Demand Response for Smart Microgrid: Initial Results

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***Abstract*—This study is an attempt to address the frequency and voltage regulation inside of an islanded microgrid. Central demand response along with an adaptive hill climbing methodology is applied to a small islanded microgrid powered by a diesel generator. All dynamic models are developed in MATLAB/Simulink®. Simulation results show that the proposed method has the potential to suppress the frequency variations and stabilize the voltage of the microgrid.**

***Index Terms*—Demand response, smart grid, microgrid.**

I. Introduction

ENABLING active participation by electricity customers in demand response has been identified by USDOE as an important feature of smart grid [1]. This feature can be effective in maintaining a balance between generation and demand, and as a result, keeping system frequency and voltage within desired limits. Demand response can especially be effective with increasing penetration of intermittent renewable power. In a power system, frequency drifts upwards or downwards, is the main indicator of excess or deficiency of generation, respectively [2]-[4]. This deviation in frequency can be controlled through demand response.

With the rapidly increased demand for electricity and interest in the use of distributed generation (DG), control of power systems are becoming increasingly harder. In isolated applications, adding a small- or medium-size DG to a distribution system may not have a significant impact on the power quality at the feeder level. However, adding a large number of DGs to the main grid can create a daunting new challenge for their safe and efficient operation, as well as the safe operation and control of the power network to which they are connected. To address this challenge, a collection of DGs, loads and storage at a given part of a distribution system are independently managed as a microgrid, which can operate in grid-connected or island mode.

Frequency and voltage control which are known as ancillary services, have always been an essential part of a power system to achieve the required power quality standards. Three different levels of frequency control (primary, secondary and tertiary control) are applied in the ancillary services. In this way, spinning and non-spinning reserves (i.e., generation, storage, and responsive load) have the primary role for controlling frequency in a short period of time between 30 seconds up to 15 minutes [2].

Typically in the conventional ancillary services, load is only controlled under severe stability conditions such as under-frequency load shedding [3]. However, in the smart grid environment and availability of more information, some customer loads with energy storage capability, such as electric water heaters (EWHs) are excellent candidates to participate in balancing generation and demand [5].

In grid-connected mode, the frequency and voltage of a microgrid is the same as that of the main grid, and frequency and voltage regulation are achieved as explained earlier, i.e., through the traditional ancillary services. However, frequency and voltage regulation of microgrids in island mode need to be addressed independently, particularly in the absence of conventional ancillary services (such as spinning and non-spinning reserves). Frequency and voltage regulation, and other power quality issues become even more important given the intermittent nature of renewable power generation sources which may be inside a microgrid.

This paper presents some initial results showing the potential of using demand response for frequency and voltage regulation at the output of an isolated diesel generator. Adaptive hill climbing (AHC) method is applied to regulate the frequency with responsive loads. Based on the frequency deviation, the amount of the responsive loads (which are assumed to be EWHs) that should be operating at any time, is determined to keep the frequency within a desired limit. Simulation results indicate that the proposed method can effectively improve the transient and steady-state frequency and voltage deviations.

II. System Description

For proof of concept, a small islanded microgrid is considered in this study. It includes a 3.125-MW, 2.4-kV diesel generator, equipped with speed governor and exciter, as a DG, along with fixed and active dynamic (responsive) loads. The system configuration is shown in Fig. 1. In general, a storage device is also a part of a microgrid; however, since the purpose of this paper is to show the applicability of AHC for frequency and voltage stabilization, a storage device is not included in the simulation studies and not shown in Fig. 1.

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The controller takes the frequency deviation signal ($\Delta f = f - f_{ref}$) as input, and based on that signal, it determines the amount of the responsive load, which needs to be disabled or enabled to keep the frequency within the desired threshold limits. The approach will also be effective for voltage stabilization, as will be shown in Section IV. This is because the output voltage of the generator depends on the amount of power demanded from the generator. Thus, by controlling the active responsive load, both the frequency and output voltage of the microgrid are regulated at the same time.

