Direct Load Control by AC Frequency Modulation

Philip J. Douglass and Shi You
Centre for Electrical Technology, Technical University of Denmark
Elektrovej-Building 325, 2800 Kgs. Lyngby, Denmark
{pjdo,sy}@elektro.dtu.dk

Abstract

Fine-grained under frequency load shedding called "demand as a frequency controlled reserve" (DFCR) has been shown to be a promising method of providing frequency regulation service from distributed loads [1]. Micro-grids with a large portion of intermittent renewable generation will benefit greatly from this technology because their low inertia.

The paper proposes a operating procedure for utilizing DFCR loads for energy balancing, expanding DFCR's well known role as a power balancing resource. The system operator can use DFCR for energy balancing by adjusting the frequency controller of generators to schedule off-nominal system frequency values.

The feasibility of the proposed system is evaluated on an existing small island power system.

I Introduction

As photovoltaic (PV) module prices continue to fall and diesel prices rise, the penetration of PV generation is expected to increase in diesel fueled isolated power systems. The amount of PV generation in an isolated system is limited by the minimum forecast daytime load in the absence of battery storage systems or curtailment. To provide reliable electric power during periods of low renewable energy sources (RES) production, a dispatchable generator must have sufficient capacity to serve the peak load. If the system contained dispatchable loads, they could be activated during periods of high RES production adding to the minimum load, and they could be deactivated during periods of low RES production, lowering the capacity requirements of the dispatchable generator.

When frequency responsive DFCR loads were field tested in a small island power system, problems arose because the devices assumed the system's mean value for frequency was always the nominal frequency, but on the island, the system frequency was observed at off-nominal values for extended periods of time. It was clear from the sampled frequency data that the system was operated in two distinct frequency regimes and this observation lead us to investigate whether these frequency regime changes could be detected and utilized.

Loads suitable for DFCR operation will typically have constraints on the energy demanded over a given time period, but some loads may have additional time constraints on their operation. These time constraints have precedence over the frequency response, and have the potential to lead to undesirable system behavior.

Modulating AC system frequency has been used to curtail production in microgrid systems [2], and frequency responsive loads have been described in [1, 3, 4], but the authors are unaware of previous work describing the modulation of frequency for controlling loads with time constraints.

This paper is organized as follows. Section II describes the behavior of DFCR in micro-grids. The proposed system operation concept is described in detail in Section III, followed in Section IV by a case study of the island of Christiansø in the Baltic Sea. Finally, Section V is a discussion and Section VI concludes the paper.

II DFCR loads in Micro-grids

A micro-grid is modeled with 4 lumped entities: dispatchable generators with droop frequency controllers, stochastic RES generators (PV modules), DFCR load and finally residual (high priority) load, see Figure 1.

Typical automatically controlled loads (such as thermostat controlled loads) operate in two states, OFF and ON, with the duty cycle controlled to keep the energy level within desired bounds. A DFCR controller will alter the phase of the duty cycle to defer energy consumption away from time periods when the grid is overloaded. The only way to create

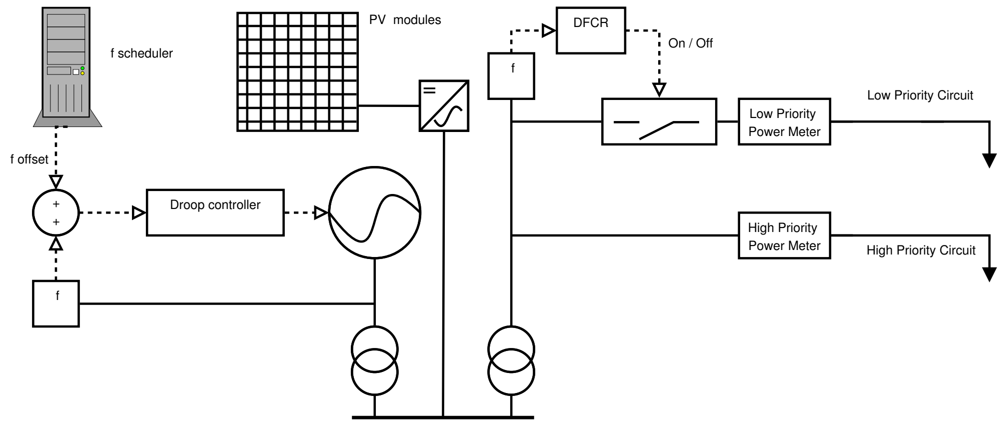

Figure 1: Oneline diagram showing relation between generator governor and DFCR. Solid lines represent electric conductors, dotted lines represent data transfer paths.

