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Frequency control within high renewable penetration hybrid systems adopting low load diesel methodologies

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Abstract

In the isolated power system, consumers are traditionally supplied with electricity produced by diesel generators. Conventional diesel generators demonstrate robust and efficient operation when connected to electrical grids with slowly varying loads. With the introduction of intermittent and stochastic renewable energy sources, such generators may not be responsive enough to retain the stability and reliability of the system. The problem becomes especially acute in cases when diesel generators are required to operate at a low load. Regulating devices (e.g. energy storage systems and/or dump load) used to improve the system reliability, increase system complexity and incur additional expenses or energy losses. This paper investigates low load diesel technology as a potential solution to high level renewable energy penetration. The focus is made on the engine time delay and the generator inertia constant that should be considered during the design of the isolated hybrid power system.

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Keywords: Low load diesel; microgrid; renewable enregy; remote area power.

1. Introduction

Many settlements located in remote areas or on islands are forced to consume electric energy from a network operating separately from the main electric power system. Traditionally such systems are dependent on diesel

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generators which have relatively low installation cost, are reliable, robust and simple in operation and maintenance [1]. However, due to the remoteness of isolated power systems, the price of supplied diesel fuel is high, resulting in significant operational expenses. The ecological footprint of diesel technology is another discouraging factor compelling the need for changes [2].

Integration of renewable energy (RE) sources (e.g. wind and solar) allows isolated communities to bring operational costs down and reduce pollutions associated with diesel fuel use. Systems comprised of both conventional and renewable energy sources are termed hybrid Isolated Power Systems (IPSs). Due to the stochastic and intermittent nature of wind and solar energy, it is difficult to predict the forthcoming power generation, which makes planning and operation of the electric power system a challenging task. The main issues are the frequency and voltage instability in the system, which force the installed diesel generators to operate inefficiently and at loads, they were not designed for [3, 4]. In a short run, it may lead to additional fuel consumption and occasional system outages. In the long run, diesel generators experience premature wear as new procedures for their scheduling and operation are established [5].

Various supporting devices and strategies can be used to improve system reliability and increase renewable energy penetration. In [6], authors used energy storage system as a virtual synchronous machine to support dynamic frequency control in a hybrid IPS. Flywheels can respond quickly enough to prevent unacceptably low frequency [7]. Supercapacitors were used in French islands for short-term backup to frequency control [8]. In [9], authors developed nonlinear control design technique for the system with high penetration of wind generation supported by dump load. Converter based-frequency support in grids with high renewable penetration level is described in [10].

Even though these technologies increase the system reliability and promote renewable generation in the system they incur significant installation costs and increase complexity of the hybrid IPS. It is also evident that present technologies, no matter how sophisticated they are, cannot eliminate conventional generation (e.g. diesel in IPS) completely. The main objective should be to minimise the power produced by diesel generators. The low load diesel engine technology has proven to significantly reduce the cost and complexity of renewable energy penetration, whilst minimising diesel fuel usage [4]. This technology facilitates additional RE source utilisation, providing additional generation as renewable energy sources are not able to contribute to the load or prevent frequency deviation. That is why selection of an appropriate diesel generator is of paramount importance.

This paper investigates low load diesel generators comparing them with other enabling technologies used in hybrid isolated power systems. The paper is structured in the following way. Simulation models of conventional generation technology is presented in Section 2. Modelling approach of the most common renewable energy sources and reasons for their stochastic nature are shown in Section 3. Supporting conventional generating technology is discussed in Section 4. Simulation results are presented in Section 5. Section 6 concludes the paper.

