Rural area electrification with variable speed diesel generator and lithium-ion battery hybrid system

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Abstract: A reliable energy source is an essential component of any modern society, yet substantial part of the world population experiencing energy poverty. This paper presents variable speed diesel generator (VSDG) and lithium-ion battery hybrid system for rural area electrification. This hybrid system can be efficiently and economically used for power supply in basic needs like power, water and communication (PWC) system. The proposed hybrid system constitute VSDG sets connecting to DC bus via fully controlled rectifiers serves as the main power supply sources and Lithium-ion battery pack linked to the DC bus through DC/DC converters serves as an auxiliary power supply. The variable speed concept of DGs helps to economic operation with diminished fuel consumption as its speed changes with load variation. The efficient separation of low frequency and high frequency components of load currents and its assignation to suitable sources helps to reduce the transients during load power fluctuations. One of the generators will be turned off when total power demand goes below a specified value and consequently significant fuel savings can be accomplished. The execution of proposed system is evaluated through MATLAB/Simulink software and its substantiation by experimental test bench.

Keywords: variable speed diesel generator; VSDG; lithium-ion battery; load sharing approach; AC/DC converter; DC/DC converter; PWC system.

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1 Introduction

The people living in rural areas of all around the world facing the problem of meeting power demand for their essential needs like PWC system (Arriaga et.al., 2013). According to an article released by the United Nations, 1.6 billion of the 7.1 billion people in the world had no access of electricity. The diesel generator (DG) is most commonly used for power supply in remote areas in those places where do not having the access of grid power. Conventionally, the constant speed diesel generator (CSDG) is most popular for reliable power supply. The main concern of CSDG is that it is running at constant speed (say 1,500rpm) irrespective of load changes which may leads to more fuel consumption and low efficiency at part load (Kumar et al., 2019). The conventional method of selecting DG set is based on peak load demand. Therefore DG set has to be oversize according to the prevalent conditions.

The average capacity utilisation of DG set as low as 30% of its rated capacity. Because of this, not all fuel burnt in combustion chamber during light load condition and fuel economy become poor. The partially burnt fuel dilutes the oil in the cylinders and may cause excessive wear in the cylinder walls and carbon build up. These harmful and destructive conditions impose severe deterioration to the engine performance and permanent engine failure (Waris and Nayar, 2008). Conventionally, DG set hybrid energy system which combines with energy storage system is commonly applied for power supply in remote areas. Unfortunately, the introduction of energy storage system also results in even longer periods of low load condition on DG set (Singh et al., 2019).

Recently, variable speed diesel generator (VSDG) has been developed where engine speed is adjusted to match with the engine power output to the load power demand. The system utilises a PMSG driven by IC engine. The above problems of CSDG can be mitigated with the application of VSDG, where the performance is satisfactory even at light load condition. In the literature of

Bellache et al. (2015) and Lidozzi et al. (2012) carried out performance analysis and comparative study of CSDGs and VSDGs. During the variation of load power, occurrence of transients due to surges is a major concern in CSDG and VSDG. In order to reduce these issues, energy storage system (ESS) is incorporated along with VSDG and is narrated in the literature (Trovao et al., 2015; Suliman et al., 2017). A CSDG and Lead acid battery hybrid system is modelled in Bolognani et al. (2011) and Bianucci et al. (2015). The various power sources are connected to a common dc bus and the design steps of DC bus with lesser number of switches and its difficulty in control are narrated in Apsley et al. (2009). A linearised modelling of AC/DC and DC/DC converters are illustrated in paper Zahedi and Norum (2013). For high power applications, a multi-source hybrid system (Diesel-wind-battery) is explicated in literature (Tankari et al., 2013). The integration of renewable energy with battery bank is depicted in literature (Prajapati and Fernandez, 2020).

The forthcoming Lithium-ion battery technology having several advantages including increased energy density and longer life span. Lithium-ion (Li-ion) batteries are an attractive proposition for use in hybrid energy operation along with Solar/DG system. In comparison with other rechargeable batteries, Li-ion provides very specific energy and large number of charge discharge cycles and the cost is also reasonable. Thus Li-ion batteries are preferred choice over other technologies such as Silver-zinc, Lead-acid and Nickel-metal-hydride (Zeeshan, 2017).

1.1 Aims and objective

The proposed hybrid system consists of two VSDG and a Lithium-ion battery to supply power in rural areas. In this model, the hybrid system is interconnected through a common DC bus bar. In order to develop a sample model, a case study has been conducted in Kadambankombai, Coimbatore district, tribal village in Tamil Nadu, India. In this village constitute of 30 houses and a community hall. Total population of this village is 168. Currently no grid power access to this village and a solar power plant of capacity 1.5 KW has been installed for meeting minimum lighting load in houses and community hall (District environmental profile for eco sensitive areas in Tamil Nadu Western region, 2015). The village peoples are facing the issue of sufficient power for meeting their essential needs like lighting loads, agriculture, and water treatment plant and communication system. The total estimated power demand for meeting lighting loads, water treatment plant and communication loads in the village is 400 kW. In this paper, we proposed power supply scheme for Kadambankombai, in order to meet their total PWC load demand.

Contribution of this paper mainly focussed on, two VSDGs are connected to a DC bus through AC/DC converter and a Lithium-ion battery is linked through a DC/DC converter. The power management strategy is so developed that the main part of load is derived from two VSDGs and retain a constant DC bus voltage at desired level. In order to mitigate the power fluctuation issues due to sudden load changes, a Lithium-ion battery is connected along with VSDG. The speed of VSDG is automatically adjusted along with change in load condition and hence fuel economy can be achieved. One of the VSDG will be turned off when total power demand goes below a specified level and the remaining VSDG will meet the low power load. In this way of intelligent switching of generators leads to efficient and economic operation.

