Constant Power Loads

ABSTRACT

As data centers reshape the energy landscape, the nature of their loads requires careful analysis for the use of on-site gensets.

Load Types

Electrical load can be theoretically classified in three general types:

1. Constant Impedance, e.g., a resistor
2. Constant Current, e.g., LED lighting
3. Constant Power, e.g., data center server loads

Constant impedance loads follow Ohms law. The voltage (V) is proportional to the current (I) flowing through the element. The proportionality factor is the impedance (X). Thus, V = X*I, and the power consumed by the load is P = V*I or $P = V^2/X$. Then, if the voltage across the element decreases, the power consumed by the element is reduced in a quadratic fashion with voltage. For example, if the voltage is reduced to 90% of rated voltage, the power consumed by the load would be 81% of what it would consume at rated voltage.

Constant current loads do not follow Ohms law and the current flowing through the element does not depend on the voltage across the element. Thus, the power consumed by the load is reduced in linear fashion with voltage. If the voltage is reduced to 90% of rated voltage, the power consumed by the load would be 90% of what it would consume at rated voltage.

Constant power loads are those that consume the same amount of power at any voltage. Thus, a reduction in voltage is accompanied by an increase in current, so the power consumed by the load remains unchanged.

Data Center loads primarily fall under the constant power category. Some UPS systems exhibit a hybrid behavior where for a voltage range near nominal voltage, the load is constant power, but when voltage drops below a set value, the UPS may enter a current limiting regime behaving akin to a constant current load.

This report focuses primarily on constant power loads and constant impedance loads, drawing comparisons between the two. At nominal voltage, for the same power rating, the two loads behave identically. As the voltage sags, their behaviors diverge so it is critical to be able to maintain voltage near nominal levels in order not to overload a generator when dealing with constant power loads.

Genset Load Acceptance Capabilities Based on Constant Impedance Loads

ISO 8528-5 sets requirements for load acceptance capabilities of engine driven generators. The size of the step load to be applied is based on engine BMEP. Larger steps are possible at the beginning of the load sequence, but the steps decrease in size as the engine approaches full load. Several performance classes are defined namely G1 (least stringent), G2, G3 (most stringent) and G4 (by agreement between manufacturer and customer). These performance classes specify the permissible voltage and frequency deviation limits allowed under each case for sudden load changes. The generator industry tests for compliance to load acceptance requirements using load banks, i.e. constant impedance type loads. Figure 1 below shows an example of a load acceptance test consisting of successive load increase/decrease of 0-25-0, 0-50-0, 0-75-0, 0-100-0 percent of rated power (these load steps are arbitrary and do not correspond to ISO 8528-5 load steps based on engine BMEP).

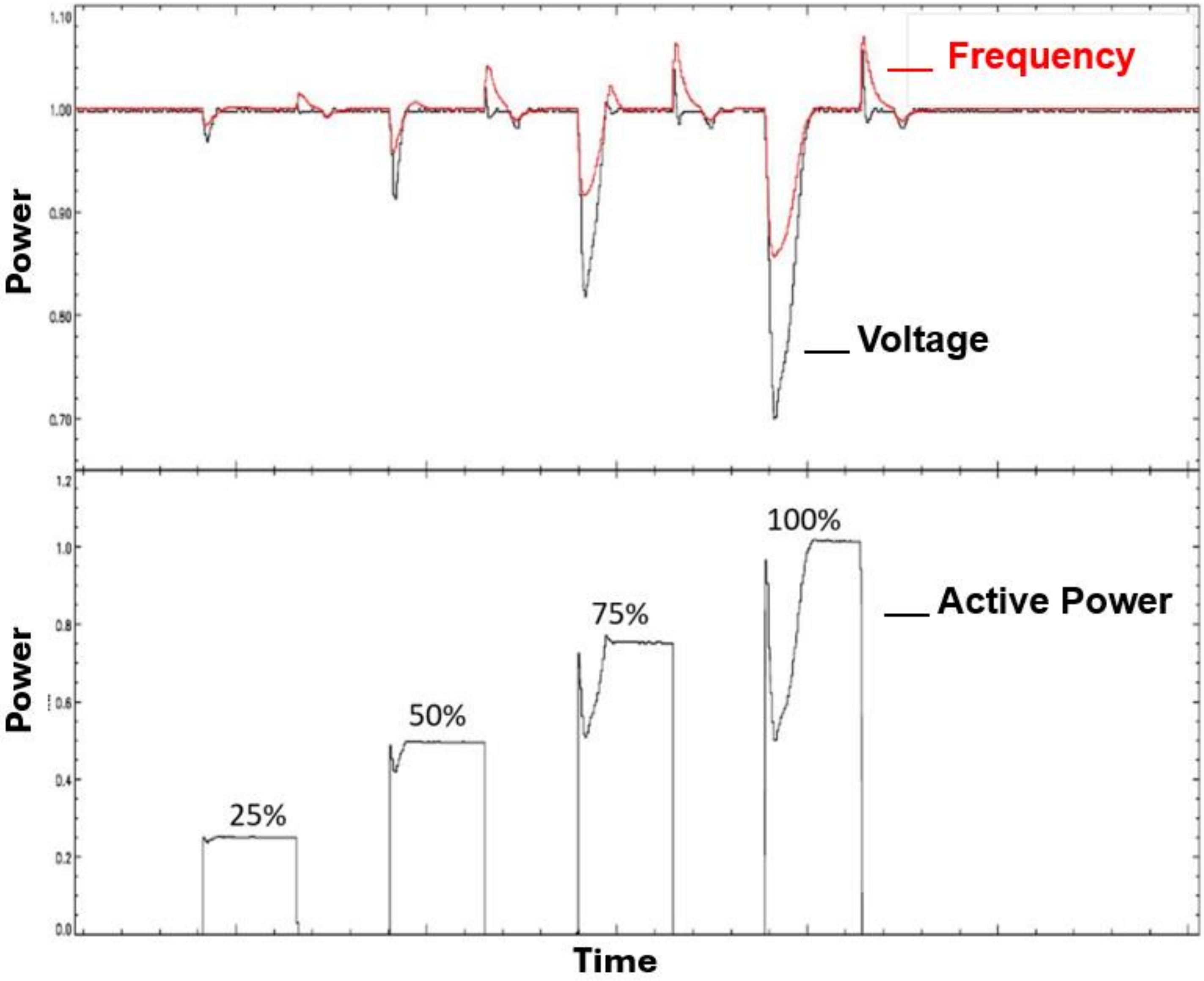

Figure 1: Genset response to sudden load change

On the upper half of the figure, the frequency deviations are shown in red, and the voltage deviations are shown in black. The bottom half of the figure shows the active power consumed by the constant impedance load (ohmic load, e.g., load bank) for each of the load step sizes. Examining the voltage and frequency plots, one can see that there is an inherited relationship between voltage and frequency. In this case, that relationship is 2 to 1 due to the volts per hertz compensation in the voltage regulator being set at 2 V/Hz (a 1% change in frequency reduces the operating voltage setpoint by 2% when frequency is below nominal value).

