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Customized Operation of Solar – Variable Speed Diesel Generator Hybrid System for Remote Power Applications

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Abstract*: Now a days, the off grid hybrid energy system is increasingly popular for remote area power applications. Conventionally, the constant speed diesel generator (CSDG) is used for the most of reliable power supply. The use of CSDG causes the poor efficiency at part/low loads. The integration of renewable energy with CSDG may lead to the inefficient operation of CSDG and high fossil fuel consumption. In this paper demonstrate the solar-variable speed diesel generator (VSDG) hybrid energy power system without energy storage element. This setup maintains a strategic distance from the high cost of battery installation and the related complex control. Incorporation of the VSDG in to solar energy system gives advantage over the conventionally used CSDG. Fuel effectiveness and economic operation can be accomplished by variable speed diesel generator. Direct feeding of power from photo-voltaic and VSDG without cycling through the battery is further increase the efficiency of the system. This paper covered the theoretical analysis, modeling and simulation of hybrid Energy System with variable speed Diesel generator. Simulation of the system using MATLAB/Simulink is presented.

Index Terms*: Stand-alone hybrid energy system; Variable speed diesel generator; Energy management; Renewable energy.

I. INTRODUCTION

Decentralized distributed generation system (DDGS) is an idea for generating power by using local energy sources near to the demand location. It can be any autonomous electricity generating systems combining renewable energy sources and traditional generators. The components normally used in a DDGS are renewable sources, diesel generators, essential loads and optional loads [1]. In common practice, remote area hybrid energy systems (HES) are outlined with batteries to store overabundance sustainable power source to be used during the day, when there are inadequate renewable sources. Due to the stochastic nature of the renewable sources, a diesel generator is needed for solid power supply. However there are huge downsides of this arrangement. Firstly, the initial cost of the system including energy storage element is prohibitive and dismal particularly small and medium scale remote zone applications. Furthermore, the battery bank is the weakest connection in the network, where the condition of charge must be checked and controlled to drag out the battery's administration life. Over that, batteries must be supplanted roughly every five to greatest ten years [2].

In a couple of years, diesel generators are utilized to charge the batteries when condition of charge is low. The battery charging process is ordinarily founded on the set point control which may be ended when the batteries are completely charged. Charging and releasing losses occur due to the wastefulness of charger and battery itself. The battery charging is also one of the commonly used procedures to keep up the least loading of the diesel generators around 40 percent to 50 percent of the constant speed diesel generator's power rating. This is prescribed by most of the manufactures to relieve the engine problem such as hydrocarbon build up, glazed piston and cylinder walls [3].In order to avoid the downsides of CSDG, the newly developed variable speed diesel generators (VSDG) can be used. The variable speed diesel generator can keep running at variable speed by utilizing power electronic converters to change the variable voltage variable frequency created by generator to the steady voltage and steady frequency in the grid. Such operation results in the engine being operated at the most efficient speed as indicated by the variable load. The investigations demonstrate that the overall fuel consumption and maintenance problem for diesel generators operated at part load ought to enhance with variable speed applications [4]. The experimental results in the literature [5] shows that the VSDG with rotor and grid side converter is able to maintain the magnitude and the frequency of the voltage wave form at constant value during the load demand variations. Unlike the grid-connected system, where the voltage and frequency are held constant by the grid, an off grid hybrid energy system requires a central component to maintain both the voltage and frequency constant. Traditionally, a central inverter is used for this purpose and it must be intended to deal with all power streams which bring about high cost because of the expanded size of the power molding unit. This paper introduces the solar- variable speed diesel generator (PV-VSDG) hybrid energy system without battery that creates a fiscally suitable option for remote region applications. Such designs keep away from the establishment and upkeep cost and in addition the perplexing control related with the batteries. The hybrid energy power supply for building concept is narrated in [6]. One example of HES application without energy storage is given in [7]

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highlighted the sample and reliable feature of a wind-diesel system. The types of batteries using in renwable energy and its drawbacks are described in [8]. The solar availability and how to track the maximum power is depicited in [9]. The dynamic characteristic of a VSDG utilizing a Permanent magnet synchronous generator (PMSG) handing-off with variable load condition have been talked about in [10].