The paper is organised as follows: the designing of variable load and its assignation strategy is given in Section 2; the modelling of subsystems (PMSG-based DG sets, lithium-ion battery pack, power converters) is given in Section 3; the power distribution and control strategies for different power resources are described in Section 4; the simulation results and discussions are presented in Section 5; the experimental validation on the reduced scale system is presented in Section 6; and the conclusion is given in Section 7.

2 Power source for PWC system

The power supply for PWC has been designed for Kadambankombai is 500KVA system and the operations are scheduled from 7.00 AM to 19.30 PM. The power consumption profile for the village is depicted in Figure 1. It has been designed for five different levels. Level A (479 KVA, 450 KW) is planned for maximum load condition, which includes lighting loads, operation of water treatment plant and the communication loads. Level B (391KVA, 365KW) relates to considerably diminished power level lower than level A. Similarly, the level for different load conditions for Level C (312 KVA, 288 KW), Level D (90 KVA, 77 KW) and Level E (50 KVA and 48 KW) are scheduled.

Figure 1 Load variations of the PWC system (see online version for colours)

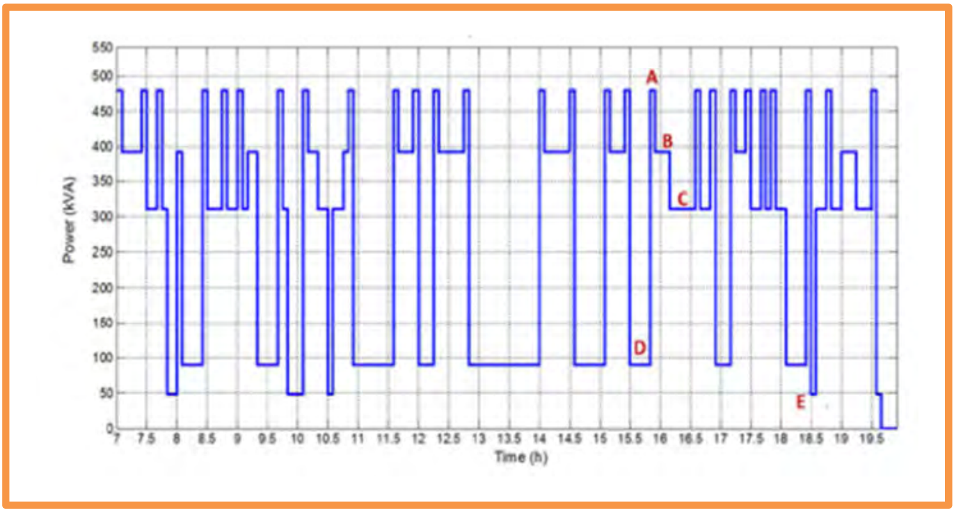
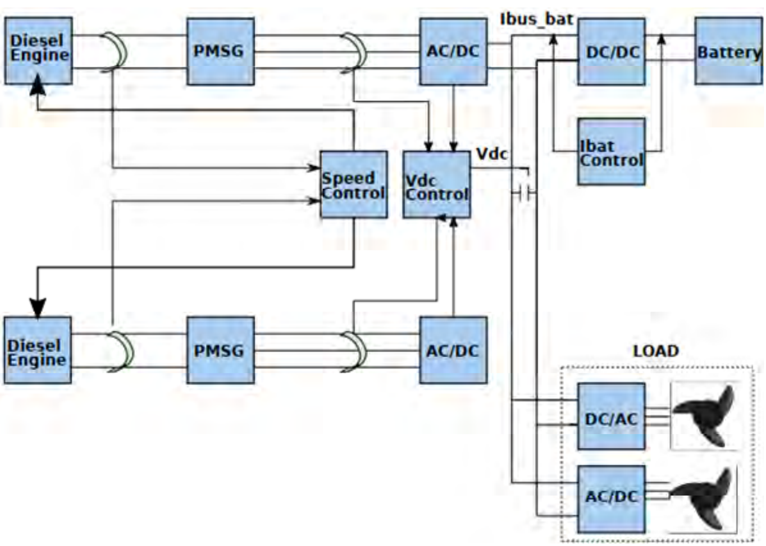


Figure 2 Proposed hybrid model (see online version for colours)



The hybrid system constitute with two idential 250 KVA, VSDGs and a Lithium-ion battery shown in Figure 2. The variation power and energy curve corresponding to load variation is depisited in Figure 3. The maximum energy needed for ESS system are assessed from power curve and can be calculated with the relation $\Delta P = P_{VSDG}\text{-} P_{Load}$. From the energy variation curve, the maximum peak occurs at $\Delta E_{max} = 44$ kWh. This value indicates the maximum rating of battery to be used is 44 KWh. In actual practice, 75% of full capacity of battery can be usable and hence for getting 44 KWh capacities, 60 KWh rated battery has been used. A comparative study of different ESS technologies in terms of their cost, energy density and specific power are given in Table 2. From the comparison, it is evident that the Lithium-ion battery has longer life and good energy density even though its cost is high. With considering the benefits of Lithium-ion battery, confirms that it has reasonable operating cost and efficient working conditions for an extensive period of utilisation.

Figure 3 Power and energy curve for ESS (see online version for colours)

