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Review

Review and experimental illustrations of electronic load controller used in standalone Micro-Hydro generating plants

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ABSTRACT

Hydraulic Governor (HG) in Standalone Micro-Hydro generating Systems (SMHS), for maintaining voltage and frequency at desired levels, is not preferred as HG is much costlier than the generator. Electronic load controller (ELC) is a cost-effective solution for this application. Resistive (dump) load at an equal rating of generator is used to maintain constant voltage and frequency at the load perturbations. However, the system receives electrical and mechanical stresses as it operates at full load throughout the life which causes degradation of its component and lifetime reduction. This paper reviews the development trends of ELC used for SMHS and identifies the shortcomings of available technology for it. After the review, it proposes a novel methodology to enhance the generator efficiency and its lifespan by reducing the amount of dump load used. Performance of generator with conventional and proposed methodologies is investigated experimentally and lifespan is estimated through temperature profile. In addition, generator protection from sensor faults is enforced in proposed controller for enhancing the reliability of the system.

Contents

1. Introduction

Economic growth and greater energy utilization are essential in raising people's living standard, as well, rural electrification using renewable and sustainable energy has a significant role in it. World Bank shows much interest in universal electricity access and clean cooking fuels through increasing the renewable energy sources [1]. Hence, the Universe focuses on the development of economically viable renewable energy for rural and remote areas [2–7]. Among renewable energy sources, hydroelectric energy is a major energy source [8], in which micro hydropower plant (MHP) is the best

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suitable for rural electrification as it does not require dam and reservoir as of convention hydropower plant [9–11]. In general, MHP operates in stand-alone and it is built with either self-excited synchronous generator or asynchronous generator for continuously varying load that creates voltage unbalance and frequency fluctuations. These perturbations develop mechanical vibrations and thermal effect, that consequence to generator lifespan deterioration [12]. Therefore, control system on turbine side or generator side must be employed to regulate output voltage and frequency during load variation. As can be seen in Fig. 1, the generator output voltage and frequency can be controlled from turbine side known as mechanical control, or it can be controlled from generator side known as electrical control, or it can be controlled from both sides known as electro-mechanical control. In turbine side control system, generator voltage and frequency is controlled by regulating the speed of turbine, which is governed by controlling the water flows. These water flows are controlled through regulating the inlet valve or opening and closing the valves in multi-pipe system [13]. These hydro turbine speed governing system is carried out using electrical controllers (analog /digital) for improving the system performance. Also, various control techniques adopted to govern the turbine speed such as, gate limit control, speed level control, speed droop control, etc., [13–18]. However, due to the less dynamic response and high expenses, the mechanical and electromechanical regulators are less preferred in MHP [19–22].

Similarly, the generator side control system regulates the voltage and frequency by employing dummy resistors during load variation which modifies the amount of power sent to dissipation circuit. The electronic controller with resistive load is also known as electronic load controller (ELC) or dump load controller (DLC). ELC advances over mechanical control system in dynamic response, reduced cost, less complexity, and maintenance [23]. In this regard, a comprehensive review of generator output control in the perspective of controller, control techniques and power electronic configuration is discussed in this paper.

In 1980, Woodward, et.al, introduced power relay based ELC scheme in hydropower plant to regulate the voltage and frequency of generator for providing good isolation between control circuitry and the power lines [24]. Soon after, in 1984, S. Kormilo, et.al replaces power relays with phase control power electronic switches for providing smooth regulation in generation system [25]. These power electronic regulatory switches are connected in between the generator terminals and the dump load to control the generator output voltage and frequency as in [13,21] and [26]. Later on, in 1990, Bonert R, et.al reforms the power electronics circuit configuration to minimize the line distortion in standalone

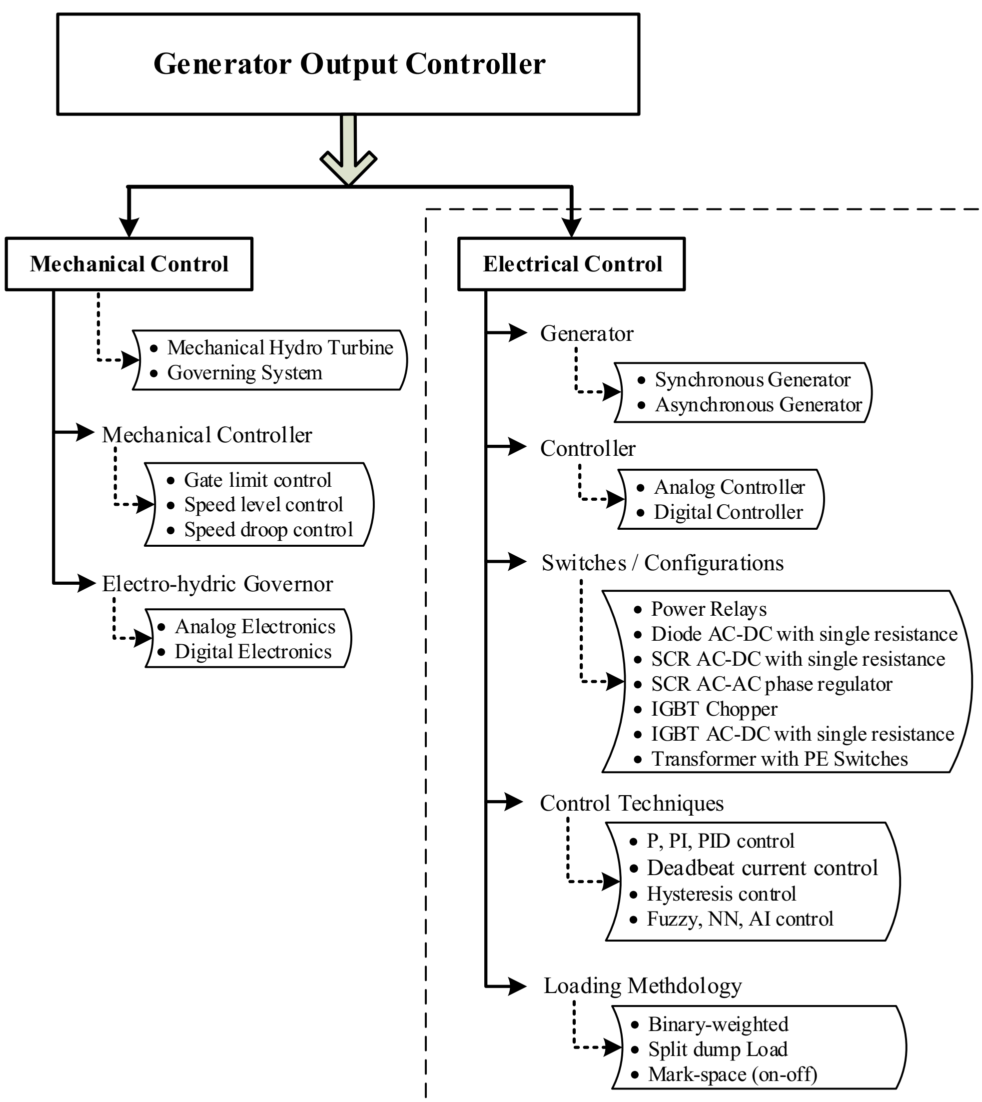


Fig. 1. Generator Output Controller.

induction generator based ELC system [27]. Eventually, ELC schemes developed with different switches and configuration like TRIAC based regulators in [28–36], SCR based controlled rectifier in [21,27,37,38], contactors with resistive load [39], and contractors with discreet ballast [40]. Meanwhile, in 1998, Insulated Gate Bipolar Transistor (IGBT) is introduced in ELC for chopping the uncontrolled rectified voltage [41]. Later, IGBT chopper is employed in ELC with various configurations of rectification circuit such as, three phase uncontrolled rectifiers with IGBT chopper [37,42–49], single phase uncontrolled rectifier with IGBT chopper [50,51], 6-pulse diode rectifier with IGBT chopper [52–55], 24-pulse diode rectifier with IGBT chopper [56]. Also in recent, bidirectional IGBT switches are used for chopping [57,58,89] and matrix converter operation [84]. Likewise, in Micro hydro generation system, IGBT switches are employed in different converter configurations such as 2-leg IGBT based voltage source converter [61,62], 3-leg IGBT based voltage source converter [63], 4-leg IGBT based voltage source converter [64,65], and 6-leg IGBT based voltage source converter [66].