For the proposed system configuration, the VSDG can be operated as Grid-Form and or Grid-Feed generator. The Grid-Form generator is able to maintain the constant grid voltage and frequency while supplying the load demand within its capacity. MATLAB simulation results of the proposed configuration are presented and discussed.

II. VARIABLE SPEED DIESEL GENERATOR

HES's initial and operation costs are always main concern for remote area applications. Numerous applications demonstrate that, diesel generators were designed to meet the peak load for a short period during the daily operation. Normally diesel generators utilized for power generation run at a steady speed to produce steady voltage and steady frequency [11]. In order to maintain a steady voltage and steady frequency, diesel engine need to keep running at synchronous speed to drive the coupled generator. For a traditional diesel generator, diesel engine realizes frequency control, while the synchronous generator controls output voltage amplitude. However, most of the time, the normal operating range of a generator is in between the defined minimum loading and the rated value. The analysis and comparison of CSDG and VSDG are potrayed in [12] – [17].

Figure 1 demonstrates an ordinary fuel efficiency curve of a diesel engine in variable speed and steady speed operation, where it demonstrates that VSDG gives fuel savings, particularly at low loads, regardless of the power converter losses. At elevated load inverter losses make a variable speed system down with efficient than a constant speed system. Thus, for a single diesel system, variable speed systems are mainly appropriate where the peak power system capability is large compared to normal load. Such system might include system sized for future extension, or estimated for top occasional burdens with a considerably littler normal load.

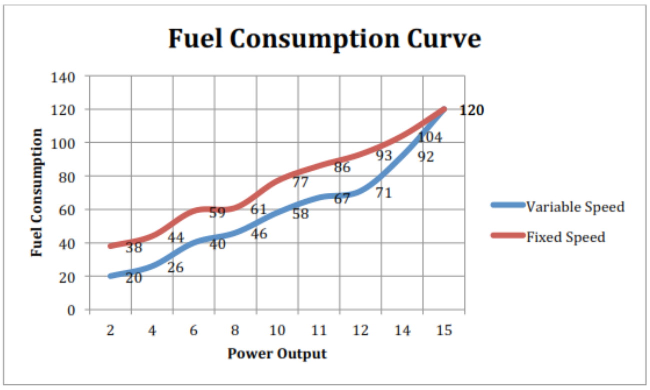

Figure 1.Classic fuel efficiency curve of a diesel engine in variable speed and steady speed

The factors that influence the fuel efficiency of variable speed operation of diesel generators incorporate diesel engine fuel utilization as an element of load demand and engine speed, the selected speed versus engine torque relationships, the power transformation effectiveness, and the connection between the execution qualities of VSDG and load outline.

III. PROPOSED SOLAR-VSDG HYBRID ENERGY SYSTEM

The proposed design based on the fundamental principle that high efficiency can be accomplished if the amount of directly supplied energy from both of the solar and VSDG is maximized. The efficiency of the direct supply energy is contrasted with the efficiency of energy cycled through battery is appeared in Table 1.

TABLE1.
SYSTEM ENERGY CONVERSION EFFICENCY

Assuming the component's efficiencies: η_{inv}= 0.9, η_{Rec} = 0.9, Derating factor[a] = 0.9, η_{Batt} = 0.85	
Gen.	**Percentage of energy**
Solar	**1. Supply directly** $\eta_{PV,\ direct} = \eta_{inv}$ x Derating factor $E_{PV,\ direct} = \eta_{PV,\ direct} \times E_{PV,\ in}$ $= 81\% \times E_{PV,\ in}$
	2. Cycle through batteries $\eta_{PV,\ cycle}$ = Derating factor x $\eta_{inv} \times \eta_{Batt}$ $E_{PV,\ cycle} = \eta_{PV,\ cycle} \times E_{PV,\ in}$ $= 69\% \times E_{PV,\ in}$
VSDG	**1. Supply directly** $\eta_{VSDG,\ direct} = 100\%$ $E_{VSDG,\ direct} = \eta_{VSDG,\ direct} \times E_{VSDG,\ in}$ $= 100\% \times E_{VSDG,\ in}$
	2. Cycle through batteries $\eta_{VSDG,\ cycle} = \eta_{Rec} \times \eta_{Batt} \times \eta_{inv}$ $E_{VSDG,\ cycle} = \eta_{VSDG,\ cycle} \times E_{VSDG,\ in}$ $= 69\% \times E_{VSDG,\ in}$

'a' derating factor is to represent the diminished productivity because of dirt at first glance and ageing of PV module [1].