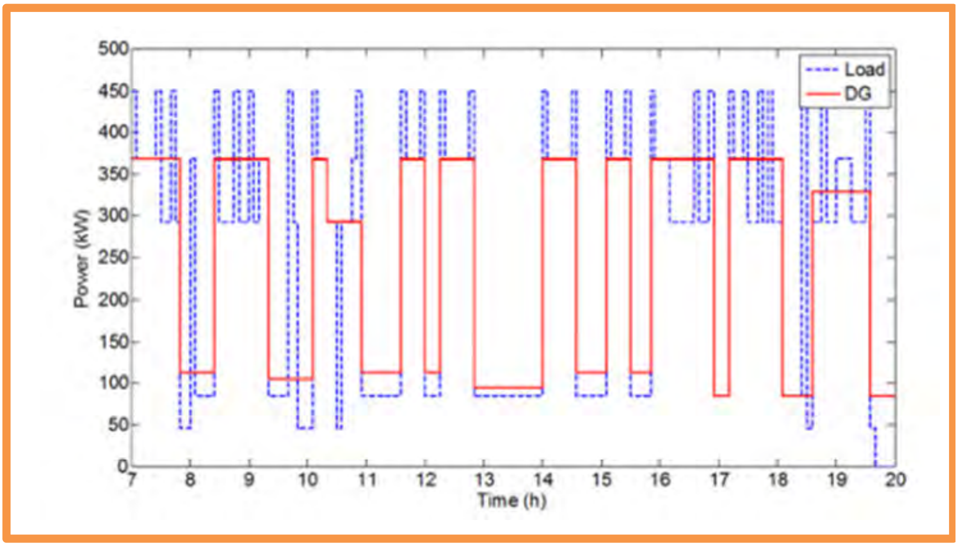


Figure 4 Power and energy curve for ESS (see online version for colours)

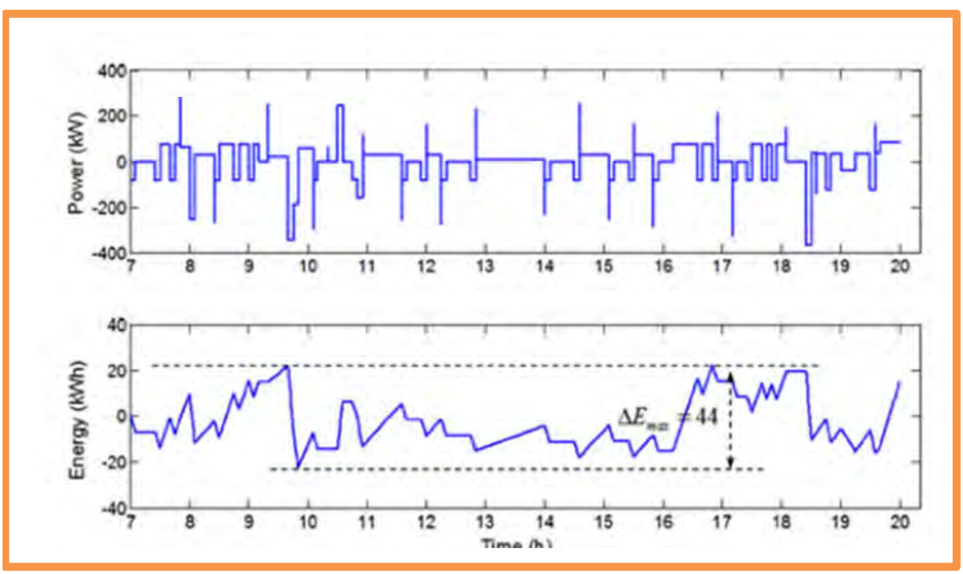


Table 1 Comparison of different battery technologies

Battery	*Specific power (W/Kg)*	*Specific energy (Wh/Kg)*	*Energy density (Wh/L)*	*Cycling life (cycle)*	*Capital cost ($/Kwh)*
Li-ion	500	150	300	10,000	2,000
Lead-acid	180	40	70	1,000	300
ZnBr	70	50	60	2,000	500
NaS	190	190	200	3,000	450
Flywheel	950	50	50	20,000	5,000
VRB	160	30	33	12,000	600
NiCd	230	65	100	2,500	1,150

3 Designing of subsystem for hybrid model

3.1 Variable speed diesel generator

The analysis of performance of CSDG and its control are analysed in paper (Maftei et al., 2009) and (Hui et al., 2013). The drawbacks of poor efficiency of CSDG at low load condition are overcome with VSDG is depicted in Haruni et al. (2010). The choice of the power-speed relationship for variable speed operation determines the system fuel consumption as a function of delivered power. Table 2 illustrates the expected improvement in fuel consumption using the variable speed operation. It has been experimentally proved that cost of energy $/kWh in fixed speed operation is $0.59 with fuel usage 18,341 L, with the same load the cost of energy in variable speed operation $0.56 with fuel consumption is 16,847 (Mathews, 2018). The speed of VSDG varies with changing load and hence fuel economy can be achieved. In the variable speed operation, the speed adjustment is obtained by the actuator. When running at variable speed, the output mechanical torque available at rotating shaft is altered by adjusting fuel injection. The engine rotating speed and fuel injection could be determined by load power versus fuel consumption map which is obtained from the field test. The rotor side control is utilised with the vector control algorithm to stimulate flux and maintain constant voltage constant frequency output from the stator. The DC bus voltage is stabilised by stator side converter. The model of VSDG developed from paper Tomilson (1998) with considering ignition delay and gain of the system.

$$\begin{aligned} \tau_m &= \left(\frac{1}{1+\tau_2 \times S}\right) \times f\left(m_f\right) \times e^{-\tau_1 \times s} \\ f\left(m_f\right) &= d_3 \times m_f^3 + d_2 \times m_f^2 + d_1 \times m_f + d_0 \\ \tau_1 &= \frac{60 \times S_t}{2 \times N \times n_{cy1}} + \frac{60}{4 \times N} \end{aligned} \tag{1}$$

The values of coefficients d_1, d_2 and d_3 are taken from the reference paper (He et al., 2012). In equation (1), τ_m indicates mechanical torque of diesel engine, m_f indicates fuel index and τ_2 is the actuator constant. For four stroke engine, *St* is set for 4, numbers of cylinder indicated by n_{cy1} and N is the speed of diesel engine. The dynamic modelling of VSDG is derived from torque fit equations of permanent magnet synchronous generator (PMSG) is shown in Coleman et al. (2008). In this equation, *Te* and *Tm* are electrical and mechanical torques and moment of inertia is *J*.