Initially, Self-Excited Induction Generator (SEIG) is employed in MHG as it is reliable, robust and cost-effective. To regulate the output voltage and frequency of the SCIG based system, numerous controllers and control techniques are used such as analog controller [24], microprocessor based ELC with the current control algorithm [28], microcontroller based fast feedforward control [34,37,68], and digital signal processor based ELC [48,69]. In addition, various control techniques are adopted to enhance the efficiency of SEIG based ELC system like, Proportional controller based ELC [70,71], PI controller based ELC [36,41,43,44,58,59,72,73] PID control [74] and harmonics elimination control using p-q control theory [75]. Later, Synchronous Generators (SG) are employed in MHP due to their high efficiency and regulation in energy production, such generator can be implemented using various controller and control strategies like, AIM 65 microcomputer [25], Proportional controller [40,54,55], PI controller [45,76], Fuzzy logic control based battery charging system [77], Micro-controller based ELC [78], PLC based load controller [39], etc. Similarly, asynchronous generators with external excitation (also known as separately excited induction generator) employed in MHP adopting various control techniques such as PI based decoupled voltage and frequency controller [64,65,79–82], PI controller based active and reactive power control [63,66], deadbeat-current-controller-based active power filter [83], Zig-zag transformer using PI controller [61,62,84] integrated electronic load controller using PLL technique [85–87], automatic generation control technique [88], transformer based ELC [89], IGBT converter based ELC [90], genetic algorithm based dumped load and multivalve control [35], DSP based reactive power control [91], quasi-oppositional grey wolf optimization algorithm based control [60,92], and other optimization control [93].

Overall, mainly, MHP is employed by self-excited synchronous or asynchronous generator and in modern plants, brushless generators are preferred for hassle free operation [8]. Phase angle control is mainly used with synchronous generators and it is less appropriate for induction generators due to lagging power factor because it increases frequency variation and waveform distortion. To lessen these effects, a binary-weighted controller is adopted in [42], however, binary-weighted controller possesses hindrance due to stepped voltage regulation and complexity in connection. To attain smooth voltage regulation with simple connection, a mark-space (on-off) ratio chopping technique has been adopted in [20,21,34,37,41–47,50,57,68,69,77,79,80,94–102]. In addition to smooth voltage regulation, unity power factor is achieved using a single resistance topology [103]. Still, phase unbalance is a problem in this method which leads to waveform distortion and derating of generator. Balancing three phases of generator, all phases are independently controlled using single-phase rectifier with chopper circuit [66]. Likewise, chopping frequency is increased for reducing waveform distortion in [27]. Most of these controllers are designed for under load conditions, but in case of overloaded generator, power factor gets lagged. To compensate this, IGBT based voltage source converter and capacitor is used under various power electronic configuration [48,61–65,72,73,83,85–91,94,99,104–113]. In addition to voltage and frequency regulation through dump load, few controllers are designed for utility purpose charging battery, heating water, etc., with harmonic filtration [58,57,77,81,97]. On the other track, PWM based VSC with various transformer configurations is discussed in [82,89,106,107,114,115]. Few schemes without dump load and valve control strategy are also being adopted in [116–118]. Moreover, using unbalanced excitation capacitor the derating of a self-excited three-phase induction generator is studied in [119]. Eventually, the development of ELC is exhibited in Table 1, in the perspective of (i) controllers and control techniques, (ii) machine types and (iii) power electronic typologies.

Although existing ELC is utilized for regulating the output voltage and frequency, it creates power wastage. Typical ELC required cooling facility for cooling dump load, especially, during the summer period and tropical regions, which increases system complexity and cost (installation cost and running cost) [85]. Some of these controllers are used for utility purpose [58,59] whereas, the efficiency and lifetime of the machine is concerned, still an issue. As the capacity of the dump load resembles plant capacity, it requires more cooling system, which affects the generator's life span. As per the survey of CIGRE [54], a major source of breakdown in hydroelectric generator is due to electrical, mechanical, and thermal stresses. Understanding these stresses are important to increase efficiency and lifespan of the generator. The lifetime of a generator depends upon environmental condition and operating stresses (electrical, mechanical and thermal). Variation of dump load with respect to the main load creates electrical and mechanical stresses, as well as, thermal stress in generator are created due to unbalance loading, continuous loading, bearing fault, etc. In existing ELC with typical dump load, afore discussed stresses are accountable. Considering this problem in existing ELC, 20 percent of dump load is reduced in the proposed strategy by increasing the reference frequency. Performance of generator and domestic appliances under reduced dump load have been experimentally investigated in this paper. Moreover, lifespan of the generator under existing and proposed strategy is estimated with their thermal effects. In addition, protection of system from load disturbances and sensor fault is embedded in the controller. Overall the paper includes; design and operation of electronic load controller with experimental arrangement and testing in Section 2, investigation of generator and domestic loads with 20 percent voltage and frequency variation in Section 3, lifetime estimation of hydroelectric generator with existing and proposed strategy is deduced in Section 4, sensor fault detection and isolation technique is implementation in Section 5, Section 6 discusses the realization of proposed strategy with result and discussions in Section 7 and concluded in Section 8.

2. Design and operation of electronic load controller

In this section, the design of an electronic load controller with hardware setup and functioning procedures is discussed.

2.1. Design of ELC

Electronic controller functions as a frequency regulator on a generator by diverting surplus electrical power to ballast resistive load [8], as in Eq. (1). As frequency is the main control variable, difference between measured frequency and desired reference frequency is considered as the error signal given in Eq. (2).

Table 1
Comprehensive review of electronic load controllers.

Sl. No	Controller/Control Techniques	Machine	Power Electronics Configuration	Year [Ref. No.]
1.	Analog Controller	SEIG	Power Relays	1980 [24]
2.	AIM 65 Microcomputer	SG	Thyristors with TRIAC	1984 [25]
3.	Electronic impedance controller	IG	3ϕ SCR controlled rectifier with chopper	1990 [27]
4.	Analog circuit based phase angle control	SESCG	TRIAC based phase angle control	1991 [28] 2012 [30]
5.	Microprocessor based ELG with the current control algorithm.	SEIG	TRIAC based phase angle control	1998 [67]
6.	PI controller based ELC and switched capacitor based VAR compensator	SEIG	Uncontrolled rectifier with IGBT based chopper for ELC Thyristor based VAR	1998 [41]
7.	Microcontroller (MC68332) based fast feed-forward control	SEIG	3ϕ phase controlled bridge with chopper	1998 [68]
8.	Double control strategy for voltage and frequency regulation.	IG	3-leg IGBT based bi-directional VSC, Bidirectional SCR for ELC	1999 [38]
9.	(Atmega-16) with PI controller based ELC	SEIG	Uncontrolled rectifier with IGBT based chopper for ELC, MOSFET chopper	1999 [120] 2013 [101]
10.	IGC with under voltage and overvoltage protection	SCIG	TRIAC based regulation system	2000 [31]
11.	PID controller with dual feedback	Dynamo	TRIAC based regulation system	2001 [32]
12.	Comparison of back to back thyristor based and IGBT based ELC	SEIG	Uncontrolled rectifier with back to back thyristor based chopper	2003 [20]
13.	Triple PI controller based ELC	SEIG	IGBT based CC-VSI and IGBT chopper	2003 [72]
14.	PI controller based power balancing	SEIG	Uncontrolled rectifier with IGBT based chopper	2004 [43]
15.	Numerical voltage and frequency controller	SEIG	Uncontrolled rectifier with IGBT based chopper	2005 [46]
16.	PIC 18F252 microcontroller with PI controller	SEIG	Uncontrolled rectifier with IGBT based chopper, TRIAC for capacitor switching	2006 [37] 2010 [34]
17.	Multi-pipe flow control with reduced dump load.	IG	Thyristor based phase control	2006 [13]
18.	Design of ELC using PI controller	SEIG	Uncontrolled rectifier with IGBT based chopper	2006 [44]
19.	Dump load control using PI controller	SG	Uncontrolled rectifier with IGBT based chopper	2007 [45]
20.	Proportional controller based load control	SEIG	Chopper circuit (Anti-Parallel IGBT) in series with dump load	2007 [70] 2010 [71]
21.	PID controller based AVR (simulation)	SESA	PSCAD based AVR	2007 [19]
22.	PI based multi-mode controller	PMSG	TRIAC with analogue controller (CI-tronic™)	2007 [29]
23.	PI based decoupled voltage and frequency controller	AG	3ϕ uncontrolled rectifier with IGBT based chopper, 3-leg IGBT based VSI	2007 [79]
24.	Hybrid excitation system with deadbeat current control strategy	SGIG	IGBT based VSI for active power filter	2007 [83]
25.	PI controller based voltage and frequency control (simulation)	IAG	4-leg IGBT based VSC with IGBT chopper.	2008 [64]
26.	PI controller based active and reactive power control (simulation)	IAG	3-1ϕ transformer with 6-leg IGBT based current controlled VSI for STATCOM, Uncontrolled rectifier with chopper for ELC	2008 [66]
27.	Decoupled control (STATCOM and ELC) using PI controller (simulation)	AG	4-leg IGBT based CC-VSI for STATCOM, 3ϕ diode rectifier with an IGBT based chopper.	2008 [65]
28.	Simultaneous active and reactive power control of two parallel IG using PI controller (simulation)	IAG	3-leg IGBT based current controlled VSI with IGBT based chopper.	2008 [63]
29.	Zig-Zag transformer based ELC using PI controller (simulation)	IAG	2-leg IGBT based VSC with IGBT chopper.	2008 [61] 2008 [62]
30.	DSP(TMS320F2812) based IGC with PI controller	SEIG	1ϕ uncontrolled rectifier with IGBT based chopper	2008 [50]
31.	Polygon wound autotransformer with 24 pulse bridge rectifier based ELC using PI controller	AG	2-3ϕ diode rectifier with 2 zero sequence blocking transformer and IGBT based chopper.	2008 [80]
32.	Integrated electronic load controller using PLL technique (simulation)	IAG	Star-delta transformer, 3-leg IGBT based VSC with IGBT chopper.	2009 [85]
33.	Integrated ELC with battery energy storage system using PI controllers (simulation)	IAG	Star-hexagon transformer, 3-leg IGBT based VSC with IGBT chopper.	2009 [81]
34.	Static VAR compensation magnetic energy recovery switch as a shunt controlled capacitor using PLL technique (simulation)	IG	Single phase full-bridge IGBT with a capacitor.	2009 [86] 2009 [87]
35.	Hybrid control of parallel micro-hydro generators using PI controller (simulation)	SG, IG	Servo motor as governor control and power electronic based dump load controller.	2010 [121]
36.	Synchronous reference frame theory based IELC (DS-1104 control board)	IAG	Star-hexagon transformer with 3-leg IGBT based VSC with IGBT chopper.	2010 [104]
37.	TS Fuzzy based multi-mode controller (DS-1104 control board)	PMSG	TRIAC phase controller	2010 [33]
38.	Variable DC-link voltage using hysteresis controller	SEIG	3-leg IGBT based voltage source converter	2010 [105]
39.	T- Connected transformer based ELC with Icosϕ algorithm implementation.	IG	T- connected transformer for reducing triplet harmonics	2010 [89]
40.	Transient Analysis of SEIG	SEIG	Single phase uncontrolled rectifier with IGBT based chopper for ELC	2010 [94] 2012 [99]
41.	Star delta transformer with H – bridge VSC based decoupled ELC. (simulation)	IAG	Star delta transformer with IGBT based H –bridge VSC, 3ϕ uncontrolled rectifier with IGBT based chopper	2010 [114]
42.	Instantaneous reactive power theory-based ELC	IAG	Zig-zag (3-1ϕ isolated transformer), 3-leg IGBT based VSC with IGBT based chopper.	2011 [106]
43.	Improved 3-leg IGBT based electronic load controller (DS-1104 control board)	IG	3-leg IGBT based VSC with IGBT chopper.	2011 [90]
44.	NN based least square (adaline) algorithm for integrated ELC	IAG	Zig-zag (Three single phase isolated transformer), 6-leg IGBT based VSC with IGBT based chopper.	2011 [107] 2012 [115]
45.	PI based single control structure for voltage and frequency regulation. (DS-1102 and DS-1103 control board)	IG	3-leg IGBT based VSC and IGBT based chopper.	2011 [108]
46.	Hybrid topology with smart loading and BESS. (DS-1102 and DS-1103 control board)	SM	3-1ϕ uncontrolled rectifier with IGBT based chopper, 3-leg IGBT based VSC and 2- IGBT based chopper.	2011 [95]
47.	Genetic algorithm and PI based dump load and multilevel valve control.	IG	TRIAC as a load phase control switch	2011 [35]

