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A Grid-Responsive Underfrequency Load-Reduction Control Scheme

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Abstract

The participation of power electronics interfaced loads or inverter-based loads has increased steadily over the last few decades and is expected to continue to increase. Such participation reduces the effect of loads on mitigating voltage and frequency variations, which is also called the self-regulation characteristic of loads. In order to restore the decreasing self-regulation characteristic of loads, an autonomous load-reduction control scheme which reduces electric loads by sending onset signals at 49.2 Hz was developed. The developed scheme reduces the active power consumption by 5% for 10 minutes. After the frequency recovers at over 49.2 Hz, the scheme allows the active power consumption to return to the pre-control level. The major benefits of the scheme are almost no extra cost of implementation and almost no inconvenience for appliance owners. Therefore, loads with this scheme are expected to be classified in the smart load category in the future. The autonomous load-reduction control scheme was implemented in a residential air-conditioner made by a major manufacturer and performed as expected.

Keywords: Autonomous control, load, load control, power system, underfrequency

1. Introduction

Power electronics interfaced or inverter-based loads have been widely introduced in Japan since the 1980s. In line with efforts to reduce the energy consumed by household appliances and the revision of the Rationalization of Energy Use Law, almost 100% of the compressors used in residential air-conditioners and refrigerators have a power electronics interfaced (inverter-driven) motor. Similarly, energy-saving lamps such as inverter-based fluorescent lamps, inverter-based high-pressure discharge lamps and even light emitting diode (LED) bulbs are now widely used. Furthermore, the termination of analog broadcasting led to widespread introduction of digital TVs. Thus, inverter-based loads are expected to increase in the future.

Load voltage characteristics and load frequency characteristics help to mitigate voltage variations and frequency variations by changing the active power load and reactive power load. This effect is known as the “self-regulation characteristics” of loads, which are summarized in Table 1.

Table 1. Effect of mitigation of voltage and frequency variation caused by self-regulation characteristics of loads

Load bus V or F	Active power load or reactive power load	Effect for voltage or frequency
Increase in voltage	Increase in active power load	Suppress voltage
Increase in voltage	Increase in reactive power load	Suppress voltage
Decrease in voltage	Decrease in active power load	Recover voltage
Decrease in voltage	Decrease in reactive power load	Recover voltage
Increase in frequency	Increase in active power load	Suppress frequency
Increase in frequency	Decrease in reactive power load	Lift up voltage → Increase in active power load
Decrease in frequency	Decrease in active power load	Recover frequency
Decrease in frequency	increase in reactive power load	Suppress voltage → Decrease in active power load

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Inverter-based loads are known as constant power loads, which means that the consumption of loads does not vary even when the voltage and/or frequency varies. The load voltage characteristics are usually represented using an index of exponential function, while the load frequency characteristics are usually represented using a proportionality coefficient. The representative load model used in Japan is as follows:

$$P = P_0\left(\frac{V}{V_0}\right)^{\alpha_P}\left(1+\frac{\beta_P}{100}\Delta f\right) \qquad Q = Q_0\left(\frac{V}{V_0}\right)^{\alpha_Q}\left(1+\frac{\beta_Q}{100}\Delta f\right) \tag{1}$$

where P_0 is the initial active power load, Q_0 is the initial reactive power load, V_0 is the initial load bus voltage, Δf is the deviation between rated frequency and load current bus frequency, α_P is the voltage characteristics index for active power load, α_Q is the voltage characteristics index for reactive power load, β_P is the frequency characteristics coefficient for active power load, and β_Q is the frequency characteristics coefficient for reactive power load.

Table 2 shows the index of exponential function and the proportionality coefficient for the active power and reactive power of representative loads. The table reveals that inverter-based devices give smaller values among the same categories, demonstrating that inverter-based loads decrease the self-regulation characteristics of loads.