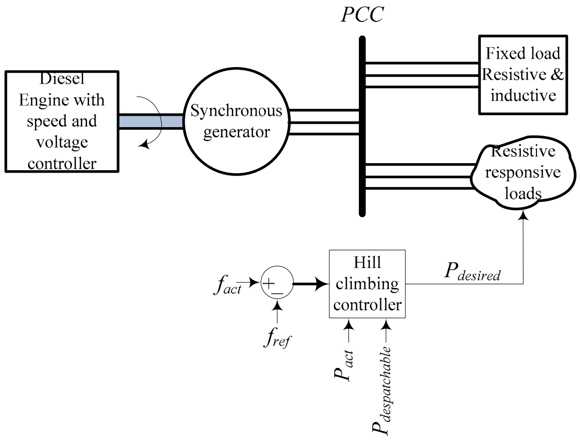


Fig. 1. Configuration of the proposed system.

This study focuses on resistive load regulation for frequency stabilization at the distribution level, where microgrids normally operate. AHC control (described in Section III) is applied to regulate the frequency by controlling the system responsive loads. Promising simulation results show the potential of the proposed demand response strategy for frequency and voltage regulation of an isolated diesel generator, which will eventually be applied to a microgrid. The responsive load is considered to be 15% of the total load, i.e., 15% of the total load is available to be controlled. Each responsive load is assumed to be a 4.5 kW electric water heater (EWH), which could be either in "ON" or "OFF" state.

The dynamic model for the diesel engine with governor and excitation controller and synchronous generator are extracted from MATLAB/Simulink SimPowerSystems toolbox [8], which are based on the IEEE standard 421.5 [9].

The dynamic load is modeled in the *d-q* frame as shown in Fig. 2. Based on the theory of *d-q* frame [10], the direct-and quadrature axis currents (i_d and i_q) can be expressed as follows:

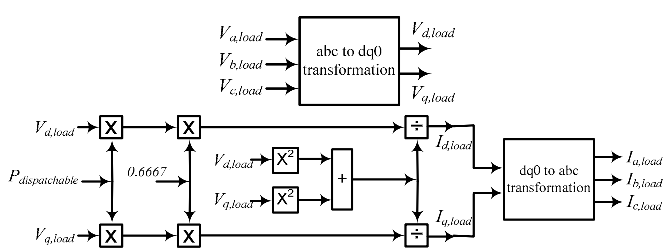


Fig. 2. Schematic of modeling of the active dynamic load.

$$i_d = \frac{2}{3} \cdot \frac{v_d}{v_d^2 + v_q^2} \cdot P + \frac{2}{3} \cdot \frac{v_q}{v_d^2 + v_q^2} \cdot Q \tag{1}$$

$$i_q = \frac{2}{3} \cdot \frac{v_q}{v_d^2 + v_q^2} \cdot P - \frac{2}{3} \cdot \frac{v_d}{v_d^2 + v_q^2} \cdot Q \tag{2}$$

where P and Q are the desired active and reactive power of the responsive load, respectively, and v_d , v_q (i_d , i_q) are the load voltage (current) in *d-q* frame. To transform the values from *abc* frame to *d-q* frame and vice versa, a phase locked-loop (PLL) is applied [10]. The voltage values in the *d-q* frame are extracted from the voltage across the load. The *d-* and *q*-axis of currents calculated are then transformed into the *abc* frame through the *dq0* to *abc* block.

III. The Proposed Control Strategy

The proposed control strategy regulates the frequency of the islanded microgrid by controlling the operation of the responsive EWHs to match the demand and generation at each instant in time. On the average, residential EWH electricity consumption accounts for about 11% of total electricity consumption and it increases to over 30% during peak demand hours [5], [6]. Therefore, there is a considerable potential for EWHs to be effective in demand response applications for frequency and voltage stabilization. When the frequency deviation, Δf, is negative (due to low generation or high demand), then a portion of the responsive loads that are operating will be turned OFF. On the other hand, when Δf is positive, a part of the responsive loads that are not operating will turn ON. Therefore, the percentage of the EWHs in the ON/OFF state is continuously adjusted, as shown in Fig. 3, to regulate the system frequency within the desired limit. Since EWHs have energy storage capability, turning them ON or OFF for a few minutes may not have a noticeable effect on the participating customers comfort level, and they may not even realize the control of their EWH. Moreover, the percentage of participating responsive load is kept to a minimum at each instant.