When the load is suddenly increased, there is a mismatch between the electrical power being consumed by the load and the mechanical power produced by the engine; hence, engine speed (electrical frequency) drops. If the change in load is modest, e.g., 25%, the impact on voltage and frequency is minor and the electrical load is immediately supplied (see bottom half of Figure 1). If the change in load is large, e.g. 100%, the frequency drop and voltage sag can be significant, and the power consumed by the load can only be sustained momentarily. As frequency decreases, so does voltage, and the power consumed by the ohmic load decreases as well. By lowering the electrical load, the mechanical load on the engine is reduced and the engine can recover and increase its output power to match the electrical load at full voltage and frequency.

Without the relief of the V/Hz compensation, the genset would not be able to accept a large block load and the engine would stall. If a large constant power load were to be switched onto the genset, it would yield a similar loading condition as not having V/Hz compensation as the power consumed by the load would be constant, regardless of voltage, and the engine would not see any load relief to be able to recover and it would likely stall.

Managing Constant Power Loads

The preceding discussion was centered on constant impedance block loads and the importance of the V/Hz compensation in the voltage regulator to allow the engine to accept large block loads. However, V/Hz compensation does not provide engine relief when working with constant power loads as lowering the voltage does not reduce the electrical power. Thus, to fully load a generator in the presence of constant power loads such loads would need to be added gradually. To illustrate this point, Figure 2 shows the walk-on of a constant impedance load being ramped from 0 to 100% in a 2 second period with 2 V/Hz setting.

On the main chart of Figure 2, the red trace corresponds to frequency and the blue trace to voltage. The graph on the lower right corner of the figure shows the power consumed by the load. As before, when the voltage sags the power consumed by the load is reduced and the engine recovers successfully walking on the load. In contrast, if a constant power load would be walked on at a rate of 50% per second the engine would stall as illustrated in Figure 3. However, if the load ramp rate would be slowed down from 2 to 8 seconds, the constant power load would be successfully walked on as shown in Figure 4.

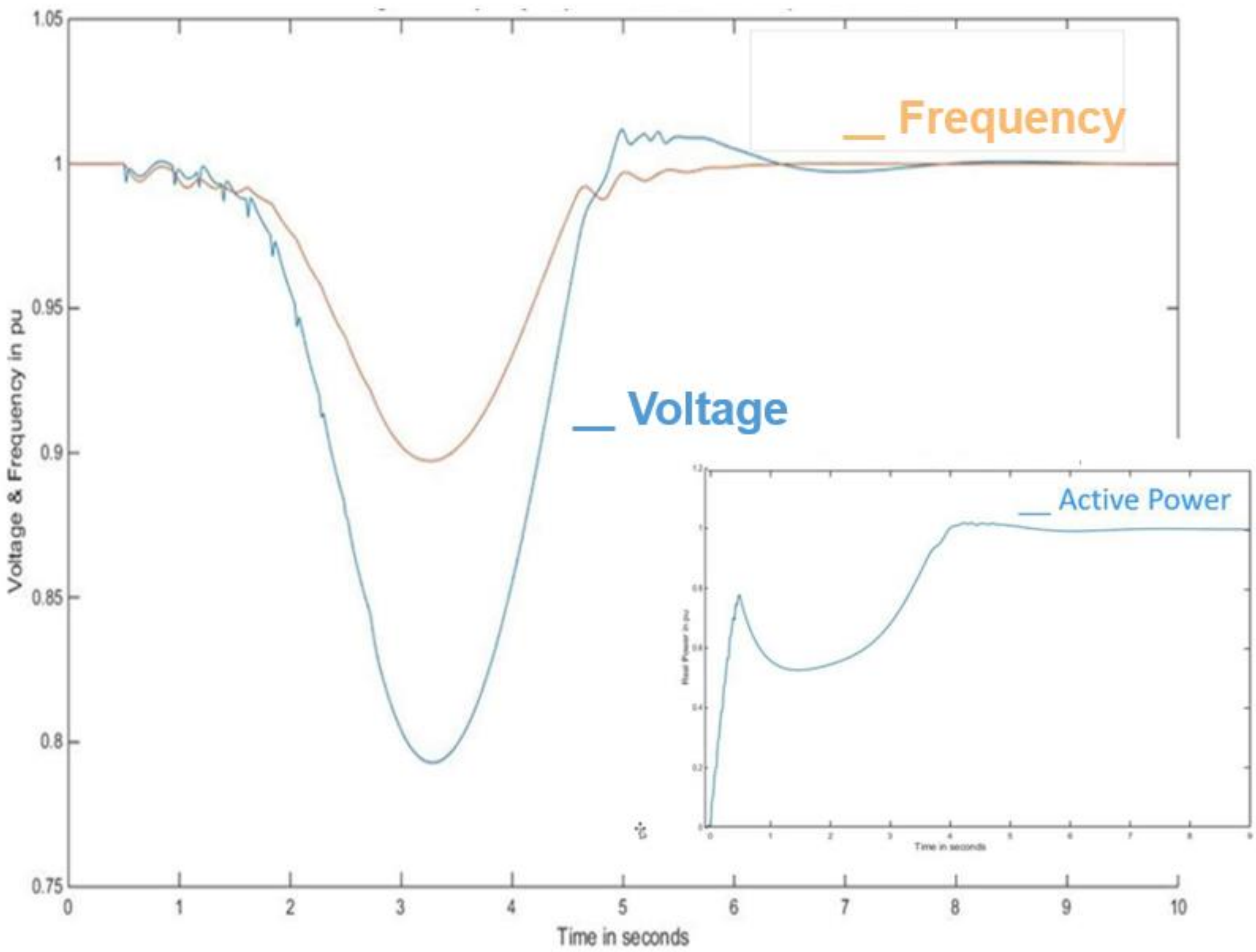

Figure 2: Load ramp from 0 to 100% over 2 seconds (constant impedance)