Table 1 (*continued*)

Sl. No	Controller/Control Techniques	Machine	Power Electronics Configuration	Year [Ref. No.]
48.	DSP (TMS320 28335) based reactive power control	IG	3-leg IGBT based VSC with a capacitor	2011 [91]
49.	Microcontroller (Atmega-32) with Fuzzy logic based ELC	SEIG	Single phase uncontrolled rectifier with MOSFET based chopper	2011 [96]
50.	Fuzzy logic control based ELC	SEIG	IGBT based CC-VSI and IGBT chopper for ELC.	2012 [109]
51.	Battery storage based ELC using PI controller (simulation)	SEIG	Uncontrolled rectifier with IGBT based chopper for ELC, resistance replaced by battery.	2012 [97]
52.	DSP (TMS320 28335) based Integral resonant single loop voltage control.	PMSM	IGBT based controlled rectifier with 4-leg VSI.	2012 [110]
53.	Hybrid control of two parallel micro hydro generators and a wind generator. (simulation)	SG, IG	3-leg IGBT based VSC with capacitor, and 3-leg IGBT based VSC with IGBT based chopper.	2013 [111]
54.	Hybrid voltage regulation with capacitor bank and STATCOM using PI controller	SEIG	4-leg IGBT based VSC and star connected capacitor bank.	2013 [112] 2013 [113]
55.	Harmonic reduction with Multi-pulse ELC using PI controller (simulation)	IAG	Multi-pulse uncontrolled rectifier bridge with the zigzag phase-shifting transformer.	2013 [82]
56.	Fuzzy logic controlled battery charging system	SG	AC-DC rectifier with DC-DC chopper.	2013 [77]
57.	Binary weighted ballast load with PI controller	PMSG SESA	IGBT switch as a chopper. (Prototype model) Uncontrolled rectifier with IGBT switch (Simulation)	2013 [42] 2015 [47]
58.	Dump load control using PI controller (simulation)	MHG	Uncontrolled rectifier with IGBT based chopper.	2013 [100]
59.	Microcontroller (Atmega-32) based ELC	SG	3 sets of Anti-parallel SCR	2014 [78]
60.	Self-tuned fuzzy PI controller based ELC	PMSG	Anti-parallel SCR as a phase control switch.	2014 [21]
61.	Split dump load technique based ELC	SEIG	Bi-directional IGBT for chopping.	2014 [57]
62.	Atmega-32 based ELC with grid synchronization unit	MHG	Solid State Relays switches between resistors and generator.	2014 [122]
63.	Atmega-328 based ELC	MHG	MOSFET switch as a chopper.	2014 [102]
64.	DS-PIC30F6010 based ELC	SEIG	3-Single phase uncontrolled rectifier with IGBT based chopper.	2014 [69]
65.	Dynamic ELC for 3ϕ induction motor drive load (DS-1104 control board)	SEIG	IGBT based VSI and uncontrolled rectifier with chopper	2014 [48]
66.	DSTATCOM-DTC drive based voltage and frequency control using PI controller	SEIG	IGBT based VSI with a capacitor	2014 [73]
67.	Distributed ELC using PI controller: Excess power to house hold water heaters. (MSP-430 Launch Pad microcontroller)	SEIG	Bi-Directional Insulated Gate Bipolar Transistor Switching method as in [36].	2014 [58] 2014 [59]
68.	Power quality control of Pico-hydro power plant using star delta and zigzag transformers	SEIG	6-Pulse Diode rectifier with IGBT chopper 24-Pulse Diode rectifier with IGBT chopper	2014 [52] 2017 [56]
69.	PI based proportional resonant derivative controller (DSP, TMS320F28335)	SCIG	IGBT chopper connected to the three-phase bus through a non-controlled rectifier.	2014 [49]
70.	PLC based load controller	SG	3 Contactors with resistive load	2015 [39]
71.	Proportional controller (30)	SG	6-Pulse Diode rectifier with IGBT chopper	2015 [53]
72.	Harmonic elimination using p-q control theory	SEIG	IGBT based VSC with DC chopper	2016 [75]
73.	AVR with PI based ballast load frequency regulator.	SG	SCR based AVR and 3-Single phase AC-AC control (TRIAC) based load frequency regulator.	2016 [76]
74.	Improved Distributed ELC with PI controller.	SEIG	TRIAC based load frequency regulator.	2016 [36]
75.	Modified ELC with PI controller.	1ϕ-SEIG	Single phase diode rectifier with IGBT chopper	2016 [51]
76.	Droop based load control using proportional controller	SG	Contactor with discreet ballast.	2016 [40]
77.	Steady state analysis of ELC with P, PI, PID controller.	SG	6-Pulse Diode rectifier with IGBT chopper	2016 [5455]

In the above table: NN: Neural Network, IG: Induction Generator, SG: Synchronous Generator, AG: Asynchronous Generator, ELC: Electronic load controller; ELG: Electronic Load Governor; AVR: Automatic Voltage Regulator; MHG: Micro Hydropower Generator; IGC: Induction Generator Controller; SEIG: Self Excited Induction Generator; IAG: Isolated Asynchronous Generator; SESA: Self excited synchronous alternator; SESCG: Self Excited Squirrel Cage Generator; PMSG: Permanent Magnet Synchronous Generator

$$P_G = P_D + P_M \tag{1}$$

$$\Delta f = F_r - F \tag{2}$$

where, P_G is power generated; P_D is dump load power; P_M is main load power; F is output frequency; Fr is reference frequency; Δf is error signal.