a smooth and reliable frequency response with OFF/ON loads is to have a population of devices with a diversifying parameter such as differing frequency thresholds. A small synchronous system will have a small population of DFCR loads, where each one may be a significant portion of the total load. Therefore, the diversity of a large population can not be counted on.

Energy constraints for loads are represented by the maximum time the device is allowed to be disconnected from the electric energy supply (t_{max_off}), and the minimum time it must remain reconnected after being disconnected (t_{min_on}). Processes with startup costs and shutdown costs, such as an induction motor's inrush current, will have additional constraints besides a minimum demand for electric energy over a given time period. The startup and shutdown costs are represented by the minimum ON time (t_{min_on}) and the minimum OFF time (t_{min_off}).

DFCR with time constraints is suitable to act as disturbance reserve, reducing load during large and infrequent drops in frequency, but is unsuitable to act as a continuous regulation resource within the normal frequency operating range. The problem with DFCR as a continuous regulation resources is acute both when RES production is high and the load low, and when RES production is low and the load is high.

When the RES production is more than the residual load, the droop controlled dispatchable generator cannot further reduce production, and the DFCR load is critical to absorbing the RES energy over-production. If the DFCR load is constrained by t_{min_off}, frequency will rise uncontrollably in the absence of alternative frequency regulation resources (i.e. dump load).

When RES production is low, the t_{min_on} constraint of DFCR can compromise the security of the system. In a scenario where the dispatchable generators do not have the capacity to supply the DFCR and the residual load simultaneously, DFCR load constrained by t_{min_on} can cause the system frequency to decline uncontrollably (until axillary frequency regulation resources such as shedding of high priority loads are activated), see Figure 2.

III Dispatch of DFCR loads

The control of distributed energy resources is typically classified as either direct or indirect [5]. Direct control corresponds to the architecture of existing utility SCADA systems where commands are issued from a centralized controller and remote terminals respond to the commands in a deterministic manner. Frequency controlled reserves are not usually considered as directly controlled because the control signal (system frequency) is not actively generated, but rather results from the intrinsic behavior of the power system. Dispatchable generators participating in frequency regulation are able to alter the system frequency by altering the parameters of their frequency controller, see Figure 4. When frequency measurements are averaged over long time periods to filter out the intrinsic volatility of the system power balance, changes in the generators' frequency regulation parameters can be detected by DFCR loads.

A droop controller will produce power proportional to the system frequency, with lower frequencies resulting in higher power output. Thus, at steady-state conditions, the frequency will indicate the amount of load on the droop controlled generator. In the presence of limited generation resources and a significant amount of frequency dependent demand, lowering the system frequency can be used as a proactive measure to balance load and generation by selective load shedding. Changing the system frequency target on some frequency regulation resources, but not others reallocates the energy production between the two groups of resources (ie. supply-side and demand-side).

The DFCR algorithm for relay-based devices described in [1] has a frequency threshold (f_{off}) below which the load is disconnected. Loads are reconnected when

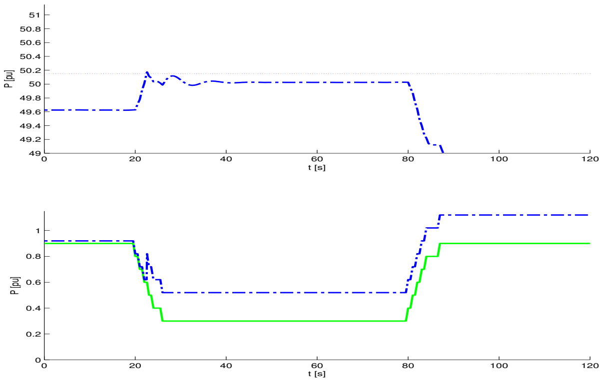

Figure 2: DFCR with t_{min_on} constraints during a transient spike in RES output. Top graph shows frequency with the black horizontal line $f_{restore}$. The bottom graphs show loads (minus RES production). The solid green line represents the residual load, the blue dashed line shows the addition of DFCR loads.