Table 2 Variable speed fuel efficiency Vs fixed speed fuel efficiency

Power output (KW)	*Variable speed operation*	*Fixed speed operation*	*Variable speed fuel consumption (mL/min)*	*Fixed speed fuel consumption (mL/min)*	*% Fuel savings in VSDG*
2	958	1,500	20	38	47
4	1,042	1,500	26	44	41
6	1,083	1,500	40	59	32
8	1,083	1,500	46	61	25
10	1,083	1,500	58	77	25
11	1,125	1,500	67	86	22
12	1,208	1,500	71	93	24
14	1,375	1,500	92	104	12
15	1,500	1,500	120	120	0

Table 3 Simulation parameters of diesel-generator unit

Names	*Parameters*	*Values*
Nominal power	P_N	200 kW
Nominal speed	N	1,500 r/min
Engine actuator time constant	τ_2	0.02 s
Engine combustion delay	τ_1	0.023 s
Engine stroke number	S_t	4
Engine cylinder number	N_{cy1}	6
PMSG stator resistance	R_s	0.087Ω
PMSG stator inductance	L_s	3.3 mH
PMSG rotor flux	Ψ_m	1.37 Wb
Total inertia of diesel-generator	J	9.374 kg-m2
Friction coefficient	f_B	0.0024

3.2 *Modelling of lithium-ion battery*

The Lithium-ion battery model has been developed with reference to Chen (2009) and Camara et al. (2010). In this battery model, I_{bat} represents current from battery and Vbat gives voltage across battery. Where, N_s and N_p are number of series parallel cells. R_Ω and R_E represents series and polarisation resistances respectively. Cc represents capacitance of battery and Voc is the corresponding open circuit voltage.

$$V_d = R_s \times I_d + L_d \times \frac{d}{dt}(I_d) - \omega_e \times L_q \times I_q$$
$$V_q = R_s \times I_q + L_q \times \frac{d}{dt}(I_q) + \omega_e \times L_d \times I_d + \omega_e \times \psi_m \quad (2)$$
$$T_e = \frac{3}{2} \times p \times \left[\psi_m + (L_d - L_q) \times I_d\right] \times I_q$$

Table 4 Simulation parameters of Lithium – Battery parameters for one cell

Names	*Parameters*	*Values*
Battery cell	$V_{bat\,\min} - V_{bat\,\max}$	2.8-1.2 V
Number of batteries in series	N_s	120
Sub-modules number in parallel	N_p	8
Series resistance of the battery	R_Ω	1.96 m Ω
Polarisation resistance	R_c	0.869 mΩ
Equivalent capacitance	C_c	96000 F

3.3 Modelling of DC/DC and AC/DC Converter

In order to condition the battery current, a DC/DC buck boost converter has been used and is shown in Figure 4. The equations (3) and (4) describe the linearised model of DC/DC converter. For boost converter, k is set for 1 and for buck converter k is set for –1.

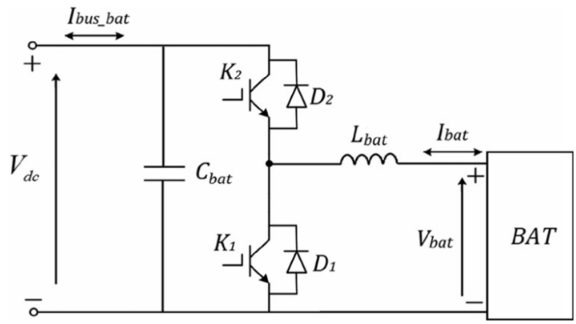
$$V_{bat} = N_s \times V_{oc} \times SoC - \frac{N_s}{N_p} \times Z_{eq} \times I_{bat}$$
$$\tau = C_c \times R_c$$
$$Z_{eq} = R_\Omega + \frac{R_c}{1 + \tau \times s} \quad (3)$$
$$V_{oc(SoC)} = 10^{-6} \times SoC^3 - 0.0002 \times SoC^2 + 0.013 \times SoC + 3.5455$$
$$V_{Lbat} = L_{bat} \times \frac{d}{dt}(I_{bat}) = k(V_{bat} - \alpha \times V_{dc})$$

$$V_{Lbat} = L_{bat} \times \frac{d}{dt}(I_{bat}) = k(V_{bat} - \alpha \times V_{dc}) \quad (4)$$

Table 5 Simulation parameters of converter models

Names	*Parameters*	*Values*
Normal DC-bus voltage	V_{dcref}	1,000 V
DC-bus Capacitor	C	30 mF
DC/DC converter side capacitor	C_{bat}	40 mF
Battery-side inductance	L_{bat}	3.5 mH

Figure 5 DC/DC converter model



$$I_{bus-bat} = \frac{I_{bat} \times V_{bat}}{V_{dc}} \tag{5}$$

The relationship between batteries generated current I_{bat} and DC bus current through battery $I_{bus\text{-}bat}$ is given in equation (5). The VSDG is linked to the DC bus through AC/DC converter and its model is developed using the relation (6). Where, I_{red1} and I_{red2} indicate two VSDG currents and load current is represented by I_{ch}. The stator current of $VSDG_1$ is represented with I_{s1}, I_{s2}, and I_{s3} and I_{sp1}, I_{sp2}; I_{sp3} are the corresponding values of $VSDG_2$. The signals S_a, S_b and S_c are the reference signal obtained by using pulse width modulation (PWM) technique. The regulation of DG output through AC/DC converter is described in Ehsan et al. (2015). The switching of two DGs is scheduled in such a way that one of the DG is turned off when power demand goes below a specified level. The second DG will meet the remaining load.

$$\begin{aligned} \begin{pmatrix} I_{red1} \\ I_{red2} \end{pmatrix} &= S_a \times \begin{pmatrix} I_{s1} \\ I_{s1p} \end{pmatrix} + S_b \times \begin{pmatrix} I_{s2} \\ I_{s2p} \end{pmatrix} + S_c \times \begin{pmatrix} I_{s3} \\ I_{s3p} \end{pmatrix} \\ C \times \frac{d}{dt}(V_{dc}) &= I_{red1} + I_{red2} - I_{bus-bat} - I_{ch} \end{aligned} \tag{6}$$

4. Power management for PWC system

4.1 Load power distribution

Initially, the total load power demand is divided into high frequency and low frequency components. The high frequency component is assigned to the batteries and low frequency components allocated to two DGs. The load demand distribution is realised by a low pass filter (LPF). The power contribution requirements assigned to the two DGs and to the lithium-ion battery.