Error signal through PI controller decides the firing angle, which determines the amount of power dissipation. Switches are fired at such firing angle to dissipated surplus power, equation (3).

$$\alpha = K_p \Delta f + K_i \int \Delta f dt \tag{3}$$

where, K_p is proportional gain and K_i are integral gain of PI Controller.

Power rating of ballast resistive load is equal to or be slightly greater than rated capacity of plant. Per phase resistance value and power consumption of dump load are calculated using Eqs. (4) and (5),

$$R = \left. \frac{3V_s^2}{K \times P_G} \right|_{\alpha=0} \tag{4}$$

$$P_D = \frac{V_s^2}{R} \left\{ \frac{1}{\pi} \left[(\pi - \alpha) + \frac{\sin 2\alpha}{2} \right] \right\} \tag{5}$$

where, R is dump load resistance value; V_S is generator phase voltage (rms value); K is dump load multiplication factor and normally considered around 1.2; α is firing angle; P_D is dump load power.

2.2. Experimental arrangement

Experimental arrangement (Fig. 2a) consists of a 3 kVA synchronous generator (S.G) driven by 3.5 kW prime mover (DC motor drive), rating of both machines is given in Table 4. As well, the enforcement of dump load controller mainly consists of sensing unit, control unit and switching unit (Fig. 2b). Frequency of output voltage is sensed and compared with reference value to control firing angle of switches.

i. Sensing Unit: The sensing circuit consists of potential transformer (VDE 0570) for measuring and providing voltage signals to zero-crossing detector circuit (ZCD). ZCD is circuited using LM741 IC for developing square wave proportional to the voltage signals. ZCD's output is fed to phase locked loop based frequency multiplier circuit (CD4046 & 74LS294) for higher resolution during F to V conversation. The circuit locks the rising and falling edge of input square wave signal with the falling edge of output signal for increasing frequency of output (approximately 10 times). As the phase locked loop is driven by positive signal transitions, output of ZCD block is locked with falling edge. Finally, the multiplied frequency signal is converted into a voltage signal using LM2907 IC and fed to comparator where the processed signals are compared with the reference value for getting error signal.

ii. Control Circuit: error signal is amplified by PI controller and reduces the steady-state error ($k_p = 1.13$ & $K_i = 0.512$), the controller gain values are obtained by trial and error tuning method. Initially, the proportional gain is tuned until the constant rate output by setting the integral term to zero. Once the obtained response is fast enough, the integral gain is tuned to reduce the steady-state error. PI controller's output is compared with high frequency carrier wave for providing pulses to switches through driver circuits. The high frequency is generated using SG3524 IC. The non-inverting amplifier based driver circuit with opto-isolator is used to provide isolation between the signals and power circuits.

iii. Switching Unit: Three-single phase rectifier (GBPC3506) with IGBT chopper (STGW40N120KD) and ACNW3190-1335 IC based opto-isolated gate driver circuit for engaging resistive load depend up on controller signal. In addition, output quantities of generator are measured and analyzed using three phase power quality analyzers (PQA – FLUKE 435) is used and input quantities of the generator (torque and speed) are measured using spring dial arrangement and tachogenerator respectively. Moreover, the surface temperature of generator under various operating conditions are measured and analyzed using a thermal analyzer (FLUKE Ti-32) and smart view software respectively.

2.3. Testing of machine

Based on theory, empirical evidence and standards (IEEE Std. 115™-2009), laboratory studies are conducted in experimental setup (Fig. 2a). Empirical evidence for analysis is obtained precisely by systematic operation of the apparatus. Generator is loaded from no load to full load and parameters (input and output) of generator is measured for plotting the efficiency, shown in Fig. 3. During loading, output voltage and frequency of the generator is maintained constant by regulating excitation and speed of prime mover respectively. From the depicted graph, it is observable that, the generator attains maximum efficiency near at 0.8p.u. load. Hence, operating the generator with 80% load is assumed to be an optimum because generator efficiency is inversely proportional to losses. Also, it is noticed that the efficiency of the generator is lesser in case of inductive loading (shown in dashed curve) due to the increase of reactive power and decrease of real power. Additionally, voltage and frequency variation of generator without regulating excitation and speed respectively under varying load is tested, shown in Fig. 4.

3. Investigation of generator and domestic loads with 20% voltage and frequency variation

The aim of this paper is to enhance the lifespan of hydroelectric generator by reducing the thermal stress. Therefore, the effect of proposed strategy (variation of voltage and frequency) on generator and consumer domestic loads are analyzed in this section.

3.1. Effect of dump load reduction in hydroelectric generator

Running the generator with reduced load (80%) provides maximum efficiency which assures loss reduction. In case of isolated generator with fixed excitation and fixed mechanical torque, operating the generator with 80% load increases frequency and voltage (Fig. 5). Percentage variances of output electrical and thermal parameters of generator during the investigation are exhibit in Table 2. As per IEEE standard 1250™-2011 and from the previous studies (Indian Electricity Rules 1956 'amended up to 25th Nov 2000'), the permissible range for grid frequency was ± 3 % of nominal i.e. 48.5 Hz to 51.5 Hz. This frequency ranges are given by manufacturers for operating the generation units [123]. In the proposed system, the change in frequency and voltage under load variation (from 1 to 0.8p.u.) are in permissible limit. Also, the result reveals that reduced dump load increases performance of generator, as well as, enhances the generator's lifespan. Moreover, the effect of voltage and frequency variation on consumer load (main load) is examined in subsequent Section 3.2.

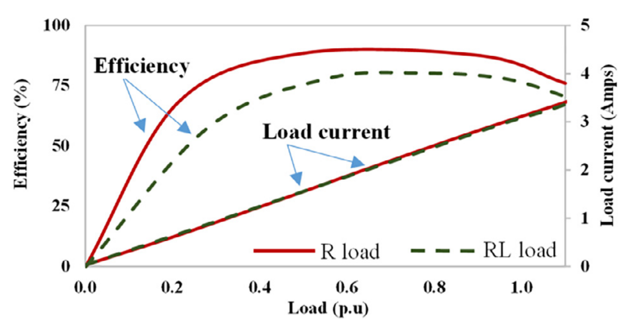
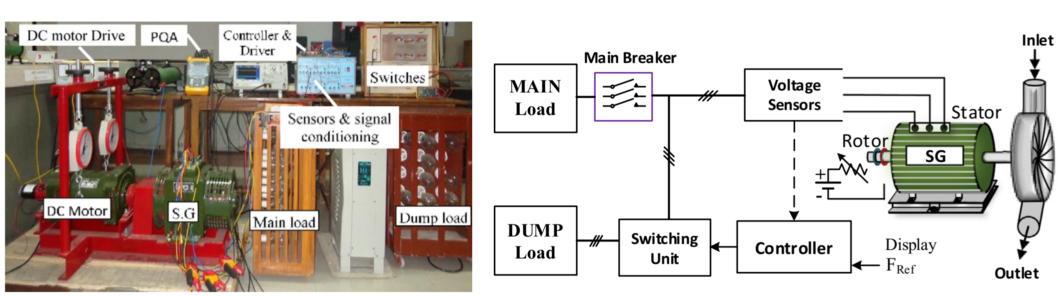


Fig. 3. Efficiency and current profile of synchronous generator.



(a) Snapshot of experimental arrangement (b) Schematic diagram

Fig. 2. Experimental arrangement of electronic load controller.