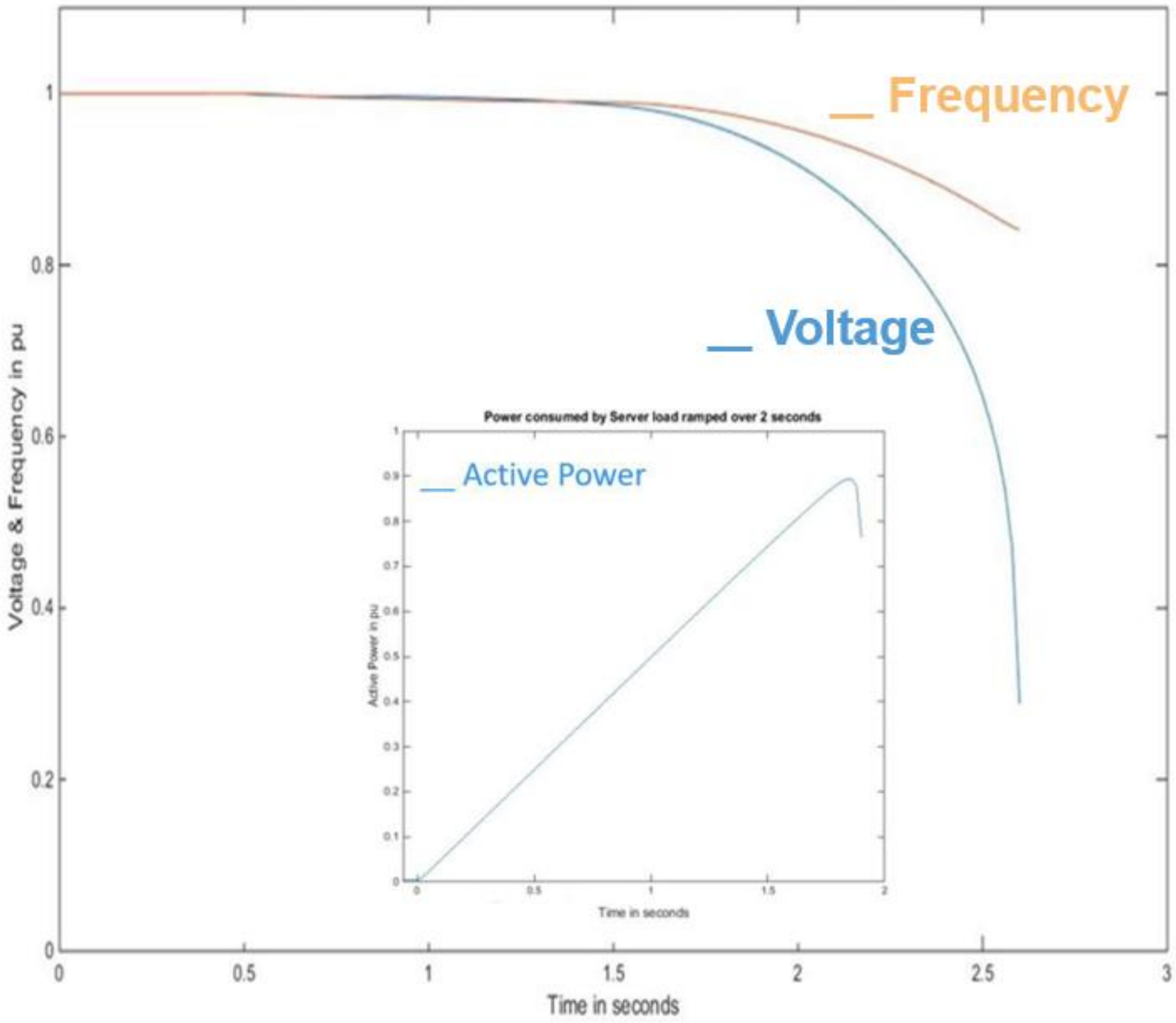

Figure 3: Load ramp from 0 to 100% over 2 seconds (constant power)

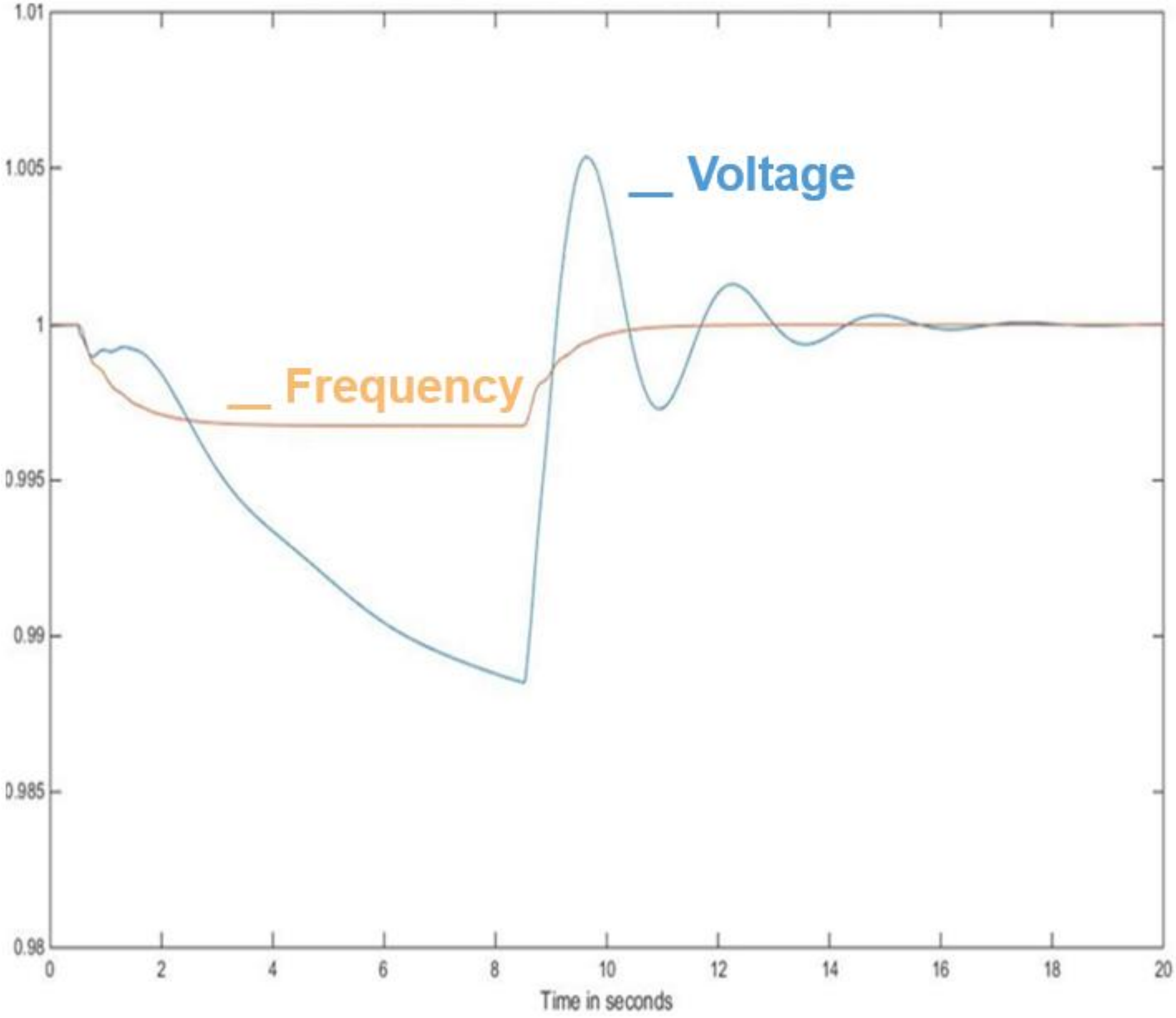

Figure 4: Load ramp from 0 to 100% over 8 seconds (constant power)

Constant Power Block Load Scenarios

At one data center there is the potential for a block load (constant power) on a diesel generator set rated at 2,750 kW 60 Hz. Two different generator choices are being considered: 1) 13.8 kV with 128 N-m-s^2 inertia and 2) 480 V with 67 N-m-s^2 inertia. The advantage of the HV generator is that inertia enhances fault ride-thorough capabilities and reduces frequency dips to sudden load increases; in addition, the reactive capability of the HV generator is significantly higher which improves voltage support.

The analysis for transient response is conducted via computer simulation. Results for the HV units are discussed first. The specific case under consideration is a step change in load (constant power type) from 0 to 50% with a power factor (PF) of 0.9. Figure 5 shows the predicted voltage sags corresponding to volts per hertz settings of 0, 1, 2, and 3 V/Hz, while Figure 6 shows the frequency dips.