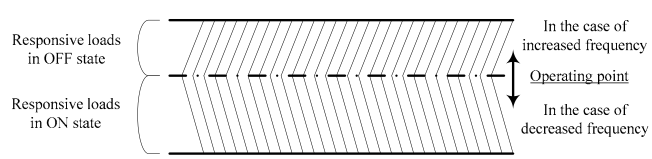


Fig. 3. The idea of responsive load control.

AHC is applied to determine the percentage of responsive loads which need to be operating at each instant in time for frequency stabilization. This technique was originally introduced for maximum power point tracking (MPPT) for photovoltaic (PV) systems [11], [12]. The original hill climbing involves a perturbation in the duty ratio of the power converter which perturbs the PV array current, which consequently perturbs the PV array voltage [11], [12]. This way, the operating point of the PV systems will move to its corresponding maximum power point based on solar irradiation and temperature variations. In this study, the above technique is used for frequency stabilization. The flowchart for this operation is illustrated in Fig. 4. Having the actual frequency at hand, the Δf can be calculated. If Δf is lower than a pre-assigned threshold value, the system is in the safe operation mode. Otherwise, the required amount of ON (or OFF) responsive load will be turned OFF (or ON) according to the sign of the frequency deviation. This loop will continue until the frequency deviation is lower than the threshold value.

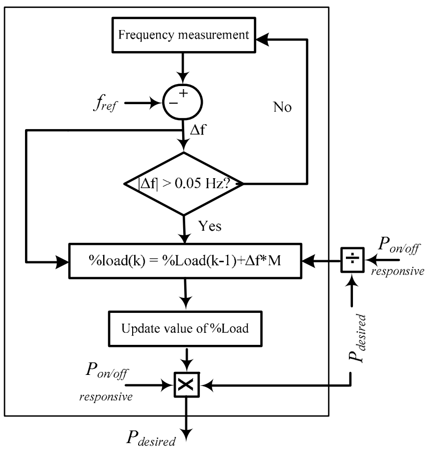


Fig. 4. The flowchart of the adaptive hill climbing technique.

In the original hill climbing algorithm, a constant perturbation parameter is defined to move the operating point to a new maximum power point. It is shown in [12] that selection of this parameter is a trade-off between improved dynamic response and steady-state performance. Also, it is concluded that it is ideal to make this parameter large during transient stage and small at steady-state. Therefore, AHC has a variable perturbation parameter [12]. In this study, the perturbation parameter is M*Δf, where M is constant used to scale down the frequency deviation, such that the required percentage of the responsive loads at any sample point *k* is obtained using the *%load* at the previous sample point (*k-1*), as shown in the flowchart in Fig. 4. A larger value for M results in improved dynamic performance, but at the same time, it results in control of more responsive loads, which may affect some of the participating customers' comfort level. This way, when the frequency deviation is large, the incremental (or decremental) step in variation of responsive loads is also large. On the other hand, the incremental step in variation of responsive loads is small for small frequency deviation. In this study M=0.1, which is considered to not very large or very small. The control algorithm is updated every 0.01 sec.

In an actual system, there are two possibilities of delay in response; one is related to the dynamic response of the loads and the other related to the delay in communication. Both delays shall be considered in the control algorithm to prevent unnecessary switching of the responsive loads. Since EWHs are purely resistive loads, they will respond to the changes very rapidly. Therefore, it can be assumed that there is no delay in their response to the changes [6]. Also, the time delay from when a request is made by a control entity to when the electrical device receives the request and acts on it, which is referred to as *latency*, should be less than 500 ms with the existing internet infrastructure [13]. In this study, a wireless network is considered as the communication protocol between the control entity and loads with latency of less than 20 msec. Longer latencies would make the settling time for the transient part of the frequency response larger, as will be shown in Section IV.

In conventional ancillary services, the maximum allowed frequency deviation for a large power system is around ±0.2 Hz, while it can be larger for small power systems with low inertia. For the British power system, this value is ±0.5 Hz [2]. In addition, a frequency dead-band of ±0.015 Hz is introduced before the controller responds to the frequency deviation signal for the British power system. This value is around ±0.01 Hz for the North American power system. As shown in the flowchart of Fig. 4, in this study, the threshold for frequency deviation is assumed to be ±0.05 Hz or ±0.083% of 60 Hz.