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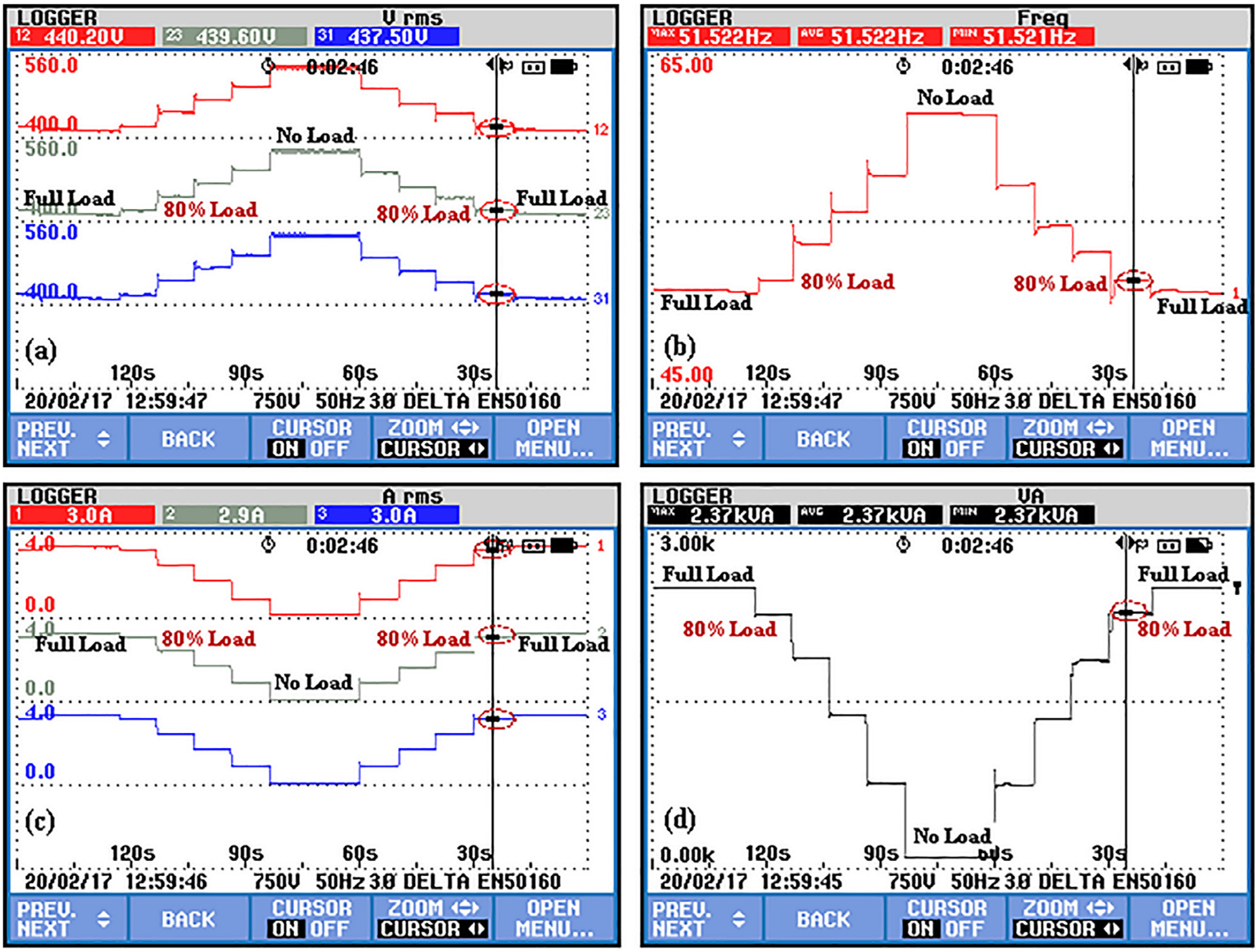


Fig. 4. Variation of output electrical quantities during load variation without regulation. (a) Voltage; (b) Frequency; (a) Current; (b) Power.

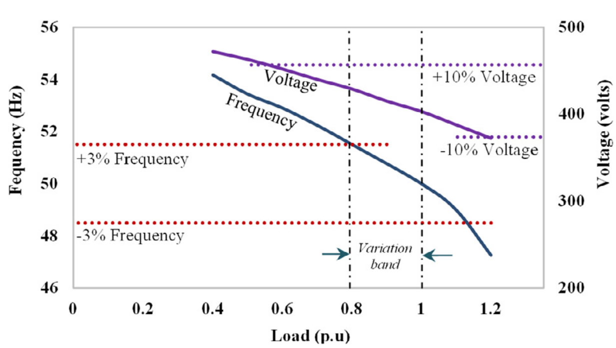


Fig. 5. Variation of voltage and frequency at different Loads.

Table 2
Variation of parameter from 1p.u. load to 0.8p.u. load.

Parameter	% Variation	
Temperature	8.4	↓
Current	18	↓
Voltage	5	↑
Frequency	3	↑

All the above values are in percentage.
↑ represents an increase in percentage.
↓ represents a decrease in percentage.

3.2. Performance of domestic loads under 20% reduced load

Reduction of dump load increases the voltage and frequency of generator. Accounting this variation (Fig. 5), an investigation is performed using different domestic loads. The domestic loads are tested in the laboratory with voltage and frequency variation (Fig. 5) using AC programmable power supply (AMETEK LX-3000). Functioning of entire domestic loads with voltage and frequency variation is presented in Table 3. From the studies, it is observed that, due to the inductive nature in fan and pump load there is a slight speed variation, whereas, no changes are observed in the other domestic loads such as lightings and heaters (due to resistive in nature). Overall, it shall be concluded that, reducing 20 percent of dump load increases performance of generator and lifespan without influencing the performance of domestic loads.

4. Lifetime estimation of hydro electric generator with full load and 0.8 p.u. Load

Source of energy from micro hydropower plant serves rural areas where grid power is inaccessible and it must be operated continuously for providing uninterrupted power. Henceforth, a system has to be developed for a continuous duty in accordance with operating stresses [119]. In practice, stator windings of hydro-electric generator are optimized for good efficiency by adding electrically active material (copper winding and insulation) [124]. The

Table 3
Effects of reduced dump load strategy on consumer loads.

Sl. No.	Load	V	F	Effects
1	Incandescent lamp	↑↑ ↓↓	↑ ↓	No variation is observed
2	Fluorescent tube	↑↑ ↓↓	↑ ↓	No variation is observed Observed flickering
3	Fan and Pumps	↑↑ ↓↓	↑ ↓	2.75% Increase in speed 2.75% Reduction in speed
4	Heating system	↑↑ ↓↓	↑ ↓	No variation is observed
5	Cooling system	↑↑ ↓↓	↑ ↓	No variation is observed
6	UPS/ Inverter	↑↑ ↓↓	↑ ↓	No variation is observed
7	Entertaining system	↑↑ ↓↓	↑ ↓	No variation is observed

↑↑ represents increase 10 % of voltage.
↓↓ represents decrease 10 % of voltage.
↑ represents increase 3 % of frequency.
↓ represents decrease 3 % of frequency.

Table 4
Machine parameters.

Machine Parameters	SG	DC machine
Voltage	415 V	220 V
Current	3.5 amps	19 amps
Frequency	50 Hz	–
Power	3 kVA	3.5 kW
Speed	1500 rpm	1500 rpm
Ext. voltage	220 V	220 V
Ext. current	1.4 amps	0.9 amps
No of poles	4	4
Type	Salient pole	Shunt

electrical insulation system has a significant act in the overall construction of generator because the prime function of insulator is to insulate electric conductors in normal operating conditions, to resist electrical stress, and to provide mechanical support over a wide range of temperature. During regular operation, hydroelectric generator often confronts electro-thermomechanical stresses. Increase in these stresses, especially thermal stress causes reductions in lifespan of the generator and leads to failure [125,126]. Thermal stress on stator winding and insulation is directly related to the generator loading. Increase in load current creates a temperature gradient between stator conductors and insulation cause thermal aging. Thermal aging is usually the breaking of chemical bonds, that results in creation of gas and water due to thermal agitation of molecules [127]. Primary, end-of-life failure mode is associated with insulation failure occurring due to deterioration at or near copper conductors in the front half of coils that are operating at or near line potential. This deterioration usually results in an in-service failure of winding [128]. Therefore, in hydroelectric generators, thermal stress occurs, particularly in peak-load. There are different methods for estimating the life span of the generators and their parts [129], in this paper using modified Arrhenius law equation (6), the lifespan of a hydroelectric generator is estimated.

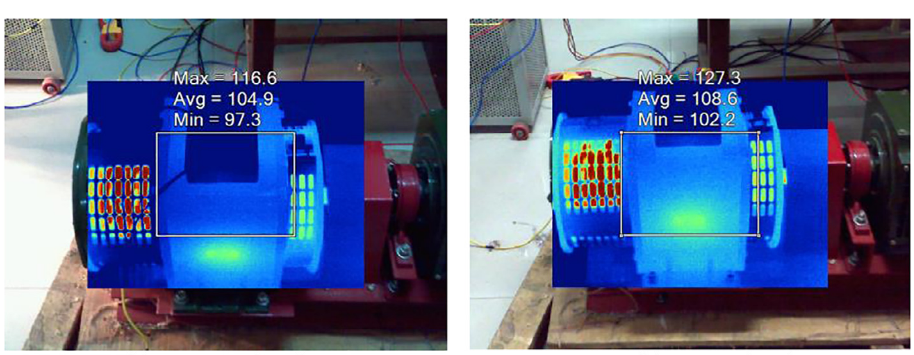
In laboratory, an experiment has been carried out with a 3 kVA synchronous generator for investigating the thermal effect on generator loaded with 0.8p.u. load and 1p.u. load individually. The generator is operated with two different load points for a specific time (2 Hrs run with 5 Hrs. interval) and their thermal effect is measured using the thermal analyzer. The measured results are further analyzed using smart view software to understand the temperature variation. The results (Fig. 6) impart that, the generator running with full load produces 8.4% more thermal effects than generator running with 80 % of load.

