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ScienceDirect
Energy Procedia 57 (2014) 1465 – 1474
Energy Procedia

2013 ISES Solar World Congress

The Distributed Electronic Load Controller: A New Concept for Voltage Regulation in Microhydro Systems with Transfer of Excess Power to Households

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Abstract

Constant voltage and frequency can be generated by a stand-alone Self-Excited Induction Generator (SEIG) driven with a fixed-speed low-head hydro-turbine when the electrical load is maintained constant by an Electronic Load Controller (ELC). In a 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. However, in the C-ELC configuration excess generated power may be wasted in a dump load. The objective of this research is to design a simplified ELC for each household to transfer the excess power for domestic consumption in addition to providing voltage regulation. Hence, a new ELC topology is proposed. This topology can be split into two parts. The first part is a regular ELC of low rated power, which should be installed at the generator site and it is responsible for precise voltage and frequency regulation and dealing with unexpected failure conditions. The second one is a simplified and inexpensive ELC which is installed in each household to direct excess power to a low wattage household apparatus in addition to participation in voltage regulation by maintaining constancy of the load power. This concept is referred to here as the Distributed ELC (DELC). One significant advantage of the proposed DELC approach is that the excess power can be utilized for domestic hot water purposes, and possibly resulting in health benefits related to improved sanitation. Moreover, the proposed topology shows more reliability compared with the C-ELC. 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, in the case of a failure in the power switches or the control circuits, the DELC has more reliable performance than a C-ELC.

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Keywords: Self-Excited Induction Generator (SEIG); Induction Generator (IG); Chopper; Insulated-Gate Bipolar Transistor (IGBT); Dump Load; Voltage Regulation.

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Selection and/or peer-review under responsibility of ISES.
doi:10.1016/j.egypro.2014.10.138

Nomenclature

ω_r	electrical rotor speed	i_{ds}, i_{qs}	stator currents in the d-q model
i_{dr}, i_{qr}	rotor currents in the d-q mode	i_{dL}, i_{qL}	load currents in the d-q model
V_{ds}, V_{qs}	stator voltage in the d-q model	V_{qr}, V_{dL}	rotor voltage in the d-q model
V_{dL}, V_{qL}	load voltage in the d-q model	L_s, L_r	stator and rotor self inductance
L_m	mutual inductance.	P	number of generator poles
T_{shaft}, T_e	shaft and electrical torques	I_{hh-max}	maximum current for each household
J	moment of inertia	R_{hh-max}	minimum load resistance for each household
V_{reff}	output reference voltage	$PI_{(n)}$	sampled calculated input for PWM
i_m	magnetizing current	$R_{re}(t)$	instantaneous load for a typical household
$R_{sp}(t)$	instantaneous special load which should be controlled by the DELC		
$I_{re}(t)$	instantaneous regular consumed current for a typical household		
T_c	considered time interval (period) for PWM signal		
$T_{on-hh}(t)$	instantaneous on-time duration for bidirectional IGBT switch		
$V_{j-er(n)}$	nth measured RMS error voltage for phase j		
$V_{j-out(n)}$	nth sampled measured RMS output voltage for phase j		
g_{js}	generated gate signals for phase j (for low-power rated ELC)		

1. Introduction

Simple and reliable stand-alone micro (i.e. 1kW to tens of kW) or pico (sub-kW) scale electrical power systems have been constructed for small communities that are geographically far from electrical generation utilities. Although, the unit production cost for a large power generation system is less expensive (per kWh) than in the case of a micro or pico scale generation unit, transmission line construction cost and the associated power losses can be excessive. Hence the growing popularity of stand-alone power generation systems. Also, driving the growth of stand-alone generation systems are factors such as: increasing concern for the environment, ever-increasing electrical energy demand, the health benefits of clean energy, limited access to conventional fuels, and advances in power electronics.

For stand-alone generation units with a power rating less than 20kW a squirrel cage self-excited induction generator (SEIG) driven by a constant speed uncontrolled turbine are favoured [1-3]. In comparison with conventional wound-rotor synchronous generators, the SEIG offers several advantages such as: reduced unit cost per generated kilowatt, ruggedness, absence of a DC-source for excitation, absence of brushes, simplicity of maintenance even by an unskilled person and self protection for some fault conditions [4,5].

The self excitation effect in induction generators (IGs) can be attained by connection of a three-phase shunt capacitor bank across the generator terminals. Although this fact was introduced by Besant and Potter in 1935 [6], in the past two decades, more attention has been given to the SEIG to mitigate the problems of poor voltage regulation and frequency variation [5]. Both terminal voltage and frequency of the SEIG can be subjected to variations with load fluctuations even when the generator is driven with a fixed speed uncontrolled turbine. Therefore, significant research has been conducted regarding these variations and several different sophisticated methods have been proposed for voltage regulation and frequency control.