In order to keep less transients during switching of load, the load current split into low frequency and high frequency components by using effective load management system. Two VSDGs are used to meet low frequency component and battery will meet the high frequency component. The LPF used to split load currents into two components effectively. For obtaining satisfactory performance, VSDGs are to be operated with above 35% of its rated value (Li et al., 2010), below which the efficiency will be lowered.

In the proposed system, the rated capacity of VSDG is set for 250 KVA and 200 Kw each. Hence 35% of 400 Kw is 140 Kw will be the operational limit of each VSDG.

Figure 5 illustrates the proposed proposed power management strategies, where three control parts can be explained: the speed control of variable-speed DGs; V_{dc} control through the PMSG side AC/DC converters; and battery control via battery side DC/DC converter.

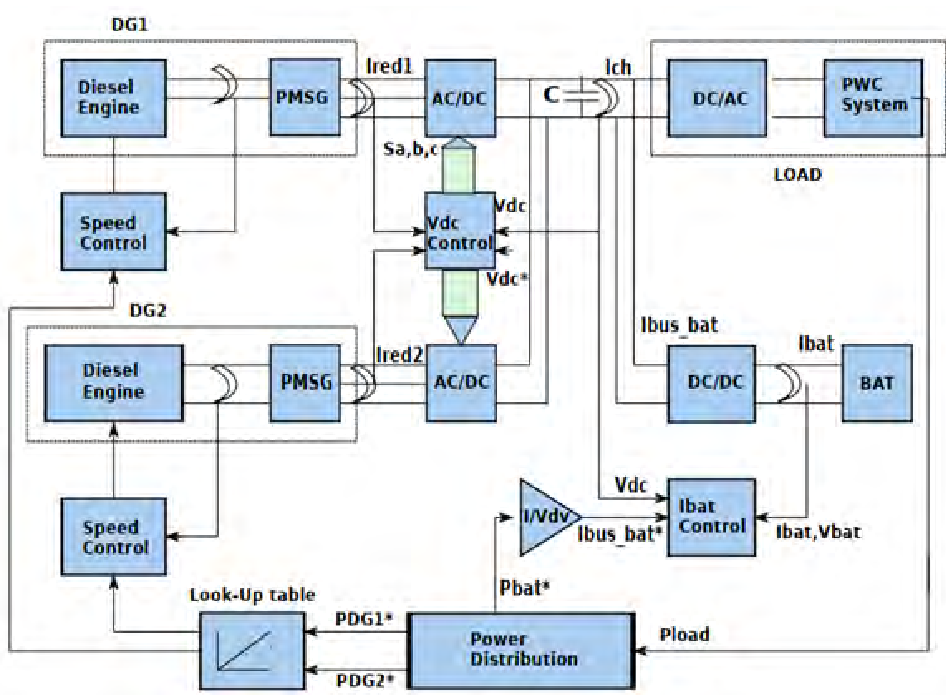
4.2 Variable speed control of the DGs

The object of the DG speed control is to adjust the engine speed for efficient operation. The look up table in p.u value (extracted from Pena et al. 2008) is used to determine the rotational speed references for the DGs according to their power. The proportional integral controller (PI) uses the error between the actual engine speed and its reference to produce required fuel flow m_f value through the actuator. Then the mechanical torque of the engine can be obtained by torque-fit equation.

4.3 DC bus voltage control

To control the DC bus voltage, two control loops are applied the inner loop of PMSG current control and the outer loop of dc bus voltage control, where the reference current I^*_q is obtained from dc-bus voltage control loop. The reference current I^*_d is fixed to zero to obtain maximum torque per ampere for the PMSG. Based on dq voltage references V^*_d and V^*_q we can obtain the three phase voltage references through the *dq-abc* transformation.

Figure 6 PWC power management system (see online version for colours)



$$\begin{pmatrix} P_{DG1}^* \\ P_{DG2}^* \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \times P_{DG}^* when P_{DG}^* < 140 Kw$$
$$\begin{pmatrix} P_{DG1}^* \\ P_{DG2}^* \end{pmatrix} = \begin{pmatrix} 0.5 \\ 0.5 \end{pmatrix} \times P_{DG}^* when P_{DG}^* \geq 140 Kw \quad (7)$$

5 Simulation and discussion

The proposed model is simulated with MATLAB/Simulink software and its validation through reduced scale test bench. For simulation study, the DC bus voltage is set for 1,000V. In this case, the load side current I_{ch} presents the total load requirement. I_{red1} and I_{red2} are the currents from DG1 and DG2. $I_{bus-bat}$ represents battery contributions on dc-bus. The Figures 7 to 14 show the performance analysis of different parameters of VSDG-Lithium ion battery hybrid system. Figure 7 shows the simulation results of load current (I_{ch}) with respect to time. The maintenance of DC bus voltage at 1,000V is shown in Figure 8. The proposed dc bus control strategy enables to keep the V_{dc} around the setting value shown in Figure 8. During the transient load change, a maximum about 10% can be seen. The currents from Lithium-ion battery $(I_{bus}\_b_{at})$ and total contribution of current from two VSDGs $(I_{red} = I_{red1} + I_{red2})$ are given in Figure 9 and Figure 10 respectively. It can be seen that the load current is decomposed into high and low frequency components. The lower frequency component is then assigned to the two DGs shown in Figure 10. The battery current and voltage according to load variation are shown Figure 11 and Figure 12. It has been seen that voltage at battery terminal is maintained constant with 5% variations due to charging/discharging operations. The currents I_{red1} and I_{red2} are the contribution from $VSDG_1$ and $VSDG_2$ and are depicted in Figure 13. The speed variations of two DGs are shown in Figure 14. It has been evident that $VSDG_2$ is turned off when total load goes below 140 Kw; VSDG1 supplying the remaining load and hence fuel efficiency can be achieved. The speed is also varies with variation of load and hence significant fuel savings can be accomplished.