Table 2. Parameters of the load model (1) and (2) for the load devices under constant frequency and voltage

Category	Load device	Inverter	α_P	α_Q	β_P	β_Q
Air-conditioner	Type A (residential)	Yes	-0.2	0.6	0.2	0.1
	Type B (residential)	Yes	-0.1	1.0	0.1	0.3
	Type C (residential)	No	0.4	5.1	1.2	-19
	Type D (industrial)	No	0.1	4.0	1.9	-7.7
Lighting	Fluorescent lamp	Yes	1.1	1.5	0.0	1.2
	Fluorescent lamp	No	4.4	3.4	-3.0	-14
	Incandescent lamp	No	1.6	1.8	0.0	0.4
	Mercury lamp	No	2.7	0.8	0.3	-1.3
Refrigerator	Type A (residential)	Yes	0.2	0.5	0.2	-0.3
	Type B(residential)	No	0.9	3.2	0.7	-7.2
Motor	Pump (11 kW)	No	0.0	0.5	5.9	0.7
	Pump (15 kW)	No	0.0	0.2	6.0	1.7
	Fan	No	0.2	2.3	4.6	-2.6
Miscellaneous	Personal computer	No	0.1	0.4	0.1	-0.3
	Analogue television	No	1.5	1.6	0.0	-0.6

One way to recover the decreasing self-regulation characteristics of loads is to vary the consumption of loads intentionally. This strategy is known as demand side management, and various techniques have been proposed for smart grid technologies. However, these approaches are inconvenient for appliance owners, and also require bidirectional communication and hence additional investment.

An autonomous underfrequency load shedding scheme was proposed by Pacific Northwest National Laboratory (PNNL) [1]. PNNL developed a Grid Friendly Appliance (GFA) controller and performed a field test involving applying the GFA controller to 150 new residential clothes dryers and 50 retrofitted residential water heaters from 2006 to 2007. The GFA controller sheds those appliances' loads for around 1 minute when the system frequency falls below a threshold of 59.95 Hz, which mitigates the frequency depth. The major advantage is that only a small investment is needed to make it feasible because bidirectional communication is not required, and it was reported [1] that appliance owners accepted and were not inconvenienced by such control of their home appliances.

This paper proposes another autonomous underfrequency load-reduction control scheme (ULCS) which does not require extra cost for implementation and does not cause inconvenience to appliance owners. The ULCS reduces electric loads by 5% by sending onset signals when the system frequency falls below 49.2 Hz (assuming that the rated frequency is 50 Hz). The ULCS sends release signals 10 minutes after it sends the onset signals on condition that the frequency depth become less than 0.8 Hz.

ULCS allows the consumption of loads to recover to the pre-disturbance level after receiving the release signal.

The rest of this paper consists of three sections. The proposed autonomous underfrequency load-reduction control scheme (ULCS) is introduced in Section 2. The ULCS which is applied to a residential air-conditioner is verified in Section 3. Conclusions are discussed in Section 4.

2. Development of Underfrequency Load-reduction Control Scheme

The proposed underfrequency load-reduction control scheme (ULCS) consists of a load-reduction scheme and a load-recovery scheme. The ULCS reduces the consumption of loads by 5% when the system frequency falls below 49.2 Hz, and recovers its consumption to the pre-disturbance level after stoppage of the load for 10 minutes on condition that the system frequency has risen over 49.2 Hz. These settings must be determined in coordination with other emergency frequency relay systems which are currently used in Japan as well as in coordination with emergency switching operations by the system operator. The load-reduction and load-recovery schemes and the approach for determining those settings are described below.

2.1. Load-reduction scheme

One of the main purposes of the ULCS is to recover the decreasing self-regulation characteristics of loads. The maximum load frequency characteristic coefficient β_P in (1) is 6%/Hz as shown in Table 2. If the ULCS is applied to all loads and the load-reduction rate is too high, excessive load reduction could occur, resulting in overfrequency due to too much load reduction. Therefore, the load-reduction rate was set at 5% relative to the rated power of the load:

$$6\ [\%/\mathrm{Hz}]\ {-0.8}\ [\mathrm{Hz}] = -4.8\ [\%] \approx -5\ [\%] \tag{2}$$

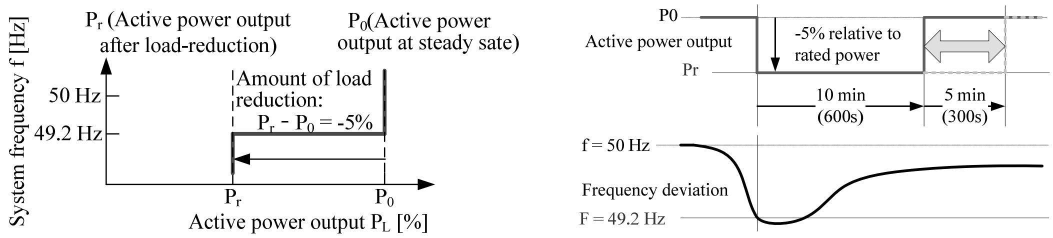
The load reduction by 5% at 49.2 Hz gives the same sensitivity of pumps, 6.0% MW/Hz. Because inverter-based loads show no sensitivity for frequency, the ULCS eventually recovers its sensitivity for frequency, and therefore, the decreasing self-regulation characteristics of loads.