2. Conventional generation in hybrid systems

2.1. Model of synchronous generator

Synchronous generator (SG) is modelled according to the standard or seventh order model [11]. The rotor is equipped by the field winding and two damping windings denoted by subscripts *fd, kq1* and *kq2*. The inductance L_{ls} is used to account for magnetic leakage in stator windings. L_{mq} and L_{md} are mutual inductances in q-axis and d-axis respectively. The stator variables are transformed to the rotor reference frame using a transformation matrix (K_s^r). Equivalent circuits in both axes are depicted in Fig. 1 (a). Original Park's equations are adapted to be used in computer simulations and for convenience are expressed in terms of reactances [12]. The complete model of synchronous generator is shown in Fig. 1 (b), in which ω_b is the base electrical angular velocity, p – short-hand notation for the operator *d/dt*, T_e and T_m – electrical and mechanical torque, and H – is the rotor inertia.

Excitation system is defined as a system that provides a direct current to the field winding and that is capable to adjust this current to get the desired performance. There are countless designs of such systems with various degrees of sophistication. The common practice is to use ones provided in IEEE standards. For the cases described in this paper excitation system of type AC1A was adopted [13].

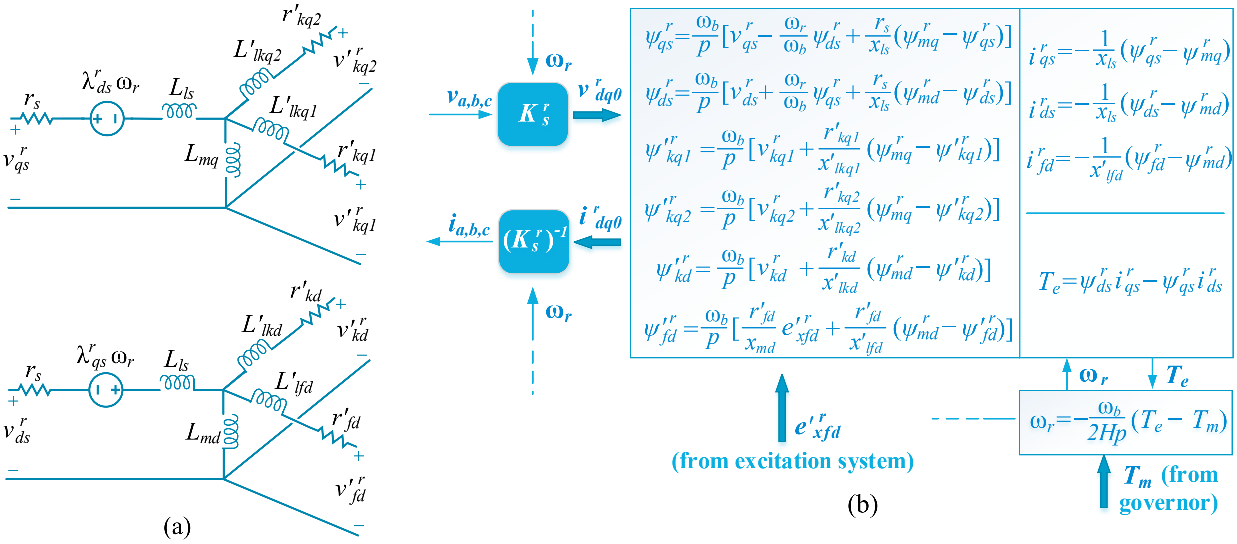

Fig. 1. equivalent circuits of a 3-phase SG; (b) computer simulation of a synchronous machine in a rotor reference frame.

2.2. Conventional diesel engine model

The model used for the simulation of the per unit conventional diesel engine system transient response is shown in Fig. 2 [14, 15]. In this block diagram the frequency variation determined by the angular speed error $\Delta\omega$ between ω and its reference value ω_{ref} is the input to the speed governor represented by the transfer function $G(s)$. When the engine speed changes, the governor identifies the variation, instructing the actuator to regulate the incremental change of the fuel flow rate needed to approach the frequency set point. The actuator model used assumes a second order relationship. The engine specific delay τ_1 represents the combustion delay, the time between the actuator fuel-injection and the production of mechanical torque [16, 17]. It has been recognized in the references that the power-stroke delay [18] and the ignition delay [19] affect the value of τ_1. For a constant engine speed of the synchronous diesel generator, the power-stroke delay may be taken to be unchanged. The ignition delay is affected by various parameters including, but not limited to the fuel cetane number, the swirl rate, the intake air temperature and pressure, and the engine design. Of note, decreasing the engine load typically increases ignition delay time [20, 21]. The load frequency dependence is considered via the load damping coefficient D. Representative values for these parameters can be found in [15-18].