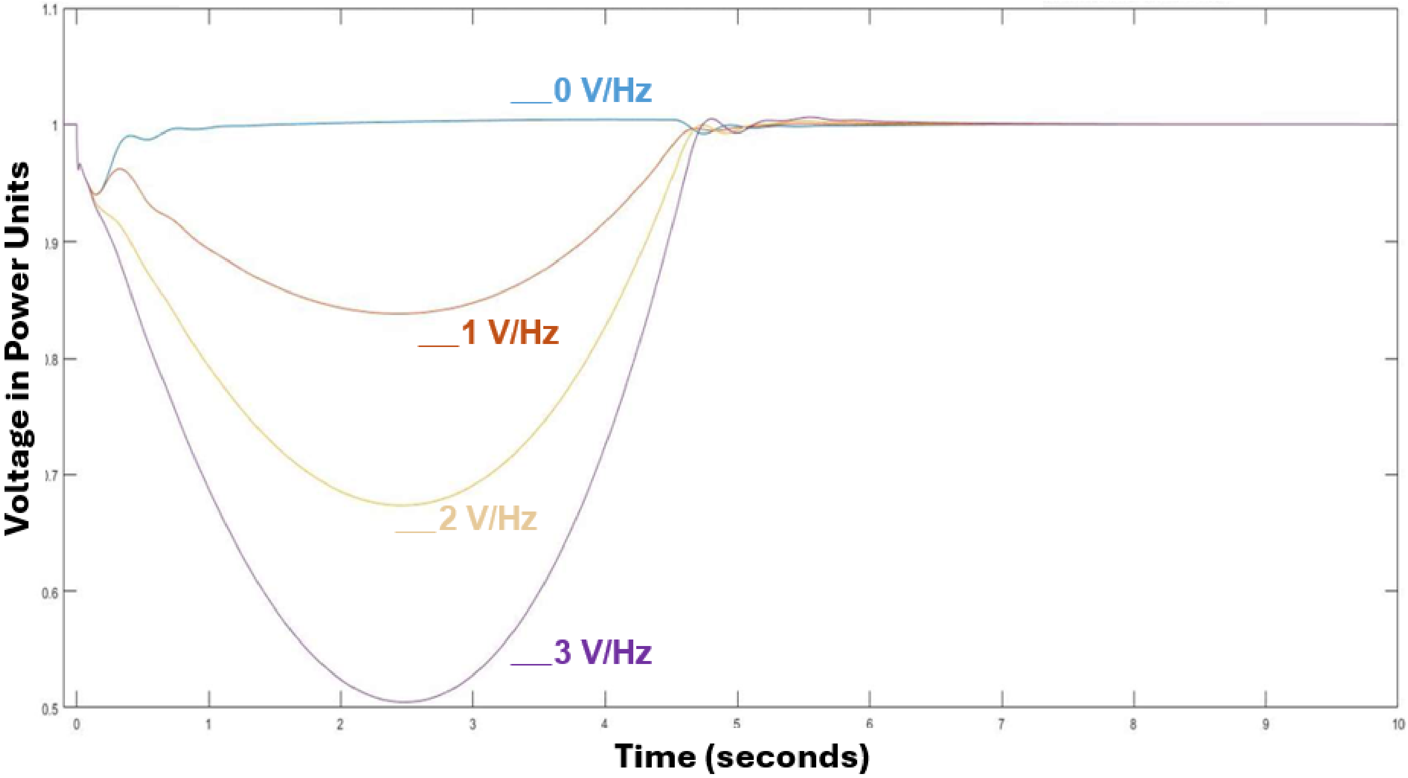

Figure 5: Voltage transient on HV generator for 50% block load (constant power)

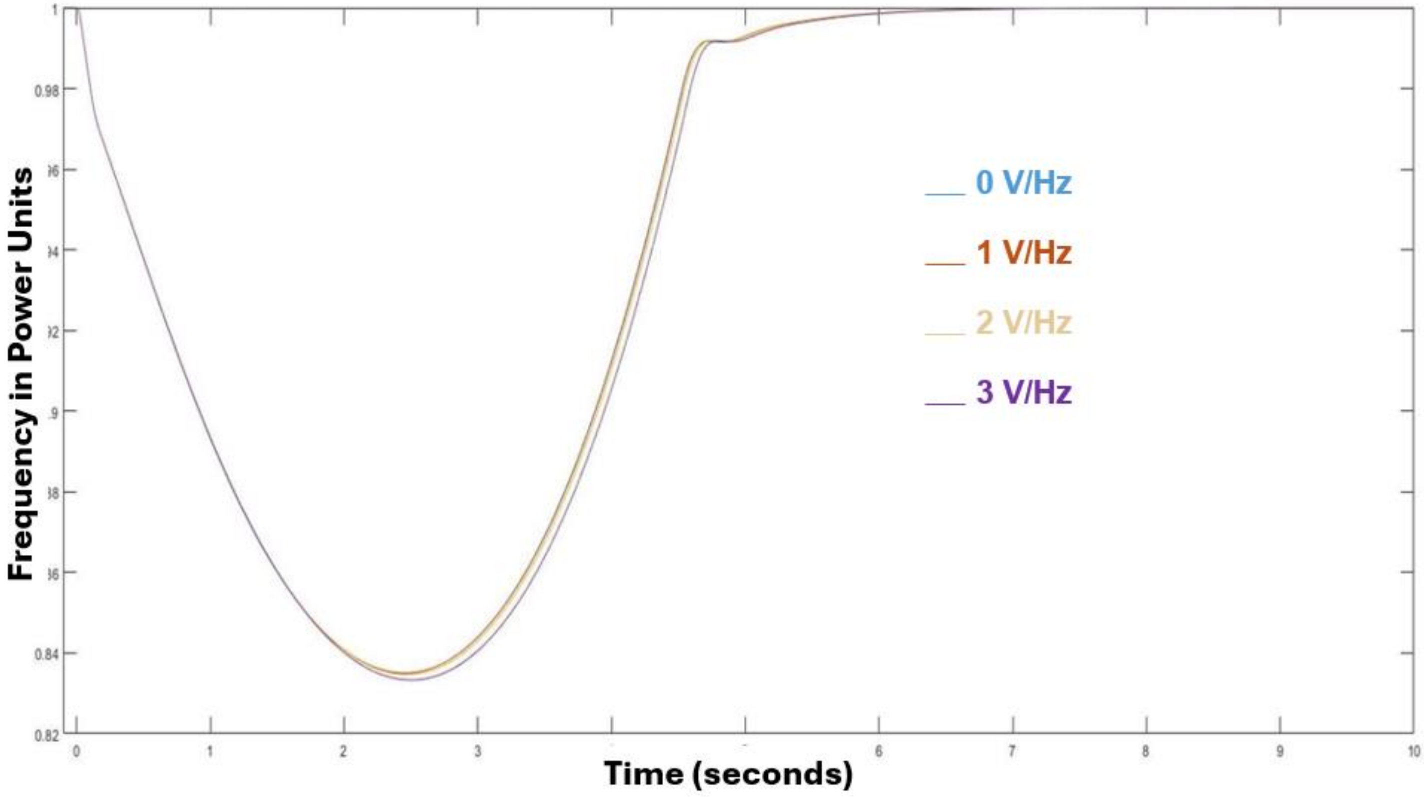

Figure 6: Frequency transient on HV generator for 50% block load (constant power)

From Figure 5, it is seen that the V/Hz setting has a profound impact on the voltage sags with the highest setting at 3V/Hz forcing the voltage down to near the minimum allowable setpoint of 50% (lowest limit for the voltage regulator used). In contrast, the frequency transient (see Figure 6) is almost unaffected by the V/Hz setting. This is due to the constant power load consuming the same amount of power at lower voltages as well as at higher voltages. Hence, the mechanical load on the engine is about the same, regardless of the V/Hz setting, and thus the speed/frequency transients are very similar. It is worth noting that for the voltage profile at 0 V/Hz (blue trace on Figure 5) the initial voltage sag, although small, is not associated with frequency dip but due to the generator having to raise excitation from no load to 50% load and the response is dominated by the exciter time constant of 0.2 seconds on the HV unit.