IV. Simulation Results

Simulation studies were conducted under different loading conditions to evaluate the performance of the proposed control strategy. In order to show the positive and negative frequency deviation, the mechanical power of the diesel engine was limited to certain maximum and minimum values, so that, frequency decrements and increments from the reference frequency (60 Hz) can be simulated.

A. No Control

Fig. 5, 6 show the frequency response of the DG system in the absence of AHC controller for light and heavy loading, respectively. In all cases, the load is changed from 1.6 MW to the level shown in the figures at t=10 sec. In the light load case, various active loads of 1.2 MW to 1.5 MW are used. Because of the availability of higher amount of generation than demand, the frequency exceeds its rated value (60 Hz). When the load is 1.3 MW or higher, the speed governor of the DG is effective in stabilizing the frequency. However, when the load goes down to 1.2 MW or lower, the speed governor of the DG fails to stabilize the frequency (Fig. 5).

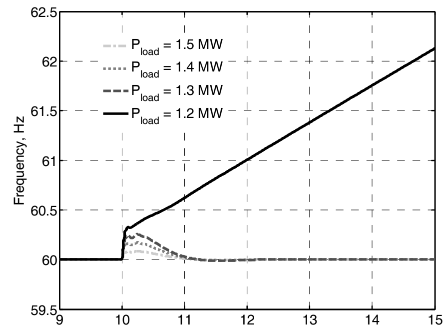


Fig. 5. Rising frequency under light loading – no control.

The system frequency response in the heavy loading case is shown in Fig. 6. The DG's speed governor is able to stabilize the frequency up to 3.2 MW. Beyond this load, e.g. at 3.3 MW load, the speed governor fails to stabilize the frequency.

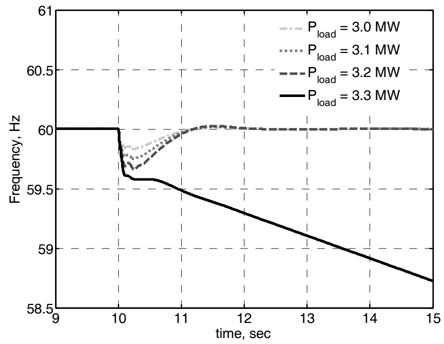


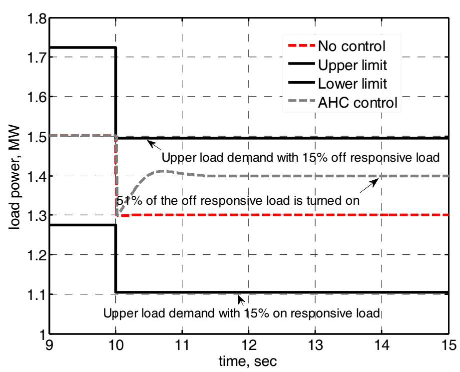
Fig. 6. Failing the system frequency under heavy loading – no control.

B. Controller enabled

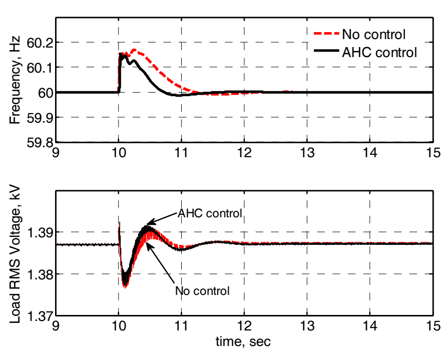
In the remainder of the simulation results shown, the system performance is compared when the AHC controller is enabled with those when the controller is disabled. The results show the improvement in the system performance under different loading conditions when the controller is enabled. In all cases, it is assumed that the ON/OFF responsive loads are %15 of the total load.

Case 1:Light loading – decrease in load

As shown in Fig. 7 (a), 1.5 MW load is suddenly switched to 1.3 MW at t=10 sec. The upper and lower limits of the responsive loads are also shown and labeled in the figure.



(a)

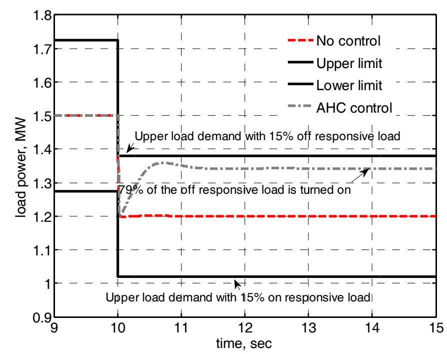


(b)

Fig. 7. (a) Responsive load power, (b) Frequency and RMS value of the voltage: P_{load} = 1.3 MW.