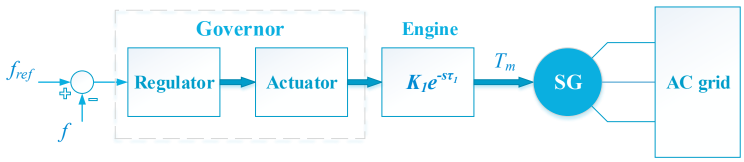

Fig. 2. Conventional diesel engine representation.

3. Renewable energy in hybrid systems

3.1. Integration of photovoltaics

A photovoltaic (PV) cell is usually made form semiconductor materials, a devise which converts solar irradiance into DC electrical power. The most commonly used model is the single diode model shown in Fig. 3 (a) [22]. A grid connected PV array is shown in Fig. 3 (b), where DC/AC converter, converter controller, RLC filter are depicted.

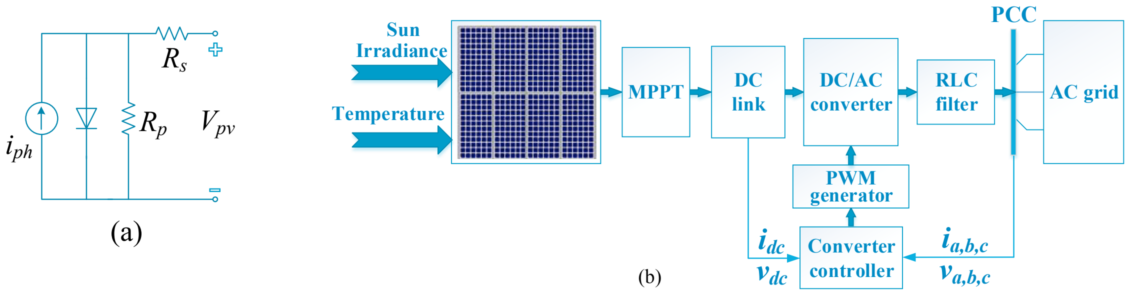

Fig. 3. (a) PV array equivalent circuit (b) grid-connected PV array

To increase the output voltage, panels comprised of multiple cells are connected in series forming PV strings. Desired value of maximum current can be obtained by connecting the strings in parallel forming a PV array. Model takes irradiance, ambient temperature and network voltage as an input and outputs the value of current flowing to the grid according to the following equation:

$$I_{pv} = N_p \left(I_{ph} - I_0 \left[\exp\left(\frac{\frac{V_{pv}}{N_s} + \frac{N_C}{N_p} I_{pv} R_s}{a N_C V_{th}} \right) - 1 \right] - \frac{\frac{V_{pv}}{N_s} + \frac{N_C}{N_p} I_{pv} R_s}{N_C R_p} \right) \tag{1}$$

where, I_{pv} and V_{pv} are the current and voltage of the PV array, I_{ph} is the light generated current of the cell, I_0 – diode saturation current, V_{th}– thermal voltage, R_s and R_p – series and parallel resistance, a – diode ideality factor, N_c – number of cells in module, N_p and N_s – number of module in parallel and series.

Maximum power point tracking (MPPT) is a technique used to extract the maximum amount of power from photovoltaic arrays at any operational instance [23]. The electrical power produced by PV arrays depends on stochastic parameters of solar irradiance and ambient temperature resulting in the need for a coordinated system control strategy when dealing with photovoltaic integration within a hybrid IPSs.