There is 12% loss of the energy from the PV generator if it is stored in the battery before it to supply load. Higher loss of energy of roughly 30% can occur, if the energy from the VSDG is used to charge the battery and then apply to load.

The power flows between components are represented by the directional convention, where the direction of arrow demonstrates a positive power. The system involves dispatchable and non-dispatchable segments. The dispatchable components such as VSDGs and secondary load are controlled to improve the system operation. A dump load is incorporated to drain the excess energy. The power produced and dumped in the system is calculated based on derived power flow strategy.

IV. POWER MANAGEMENT STRATEGY

The general power organization strategy for the system with an incorporated sustainable energy is portrayed in Figure 2. The sustainable energy source has most elevated need to supply the essential load demand.

The net load, NL, is described by the distinction between the output from the renewable energy generator power supply and essential load.

$$NL = P_{Load,ess} - P_{PV,\ inv} \qquad (1)$$

At any instant, when there is overabundance power after supplying the load, ie, NL < 0, the grid form generator will work at least permissible loading and the extra power created is deplete through the dump load. Whenever there is deficiency of energy where the NL is more prominent than the minimum loading but lesser than the rated value of grid form generator, grid form generator will meet the net load. If of 6a.m and 6p.m is most important and the major part of load demand can be supplied by the sustainable energy during this day time. Moreover from these conditions, there are other conceivable system working modes.NL increases the grid form generator's power rating, grid-feed generator is started to increase the power supply.

Without involvement of solar power in the night and system operation with involvement from solar power during the day time. For some areas, input from PV generator in the vicinity. Fundamentally, a solar-VSDG hybrid power system has two different daily working conditions, ie, system operation.

The power produced, supplied and dumped in the system is calculated based on the following proposed algorithm. Nine different cases were presented.

CASE 1

If

$P_{PVinv(t)} \le P_{Load,ess(t)}$ &

$|P_{PV(t)} - P_{Load,ess(t)}| + P_{Load,opt(t)} < P_{rated,GForm(t)}$ &

$|P_{PVinv(t)} - P_{Load,ess(t)}| + P_{Load,opt(t)} \ge P_{min,GForm(t)}$

Then

$P_{GForm(t)} = P_{Load,ess(t)} - P_{PVinv(t)} + P_{Load,opt(t)}$

CASE 2

If

$P_{PVinv(t)} \le P_{Load,ess(t)}$ &

$|P_{PV(t)} - P_{Load,ess(t)}| + P_{Load,opt(t)} < P_{rated,GForm(t)}$ &

$|P_{PV(t)} - P_{Load,ess(t)}| + P_{Load,opt(t)} < P_{min,GForm(t)}$

Then

$P_{Dump(t)} = \mathrm{PVinv(t)} + P_{min,GForm(t)} - P_{Load,ess(t)} - P_{Load,opt(t)}$

CASE 3

If

$P_{PVinv(t)} \le P_{Load,ess(t)}$ &

$|P_{PVinv(t)} - P_{Load,ess(t)}| + P_{Load,opt(t)} \ge P_{rated,GForm(t)}$ &

$|P_{PVinv(t)} - P_{Load,ess(t)}| + P_{Load,opt(t)} - P_{rated,GForm(t)} > P_{min,GFeed(t)}$

Then

$P_{GForm(t)} = P_{rated,GForm(t)}$

$P_{GFeed(t)} = P_{Load,ess(t)} - P_{PVinv(t)} + P_{Load,opt(t)} - P_{rated,GForm(t)}$

CASE 4

If

$P_{PVinv(t)} \le P_{Load,ess(t)}$ &

$|P_{PVinv(t)} - P_{Load,ess(t)}| + P_{Load,opt(t)} \ge P_{rated,GForm(t)}$ &

$|P_{PVinv(t)} - P_{Load,ess(t)}| + P_{Load,opt(t)} - P_{rated,GForm(t)} \le P_{min,GFeed(t)}$

Then

$P_{GForm(t)} = P_{rated,GForm(t)}$

$P_{GFeed(t)} = P_{min,GFeed(t)}$

$P_{Dump(t)} = P_{PVinv(t)} + P_{rated,GForm(t)} + P_{min,GFeed(t)} - P_{Load,ess(t)} - P_{Load,opt(t)}$