Another important setting is the threshold of frequency for the load reduction. The load reduction triggered by the ULCS should be coordinated with load shedding and/or other emergency control actions triggered by the frequency relay system. The frequency relay systems have various control actions for preventing abnormal frequency. Emergency control by DC control devices and pumped storage generator tripping are major initial emergency control actions when the system frequency falls below 49.5 Hz. If the system frequency still falls on account of the above-mentioned emergency control actions, load shedding by underfrequency relays at substations is the next action. The loads are shed when the system frequency is below 48–49 Hz. The ULCS should be invoked before load shedding, and should also be invoked after the above initial emergency control actions. In order to satisfy those two constraints, 49.2 Hz was selected as the frequency threshold (see Fig. 1 (a)).

2.2. Load-recovery scheme

The load-reduction should not be released while emergency operation actions are performed. Clearly, generation must be urgently increased for recovering the system frequency when it falls below 49.2 Hz. The system operators must start pumped storage generators or available gas turbine generators which can increase their outputs quickly. In general, it takes about 10 minutes to complete the starting of such generators, and so 10 minutes was selected as the on-delay timer of release signals of ULCS (see Fig. 1 (b)).

The recovery characteristics are shown in Fig. 1 (b). Most of the loads can recover promptly or within a few minutes. However, large-capacity generators cannot increase their outputs quickly. In general, the increasing speed of an automatic frequency controller (AFC) can be considered to be 1–2% MW/min [2]. Therefore, the loads need to adjust the recovery speed of their consumption in accordance with the speed of the AFC; in other words, the loads must recover their consumption over 5 minutes in order to coordinate with generation. However, it is difficult to control the recovery speed without incurring extra cost. To overcome this difficulty, the introduction of a random timer was proposed. The ULCS selects the timing of its recovery randomly in the range of 0 to 5 minutes. Thus, the behavior of the total loads becomes a ramp recovery, the speed of which is 1% MW/min.



(a) self-disconnection characteristics (b) recovery characteristics

Fig. 1. Proposed self-disconnection characteristics and recovery characteristics of residential air-conditioner.

3. Verification of Underfrequency Load-reduction Control Scheme Using Residential Air-conditioner

The ULCS was implemented in a residential air-conditioner (AC) made by a major manufacturer. The test conditions are shown in Table 3. Because each item has two different conditions, the total number of test cases is 16. In order to implement the ULCS in the AC, the following two restrictions caused by modification of the AC with no extra cost needed to be solved: 1) The accuracy of measuring absolute frequency is low. 2) Controlling the recovery rate or recovery speed is difficult. The first restriction results from the use of a ceramic oscillator, and the second one is related to load reduction using a current control limiter.

In order to solve 1), the frequency deviation instead of the absolute frequency was introduced. The frequency deviation is derived by subtracting the present frequency from the reference frequency. The 0.2-second moving average was used to derive the current frequency, while the 1-hour moving average was used to derive the reference frequency. In order to solve 2), a random on-delay timer for releasing signals was introduced. The randomness of the timer was achieved using a counter which is reset every 300 seconds and memorizes the time duration that the AC operated up to the load reduction.

Table 3. Test condition for residential air-conditioner

Conditions	Setting mode or value
Operating mode	Cooler/Heater
Operating rate of power	Full power/Partial power
Timing of stepwise increase in frequency	Several seconds after onset signals are sent/300 s* after onset signals are sent
Change in active power during load reduction	Increase/Decrease

*Note: 300s instead of 600 s was set in order to shorten the testing time period.

3.1. Threshold frequency of ULCS

The threshold frequency when the ULCS reduced the active power consumption of the residential AC was verified, and was found to be 0.7 Hz for all 16 cases. Because 0.7 is larger than 0.5, the ULCS does not adversely influence the first emergency control actions such as pumped storage generator tripping.