These methods can be divided into two categories: voltage regulation by means of (a) a variable Volt-Ampere Reactive (VAR) source and (b) voltage regulation based on a resistive dump load. In the first category voltage regulation can be done by series or shunt capacitors [7-8], switched based shunt capacitors [9], static VAR compensator [10-11] voltage or current source converter based STATtic COMpensator (STATCOM) [11,12]. However due to the complexity associated with variable VAR source methods, their utilization for pico or micro scale generation is not recommended, especially since it is desirable that routine maintenance can be completed by an operator with a minimal of electronics training.

In hilly remote areas hydro-driven uncontrolled low-head turbines are preferred. Such systems have fairly constant mechanical input power. Voltage and frequency regulation for a SEIG in hilly remote area can be achieved by constancy of load power [13]. For this reason the generator output power should be maintained constant (or near constant) even if there are instantaneous variations experienced in consumer loads. A shunt resistive dump load can be utilized at the generator site to keep the SEIG output power constant. Electronic Load Controllers (ELCs) employ power electronics to adjust power in the dump load.

Several different methods of voltage regulation based on the ELC approach have been proposed in the past two decades. Among them are: phase angle control, binary weighted switch resistors, and a variable mark-space ratio chopping method, all reported by Smith [14]. The phase angle control approach can be challenging for the SEIG due to a variable lagging power factor. Despite producing unity power factor, the complexity associated with wiring of the switching devices, discrete control of the output power, and cost of the required resistive loads are the main bottlenecks of the binary weighted switch method. On the other hand, the variable mark-space ratio method, proposed by Smith [14], has been used in one form or another by several researchers.

For instance, in the impedance controller approach [15,16], voltage regulation can be achieved using an uncontrolled rectifier and a chopper switch connected to the dump load. An improved ELC method has been proposed by Singh [17], replacing the uncontrolled rectifier with a 2-level IGBT based converter to achieve voltage regulation for both balanced and unbalanced loads. Later, a new method based on use of a 2-level converter and without the chopper was proposed by Youssef [18]. In this method the terminal voltage is regulated by variation of the converter modulation index in order to change the DC side voltage and adjust the power consumption in the dump load.

A simple, inexpensive and reliable ELC method based on use of the anti-parallel Insulated-Gate Bipolar Transistor (IGBT) switch was proposed by Ramirez [3]. The rectifier circuit was eliminated and with help of the bi-directional switch the 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.

Although all the proposed methods are effective in voltage regulation and frequency control, transferring valuable generated power to a dump load at the generator site can be considered a disadvantage associated with the C-ELC approach. It should be noted that around 2.4 billion people in developing countries rely on traditional biomass for their daily energy needs. For example, in the remote areas of the Nepal, trees are utilized as firewood for indoor cooking, heating and lighting. An indoor open fire and the associated smoke can have a direct effect on the health of people. Some syndromes such as asthma, eye, heart and respiratory diseases are not uncommon, and may be responsible for a low life expectancy.

A load limiter is usually implemented in remote villages instead of electricity meters, hence, a constant monthly maintenance fee is paid by consumers related to the power rating of the installed load limiter, which means in effect, that consumers pay for excess generated power which is directed by the ELC to a dump load at the generator site. Hence, transferring this excess generated power to households, to be used for domestic hot water, instead of the dump load may have a direct impact on health of these small communities, as well as increasing the system efficiency. To determine if the 200W power level provided to each household is sufficient to heat an adequate amount of water for domestic proposes, consider the following: A mass of water is heated by a 200W heating coil for 10 hours (approximately over night) with a temperature change from $10°C$ to $60°C$. The mass of water can be found by:

$$m = \frac{\Delta E}{c\Delta T} = \frac{200\frac{J}{s}\times 10\times 3600s}{4187\frac{J}{kg°C}\times 50°C} = 34.4\text{kg} \tag{1}$$

where m is the mass of water that is heated, ΔE is the heated energy given to the water, c is the specific heat capacity of water and ΔT is the change in temperature of the water. For a developing country a domestic hot water container of about 25kg of water (i.e. less than the 34.4kg above, assuming some losses in the heating system) should be quite useful.

The objective of this study is to develop a new ELC topology. This topology can be split into two parts. The first part is a regular ELC of low rated power, which should be installed at the generator site and it is responsible for precise voltage regulation. It is worth noting that, the voltage variation sources in this study arise from fluctuation in consumer loads and variation in hydro system mechanical output power. The controller for the low-power rated ELC is designed based on the Proportional Integral (PI) concept in a closed loop control system. The second part of this proposed approach is a simplified and inexpensive ELC which should be installed at each household to direct the excess power to a low wattage household apparatus, beside its main task, participation in voltage and frequency regulation. It should be noted that the household controller is designed based on an open loop control concept and with inexpensive Pulse Width Modulation (PWM) integrated circuits. With help of this inexpensive controller, the maximum allocated power can be consumed by each household instead of wasting power at the generation site. This concept is referred to here as the Distributed Electronic Load Controller (DELC) concept (one per household).