Results for the LV generator are presented next. For this case, the step size of the constant power load was reduced to 45% as a 50% step caused the engine to stall. Figure 7 shows the voltage transient for the various V/Hz settings. The impact of V/Hz setting is even more pronounced than for the HV case, and for the highest setting at 3 V/Hz the voltage sags up to the minimum allowable setpoint of 50% (lowest limit for the voltage regulator used). This difference is attributed to the frame of LV generator being significantly smaller than the HV generator.

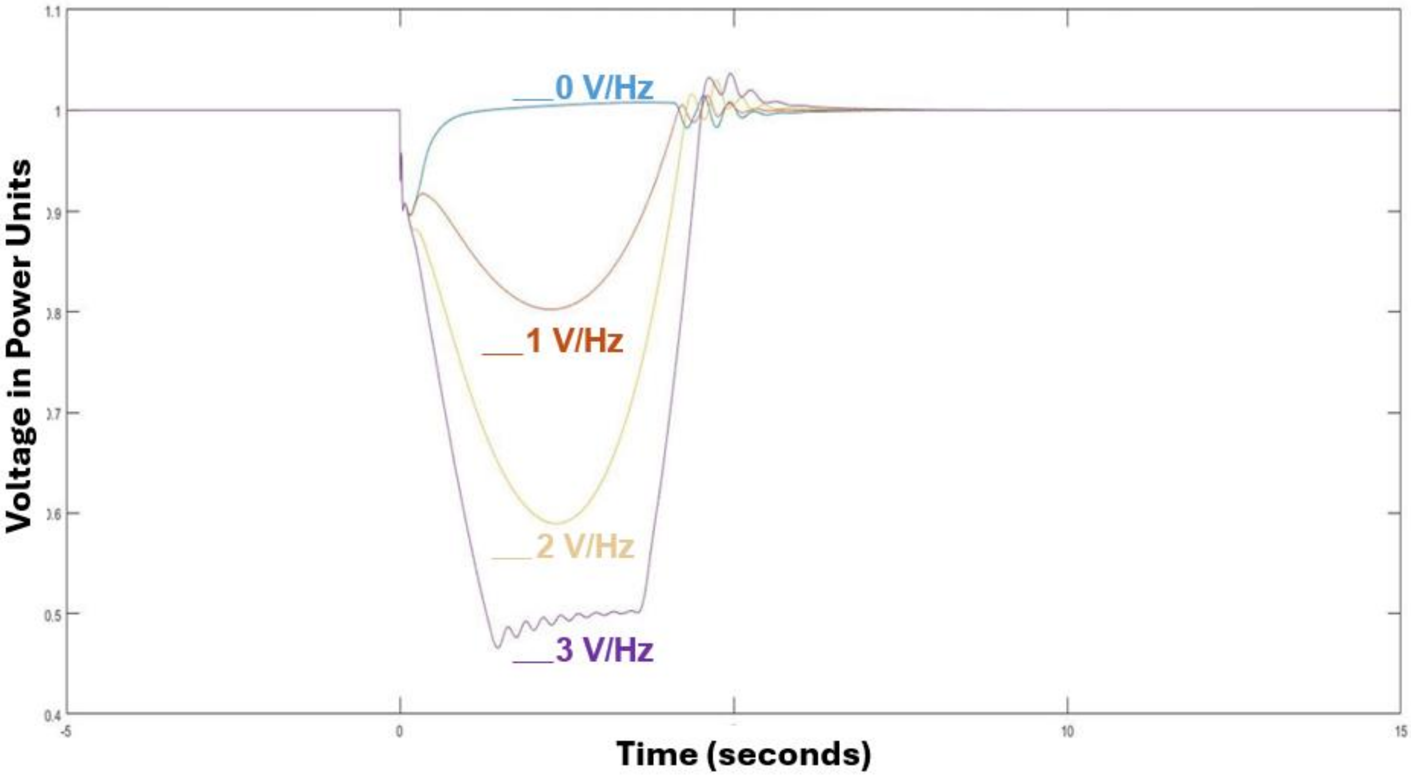

Figure 7: Voltage transient on LV generator for 45% block load (constant power)

As in the HV case, the frequency transients (see Figure 8) are almost unaffected by the V/Hz setting except for slightly larger sags and longer recovery time for higher V/Hz settings, but still the differences are minor.