As shown, 51% of the responsive loads are gradually turned on by the AHC to stabilize the frequency. The frequency and voltage profiles are shown in Fig. 7(b). It is clear from the figure that the transient behavior of the frequency response is improved when the AHC controller is applied. It is also clear that the oscillations in the transient part of the output voltage of the DG are reduced when the AHC controller is enabled.

Fig. 8 shows the generator frequency and voltage response due to a sudden change in demand from 1.5 MW to 1.2 MW at t = 10 sec. Fig. 8(a) shows the load change, the upper and lower limits of load demand, and the response of the responsive loads in the direction to stabilize the frequency and voltage. It is noticed from this figure that 79% of the responsive loads (which were in the OFF state) are turned ON at steady-state in order to stabilize the frequency to the desired level, whereas the frequency will go out of range under no control, Fig. 8(b). It is also clear from this figure that the oscillations in the generator voltage under AHC control are reduced considerably and the voltage is stabilized at the desired level at steady-state.



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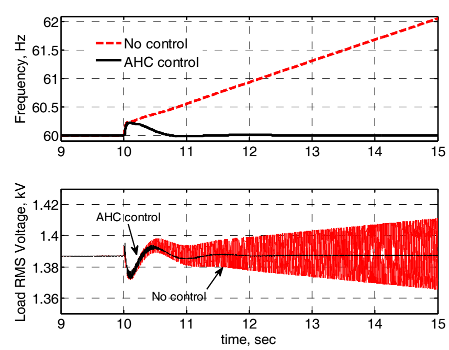
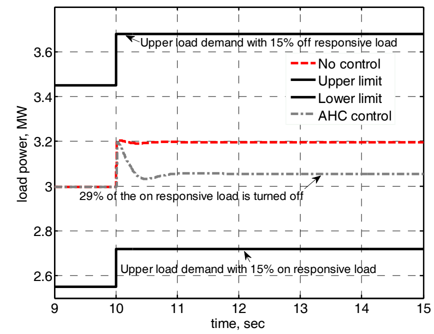


(b)

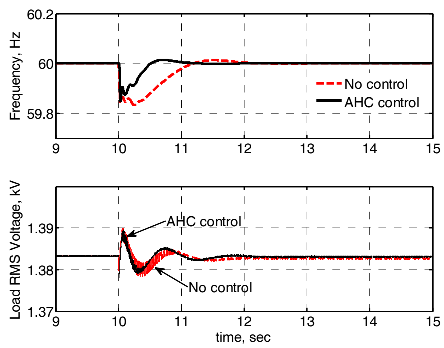
Fig. 8. (a) Responsive load power, (b) Frequency and RMS value of the voltage: P_{load} = 1.2 MW.

Case 2:Heavy loading – increase in load

In this case, the load is suddenly increased from 3.0 MW to 3.2 MW, Fig. 9 (a). The load demand for both the no control and with AHC controller is also shown. It can be seen that at steady-state, 29% of the responsive loads (which were ON) are disabled to improve the frequency response, as shown in Fig. 9 (b). In addition, the voltage ripples are again suppressed considerably and the voltage remains stable when the AHC controller is enabled.

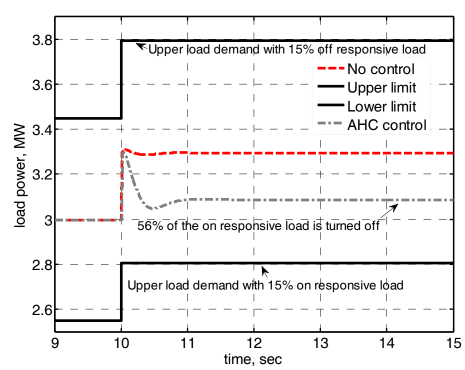


(a)

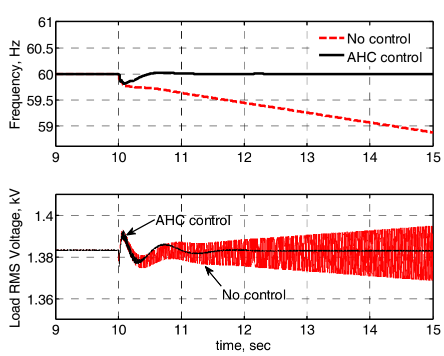


(b)

Fig. 9. (a) Responsive load power, (b) Frequency and RMS value of the voltage: P_{load} = 3.2 MW.