3.2. Integration of wind energy

Wind turbines transform kinetic wind energy into electric energy, and are modelled using various sophisticated techniques and elements. Many hybrid IPSs adopt wind turbines, with the most common design comprised of a wind turbine, gearbox, doubly fed induction generator (DFIG), harmonic filters, and a back-to-back PWM partial power converter. A block diagram of such a system is presented in Fig. 4 [24].

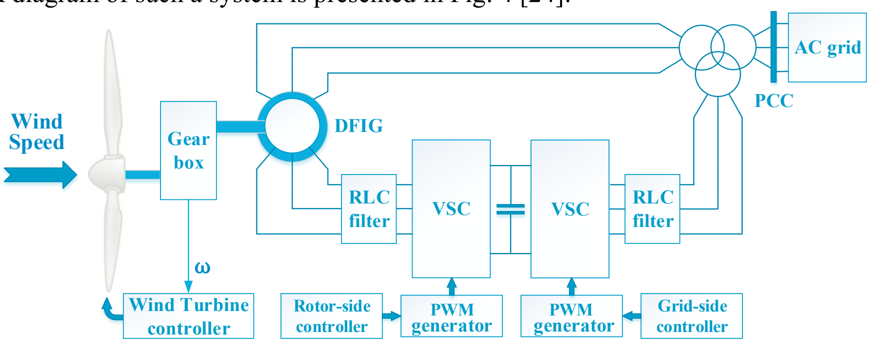

Fig. 4. Grid-connected wind energy conversion system.

DFIG is basically a wound rotor induction machine, in which the power circuits are governed by the rotor-side and grid-side controllers to achieve variable speed operation. Therefore, the power flow in the rotor circuit is bidirectional depending on the operation mode. Electric power supplied from the stator is unidirectional and always flows to the grid. Similar to the SG, DFIG is modelled using a set of differential equations as shown in Fig. 5 (b).

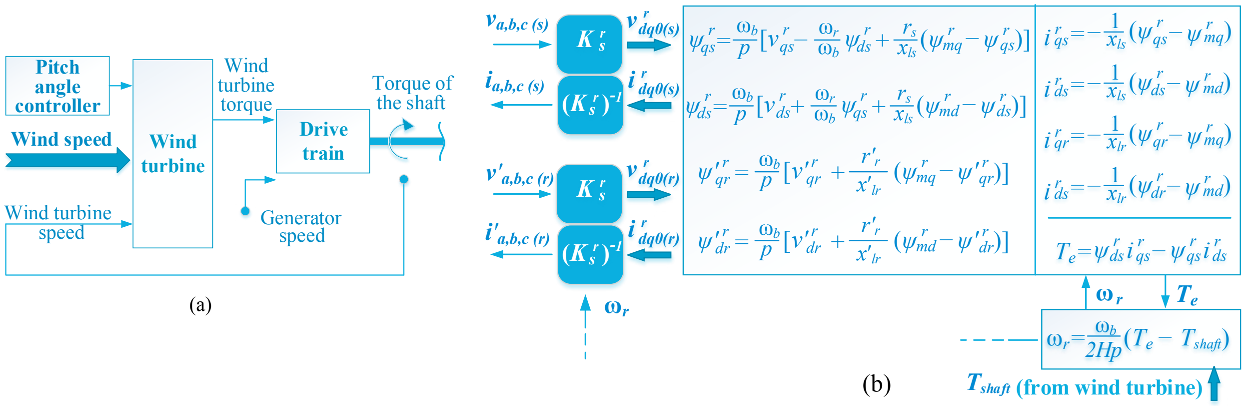

Fig. 5. (a) block diagram of the mechanical system of a wind turbine; (b) computer simulation of a wound rotor induction machine.

The model of a wind turbine is based on the following equation:

$$P_m = c_p(\lambda, \beta)\frac{\rho A}{2} v_{wind}^3 \tag{2}$$

where P_m – turbine mechanical power, c_p –performance coefficient of the turbine, ρ – air density, A – turbine swept area, w_{wind}–wind speed, λ, β – tip speed ratio and blade pitch angle. Pitch control is used to adjust the angle of attack of the blades with respect to the wind by means of turning the blades in their longitudinal axis. By changing this angle, the captured power can be either increased or decreased. The typical block diagram of the complete mechanical system is shown in Fig. 5 (a).

