \) is equal to zero)](image)
After calculation of the magnetizing current the magnetizing inductance can be calculated by the following equation:

$$L_m = -0.0001615i_m^3 + 0.00559i_m^2 - 0.06621i_m + 0.5515$$

(3)

It is worth remembering that the coefficients in abovementioned equation have been calculated by a synchronous speed test [27] on the selected induction generator. The selected induction generator in this investigation was a 3 kW Donley induction machine with $R_s = 2.1\Omega, R_r = 1.4\Omega$ and $L_s = L_r = 8.4\text{mH}$ [28].

By substituting the magnetizing inductance in the motion equation the electromagnetic torque of the SEIG can be obtained [16], as follows. The well known motion equation is given by:

$$T_e = \frac{3P}{2}L_m(i_{qf}i_{dr} - i_{ds}i_{qr})$$

(4)

where $T_e$ and $P$ are the developed electromagnetic torque and the number of generator poles, respectively.

By considering that electromagnetic torque is balanced by shaft torque, the derivative of the rotor speed can be expressed as:

$$\frac{d\omega_r}{dt} = \left(\frac{P}{f}\right)\frac{T_{shaft} - T_e}{J}$$

(5)

where $T_{shaft}$ and $J$ are the shaft torque and moment of inertia, respectively.

The IG Simulink block diagram is illustrated in Fig. 2. The dynamic study is focused on instantaneous and RMS values of the electrical variables and their related harmonic contents. The IG block diagram consists of four separated subsystems. These sub-systems are: (a) “Input Data”, (b) “Generator d-q Current”, (c) “Calculated data”, and (d) “Output Circuit”. The generator specification, selected excitation capacitor bank capacity, initial voltage of excitation capacitors, turbine speed, and other initial values are placed in “Input Data” subsystem. The “Generator d-q Current” consists of the state space equations of the induction generator in the d-q frame. Required data such as magnetizing current and inductance, shaft and electromagnetic torques, and so on are calculated on the “Calculated data” sub-system. Output characteristics of the system including the selected ELC configuration and consumer load pattern variation are placed in the “Output Circuit” sub-system.

3. Proposed Electronic Load Controller

3.1. Proposed ELC topology

A typical system, comprising of prime mover, induction generator, excitation capacitor bank, three-phase unbalanced loads, electronic load controllers and their related control circuits to generate gate signals for the utilized IGBT switches, is illustrated in Fig. 3a. The proposed ELC topology for each phase is depicted in Fig. 3b. This topology can be compared with that from [4] illustrated in Fig. 3c. The main part of the ELC in the proposed topology is a chopper switch. This chopper switch has been replaced by an ideal switch ($S_J$) in the illustrated figures. It should be noted that in experimental and simulation investigations this ideal switch should be replaced by bi-directional IGBT switches [4, 23]. In the proposed topology, the ELC consists of two series resistances and one chopper switch. When the chopper switch is closed, a portion
of dump load can be connected in parallel with the consumer loads. For sake of clarity, the equivalent circuit of this configuration related on the chopper switch condition is depicted in Fig.4. In this regard, when the chopper switch is off, the total dump load is \( R_{dj1} + R_{dj2} \) and when the chopper switch is on, the load connected by the ELC to the system is equal to \( R_{dj1} \). These conditions are depicted in Fig. 4a and Fig. 4b, respectively. The equivalent circuit diagram of the proposed method in [4] is depicted in Fig. 4c and Fig. 4d. A comparison between these figures shows, in the proposed method by Ramirez [4, 23], and generally in all ELC approaches based on chopper and dump loads, when the chopper is off, the dump load is not connected to the induction generator (Fig. 4c), 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. In the following paragraphs the design procedure of the proposed ELC is presented.

3.2. Design Procedure of the Proposed ELC

The design procedure of the proposed ELC is explained in this section. The total consumer instantaneous load resistance for each phase can be estimated by measuring phase current and voltage. The load resistance is:

\[
R_{\text{load}}^j(t) = \frac{V_j(t)}{i_{RLj}(t)}
\]

where \( R_{\text{load}}^j(t) \), \( V_j(t) \) and \( i_{RLj}(t) \) with \( j = a, b, c \), are the estimated total consumer loads, phase voltage and phase current, respectively.