(a)



(b)

Fig. 10. (a) Responsive load power, (b) Frequency and RMS value of the voltage: P_{load} = 1.3 MW.

As shown in Fig. 10 (a), a 3-MW load is suddenly increased to 3.3 MW. The upper and lower limits of the load demand considering the 15% responsive load along with the load demand for both the no control case and with the AHC controller are also shown in the figure. By turning OFF 56% of the responsive loads which were ON, the frequency of the system is preserved in the standard range. Fig. 10 (b) shows the frequency and voltage profile of the system. The proposed AHC controller stabilizes the frequency, whereas the frequency goes out of range when the controller is not enabled. As in the previous cases, the voltage is also stabilized when the AHC controller is enabled.

C. *Effect of latency on frequency response*

The simulation results given above are all for a latency of 20 ms. Under longer latencies, it takes longer time for the responsive loads to receive the control commands from the AHC, and as a result their response for controlling the frequency will be delayed. Fig. 11 shows the effect of longer latencies on the transient behavior of the frequency response under light loading (1.3 MW). It is clear from the figure that the controller is more effective during the transient period for lower latencies.

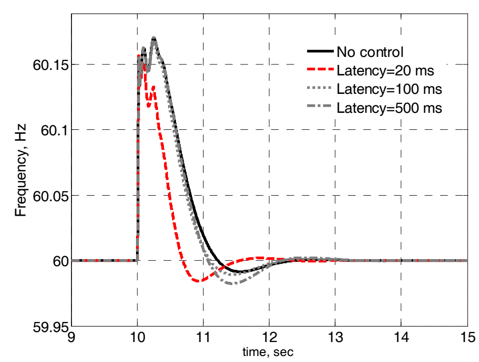


Fig. 11. The impact of latency on the frequency response, P_{load} = 1.3 MW.

Fig. 12 shows similar simulation results for 1.2 MW of load. It is noticed that under no control, the speed governor is not able to stabilize the frequency, but the frequency is stabilized when the controller is enabled. However, more oscillations are observed in the frequency response as latency is increased.

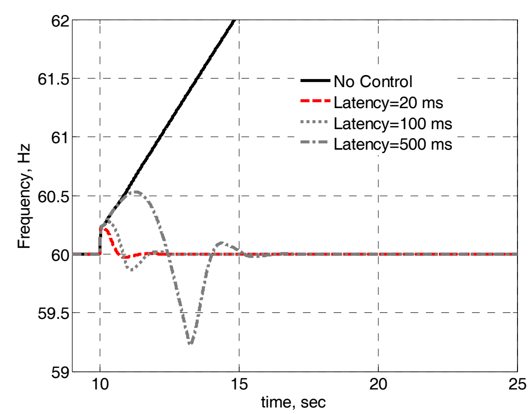


Fig. 12. The impact of latency on the frequency response, P_{load} = 1.2 MW

V. Future Work

In this study, the percentage of the responsive load needed to stabilize the frequency is updated every 0.01 sec. when the frequency deviation is out of the dead-band range. Under this condition, this amount of manipulated responsive load is not necessarily the minimum possible to bring the frequency to its reference. This is because the responsive load is changing faster than the system inertia. Although the present algorithm would be beneficial at the beginning of the frequency deviation to improve its transient behavior, it can reduce the customers' comfort level. Future work will include finding ways to stabilize the frequency while dispatching minimum amount of responsive load.

VI. Conclusion

A demand response-based frequency control strategy is proposed in this paper for an islanded microgrid using the AHC method. Simulation results show that the demand response can be properly applied in the islanded microgrid to regulate both the frequency and voltage profile at the same time. It is also shown that, the transient part of the frequency profile is improved under sudden load disturbances. The proposed approach is suitable for smart grid applications, where control of responsive loads will be achievable through robust two-way communication.

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