CASE 5

If

$P_{PVinv(t)} > P_{Load,ess(t)}$ &

$|P_{PVinv(t)} - P_{Load,ess(t)}| > P_{Load,opt(t)}$

Then

$P_{GForm(t)} = P_{min,GForm(t)}$

$P_{Dump(t)} = P_{PVinv(t)} + P_{min,GForm(t)} - P_{Load,ess(t)} - P_{Load,opt(t)}$

CASE 6

If

$P_{PVinv(t)} > P_{Load,ess(t)}$ &

$|P_{PVinv(t)} - P_{Load,ess(t)}| \le P_{Load,opt(t)}$ &

$|P_{PVinv(t)} - P_{Load,ess(t)}| + P_{rated,GForm(t)} > P_{Load,opt(t)}$ &

$|P_{PVinv(t)} - P_{Load,ess(t)} - P_{Load,opt(t)}| > P_{min,GForm(t)}$

Then

$P_{GForm(t)} = P_{Load,ess(t)} - P_{PVinv(t)} + P_{Load,opt(t)}$

CASE 7

If

$P_{PVinv(t)} > P_{Load,ess(t)}$ &

$|P_{PVinv(t)} - P_{Load,ess(t)}| \le P_{Load,opt(t)}$ &

$|P_{PVinv(t)} - P_{Load,ess(t)} + P_{rated,GForm(t)}| > P_{Load,opt(t)}$ &

$|P_{PVinv(t)} - P_{Load,ess(t)} - P_{Load,optt)}| \le P_{min,GForm(t)}$

Then

$P_{GForm(t)} = P_{min,GForm(t)}$

$P_{Dump(t)} = P_{PVinv(t)} + P_{min,GForm(t)} - P_{Load,ess(t)} - P_{Load,opt(t)}$

CASE 8

If

$P_{PVinv(t)} > P_{Load,pri(t)}$ &

$|P_{PVinv(t)} - P_{Load,ess(t)}| \le P_{Load,opt(t)}$ &

$|P_{PVinv(t)} - P_{Load,ess(t)} + P_{rated,GForm(t)}| \le P_{Load,opt(t)}$ &

$|P_{PVinv(t)} - P_{Load,ess(t)} + P_{rated,GForm(t)} - P_{Load,opt(t)}| > P_{min,GFeed(t)}$

Then

$P_{GForm(t)} = P_{rated,GForm(t)}$

$P_{GFeed(t)} = P_{Load,pri(t)} - P_{PVinv(t)} + P_{Load,sec(t)} - P_{rated,GForm(t)}$

CASE 9

If

$P_{PVinv(t)} > P_{Load,ess(t)}$ &

$|P_{PVinv(t)} - P_{Load,ess(t)}| \le P_{Load,opt(t)}$ &

$|P_{PVinv(t)} - P_{Load,ess(t)} + P_{rated,GForm(t)}| \le P_{Load,opt(t)}$ &

$|P_{PVinv(t)} - P_{Load,ess(t)} + P_{rated,GForm(t)} - P_{Load,opt(t)}| \le P_{min,GFeed(t)}$

Then

$P_{GForm(t)} = P_{rated,GForm(t)}$

$P_{GFeed(t)} = P_{min,GFeed(t)}$

$P_{Dump(t)} = P_{PVinv(t)} + P_{rated,GForm(t)} + P_{min,GFeed(t)} - P_{Load,ess(t)} - P_{Load,opt(t)}$