The remainder of this paper is organized as follows. A brief explanation of a matrix formulation d-q modeling (well accepted by electromagnetic machine designers) for transient analysis of the SEIG is presented in Section 2. The proposed DELC and the low-power rated ELC topology, their related mathematical calculations are provided in Section 3. Simulation results are presented in Section 4. Section 5 provides conclusions for the paper.

2. System Modeling

A modular Simulink model (i.e. MATLAB\SIMULINK from MathWorks) for transient analysis of the three-phase SEIG in a stationary reference frame is constructed based largely on the modeling approach of [19]. To obtain the dynamic response of the SEIG a standard matrix formulation [20] exploiting the d-q model of the SEIG is utilized. To simplify the simulation procedure this matrix has been arranged in the form of a state-space equation, as also presented in [20]:

$$p\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \\ V_{dL} \\ V_{qL} \\ i_{dL} \\ i_{qL} \end{bmatrix} = K\left\{\begin{bmatrix} R_sL_r & -\omega_r L_m^2 & -R_rL_m & \omega_r L_r L_m & L_r & 0 & 0 & 0 \\ \omega_r L_m^2 & R_sL_r & \omega_r L_m L_s & -R_rL_m & 0 & L_r & 0 & 0 \\ -R_sL_m & \omega_r L_r L_m & R_rL_s & \omega_r L_s L_r & -L_m & 0 & 0 & 0 \\ -\omega_r L_m L_s & -R_sL_m & -\omega_r L_s L_r & R_rL_s & 0 & -L_m & 0 & 0 \\ 1/CK & 0 & 0 & 0 & 0 & 0 & -1/CK & 0 \\ 0 & 1/CK & 0 & 0 & 0 & 0 & 0 & -1/CK \\ 0 & 0 & 0 & 0 & 1/LK & 0 & -R/LK & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/LK & 0 & -R/LK \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \\ V_{dL} \\ V_{qL} \\ i_{dL} \\ i_{qL} \end{bmatrix} + \begin{bmatrix} -L_r & 0 & L_m & 0 \\ 0 & -L_r & 0 & L_m \\ L_m & 0 & -L_s & 0 \\ 0 & L_m & 0 & -L_s \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{dr} \\ V_{qr} \end{bmatrix}\right\} \tag{2}$$

where $K = 1/(L_m^2 - L_rL_s)$ and $p = \frac{d}{dt}$

Since a SEIG operates near the saturation region, with non-linear magnetizing characteristics, the magnetizing current should be calculated based on instantaneous stator and rotor currents. Calculation of the magnetizing current (i_m) in the d-q model is shown in the following equation [20]:

$$i_m = \sqrt{(i_{ds} + i_{dr})^2 + (i_{qs} + i_{qr})^2} \tag{3}$$

Magnetizing inductance should be calculated for the selected induction generator by a synchronous speed test [20]. The relationship between magnetizing current and mutual inductance for a 3 kW Donly induction machine with $R_s = 2.1\Omega$, $R_r = 1.4\Omega$ and $L_s = L_r$ =8.4mH [21] is exploited and shown in the following equation.

$$L_m = -0.0001615 i_m^3 + 0.00559 i_m^2 - 0.06621 i_m + 0.5515 \tag{4}$$

Neglecting friction terms (modeling friction components is not necessary at the stage of concept development), the electromagnetic torque balance equation can be written as:

$$T_{shaft} = T_e + J\left(\frac{2}{P}\right)\frac{d\omega_r}{dt} \tag{5}$$

A linear relation between shaft torque and speed is assumed here (a refined model would take into account the turbine characteristics which we have yet to do). This linear relation is represented in equation (6).

$$T_{shaft} = a - b \times \omega_r \tag{6}$$

where "a" and "b" are constant and should be selected based on machine characteristics.

3. Proposed Distributed Electronic Load Controller

As noted above, electricity meters are rarely used in remote areas and so consumers are charged a monthly fee based on the power limit for a given household. In a conventional ELC system power may be wasted in a dump load at the generator site. This problem can be solved by installation of a separate ELC for each household, i.e. the Distributed Electronic Load controller (DELC) concept. With the help of the DELC in each household, the excess power at each household can be utilized for domestic hot water possibly leading to health related benefits. This excess power can be directed to a low wattage apparatus such as space heating device or water heating system. Beside this significant benefit, the proposed DELC is more reliable than the conventional ELC since a failure in one ELC unit will not significantly impact in the entire power network. This new proposed DELC configuration for "n" households per phase is depicted in Fig. 1. This figure consists of a prime mover, an induction generator, the excitation capacitor bank, three-phase unbalanced household loads, the DELC and their related control block diagrams, and low-power rated ELC which has been installed at the generator site for the purpose of back-up control in fault conditions and to provide control in response to the small variations in the water flow rate. The selected ELC and DELCs circuitries have been inspired from research in [3] but with different controller strategies.