Considering variation in temperature variation, the lifespan of generator stator winding is estimated with few assumptions as follows;

i. The lifespan of generator stator winding is 50,000 hrs.
ii. The temperature of generator is computed in steady state.
iii. Surface temperature of machine is 20 °C lesser than the stator winding temperature.
iv. Insulation temperature of machine is 10 °C greater than the winding temperature.
v. Only thermal stress has been considered, as the level of electro-mechanical stress is very low in comparison.

$$\xi_L = \lambda_L C^{-\left(\frac{I_T - T_W}{T_{\Delta b}}\right)} \quad (6)$$

where, ξ_L is estimated winding lifespan, λ_L is winding lifespan, C is constant (0.5), I_T is temperature index. According to IEC 216, 1987 standard, temperature index (I_T) provides information about a thermal endurance profile (TEP) for the thermal evaluation of individual insulation material. Based on the definition, the I_T is a figure that equates to the temperature in centigrade, which is derived through extrapolation of a thermal endurance curve up to a specified period of time, typically 20,000 h [128]. T_w is average winding temperature and $T_{\Delta b}$ is base difference insulation and winding temperature (10 °C). Using above equation, the lifespan of generator has been computed for full load and reduced load, from the calculated solution, it is proved that the electronic load controller with reduced dump load provide sufficient advantage and increases the lifespan (strength) of the stator winding by 52.62 percent. The insulation aging at an exponentially faster rate with respect to an increase in operating temperature. Hence, reducing the load slightly further



(a) 0.8 p.u. load (b) 1 p.u. load

Fig. 6. Temperature variation under reduced dump load and full dump load in °F.

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reduces operating temperature and greatly reduces the rate of thermal aging.

5. Sensor fault detection and isolation

In the controlling process, sensor fault may cause degradation in control performance, disastrous accident or system shut down. Above sensor fault have different types like gain fault, short faults, open circuit fault, noise faults, and constant faults. The absence of signal from the voltage sensor creates an open circuit fault, which is considered in this paper. In this case, due to the drop out of voltage sensor signal causes overloading in generator by adding dump load with the main load. Hence sensor fault detection and isolation (SFID) technique is adopted to avoid overloading the machine through open circuit fault detection. Usually, sensor faults depend on hardware and software redundancy, which is costly and hard to implement in real time. Literature studies say that, observation technique is carried out for the identification and isolation of sensor fault [130–132]. In these techniques, faults are detected by comparing the measured values with the estimated values, which requires a system model and their respective parameters. Moreover, multiple sensor fault is very hard to detect, hence, this paper adopts the diagnostic fault detection method [133] that works by measuring phase voltage only. The balance three-phase voltage (V_{abc}) is given as,

$$\boldsymbol{V_{abc}} = \begin{cases} \boldsymbol{v_a} = \boldsymbol{V_m}\sin(\boldsymbol{\omega t} + \theta) \\ \boldsymbol{v_b} = \boldsymbol{V_m} sin(\omega t - \frac{2\pi}{3} + \theta) \\ \boldsymbol{v_c} = \boldsymbol{V_m} sin(\omega t + \frac{2\pi}{3} + \theta) \end{cases} \tag{7}$$

where V_m is voltage amplitude, ω is angular frequency, and θ is initial phase angle.

The modulus of Park's vector($|\boldsymbol{V_s}|$) is obtained through applying the Park transformation to input phase voltages and it is given as,

$$\mathbf{v_d} = \sqrt{\frac{2}{3}}\mathbf{v_a} - \frac{1}{\sqrt{6}}\mathbf{v_b} - \frac{1}{\sqrt{6}}\mathbf{v_c} \tag{8}$$

$$\mathbf{v_q} = \frac{1}{\sqrt{2}}\mathbf{v_b} - \frac{1}{\sqrt{2}}\mathbf{v_c} \tag{9}$$

$$|\mathbf{v_s}| = \sqrt{\mathbf{v_d^2} + \mathbf{v_q^2}} \tag{10}$$

where $\boldsymbol{v_d}$ and $\boldsymbol{v_q}$ are the Park's vector component.

To normalize phase voltage ($\boldsymbol{V_{abc}N}$), phase voltage is divided by Park's vector modulus is given as,

$$\mathbf{V_{abc}N} = \frac{\mathbf{V_{abc}}}{|\mathbf{V_s}|} \tag{11}$$

And, it is proved that the Park's vector modulus can be given by,

$$|\mathbf{v_s}| = \mathbf{V_m}\sqrt{\frac{2}{3}} \tag{12}$$

Due to normalization, the normalized phase voltage will always take values within the range of $\pm\sqrt{2/3}$ and it is independent of measured phase voltage amplitude, therefore the normalize the phase voltages are given as,

$$\mathbf{V_{abc}N} = \begin{cases} \mathbf{v_a}N = \sqrt{\frac{2}{3}}\sin(\omega\mathbf{t} + \theta) \\ \mathbf{v_b}N = \sqrt{\frac{2}{3}}sin(\omega t - \frac{2\pi}{3} + \theta) \\ \mathbf{v_c}N = \sqrt{\frac{2}{3}}sin(\omega t + \frac{2\pi}{3} + \theta) \end{cases} \tag{13}$$

$V_{abc}N$is always within range of ±0.8165. Likewise, the instantaneous maximum value $|v|_{abc}^{max}$ under normal operating condition is approximated by,

$$|\mathbf{v}|_{\mathbf{abc}}^{\mathbf{max}} \approx \mathbf{V_m}\left\{\frac{\sqrt{3}}{2} + \left(1 - \frac{\sqrt{3}}{2}\right)|\mathbf{cos}(3\omega\mathbf{t} + \theta)|\right\} \tag{14}$$

Similarly, differential protection in the system takes care of ground fault, but the sensor fault may remain undetected. To detect the sensor fault, a variable '*d*' is introduced. '*d*' is calculated using Eq. (12), which is zero under normal balance flow of voltage.

$$\mathbf{d} = \frac{\omega}{2\pi}\int_0^{\frac{2\pi}{\omega}} |\mathbf{v_{aN}} + \mathbf{v_{bN}} + \mathbf{v_{cN}}|\mathbf{dt} \tag{15}$$

SFDI algorithm (Fig. 7) is embedded in the electronic load controller. The reliability of the developed algorithm is investigated by creating a sensor fault in the healthy system (fully loaded test machine equipped with SFDI based reduced dump load control strategy) and the proper result was obtained. At the instant of fault, the system is stopped with 5 s delay as depicted in Fig. 8.

6. Implementation of proposed strategy

Micro hydro power plant generates electricity utilizes natural flow of water and generating during demand period is not usually practiced [10]. As well, due to inefficiency of mechanical governor system, water flow is not regulated to generate the required power during demand period. This constrains makes most of the MHP to accept ELC, which engages the generator with full load at all the times for maintaining output voltage and frequency constant [8]. Operating the generator with full load perpetually develop operating stresses and degrades its component, results in poor efficiency and lifespan reduction. Hence, an inventive approach is introduced in this paper for enhancing generator efficiency and extending gen-

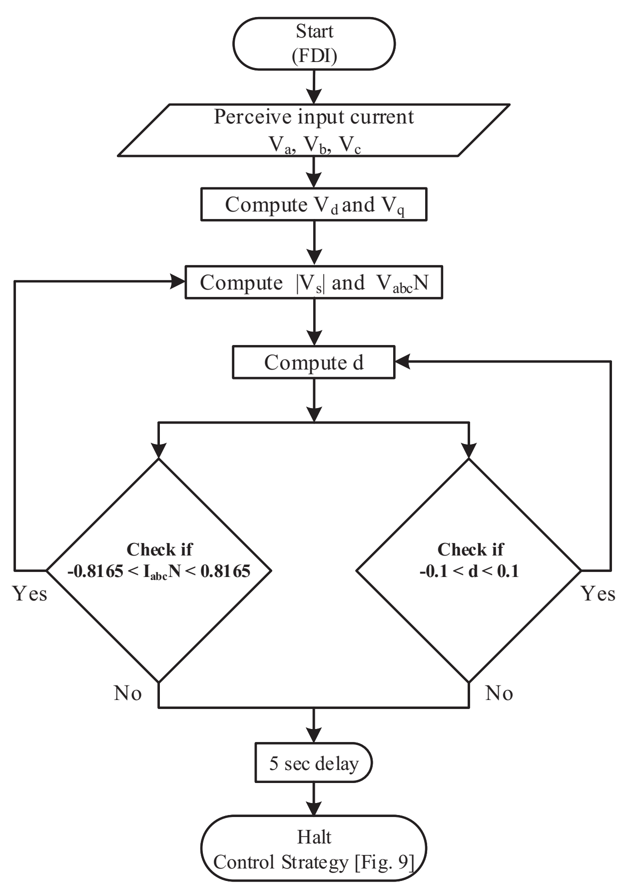


Fig. 7. Flow diagram for sensor fault detection and isolation.