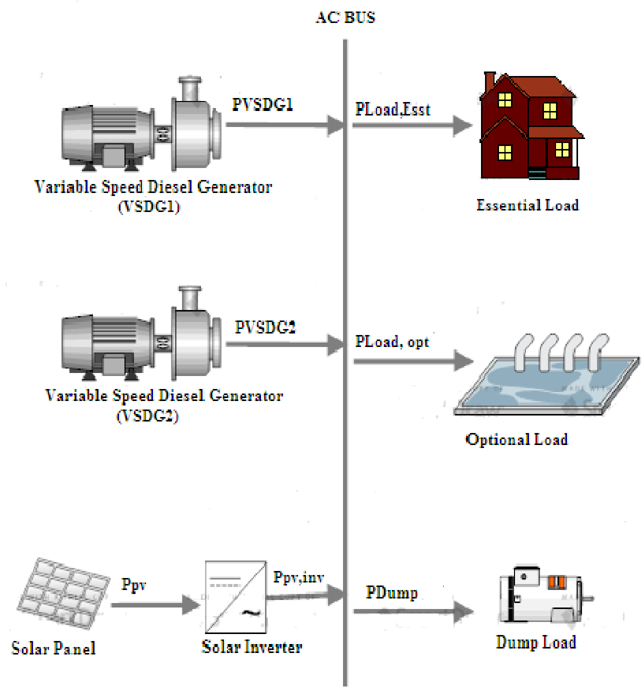

Fig2. Proposed PV-VSDG HES Configuration

If the power fed from PV panel is lesser than essesntal load, and when the optional load is added with essential load, the total load demand is equal to or greater than the minimum loading of grid form generator, it is economical to operate grid form generator along with PV panel, depicted in CASE 1. In CASE 2, if the PV power is not sufficient to supply essential load, it is desirable to switch on grid form generator, but still the total load including optional load is lower than total power generation, dump load is added for efficient operation. Similarly different configuration for supplying essential load and optional load with PV panel, grid form gerenator and grid feed generator is developed CASE 1 to CASE 9. It is desirable to operate all power generation system in maximum efficiency; dump load is added when desired. The system operation is elaborated in next section using MATLAB/Simulink simulation model.

V. SIMULATION RESULTS

The system considered in this study comprises 30kW solar generation and two 30kW VSDGs and the simulation is performed utilizing *MATLAB/Simulink*. The load following operation strategy is received to dispatch the VSDGs. The estimation of the load demands data and solar irradiation of a selected site are utilized for simulation is shown in Figure 3 and Figure 4 respectively.

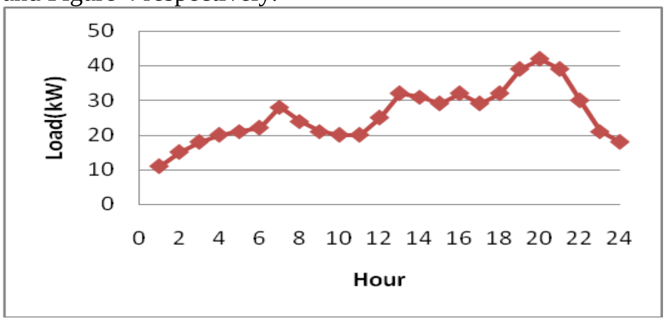

Figure 3. Estimated village load profile for the selected site.

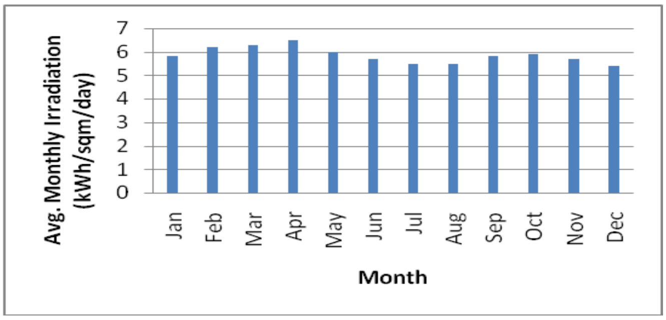

Figure 4. Average monthly irradiation for a selected site

The MATLAB simulation model of Permanent Magnet VSDG is shown in Figure 5. The vector control is used to control the speed of VSDG in accordance with dynamic variation of load. The grid voltage is adjusted to maintain a constant value for all variations of speed and load power.

The dynamic performance of Permanent Magnet VSDG is simulated is shown in Figure 6 to Figure11. The rated output is delivered for rated speed of 3000rpm. The simulation time is set for 2 seconds. After the one second the load is changed to half of rated value and correspondingly the speed is changed from 3000 rpm to 1500 rpm shown in Figure 6. The grid voltage is remains constant for the distinctive load/speed variation, which is the necessary and sufficient condition for the variable speed operation is depicited in Figure 7. Figure 8 shows that, the grid current is decreased when the loads reduced to half and subsequently the speed. The DC link voltage is maintained constant for the entire operation of the system is shown in Figure 9. The dynamic behavior of the proposed system demonstrates the effective speed control for different load levels. Hence the fuel savings can be achieved through variable speed operation as it consume small amount of fuel for low load condition.