The design procedure for the proposed topology can be split into two parts: (a) the DELC design and (b) the low rated ELC design. The rated generator power in this study is equal to 3kW. This power can be allocated to 15 households. The allocated power for each household is equal to 200W. The regulated input voltage can be considered equal to 220Vrms. Based on aforementioned assumptions, the maximum allocated current and the total household load can be calculated as:

$$I_{hh-max} = \frac{200W}{220V} \cong 0.9A = 900mA \quad (7)$$

$$R_{hh-max} = \frac{220V}{900mA} = 222\Omega \quad (8)$$

This load can be obtained by parallel connection of regular household loads such as lighting, radio or TV and a special load such as a small water heater or space heater. It is worth noting that the regular household loads can be controlled by themselves, for example the TV can be turned on or off at any time. But the selected special load which in this research is a water heater, should be controlled by the proposed DELC. Which means the DELC must send the excess allocated power to the water heater. So, the intended purpose of the proposed DELC is twofold. The first one is voltage regulation and the second one is proper consumption of the generated power. The mathematical relation between regular and special loads can be given by:

$$R_{hh-max} = R_{re}(t) \parallel R_{sp}(t) = \frac{R_{re}(t)R_{sp}(t)}{R_{re}(t)+R_{sp}(t)} \quad (9)$$

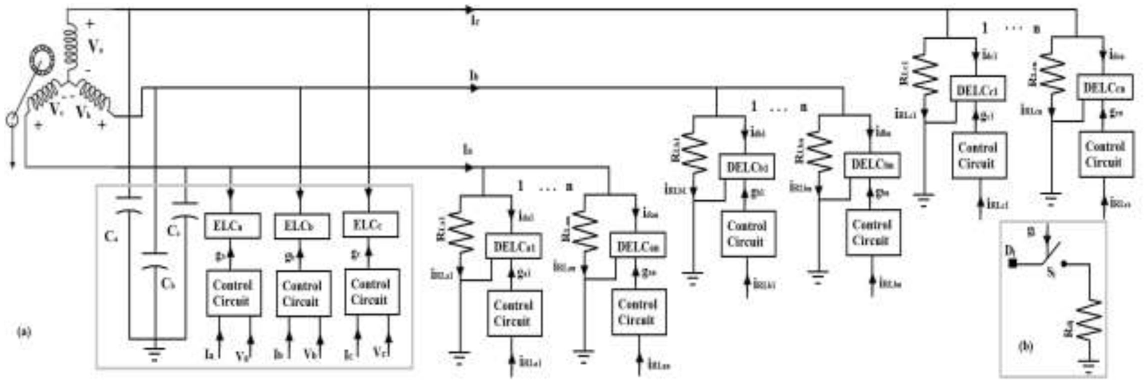

Fig. 1. (a) DELC configuration, including SEIG, capacitor bank, and low rated ELC, n separated DELC per phase and related gate control blocks.

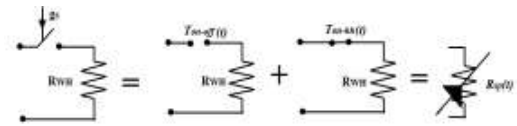

Fig. 2. Equivalent circuit of the proposed DELC

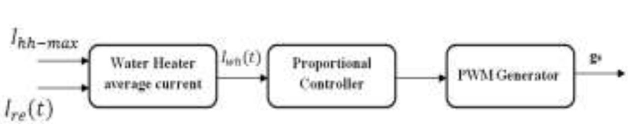

Fig.3. A simple block diagram of the utilized control strategy in the proposed DELC

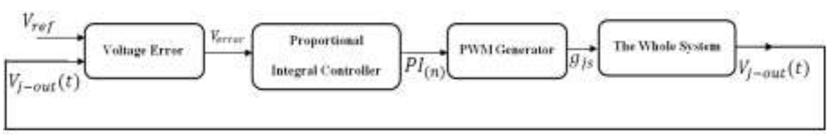

Fig. 4. Utilized control strategy for the low rated ELC

The allocated power to the water heater depends on the instantaneous consumption of the regular loads. Based on the constancy of the load for each household, the instantaneous required resistor of the special load can be calculated as:

$$R_{sp}(t) = \frac{R_{hh}R_{re}(t)}{R_{hh}-R_{re}(t)} \quad (10)$$

This variable resistor can be obtained by a constant ($R_{WH} = 225\Omega$) water heater resistance in series with a bi-directional power electronic switch [3] which will be controlled by Pulse Width Modulation (PWM). A simple schematic diagram of this configuration is depicted in Fig. 2. The total input resistance of this configuration can be given by [3]:

$$R_{sp}(t) = \frac{R_{WH}\times T_c}{T_{on-hh}(t)} \quad (11)$$

A very simple proportional open loop control strategy is considered to obtain the appropriate signal for the PWM circuit. The main responsibility of this controller is to calculate $T_{on-hh}(t)$. A simple block diagram of the utilized controller for proposed DELC is depicted in Fig. 3. It is worth mentioning that:

$$I_{re}(t) = \frac{220V}{R_{re}(t)} \quad (12)$$

The low rated ELC is responsible for precise voltage regulation. In the case of safe operation and with fixed speed turbine, an approximate voltage regulation with acceptable accuracy can be achieved by the DELCs. In this condition the low-power rated ELC is used for increasing the voltage regulation. However in the case of fluctuations in the water flow, resulting variation in generator speed and its related produced power or any failure in each household power system, the low-power rated ELC would be responsible for providing of the required dump load to regulate the output voltage. This dump load can be calculated based on the allocated power to each household.

Regarding the allocated power to each household and for sake of increasing the system reliability in the case of failure in the IGBT switches (for example one or two DELCs in each phase), the considered dump load for the ELC in each phase should be able to consume 30% of the generated power (1.5 ×each household power). Based on equation (8) the minimum dump load resistor should be equal to 148Ω. Hence a 150Ω series resistor with a bidirectional power electronic switch is considered for the low-power rated ELC at the generator site. The controller idea for low-power rated ELC is similar to the utilized controller in a DELC. Depending on the consumed power in each phase, bi-directional IGBT switches with help of PWM are used to control the dump load resistance and maintain the constant power consumption. A different and slightly complicated control strategy based on closed loop control system is considered for the low-power rated ELC. The block diagram for this system is illustrated in Fig. 4. It should be noted that for the DELC, the boundary of the design has been considered based on the installed fuse restriction, but for the low-power rated ELC, and due to importance of the voltage regulation, the generator output voltages are considered as a control variables (for each phase). In the control procedure, after measuring of one typical phase voltage, the voltage error can be calculated as:

$$V_{j-er(n)} = V_{j-out(n)} - V_{reff} \quad (13)$$

The outputs of the PI controllers to maintain output voltage constant at the nth sampling instant can be expressed as:

$$PI_{(n)} = K_i\left(V_{j-er(n)} - V_{j-er(n-1)}\right) + K_pV_{j-er(n)} \quad (14)$$

The calculated $PI_{(n)}$ for each phase should be applied to the PWM generator to produce appropriate gate-drive signals for the IGBT switches.

4. Simulation Results

A set of simulation results are presented here to investigate the feasibility and performance of the proposed DELC approach. The simulation was done in the MATLAB\SIMULINK environment and the proposed technique was applied to voltage control of a 3 kW, 220 V Donly IG. The selected IG is driven at a speed of $316 rad/sec$, with three phase excitation capacitor bank equal to $60\mu F$, charged with initial voltages equal to 10V, 10V, and -20V. The generator output voltages and frequency reach steady state values at $t = 0.75\ sec$.

The number of considered households per phase (for the considered DELC system) is equal to 5, and allocated current for each household based on the generator nameplate is approximately 0.9A. The households three phase loads, the proposed DELC, and the low-power rated ELC are connected to the generator at $t = 1.5\ sec$. Two different sudden (step) variations of household loads are applied at $t = 5\ sec$ and $t = 8.5\ sec$, respectively. The assumed load pattern for the households is tabulated in Table. 1. The total load per phase has been calculated and shown in the last row of the table. It is worth mentioning that due to sudden changes in consumer loads, high overshoot can be seen in output power. In practical situations, due to more smooth variations in consumer loads this overshoot will be less.

Shown in Fig. 5 are several typical system specifications such as magnetizing inductance, magnetizing current, instantaneous output voltage, RMS value of the output voltage, instantaneous consumed current by regular loads for one household, the related (chopped) transfer current to the water heater for the selected household, and the output frequency. The instantaneous chopped current that should be transferred to the water heater system has been illustrated in an extended time for the three separated load regions. These extended figures have been depicted in Fig. 5(f). The regulated output voltage and output frequency, for the entire system have been depicted in Fig. 5d and Fig. 5g. These results show that the proposed topology maintains the output voltage and regulates the frequency. It is worth noting that the main responsibility for voltage regulation are done by the installed DELCs and more precisely control of the voltage can be achieved by the low-power rated ELC. Just for sake of clarity and for the next results, the RMS voltage and current values are used.