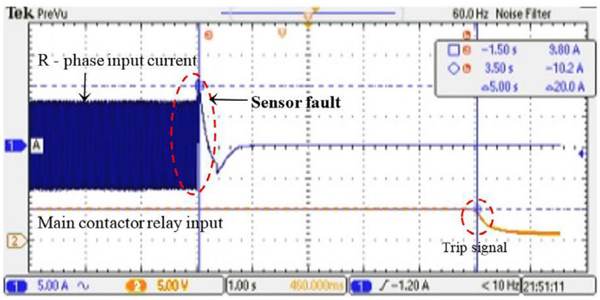


Fig. 8. Experimental result for sensor fault and isolation.

erator lifespan by reducing 20 percent of dump load from its rating. The dump load is supplemented for main load and it is toted up by the controller output, as shown in Fig. 9.

As the frequency is directly proportional to load variation in isolated hydro generator, it is considered as the prime factor. Hence the reference frequency is increased for reducing the dump load value. In the test machine, 3 percent frequency (1.5 Hz) is increased for reducing 20 percent of dump load. Hence, employing proposed control strategy, the thermal effects and power wastage is considerably reduced (Table 2) without any extensive modification. In addition to this, the protective futures against sensor fault and overloading is embedded in the controller. Adopting the same controller for different rated generator and different moment requires reference frequency readjustment feature. Therefore, external reference frequency (F_r) adjusting provision is provided in proposed shown in Fig. 10. Also, in the proposed strategy, dump load can be reduced without interrupting the process. Actual operation of the system was successfully verified through experimentation. Additionally, overload protection features are also provided in the proposed control strategy. In case of overloading, input line current increases above the rated value, as well, voltage and frequency get drooped. The reduction in generator frequency (F) due to increased load has multiple adverse effects on overall system performance [51].

i. Frequency reduction causes drop in system voltage (V_G) due to shifting of magnetizing characteristics towards downward direction and considering (V_G/F) ratio constant.
ii. Increasing active power with constant input power (speed), reduces the frequency to meet the core losses. Therefore, the system frequency reduces during overloading.

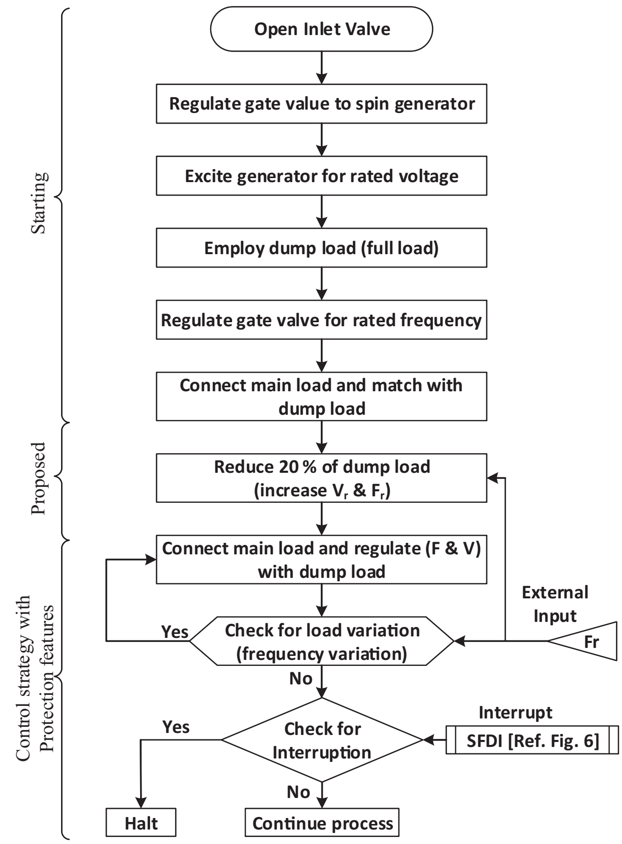
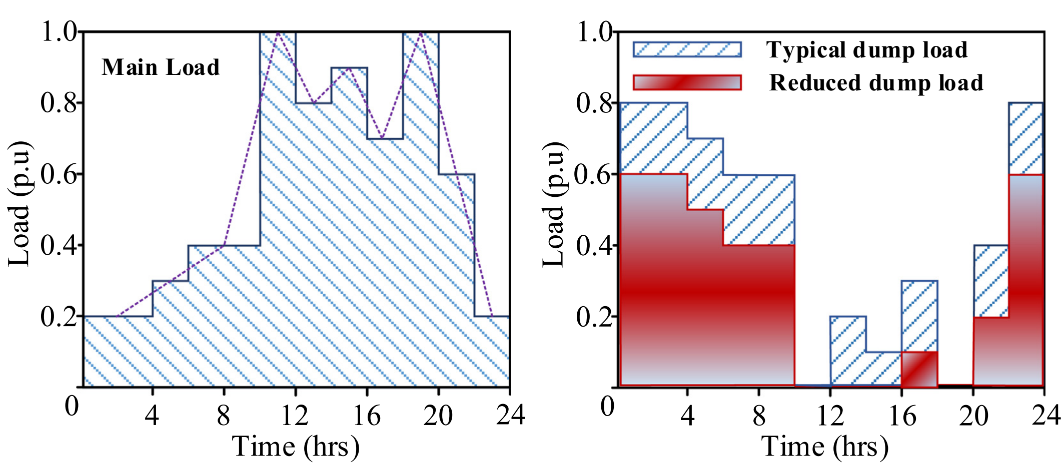


Fig. 10. Flow diagram of the proposed strategy.

iii. In case of SCIG, the reduction in system frequency increases capacitive reactance (X_c) of capacitor bank ($X_c = 1/2\pi f_c$), which decreases system voltage due to shifting of operating point towards downward direction on magnetizing characteristics.

Therefore, if generator output frequency decreases beneath the preloaded value, the signal to main breaker will be stopped with an alert to protect the system. Once the output reaches steady state, the reference frequency can be adjusted for automatic



(a) Load duration curve (b) Dump load variation curve

Fig. 9. Typical load curve of a micro hydropower plant.

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management cycle. The overall flow diagram with starting of generator, reduction of dump load future with protection system is depicted in Fig. 10.

7. Result and discussion

The proposed reduced dump load controller is developed and experimented in a 3 kVA SG with varying load to study performances of the controller under steady-state and dynamic state. Using experimental arrangement (Fig. 2), load test on unregulated isolated SG is carried out for studying the performance, and the results are shown in Fig. 4. As well, Figs. 11 and 12 show the performance of the SG under varying load with typical DLC and proposed RDLC strategy. The experimental results shown are measure using three-phase power analyser (Fluke 435). The change in parameters with respect to main load variation Fig. 11 (a) and (b), are discussed below:

In the proposed reduced dump load strategy, voltage at generator terminal gets increased by 4.57 % from the existing full load shown in Fig. 11(c) and (d). As per 1250^{TM} -2011 IEEE standard