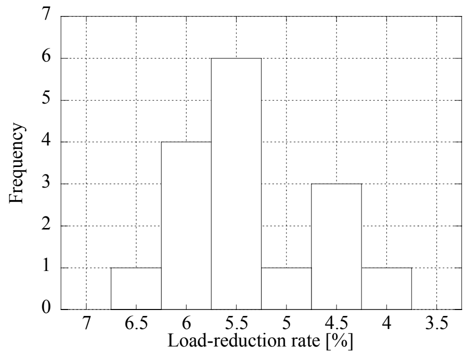
3.2. Load-reduction amount

The load-reduction amount was verified by subtracting the fixed consumption of the AC immediately after the load reduction from that before the load reduction. The consumption of the AC varied continuously, and so if the AC showed a fixed consumption for a few seconds, this was treated as the fixed consumption of the AC.

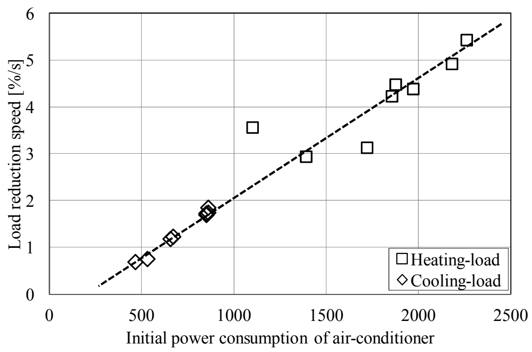
The distribution of the load-reduction rate is shown in Fig. 3 (a). The median value of the distribution was 5.4, which was larger than the value of the design specification. This mismatch of values can be fixed by changing the current control limiter of the AC.

3.3. Speed of load-reduction

The time required for the load reduction is another important factor for evaluating the mitigating performance of the frequency drop. Because the speed of frequency drop can be changed depending on the regulating energy of the power system as well as the imbalance between demand and generation, the maximum speed of frequency drop cannot be derived without a detailed time-domain simulation. According to historical data in Japan, a frequency drop of more than 1 Hz/s was measured at an isolated power system after system separation. Figure 3 (b) shows the relationship between the initial power consumption of the AC and the load-reduction speed. As shown, although the load-reduction amount is almost the same (see Fig. 3 (a)), as the initial power consumption of the AC is small, it takes longer to achieve the same load-reduction amount (see Fig. 3 (b)). In other words, the load-reduction amount per second is proportional to the initial power consumption of the AC, which means the percentage of the load-reduction among the total loads per second is almost the same regardless of the initial power consumption of the AC.



(a) Distribution histogram of load-reduction rate



(b) Load-reduction speed relative to initial power consumption

Fig. 3. Distribution histogram of load-reduction rate and load-reduction speed relative to initial power consumption.

3.4. Timing of load-recovery

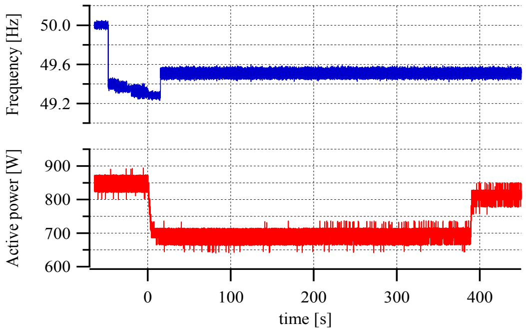
The timing of the load-recovery of ACs was validated under the test conditions shown in Table 3. Most of the mismatch between the assumed load-recovery time and the actual load-recovery time was around a few seconds. Some examples are described in Section 3.5.

3.5. Correct operation and correct non-operation

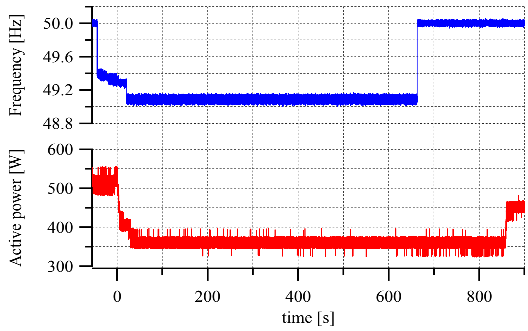
The correct operation and the correct non-operation of the ULCS were validated under the test conditions shown in Table 3. Representative measured responses of frequency and active power consumption of the AC are shown in Fig. 4.