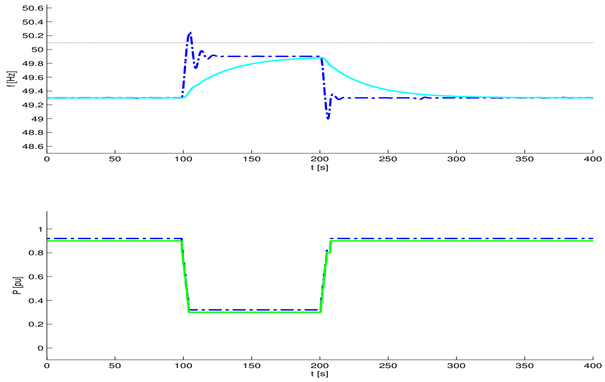

Figure 3: The top graph shows the system frequency (dark blue) and the frequency subjected to a low pass filter (light blue). $f_{restore}$ for the filtered frequency is the solid black line. The system frequency does not stay above the threshold long enough for the filtered value to cross the reconnect value, so the DFCR remains off.

system frequency is above a second, higher threshold frequency ($f_{restore}$), creating a simple deadband. A wide enough deadband would avoid spurious changes to DFCR state, but this has the disadvantage that when the system resides inside the deadband the DFCR state is uncertain because it depends on historical frequency deviations rather than the current frequency.

To narrow the deadband while avoid spurious switching DFCR state, the DFCR can pass the frequency samples through a low pass filter before comparing the value to preset thresholds. A moving average or exponentially-weighted moving average filter could be utilized.

A similar algorithm was described in [6], where different cutoff frequencies existed for short-term frequency deviations (i.e. 1s) and longer-term deviations (i.e. 5 min.). This algorithm is well suited for the proposed scheme because a small but consistent deviation from nominal frequency on a long time scale will force devices into either the ON or OFF state. Changes to the long-term average frequency are feasible to provoke, even when the frequency varies widely in the short-term.

Figure 3 shows how DFCR with a low pass filter will not change state when subject to steep ramps of RES generation.

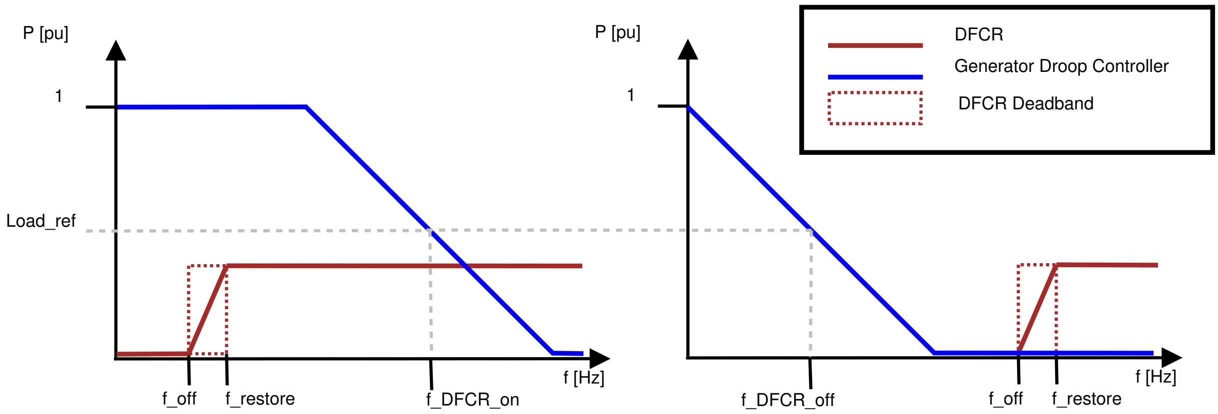

Figure 4: Left: DFCR devices dispatched in ON state by allocating droop controlled reserves to well above f_{off}. Right: DFCR devices dispatched in OFF state by operating droop controlled reserves well below $f_{restore}$.