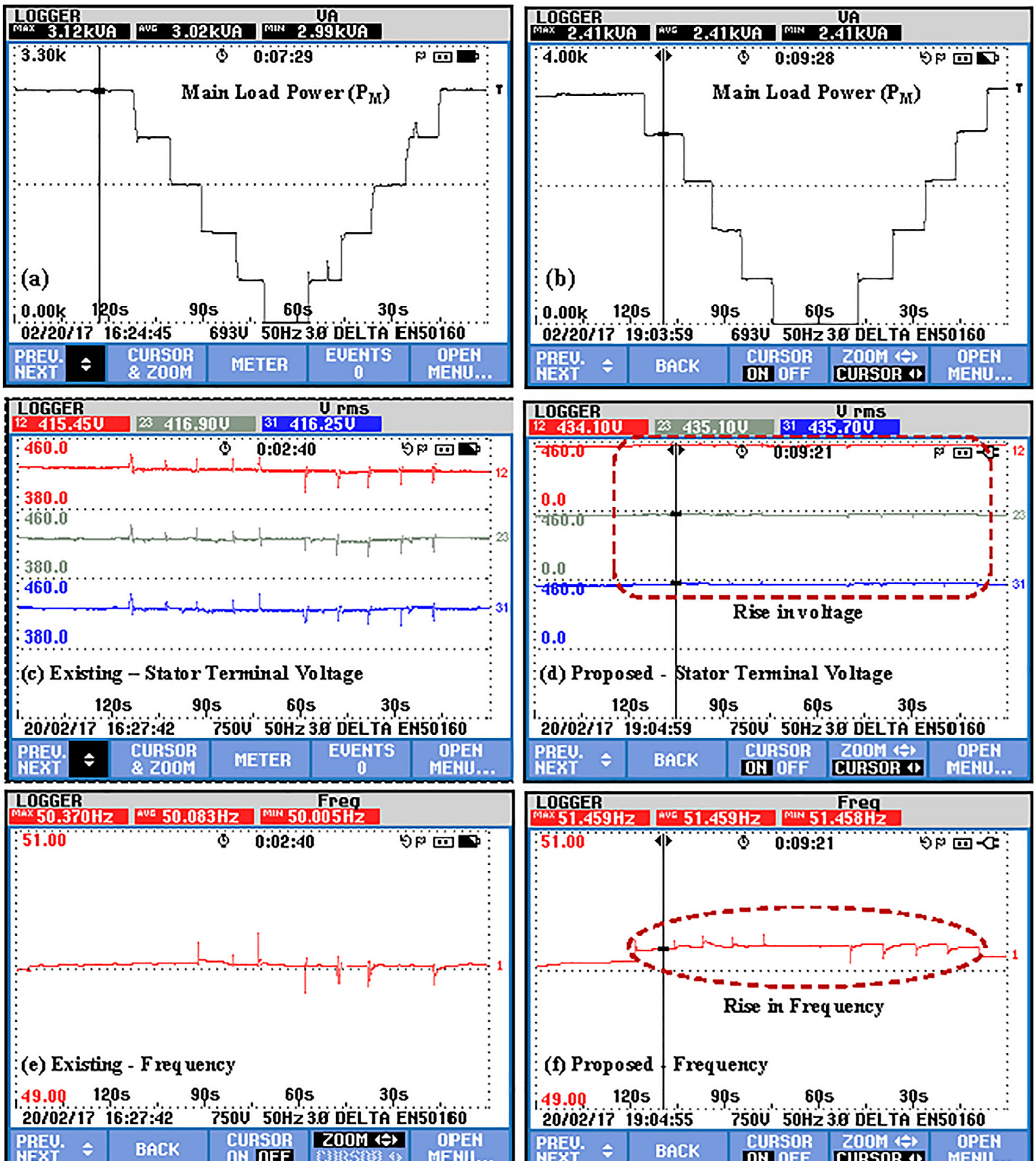

Fig. 11. Output electrical parameter of generator between existing and proposed strategy Existing - (a) Power; (c) Voltage; (e) Frequency Proposed - (b) Power; (d) Voltage; (f) Frequency.

and from the previous studies [123], voltage rise due to reduction in load is in acceptable limit. In fact, voltage rise weakens the insulation system, whereas it depends upon the percentage of rise. Therefore, considering the studies and standards, it can be concluded that the machine with proposed strategy does not influence the generator and the load connected to it.

Fig. 11(f) shows the rise in frequency from the conventional full load strategy as in Fig. 11(e). As per 1250^{TM} -2011 IEEE standard and from the previous studies and frequency rise due to reduction in load is in acceptable limit. In fact, rise in frequency influences the load with inductance, whereas it depends upon the percentage of rise. Therefore, considering the studies and standards, it can be concluded that the 2.74% of frequency rise does not impact the generator and the load connected to it.

Similarly, Fig. 12(a) and (b) shows the current profile of existing and proposed strategy respectively. The current in the proposed strategy is 17.4% decreased from the conventional strategy, which indirectly entails reduction in thermal effect and enhancement of

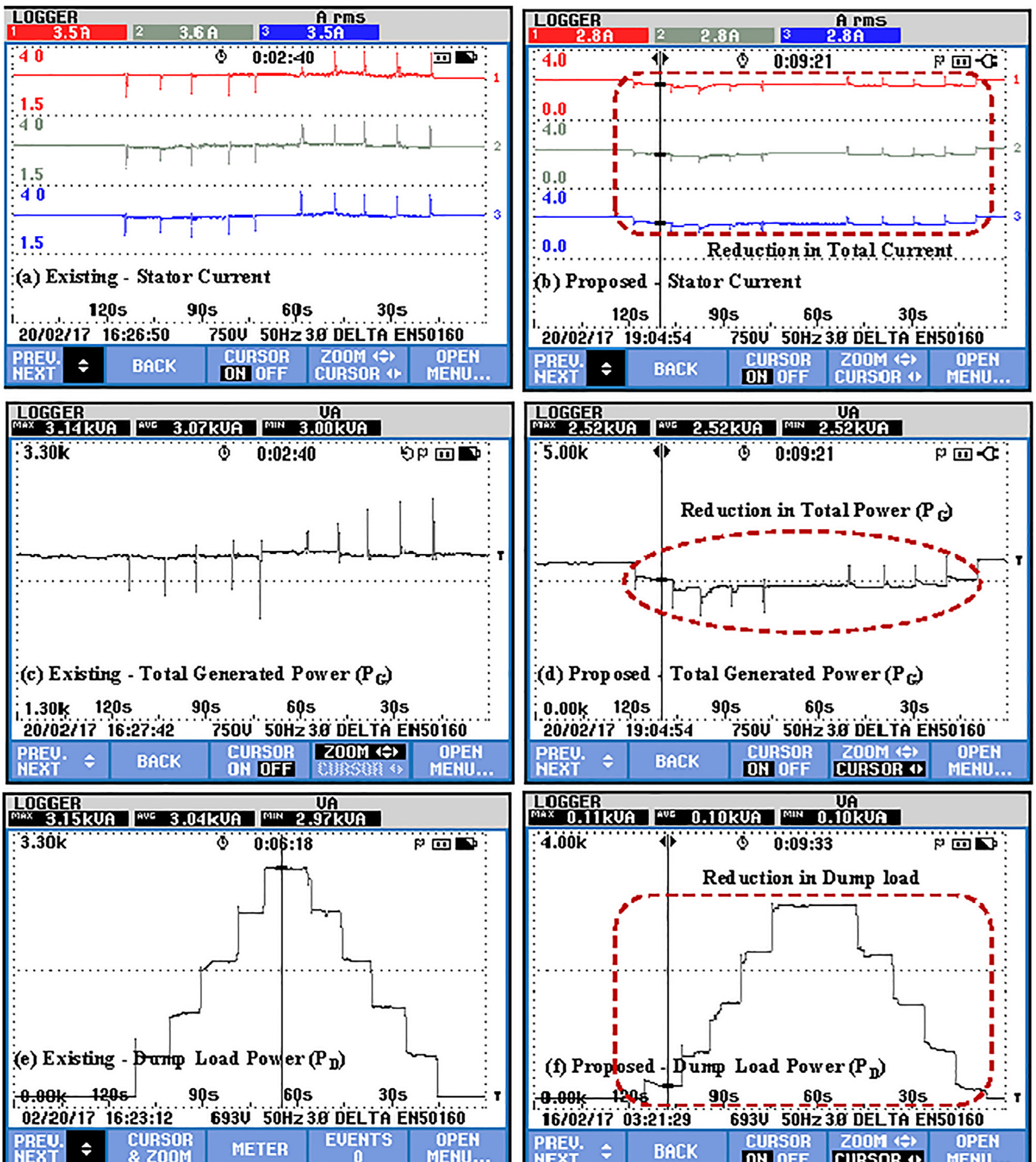

Fig. 12. Output electrical parameter of generator between existing and proposed strategy Existing - (a) Current; (b) Main Load power; (c) Dump load power Proposed - (b) Current; (d) Main Load power; (f) Dump load power.

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generator life span. Also, the reduction in current reduces the electrical and mechanical effect of the generator, especially, during load changing [134].

Likewise, the generator total output power (P_G) with existing and proposed method is shown in Fig. 12(c) and (d) respectively. Utilizing the proposed scheme, 21.0 % of power consumption is reduced from the existing method. This strategy not only reduce the power consumption, but also reduce the aging of generator due to full loading at all times.

Fig. 12(e) and (f), shows dump load power (P_D) with respect to the main load as in Fig. 11(a) and (b). In the proposed method, 20 % of dump load is reduced from the rated value. This reduction consumes less power, that benefits in less wastage and less cooling effect in cost reduction compared to the typical rated dump load electronic controller.

Considering the thermal effect, the results in Fig. 6 impart that the generator running with full load (100 % load) produces 8.4 percent more thermal effects than generator running with reduced load (80 % load). Comparing the thermal effect between fully loaded and reduced loaded generator, the results are externalized using Eq. (6). The results show that the fully loaded synchronous generator is more affected than the reduced loaded synchronous generator. It is noticed that the electronic load controller with reduced dump load provide sufficient advantage and increases the life span (strength) of the stator winding by 52.62 percent. The insulation aging at an exponentially faster rate with respect to an increase in operating temperature. Hence, reducing the load slightly further reduces operating temperature and greatly reduces the rate of thermal aging.

8. Conclusion

ELC receives significant attention in stabilizing the output of MHP. Using the typical ELC system, the lifetime of generator is reduced due to continuous full load operation. Hence, the paper proposes reduced dump load technique in ELC that brings down operating stresses, especially the thermal stress from 127.3 °F to 116 °F. Experimented result and analysis manifests that, employing reduced dump load strategy increases generator life span up to 52.62 %. Besides, protection of generator from overloading and sensor fault is taken care. The open circuit sensor fault detection and isolation algorithm is embedded in the controller to protect the system from overloading during sensor failure. Overall, the proposed system can be easily adopted in the existing dump load strategy and it is cost effective.

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