4. Enabling technology

4.1. Dump load

The dump load is used to dissipate the electrical power produced by renewable energy sources when generation exceeds consumption [4]. Dump load control adjusts the value of a variable resistor based on the reference power or frequency deviation as shown in Fig. 6 (a). In computer simulations the dump load can be modelled as a controlled current source that injects negative current into the grid resulting in the increased or decreased power consumption.

4.2. Battery storage

A battery energy storage systems (BESS) can be used to absorb or supply active and reactive power flexibly, allowing the BESS to regulate systems frequency and voltage. It can act as a primary frequency controller or as a supporting device to assist conventional generation units. The control scheme is shown in Fig. 6 (b).

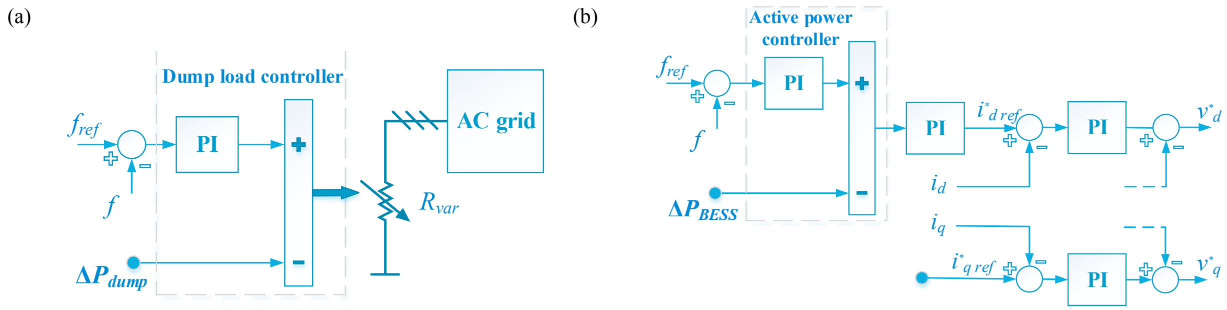

Fig. 6. (a) block diagram of the dump load controller; (b) block diagram of the BESS controller.

4.3. Diesel engine model for low load applications

Low Load Diesel (LLD) allows an engine's full capacity to be utilized by removing the engine's low load limit, 30~40% of the rated capacity as set within the conventional diesel engine. LLD offers hybrid IPSs significant commercial and environmental benefits by providing an additional 30–40% of engine capacity in support of improve RE utilisation [25]. The lower you can run your diesel generation, the larger allocation of load can be dispatched to RE technologies. LLD requires no new hardware, adopting the existing diesel assets, without modification to the mechanical or electrical architecture. For this reason, LLD shares a similar model to that of the conventional diesel engine. The main distinction comes from the larger value of τ_1, due to the lower operating load with longer ignition delay. Using the Watson [26, 27] formulation to predict the ignition delay, the value for the LLD is 0.3~0.5ms higher than that for the conventional.

5. Enabling technology

The simulation considers four operational scenarios, with consideration for the advantages and weaknesses of different enabling technologies and approaches. The simulation runs for 35s, with the load and RE resource unmodified across all case studies presented. Prior to *t =10s* the hybrid IPS experiences steady state conditions, as presented in Table 1.

Table 1. Initial conditions.

IPS equipment	Power (p. u.)
PV array	~ 0
Wind turbines	0.6
Static load	– 1
Other technology or combination of technologies (depending on case study)	~ 0.4
Total	0

At time interval from *t=10s to t=20s* irradiance energy changes from 100W/m^2 to 1000W/m^2, resulting in the power increase generated by the PV array (~ 0 to 0.2 p. u.). At *t* = 23s a significant step change in the consumer load occurs (–1 to –1.5 p. u.). The simulation has been considered to assess system stability and resilience under extreme operating conditions. The goal is to maximize the power produced by RE sources provided the appropriate level of system stability. Detailed description of each case study is presented below.