Table 1 the considered households' loads pattern with two step changes in 5 and 8.5 seconds.

Output phase	a				b				c			
Connection Time (S)	0-1.5	1.5-5	5-8.5	8.5-12	0-1.5	1.5-5	5-8.5	8.5-12	0-1.5	1.5-5	5-8.5	8.5-12
Household load 1(Ω)	NL	700	477.27	323.07	NL	800	444.44	307.69	NL	1000	545.5	324.3
Household load 2(Ω)	NL	1000	500	307.7	NL	800	444.44	285.71	NL	1400	646.2	357.4
Household load 3(Ω)	NL	1200	545.5	339.6	NL	1600	685.7	369.2	NL	800	480	313.04
Household load 4(Ω)	NL	1300	650	358.6	NL	1200	545.5	324.3	NL	800	533.33	320
Household load 5(Ω)	NL	1400	583.3	337.3	NL	1500	521.7	298.9	NL	1600	685.7	346.4
Total Loads(Ω)	NL	202.89	104.21	65.88	NL	228.57	112.67	67.226	NL	183	103.83	64.66

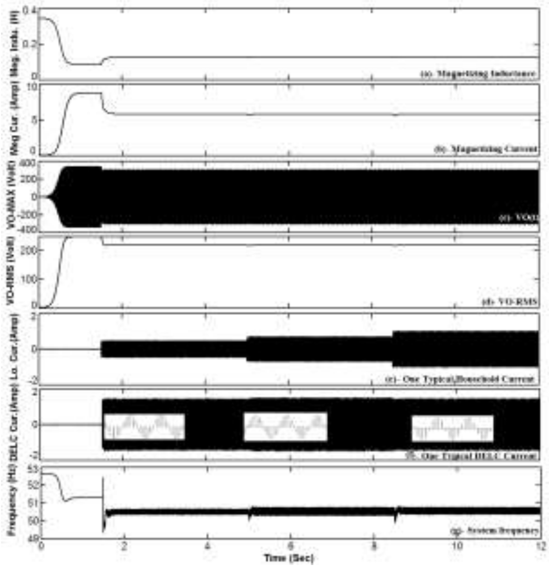

Fig. 5. Typical system characteristics, (a) magnetizing inductance, (b) magnetizing current, (c) instantaneous output voltage, (d) RMS output voltage, (e) considered load current for a typical house hold in phase "a", (f) the DELC chopped current, and (g) the system frequency.

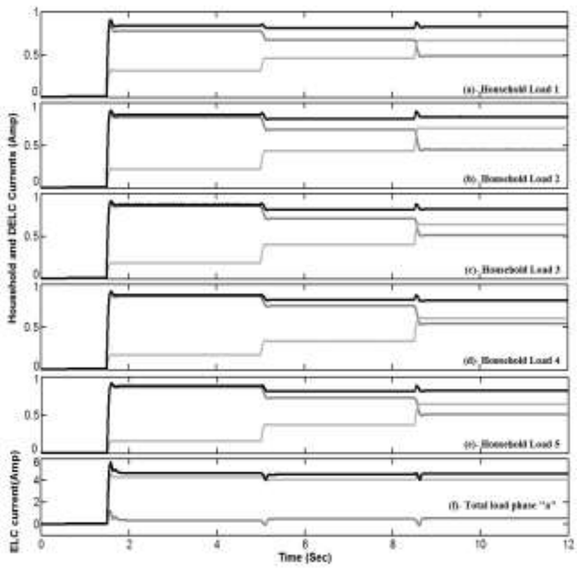

Fig. 6. System current consumption, (a) to (e) current consumption if all households are connected to phase "a" based on selected load pattern in Table 1, including regular load current with light gray shaded, DELC current with dark gray shaded and the total current with block color, (f) current consumption in the phase "a" including the households total consumption, shaded with light gray, the ELC current, shown with dark gray, and total current for phase "a" with block shaded

As mentioned in the previous section, the control strategy can be split into two modes: a simple open loop controller which should be installed in each house, and a low-power rated ELC based on closed loop control strategy which must be installed at the generator site for each phase. The performance of these proposed controllers for a typical phase (phase “a”) and for all connected households (5 households) is depicted in Fig. 6. In this figure the households current consumption including regular and special loads is depicted in part (a) to (e) and the total consumption for the selected phase including ELC performance is depicted in part (f). In this figure and for part (a) to (e), the RMS value of the consumed current for the regular loads by each household are shown in light gray, the RMS value of the special load current which is related to the regular consumption of each household is in dark gray, and the total consumed current per household is shown in black. For part (f), the total consumed current by households (including DELC) is shown in light gray, the current drawn by ELC is dark gray and the total current consumption of the system for the selected phase is shown in black.