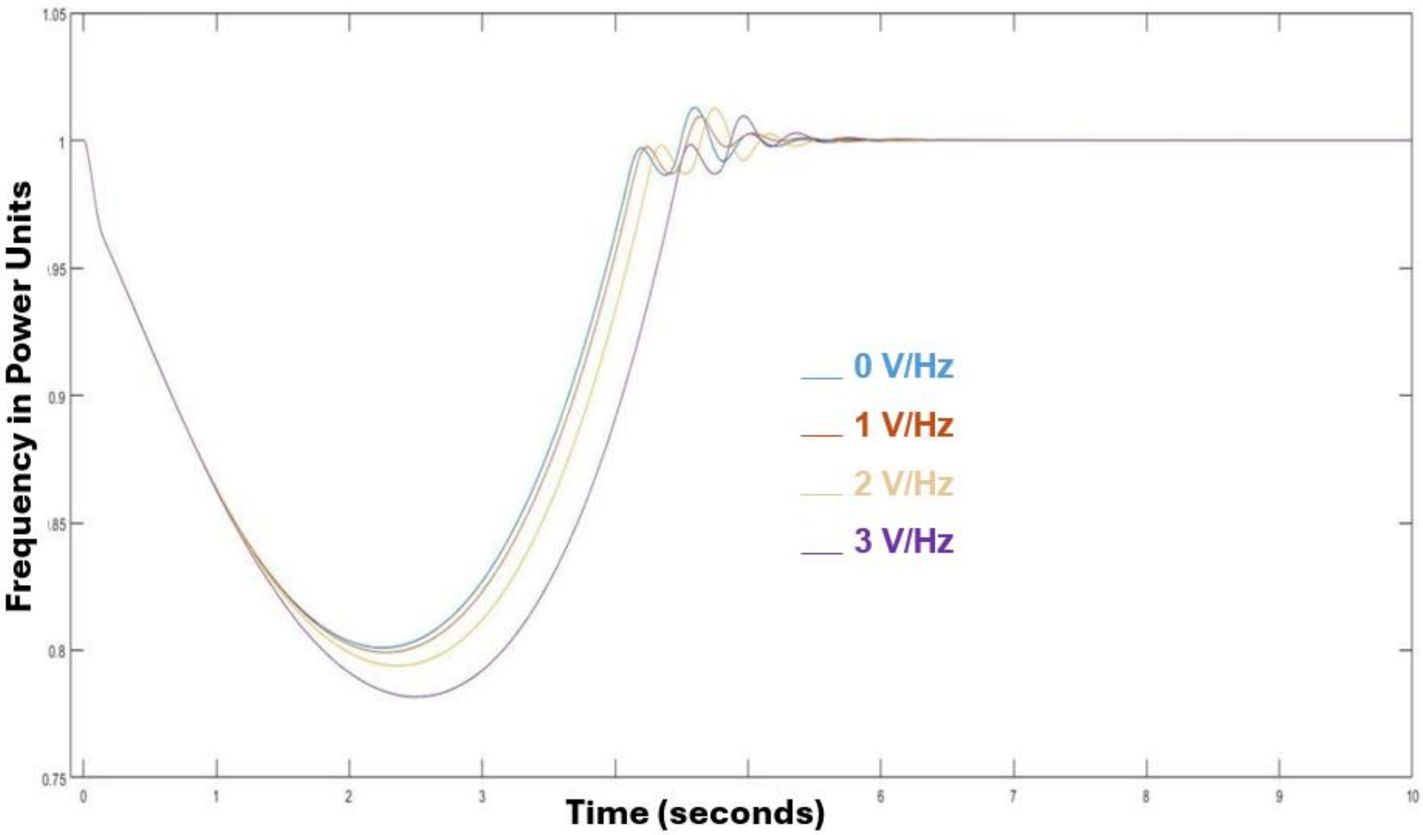

Figure 8: Frequency transient on LV generator for 45% block load (constant power)

As mentioned in the load types description, some UPS systems exhibit a hybrid behavior where for a voltage range near nominal voltage, the load is constant power but when the voltage drops below a set value, they enter a current-limiting regime behaving akin to a constant current load. To investigate that behavior, and how it would aid in the recovery of the engine, the following test case is used on the LV generator.

The constant power step size is increased to 50% (from 45% in previous case), but at 90% voltage the constant power load transitions into constant current mode. Thus, the power consumed by the load is reduced linearly as the voltage falls below 90%. The voltage regulator is set to have a 0 V/Hz for slope 1 and 2 V/Hz for slope 2 (see Figure 9).

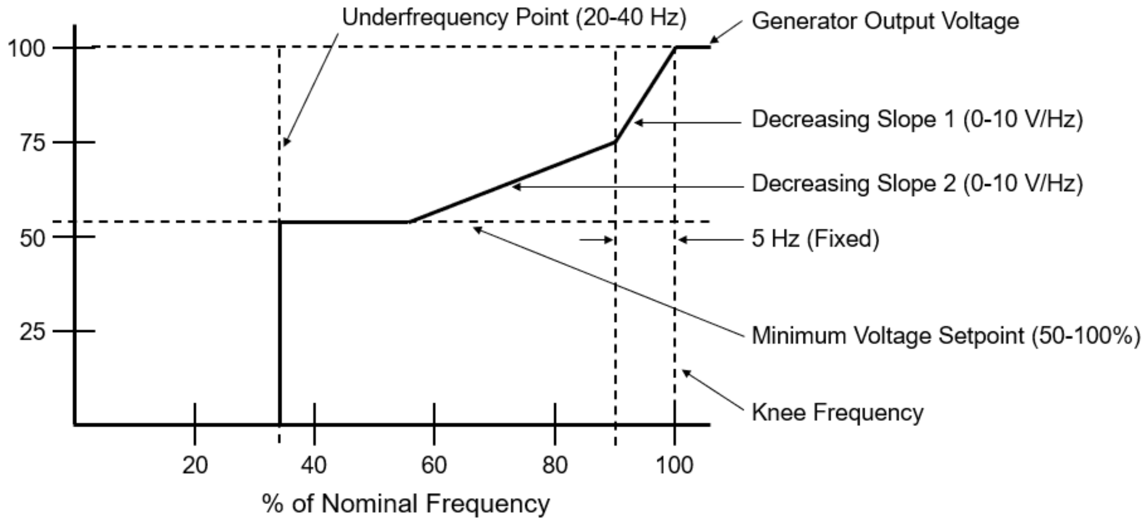

Figure 9: Voltage regulator V/Hz curve

Figure 10 shows the apparent (blue), active (red), and reactive (yellow) power consumed by the UPS load. Note that at about one second after the load is applied the power consumption begins to decrease as the voltage falls below 90%. This reduction in power allows the LV unit to recover and accept the 50% constant power load if the current is kept constant at voltages below 90%. The voltage and frequency transients are shown in Figure 11. As it can be seen from the figures, the use of current limiters on constant power loads may extend the load acceptance of constant power loads to larger step sizes, but not to the extent of constant impedance type loads.