The coordinated operation and performance of two Variables speed Diesel Generator and a solar panel is demonstrated in Figure 12. The three different sources and three loads were coordinated and controlled for optimum and efficient operation based on proposed algorithm. The recommended system configuration abides the stochastic behavior of load demand and fluctuations of the PV generator power supply by executing diesel generator dispatch methodology to guarantee the energy balance in the system. When the solar resource is available, the PV generator power is provided straightforwardly to the load and the grid form generator complements the difference between the renewable energy supply and the load demand. At the point when the PV power is high enough to supply the load demand, the grid form VSDG will be controlled to operate at its minimum loading. There will be surplus power if the PV power is higher than the load demand. On the other hand, when PV power is inaccessible, the grid-form generator will supply the power demand within the rated capacity. In the event that the demand exceeds the grid form generator capacity, the grid-feed generator will be activated and brought on-line. The excess power generation can be suppressed using a dump load.

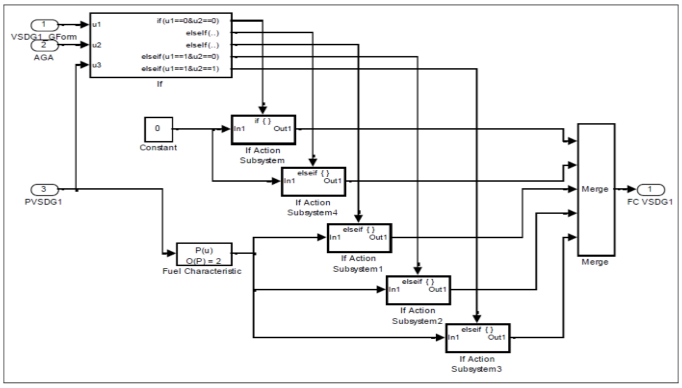

Figure 5. MATLAB/Simulink model of Permanent Magnet VSDG

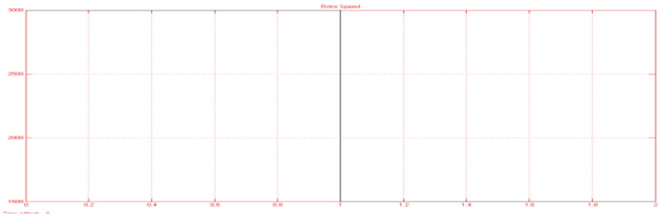

Figure 6: Speed variation at two different load conditions

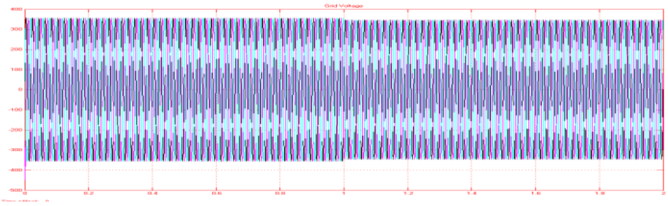

Figure 7: Terminal voltage at two different load and speed conditions

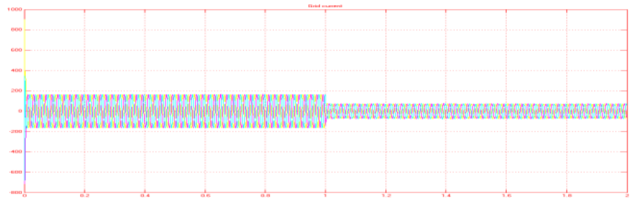

Figure 8: Load current at two different load and speed conditions

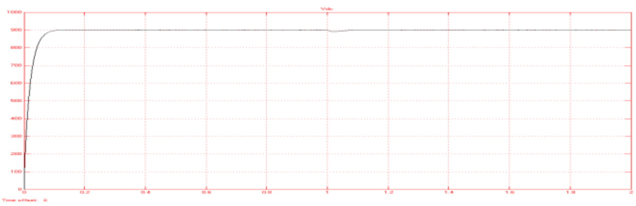

Figure 9: Constant DC link voltage at two different load and speed conditions

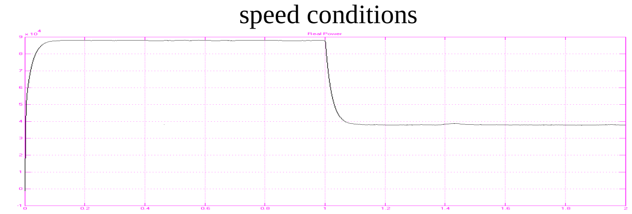

Figure 10: Real power output at two different load and speed conditions

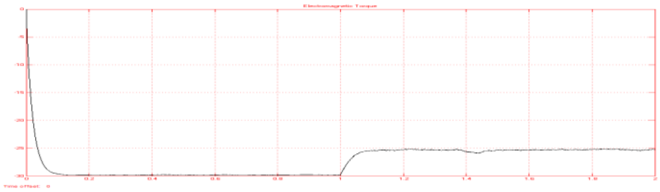

Figure 11: Electromechanical torque at two different load and speed conditions