Fig. 4 (a) shows an example of correct operation of the ULCS with load-recovery. After the load reduction was performed at 0 second, the frequency was set to 49.5 Hz which was higher than the frequency threshold of the ULCS. At 391 seconds in Fig. 4 (b), the active power consumption of the AC started to be recovered. Because the assumed load-recovery timing was 390 seconds, the mismatch of its load-recovery timing between them was just one second.

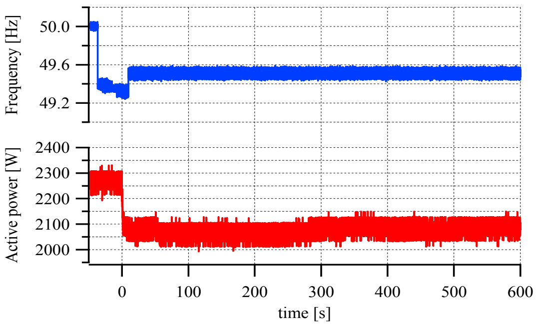
Fig. 4 (b) shows another example of correct operation of the ULCS with load-recovery. After the load reduction was performed at 0 second, the frequency was set to 49.1 Hz which was lower than the frequency threshold of the ULCS. Although the assumed load-recovery timing was set to 199 seconds, no load-recovery was shown at 499 seconds in Fig. 4 (b). On the other hand, because the frequency was set to 50.0 Hz at 663 seconds, the active power consumption of the AC started to be recovered at 859 seconds which was 196 seconds after the frequency became higher than the frequency threshold and that value was close to the previously-mentioned assumed recovery timing (199 seconds).



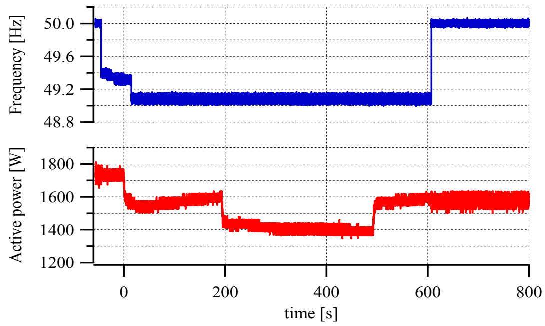
(a) Cooling-load, full power, 50Hz



(b) Cooling-load, partial power, 50Hz



(c) Heating-load, full power, 50Hz



(d) Heating-load, partial power, 50Hz

Fig. 4. Measured response of frequency and active power consumption of AC.

Figure 4 (c) shows an example of correct operation of the ULCS without load-recovery. After the load reduction was performed at 0 second, the frequency was set to 49.1 Hz. At 50 seconds in Fig. 4 (c), the active power consumption of the AC was slightly reduced. Therefore, no load-recovery was shown although the assumed load-recovery timing was 518 seconds.

Figure 4 (d) shows another example of correct operation of the ULCS without load-recovery. After the load reduction was performed at 0 second, the frequency was set to 49.1 Hz. At 193 seconds in Fig. 4 (c), the active power consumption of the AC was forcedly reduced by increasing the setting temperature. Moreover, the active power consumption of the AC was forcedly increased at 492 seconds in Fig. 4 (d) which is shorter than the assumed load-recovery timing (565 seconds). Regardless of the intentional load-recovery at 492 seconds, no more load-recovery appeared at 565 seconds in Fig. 4 (d).

The first two examples showed correct operation of the ULCS for load-recovery, while the last two examples showed correct non-operation of the ULCS for load recovery.

4. Conclusions

An autonomous grid-based underfrequency load control scheme which reduces electric loads when the system frequency depth exceeds 0.8 Hz was developed. The control scheme operated with the currently used SIPS in a coordinated manner. Therefore, the response of the control scheme precedes that of underfrequency relay operation at a substation and the response of pump storage tripping precedes that of the control scheme.

The control scheme sends release signals 10 minutes after sending the onset signals on condition that the frequency depth becomes less than 0.8 Hz. Therefore, the system operator has more time in which to complete some initial emergency actions. The developed load control scheme allows the active power consumption to recover to the pre-control level after sending the release signal. However, the time delay of the recovery is randomly selected within the range of 0 to 5 minutes to enable large-capacity generators to follow the increase in demand due to the load recovery.

The benefits of the control scheme are as follows:

- No extra cost for implementation and no inconvenience for appliance owners
- Increased possibility for reducing the frequency depth in the case of a significant frequency drop, thus raising the possibility of avoiding underfrequency relay operation
- The randomly selected recovery timing avoids unfairness among appliance owners.

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