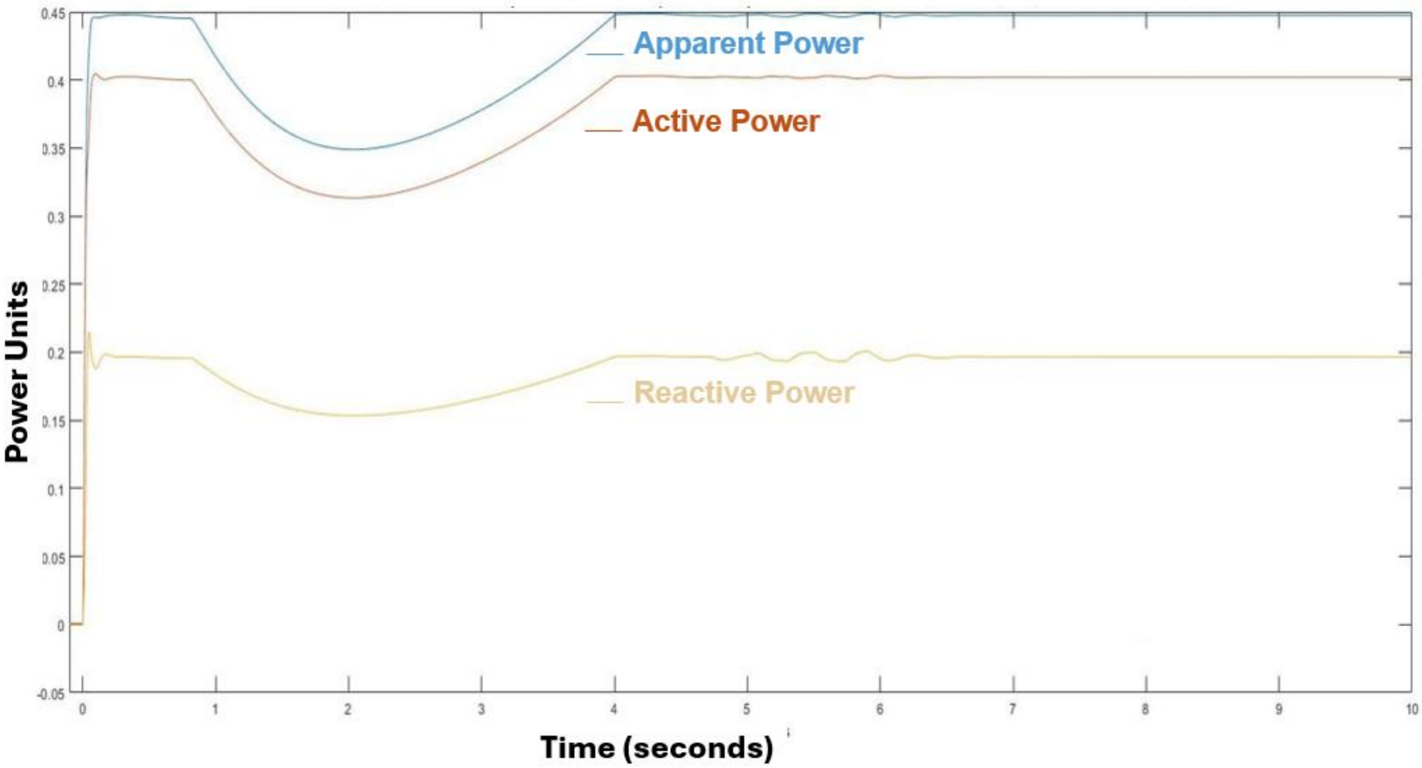

Figure 10: Power consumption for 50% step on constant power load step with current limiter

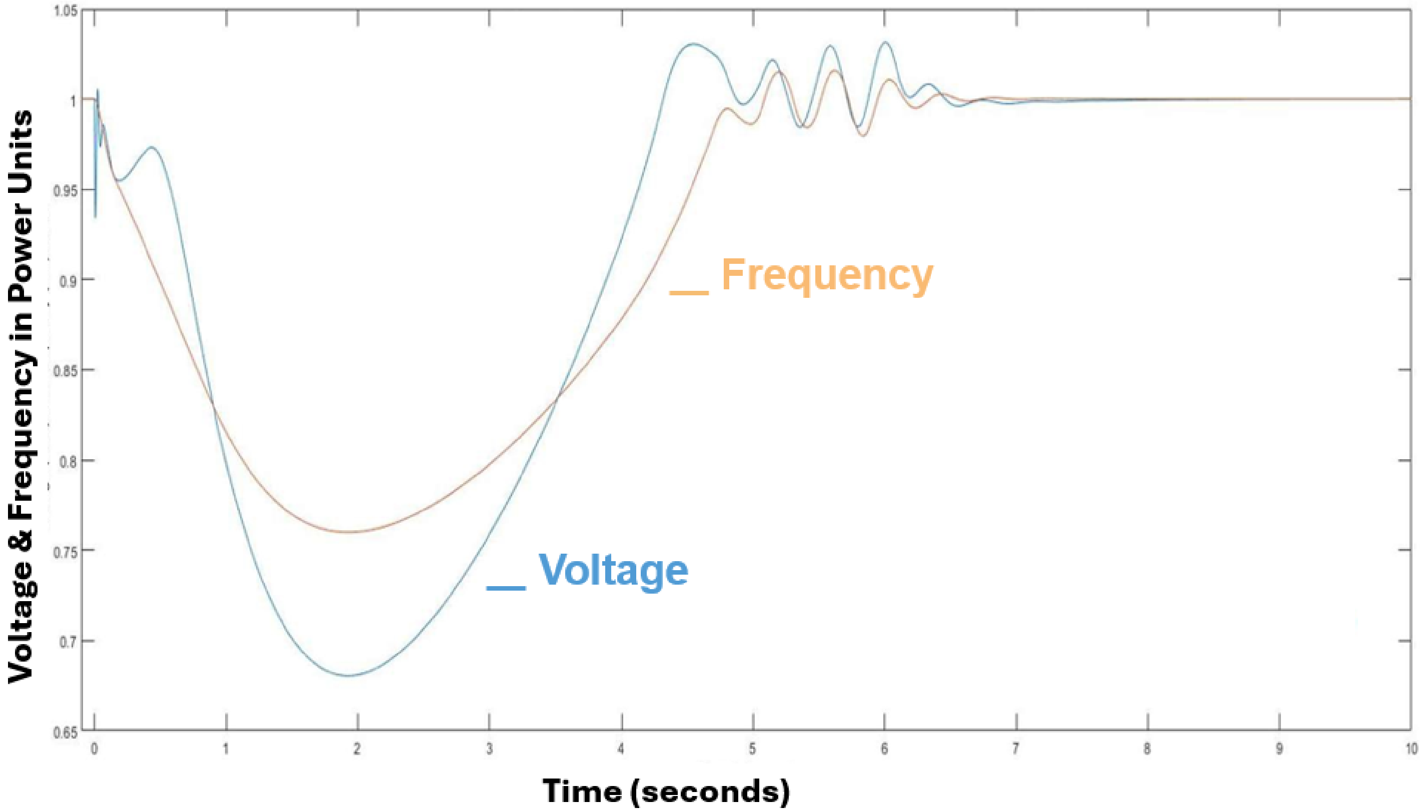

Figure11: Voltage (blue) and Frequency (red) transients for 50% constant power load change

Influence of power factor on constant power load acceptance capabilities

The preceding cases were all run at 0.9 lagging PF. In this section, the test case scenario for the HV unit is revisited but the power factor is changed to 0.8 (lag), 1.0, and 0.95 (lead). A true constant power load is used (no current limiter), the step size is 50% rated power, and the V/Hz setting is set to zero. Figure 12 shows the voltage response to the 50% step on constant power load for power factors from 0.8 lagging through 0.95 leading. While there are minor differences in the response, from a practical standpoint the differences are inconsequential. For the leading power factor case, there is a momentary voltage swell of less than 5 percent attributed to switching on the capacitive element of the load. As for PF effect on frequency, see Figure 13, as expected PF only changes the reactive load, having no impact on engine load (engine responds to kW load). The reactive load only drives changes in excitation levels.