Figure 7 Load current variations (see online version for colours)

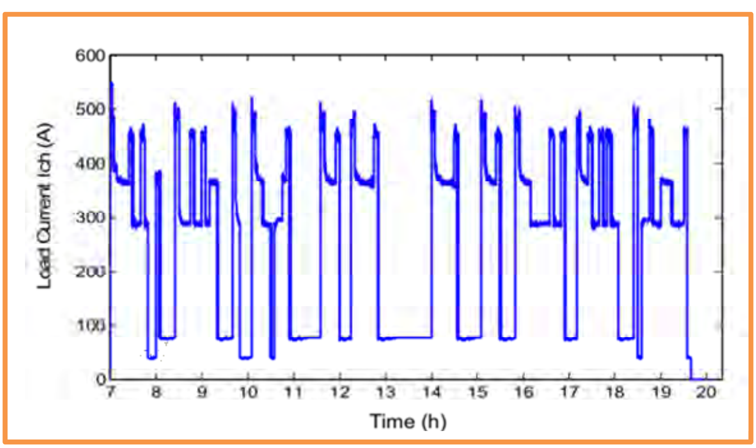


Figure 8 Regulated DC bus voltage (see online version for colours)

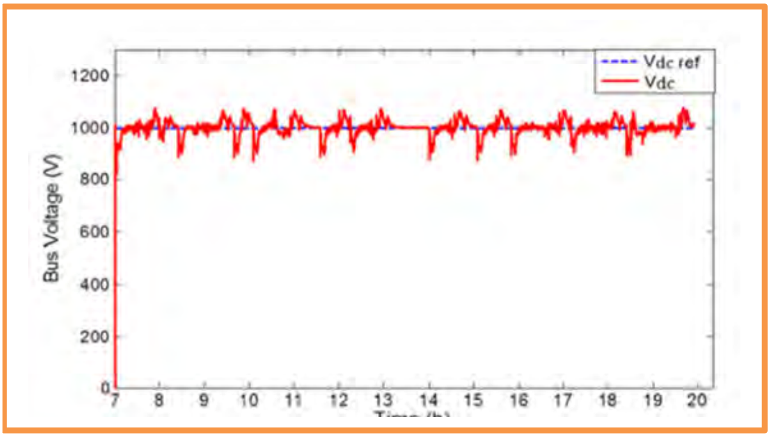


Figure 9 Current from li-ion battery pack in DC bus (see online version for colours)

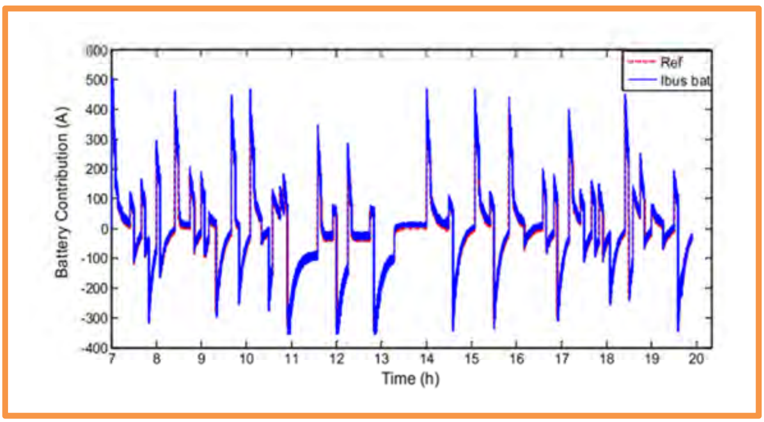


Figure 10 Total current from two VSDGS (see online version for colours)

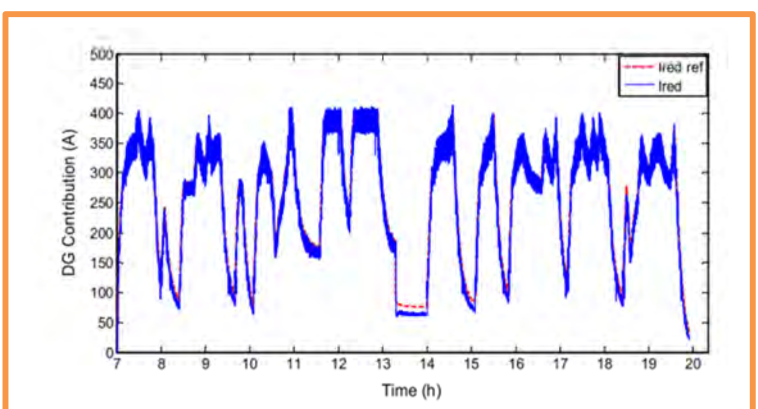


Figure 11 Current from lithium-ion battery pack (see online version for colours)

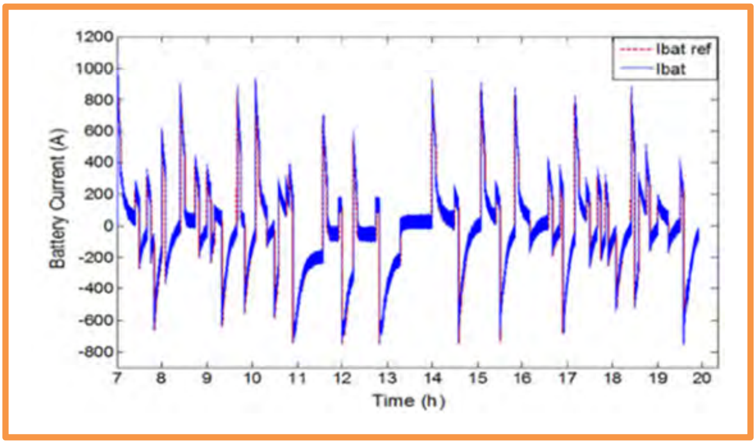


Figure 12 Terminal voltage of battery (see online version for colours)