The minimum consumer load resistances can be calculated based on the selected generator rated power and its corresponding output voltage by the following equation:

\[
R_{L_{\text{min}}} = \frac{v_{\text{rated}}^2 \times 3}{P_{\text{rated}}}
\]

where \( R_{L_{\text{min}}} \) is the resistance corresponding to the minimum load which should be connected to the generator to consume its rated power. \( P_{\text{rated}} \) and \( v_{\text{rated}} \) are rated power and rated voltage of the selected generator.

Fig. 3. (a) SEIG, excitation capacitor bank and ELC blocks and associated gate control circuit blocks, (b) the proposed ELC topology, and (c) utilized topology in [4]

Fig. 4. Equivalent loads seen by ELC terminals, proposed ELC when \( S_j \) is (a) open, (b) closed, conventional ELC topology when \( S_j \) is (c) open, (d) closed, and (e) associated generator terminal resistance based on aforementioned topologies
Based on Fig. 4(b) when the chopper switch is closed, the dump load resistance for each phase is equal to $R_{dj1}$. To consume the rated generator power in the no-load condition this portion of dump load should be equal to:

$$R_{dj1} = R_{L_{min}} \quad (8)$$

where $R_{dj1}$ with $j = a, b, c$, is the first portion of the dump load.

When the chopper switch is open the total dump load resistance (Fig. 4(a)) is:

$$R_d = R_{dj1} + R_{dj2} \quad (9)$$

where $R_{dj2}$ with $j = a, b, c$ is the second portion of the dump load. This portion can be connected or disconnected to the system by the copper switch. The total dump load which can be connected to system when the chopper switch is on, is $R_d$.

In engineering practice, the selected generator for a small community should be oversized between 20% and 30%. Thus, it may be possible to dissipate a minimum of 20% of the generated power continuously in dump loads (possibly used for community water heating or public lighting). This concept has been utilized to calculate the $R_{dj2}$.

Based on a maximum 20% constant consumption by dump loads, $R_{dj2}$ can be calculated as:

$$R_{dj2} = 4 \times R_{L_{min}} \quad (10)$$

So with the help of the chopper switch, the average apparent dump load resistance seen by the ELC output terminals (between $D_j$ and ground of the Fig. 4(a) and Fig. 4(b) can be variable between $R_{L_{min}}$ and $5 \times R_{L_{min}}$ (when $S_j$ is closed or open, respectively). The switching pulse for the chopper circuit can be produced by a pulse width modulation (PWM) method in the control circuit. In the PWM method, each sampling period can be split into two time intervals. These two time intervals are named the chopper on-time duration and chopper off-time duration. So the average resistance of the proposed circuit seen by chopper terminals is:

$$R_{djav}(t) = \frac{(R_{off-IGBT}) \times T_{c-off} + (R_{on-IGBT}) \times T_{c-on}}{T_c} \quad (11)$$

where $R_{off-IGBT}$ and $R_{on-IGBT}$ are the IGBT switch off and on resistances, and $R_{djav}(t)$ is the average calculated resistance as seen by chopper terminals. $T_c$, $T_{c-off}$ and $T_{c-on}$ are selected period for the PWM sawtooth waveform, chopper off-time duration, and chopper on-time duration, respectively. Considering the ideal condition ($R_{off-IGBT} = \infty$ and $R_{on-IGBT} = 0$), equation (11) can be simplified as:

$$R_{djav}(t) = \frac{R_{dj2} \times T_{c-off}}{T_c} \quad (12)$$

The total dump load resistance seen by the ELC terminals, $R_{djav}(t)$, can be obtained by:

$$R_{djav}(t) = R_{dj1} + R_{djav}(t) \quad (13)$$

The main idea in ELC design is maintaining load constancy, so $R_{djav}(t)$ should be adjusted for changes in the instantaneous consumer power in each phase. On the other hand $T_{c-off}$ should be determined by the PWM modulator based on instantaneous consumer loads ($R_{loadj}(t)$). The relationships among generator rated power for each phase $P_{outj}$, the total instantaneous consumed power by consumers $P_{j}(t)$ and the average consumed power by the dump load to keep the power constant in the system are given by:

$$P_{outj} = P_{djav}(t) + P_{j}(t) \quad (14)$$
Assuming a constant output voltage and power for each phase, equation (14) can be written based on consumer loads per phase and dump load resistances:

$$R_{Lmin} = R_{12} = R_{dav}(t) || R_{load}(t)$$  (15a)