The first case study represents a common approach to hybrid IPS configuration. This case includes conventional diesel, wind turbine, solar photovoltaic generation, and a dump load. The conventional diesel generator has an operational limit of 30% (operation is permitted only within the range from 0.3 to 1 p.u.). As a result, the synchronous generator is only able to ensure the power balance only up to the 15th second, Fig. 7 (a), after which time it reaches its low load limit and starts to generate constant power (Fig. 7 (a) black line). The dump load is used to dissipate any excess RE generation (Fig. 7 (a) red line). At the moment of the disturbance both the conventional generator and dump load try to stabilize the system, however, it is evident from Fig. 8 (black dashed line) that the frequency drop poses significant challenges.

The second case study introduces one way to improve the system stability. The case is identical to case study one, except that an additional conventional generator is dispatched into the system, increasing the available spinning reserve to dampen system response. For the sake of simplicity both generating units are chosen to be the same. As a result of the increased inertia, system frequency response is within the approved range (Fig. 8, black solid line). Of note, the dump load dissipates a lot of electricity, increasing the cost and environmental impact of this methodology (Fig. 7 (b)).

The third case study considers the current state of the art approach to RE integration. It considers conventional diesel generation, wind turbine, solar photovoltaics and a battery energy storage system. When the diesel generator hits its low load limit, the battery starts to store the energy and regulate the frequency of the system. As oppose to case studies 1 and 2, the stored energy is not wasted and can be later injected back to the grid to displace diesel generation. During the disturbance the battery assists conventional generation, keeping the frequency close to its nominal value

(Fig. 7 (c) and 8). The main disadvantages of such an approach are the high capital cost and the additional control complexity. With emerging markets such as Asia and Africa, representing the majority of global hybrid IPS activity [28], expensive and complicated methodologies offer limited appeal.

The final case study considers the substitution of conventional synchronous generators presented in case study 2 with low load diesel technology. These two LLD units allow RE sources to operate at the full capacity without excessive RE spill. LLD application offers improved system inertia in comparison to case study 1, yet eliminates the need for a BESS. The frequency response is comparable to that of the alternative solutions proposed, yet delivers a substantially lower cost of energy.