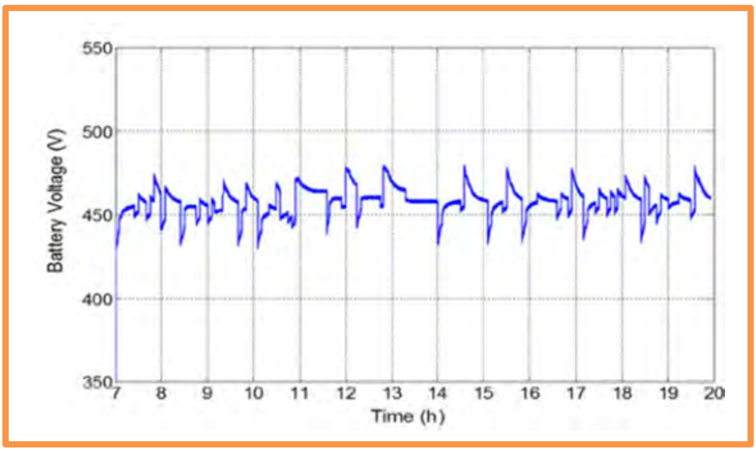


Figure 13 Current sharing from $VSDG_1$ and $VSDG_2$ (see online version for colours)

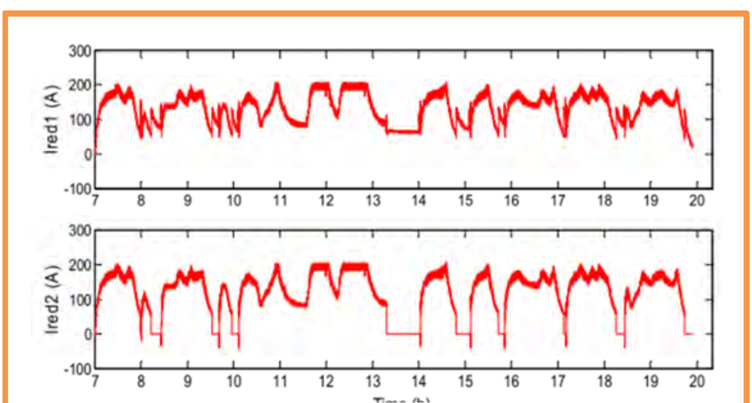


Figure 14 Speed adjustment of $VSDG_1$ and $VSDG_2$ (see online version for colours)

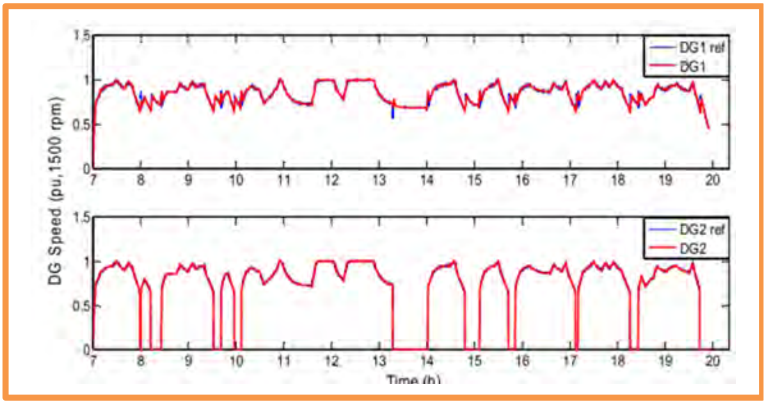


Figure 15 Experimental test bench (see online version for colours)

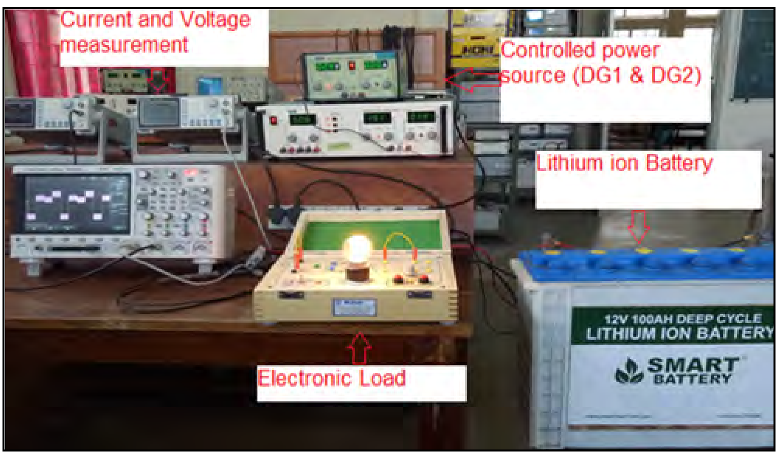
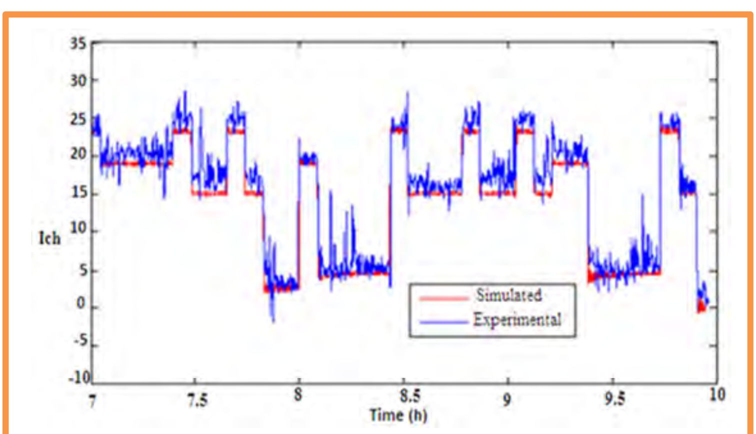