Hence:

$$R_{dav}(t) = \frac{R_{Lmin} \times R_{load}(t)}{R_{load}(t) - R_{Lmin}}$$  (15b)

By replacing $R_{dav}$ by $R_{Lmin}$ in (13) and substituting (15b), the average dump load resistance as seen by the chopper switch terminals can be calculated by:

$$R_{dav2}(t) = \frac{R_{Lmin} \times R_{load}(t)}{R_{load}(t) - R_{Lmin}} - R_{Lmin}$$  (16)

The appropriate gate signal for the chopper can be generated by comparison of $R_{dav2}(t)$ and a sawtooth waveform.

4. Simulation Results

A set of simulation results are presented here to investigate the feasibility and performance of the proposed ELC. The simulation was done in MATLAB SIMULINK and the proposed ELC topology is applied to voltage control of a 3 kW, 220V Donly IG. The selected IG was driven at a speed of 316, rad/s with three phase star-connected excitation capacitor bank equal to 60μF, which has been charged with initial voltage equal to 10V, 10V, and -20V. The generator output voltages and frequency reach steady state at $t = 0.75$ sec. The three phase utilized unbalanced consumer loads in this simulation with two sudden (step) variations is tabulated in Table 1. The consumer load and the proposed ELC are connected to the generator at $t = 1.75$ sec. Two different sudden (step) variations in consumer loads are applied at $t = 5.5$ sec and $t = 8.5$ sec, respectively.

Shown in Fig. 5 are several typical system quantities, such as: magnetizing inductance, magnetizing current, RMS value of the regulated output voltage with help of the proposed ELC, instantaneous generated power with the proposed ELC and without ELC, and instantaneous output voltage. In this figure magnetizing inductance and current are depicted in part (a) and (b). The RMS output voltage with and without the ELC is depicted in Fig. 5c. The voltage fluctuation for system including the proposed ELC is around 4 V RMS or 1.8%. It should be noted that Fig. 5c shows the transient voltage amplitude. For steady state conditions the RMS output voltage fluctuation is less than 1%. The output voltage fluctuation without ELC is equal to is equal to 248-217V = 31 V RMS or 14.3%. The three phase output power with and without the proposed ELC is shown in Fig. 5d with black and gray lines, respectively. In steady state the output power with ELC is approximately constant and equal to 3.05 kW, but the output power of the IG without ELC varies between 0.2 to 3.05 kW because of the three-phase unbalanced load pattern shown in Table 1. These results demonstrate that the proposed ELC topology regulates voltage, controls frequency and draws the rated power from the IG independent of instantaneous consumer loads, even when the system is unbalanced.

The instantaneous three phase currents in the system including the consumer current and three separate ELCs are depicted in Fig. 6 and Fig. 7. Note that in Fig. 7, there are three different load conditions, and hence a single cycle of the ELC current is shown corresponding to each load condition. The average power for each phase including unbalanced consumer loads, dumped power and total power is depicted in Fig. 8. The total consumed power in each phase is approximately 1kW.

<table>
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<tr>
<th>Table 1. The considered consumer load pattern with two step changes at 5.5 seconds and 8.5 seconds.</th>
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<tr>
<td><strong>Consumer loads</strong></td>
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<tr>
<td><strong>Connection Time (S)</strong></td>
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<tr>
<td>Phase “a” load (Ω)</td>
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<td>Phase “b” load (Ω)</td>
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<td>Phase “c” load (Ω)</td>
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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.
5- Conclusion

A simple and novel Electronic Load Control configuration for microhydro power systems is presented in this paper. An induction generator is used. The main objective for the proposed method is to decrease the stress on the generator stator windings. This objective is achieved with a new topology for the chopper circuit. Simulation results demonstrate that the proposed ELC provides high quality operation for the full range of consumer loads, even with unbalanced three phase loads. Since fewer power switches are needed (3 bi-directional power switches compared with 7 uni-directional power switches), it is more cost effective and reliable compared with ELC topologies based on rectifier or converter structures. Moreover, decreasing the stator stress may have a direct effect on increasing the induction generator longevity.
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6. References