Another advantage, related to the proposed topology is increasing the system reliability. In a conventional system based on one ELC at the generator site, any failure in IGBT switches causes large voltage fluctuations. In the proposed topology, each IGBT switch has to cope with a partial power transferring. Failure in one or two components has a partial effect in the system performance. Different scenarios for failure have been considered and the performance of the system has been investigated. The RMS values of the output voltage for phase “a” and total output power of the IG in the case of failure based on the considered scenarios are illustrated in Fig. 7 and Fig. 8. The considered failure scenarios have been applied for all three phases simultaneously, but results for one typical phase (phase “a”) only are depicted. Output voltage and total output power of the IG in the no load condition are illustrated in Fig. 7(a) and Fig. 8(a) just as a reference for other considered situations. The objective of the controller is to maintain the output voltage equal to 216 Volt (set point for ELC controller), hence in each failure situation, the percent of the voltage fluctuation is calculated based on this reference value. The output voltage and total power in the case of failures for all installed IGBT switches, including DELCs and low-power rated ELC are illustrated in Fig. 7(b) and Fig. 8(b). In this mode, the output voltage fluctuation is 10.2% and system power consumption is less than the generated power, resulting in acceleration of the generator. Performances of the system in the case of failure for all installed IGBT switches in the DELCs are shown in Fig. 7(c) and Fig. 8(c); maximum voltage fluctuation in this condition is 6.5%. The output voltage for phase “a” and the total IG output power in the case of failure in two DELCs among 5 households and failure for the installed IGBT switches in the low-power rated ELC are depicted in Fig. 7(d) and Fig. 8(d). The voltage fluctuation in this case is 5.3%. The output variables in the case of failure of two IGBT switches among 5 installed DELCs in each phase are shown in Fig. 7(e) and Fig. 8(e); the related voltage fluctuation is 1.6% and the total output power of the IG is approximately 3000W. Performance of the system in the case of failure of one IGBT switch per phase are depicted in the part (f) and (g) of Fig. 7 and Fig. 8. The consequence of failure in the DELC has been depicted in part (f), and system performance in the case of failure in the ELC has been shown in part (g). For both conditions, the voltage fluctuations are less than 1%. And finally the system performance in normal conditions, without any failure is illustrated in Fig. 7(h) and Fig. 8(h). Simulation results show, the proposed topology has a very robust performance in the case of failure for one or two IGBT switches in each phase. The consequence of a failure for one IGBT switch in the C-ELC can be a major problem especially when the total consumer power consumption is close to its minimum value.

To show the proposed system capability to deal with fluctuations in the water flow rate, a sinusoidal distortion has been considered in the water flow rate and performance of the system with and without the low-power rated ELC is depicted in Fig. 9. In this case, the generated output power by the hydro system will fluctuate between 3000 and 3600W (permitted for only periods). The output power with the low-power rated ELC and without ELC are shown in part (a) and part (b). In the system with the low-power rated ELC, excess power is dissipated in the dump load, resulting in constant output voltage and constant frequency. This output voltage is depicted in Fig. 9(c). The system without an ELC is not successful in dissipating power, resulting in fluctuation in output voltage and accelerating of the machine. The output voltage in this case is depicted in Fig. 9(d). Output voltage fluctuations in these two cases are 0.5% and 4.6%, respectively.

5. Conclusions

A new Electronic Load Controller configuration, referred to here as a Distributed Electronic Load Controller (DELC), is presented in this paper. The main objective for this proposed DELC approach is the transfer of excess power for domestic consumption such as water heating or space heating, in addition to providing voltage regulation. This objective has been achieved using bi-directional IGBT switches in a DELC that is located in each consumer household. Since the DELC makes use of available power that otherwise would go to a dump load, the proposed system can be considered more efficient compared with conventional ELC, in the sense that the DELC system capacity factor will be much higher than for the conventional system. Moreover, simulation results show the proposed DELC topology has several other significant advantages compared with the conventional ELC. First of all, the proposed topology can be used in the case of unbalanced three phase loads, which is very popular in microhydro systems. Furthermore, the proposed DELC topology is more reliable than conventional ELC since a failure in one DELC unit will not significantly impact in the entire power network. Also, because of the installation of a low-power rated ELC at the generator site; the proposed approach has the ability to handle an overload mechanical turbine power of about 20% due, for example, to changes in the water flow rate.