Figure 16 Measured load current (see online version for colours)



6 Validation of simulated results

In order to validate the simulated results, a reduced scale test bench have been set up in our laboratory. To emulate the characteristics of $VSDG_1$ and $VSDG_2$, two voltages controlled dc source is used. A 12V, 100Ah Lithium-ion battery is used and is connected to DC bus through DC/DC buck-boost converter. The programmable electronic load is used to emulate the PWC load. The scale factor taken as 500 reductions in load power and the DC bus reference voltage is set as 12V. The PIC18F4431 is used to execute the control algorithm. Figure 16 shows measured load current from experimental setup and which is combine with simulated result. Measured lithium-ion battery current is shown in Figure17. Current generated from $VSDG_1$ and $VSDG_2$ are shown Figure 18 and Figure 19. DC bus voltage maintained at 42V is depicted in Figure 20. While observing the experimental results, it has been clear that simulation results are in consistent with experimental results.

Figure 17 Lithium-ion battery current (see online version for colours)

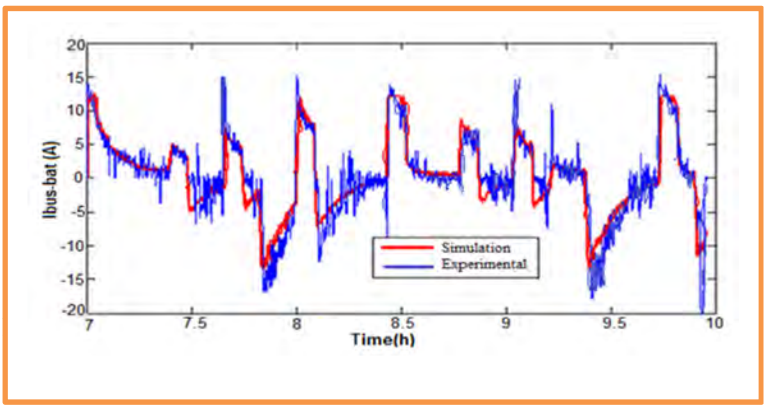


Figure 18 Current obtained from $VSDG_1$ (see online version for colours)

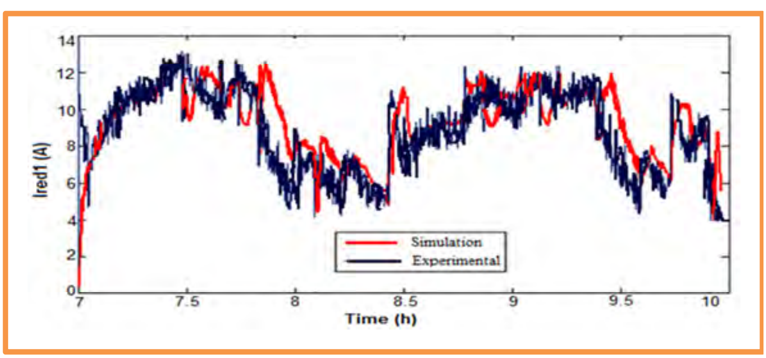


Figure 19 Current obtained from VSDG2 (see online version for colours)

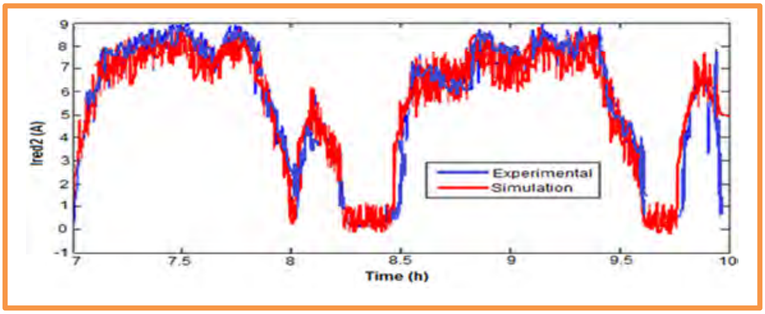
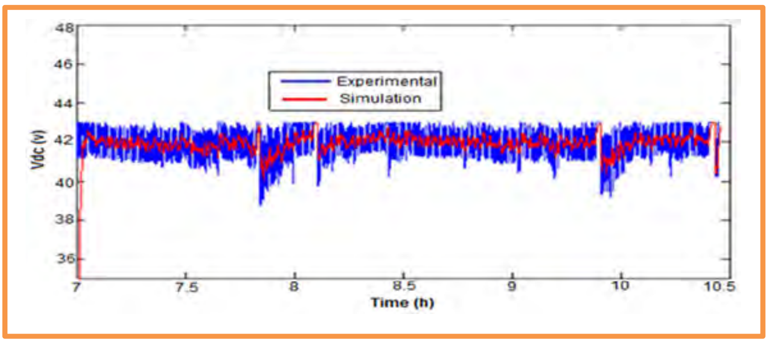


Figure 20 DC bus voltage (see online version for colours)



7 Conclusions

This work demonstrates the design and plan of efficient and economic hybrid power source for PWC system in tribal village. The benefits includes the separation and assignation of high frequency and low frequency components of load currents into one battery pack and two VSDGs which helps to reduce the transients during the sudden load changes. The speed of VSDG can be varied according to load variation and hence fuel economy can be achieved. The dc bus voltage and the current control methods are proposed and evaluated through the hybrid system simulations. The simulation and experimental results shows that the DC bus voltage maintain constant irrespective of load variation. In addition that, when low frequency load component is high, each DG contribute 50% of total load and when load demand goes low, one of the DG shut down to avoid the inefficient operation in under load condition. The simulated results are validated through reduced scale experimental setup and 10% variation found in results which is acceptable.

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