At the starting point as shown in Figure 12, VSDG1 operates as grid-form generator, the essential load alone is applied and the optional load is deactivated. The excess power will be generated, which is the difference between primary load and grid form generation. The surplus power is produced under two conditions, that is when PV generator power is high and the sum of power generates from renewable and grid forming VSDG is higher than the total load demand. Another situation is amid the solar resource is unavailable and the grid feeding VSDG is on-line and controlled to operate at minimal loading. Instead of dumping the surplus power, an optional load can be switched on to reduce the amount of P_{dump}. A static load will be switched on at 5[th] second as optional load. The additional load requirement will be met by grid feed generator which is activated in the same instant. The excess power generation is suppressed by dump load. The total load requirements (essential and optional load) have been met by two generators (grid-form and grid-feed) and the PV panel When the demand is decreased below the capacity of the grid-form generator, the grid feed generator is deactivated. The VSDG1 and VSDG2 are selected alternatively as grid-form and grid-feed generator to balance their working periods in order to facilitate the maintenance schedule.

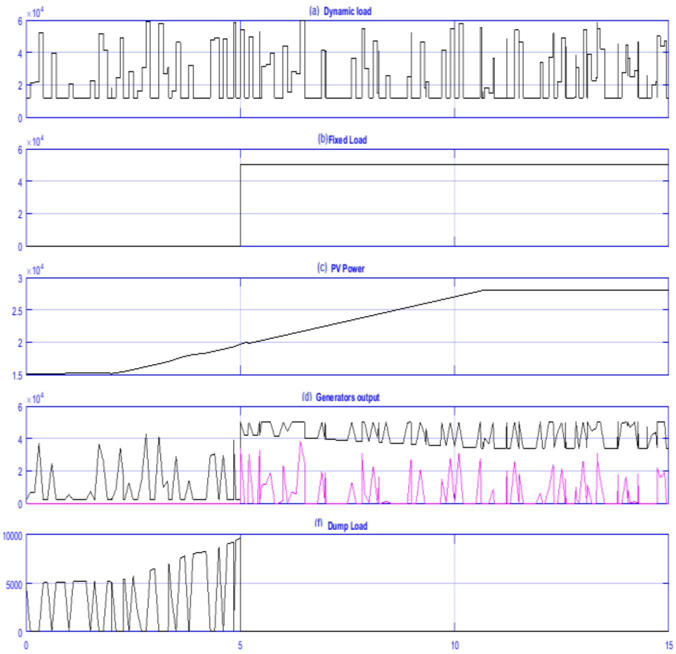

Figure 12: The dynamic performance of Solar-VSDG hybrid system

VI. CONCLUSION

The proposed PV-VSDG hybrid energy system configuration creates a feasible alternative of power supply system for remote area applications without relying on the energy storage element. It is expected to reduce the initial capital cost and battery replacement cost amid the entire service period. Most importantly, the energy efficiency is enhanced as the energy from PV and VSDG is supplied directly to the essential and optional load without cycling through the energy storage element. The benefits can be increased the aggressiveness of such battery less systems as contrasted with those stand alone hybrid energy system with energy storage element and constant speed DG system. By applying VSDG in decentralized distribution system, issues due to constant speed constant speed diesel generator can be avoided. Also the variable speed characteristics of proposed generation system, it can save significant amount fuel mostly in light load condition.

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