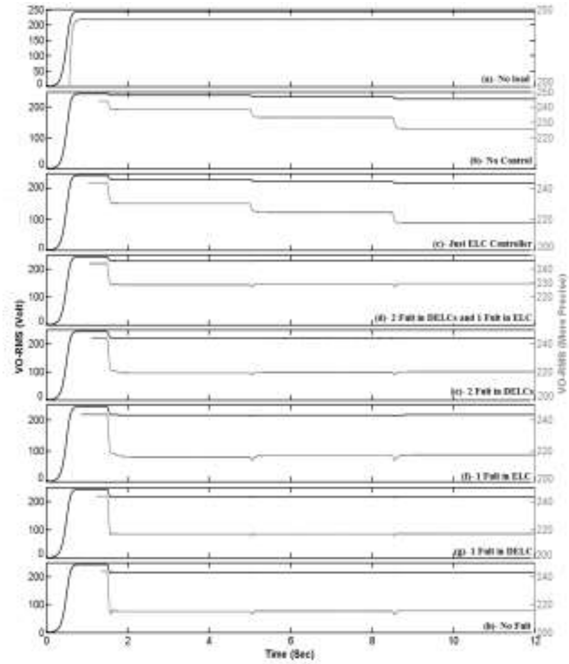

Fig. 7. The output voltage of phase "a" based on different failure scenarios which maybe happen in system, (a) no-load output voltage, (b) output voltage in the case of failure for all IGBT switches, (c) output voltage in the case of failure for all IGBT switches installed in DELCs, (d) output voltage in the case of failure among 2 IGBT switches installed for 5 households and failure in the ELC switch, (e) output voltage in the case of failure among 2 IGBT switches installed for 5 households, (f) output voltage in the case of failure in one household IGBT switch, (g) output voltage in the case of failure in installed IGBT switch for the ELC, and (h) output voltage without failure.

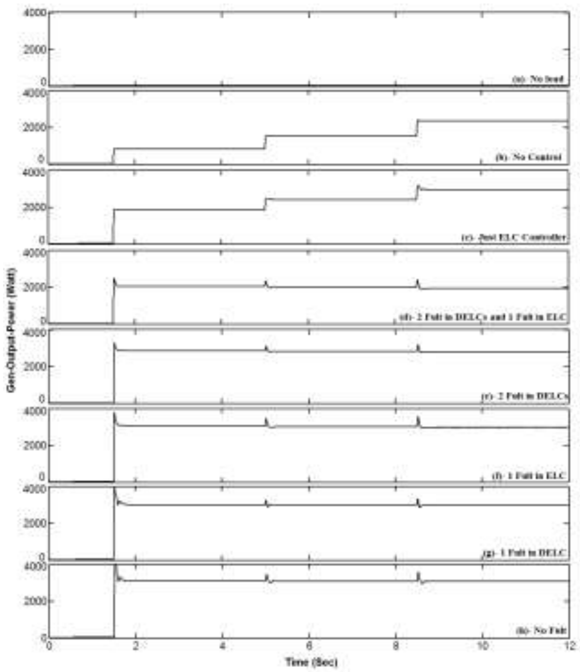

Fig. 8. The total output power of induction generator based on different failure scenarios which maybe happen in system, (a) no-load output power, (b) output power in the case of failure for all IGBT switches, (c) output power in the case of failure for all IGBT switches installed in DELCs, (d) output power in the case of failure among 2 IGBT switches installed for 5 households and failure in the ELC switch, (e) output power in the case of failure among 2 IGBT switches installed for 5 households, (f) output power in the case of failure in one household IGBT switch, (g) output power in the case of failure in installed IGBT switch for the ELC, and (h) output power without failure

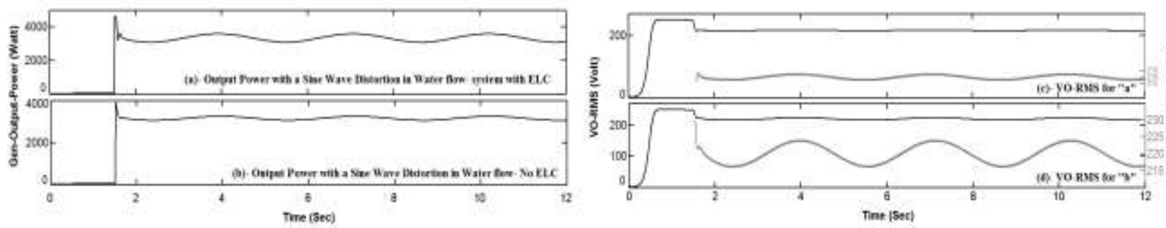

Fig. 9. Output voltage and power in the case of sinusoidal distortion in water flow rate, (a) output power for system with low rated ELC, (b) output power for system without low rated ELC, (c) output voltage for system with low rated ELC, and (d) output voltage for system without low rated ELC,

Acknowledgement

We would like to express our sincere appreciation to *Dr. David Wood*, NSERC/ENMAX Industrial Research Chair in Renewable Energy, for his inspiration and valuable insights in defining the issues of microhydro system operation in Nepal and other developing world countries. The research described in this paper is the first stage of a *Grand Challenges Canada* project to improve rural health in developing countries by the provision of clean renewable energy.

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