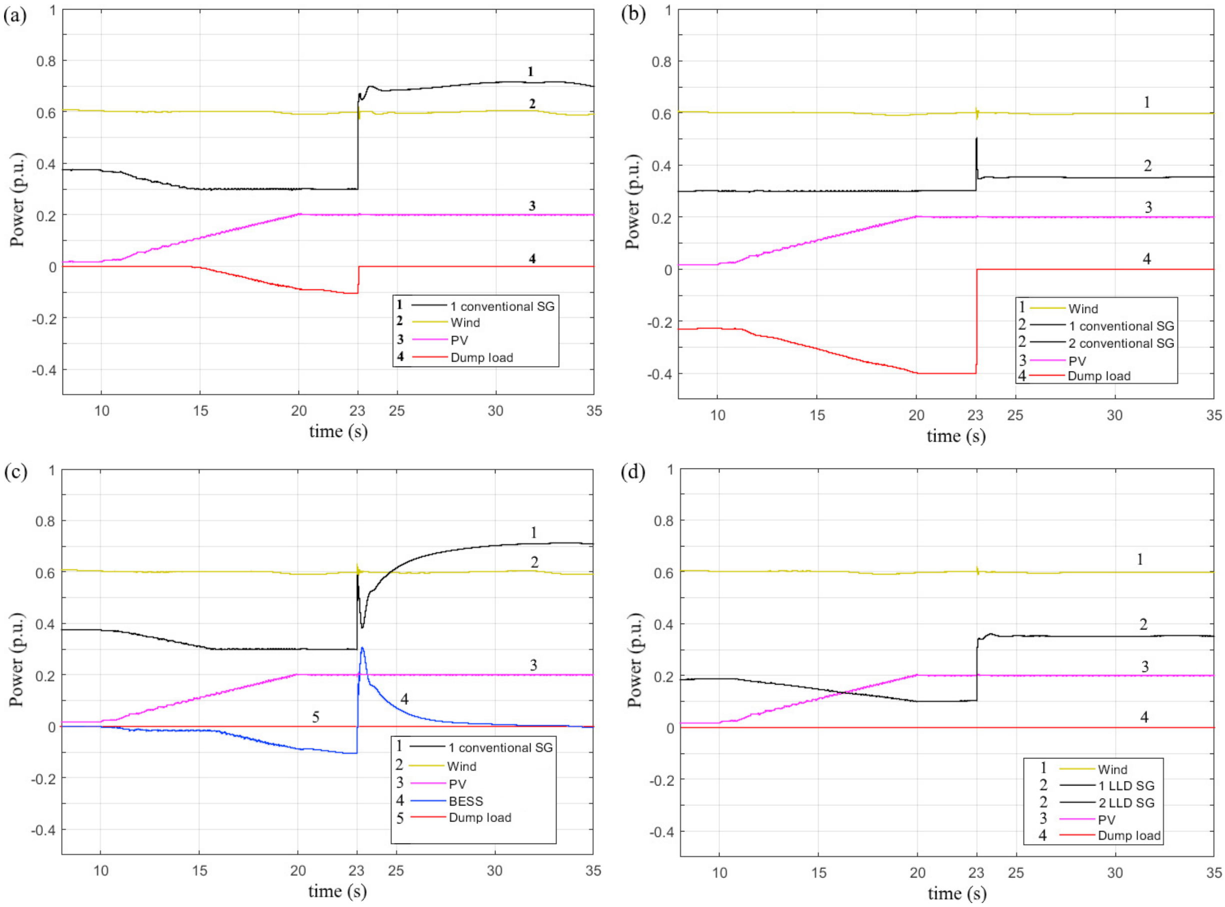

Fig. 7. (a) case 1; (b) case 2; (c) case 3; (d) case 4.

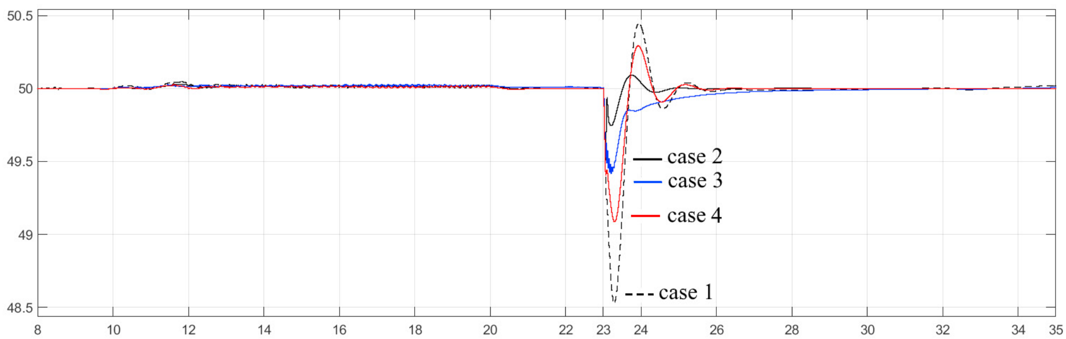

Fig. 8. Frequency response for case studies 1-4.

6. Conclusion

Hybrid isolated power systems supplied by renewable energy sources still depend on diesel generators both for stability and reliability reasons. The key challenge for these systems remains selection of suitable enabling technologies, able to provide system stability under high RE penetrations, yet for minimum capital investment. This paper has demonstrated the performance of low load diesel generators under extreme operation conditions. For the modelled scenario it was shown that low load diesel technology can provide high renewable penetration and proper stability margin without the need for expensive energy storage equipment.

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