IV Case Study: Christiansø

Christiansø is a decommissioned naval base which is a popular tourist destination. Around 100 people live permanently on the 0.22km^2 island. Their electric power system is composed of 4 diesel powered generators, two with a rating of 180kW, one 130kW and one 60kW. At the moment, there is no renewable electricity generation, though the wind and solar resources are available.

Two bottle cooling refrigerators with DFCR functionality have been installed as part of an ongoing experiment [7]. Frequency measurements were collected when the DFCR functionality was disabled to characterize the system.

Two modes of operation were observed, and within each mode, the frequency measurements fit well into a normal distribution, with the average value of 50.00Hz for group one and 50.11Hz for group two. The standard deviation for group one was 43.4mHz, for group two 137.3mHz. The moving average of high resolution frequency measurements from group two was found and the standard deviation of these filtered values was 48mHz.

The normal distribution of frequency samples implies that 99.9999% of the time the value will be within $\pm 5\sigma$ of the mean. Conversely, the system frequency will be farther than $\pm 5\sigma$ from the mean approximately 50 milliseconds per day. If the generators were set to produce at $f_{DFCR\_on} = f_{restore} + \sigma = f_{off} + 5\sigma$, then the filtered frequency would be above $f_{restore}$ 84% of the time, and below f_{off} 25ms per day.

With a deadband $4\sigma = 200mHz$, then the average frequency to dispatch DFCR in the ON state with high confidence would be $f_{DFCR\_on} = 50.150Hz$. To be highly certain that the DFCR devices are OFF, the average frequency would have to be $f_{DFCR\_off} = 49.850Hz$. This range of frequency offsets is slightly larger that that already observed during normal operation on Christiansø, but considered feasible without significantly effecting the functioning of conventional loads. Alternatively, if $f_{DFCR\_on} = f_o$, the $f_{DFCR\_off} = f_o - 6\sigma = 49.700Hz$.

The EN 50160 standard [8] used in Europe requires that island power system maintain their frequency at $50Hz \pm \%2$ ($49Hz$ to $51Hz$) for 95% of a week and $50Hz \pm 15\%$ ($42.5Hz$ to $57.5Hz$) for 100% of the time. A mean value of 49.700Hz gives a margin to the statutory minimum frequency of $700mHz$, which is acceptable during unfaulted operation.

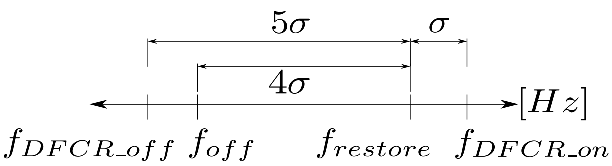

Figure 5: Relative placement of DFCR frequency thresholds and generator setpoints.

Parameter	Relative Value	Value
f_o		50Hz
σ		50mHz
f_{off}	$f_o - 2\sigma$	49.9Hz
$f_{restore}$	$f_o + 2\sigma$	50.1Hz
f_{DFCR_on}	$f_{restore} + \sigma$	50.150Hz
f_{DFCR_off}	$f_{off} - \sigma$	49.850Hz

Figure 6: Suggested parameter values for DFCR operation on Christiansø with thresholds symmetric to f_o

V Discussion

The difference between target frequency values would have to be larger than the typical variation of frequency (i.e. $> 5\sigma$) but if disturbances pushed the system frequency into a neighboring frequency band, the autonomous action of the DFCR would act to restore the frequency to the targeted value. The utility's load control performance would depend on how closely the autonomous action of the DFCR conformed to pre-established schedules. By designing the DFCR threshold levels and target frequencies, arbitrary levels of load control performance can be achieved. Metrics for measuring frequency quality would be redefined as deviations from the target frequency, not deviations from nominal.

VI Conclusion

The paper has proposed a new operating concept which utilizes DFCR, a highly distributed under frequency load shedding method, as part of direct load control scheme. Frequency sensitive loads are dispatched by adjusting the generators' frequency controller to target off-nominal frequencies. The feasibility of this concept was demonstrated by simulations, and by analyzing data collected from an operating small island power system. The analysis shows that DFCR loads can be dispatched with high reliability without endangering the system's ability to remain within the range of acceptable frequencies.

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