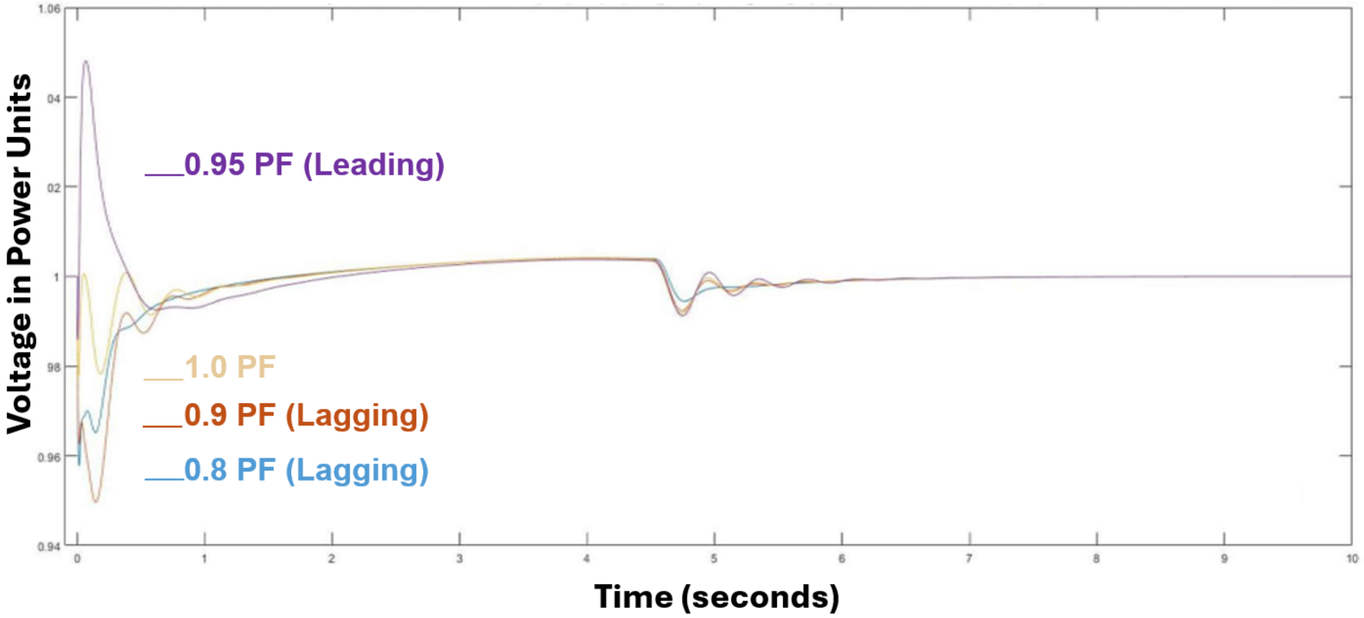

Figure 12: Voltage transients for 50% constant power load change at various PF

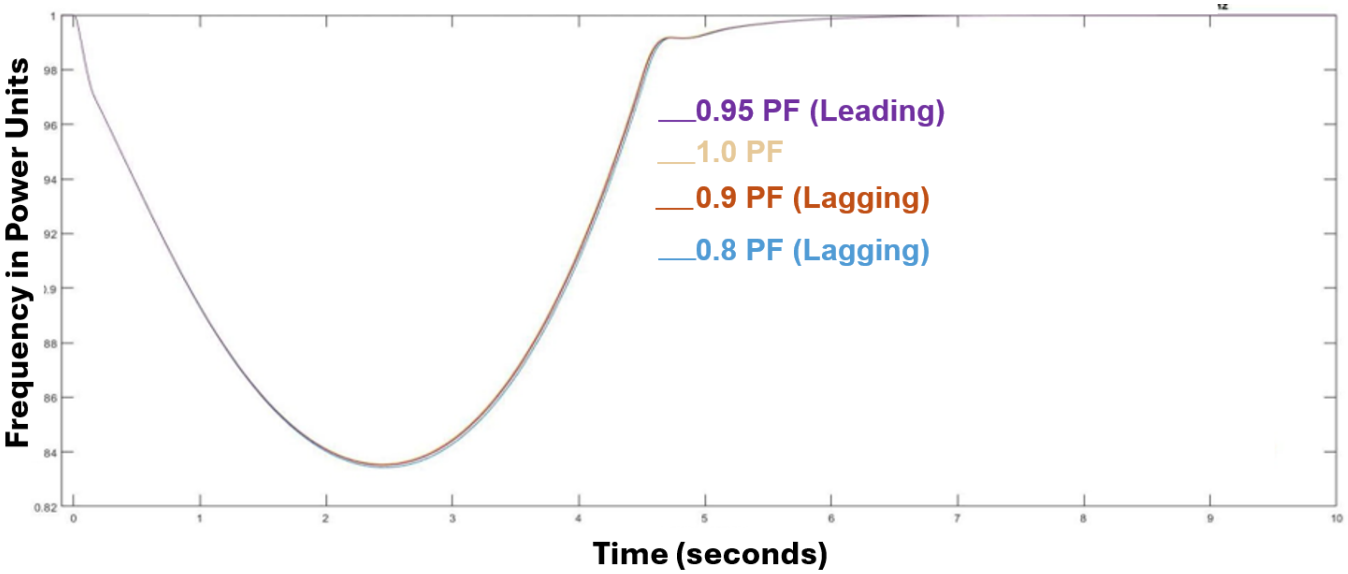

Figure 13: Frequency transients for 50% constant power load change at various PF

Summary and Conclusions

Three different types of loads are discussed in this document: 1) constant impedance, 2) constant current, and 3) constant power. While constant impedance loads are the most common, constant power loads are most prevalent in data centers. There are a number of standards that set requirements for the performance of engine-drive generators with ISO 8528 being the most relevant. The requirements are typically based on acceptance of constant impedance loads (load bank tests). However, the capability of a generator to supply a constant impedance load may not be indicative of its ability to accept a different type of load.

For constant impedance type loads, the results shown in Figure 1 depict how important V/Hz compensation is for an engine-driven generator to handle large block loads. The V/Hz compensation ties operating voltage to frequency. If frequency is nominal, so is the voltage. If a sudden load is applied, the engine slows down until it can build the necessary mechanical power to match the load. As the engine slows down, frequency drops and the operating voltage is reduced. At lower voltages, the initial electrical load is reduced, the engine sees lower braking torque from the generator, is able to build power and increase speed back up to nominal frequency and voltage fully supplying the load. For constant impedance loads, it is always recommended to use V/Hz.

For constant power type loads, the V/Hz compensation does not have the intended effect of lowering the power consumed by the load as in the constant impedance case. If a constant power load is applied, the engine slows down resulting in a lower operating voltage and higher current as the power remains constant. Since the engine does not see any reduction in braking torque, it has a harder time to recover in comparison to the constant impedance load case. Since the load on the engine would be about the same for any V/Hz setting, there is no real benefit in using V/Hz compensation when supplying constant power loads. In fact, V/Hz compensation may be a hindrance since reducing voltage leads to higher currents and more losses.

For applications that would use a mixture of load types, V/Hz compensation would still be recommended as it would improve engine recovery. The case of a UPS system exhibiting a hybrid behavior of constant power and constant current was presented, where V/Hz compensation enabled the engine-generator to handle a larger load step.

Another important observation is that near nominal voltage, all types of loads consume the same amount of power. So, if the loads were applied slowly with minimal impact on voltage the transient response would be indistinguishable regardless of load type. This was demonstrated by the case where a constant power load is ramped from 0 to 100% power. If the ramp is fast (2 seconds in Figure 3), the engine stalls. If the ramp is slow (8 seconds in Figure 4), the load is successfully transferred. As a rule of thumb, if a constant power load is ramped at a rate slower than the engine's ability to build up power, the impact on voltage and frequency deviations would be minimal and the load would be successfully walked on. Roughly, if an engine-drive generator can handle a 100% block load and fully restore voltage and frequency within X seconds, it would be able to accept a constant power load if power is ramped at a rate of <100/X % per sec.

The impact of load power factor was also examined, and its effect was found to be negligible.

Note: the preceding analysis was based on simulations results using computer models that are approximations of actual systems. Model parameters were obtained from a combination of component datasheets, measured values, calculated values from available data, and others (such as controller gains) were adjusted to match experimental results as close as possible. Simulation results are representative of actual system behavior, but they are not a guaranteed prediction of actual performance.

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